

RÉPUBLIQUE ALGÉRIENNE DÉMOCRATIQUE ET POPULAIRE
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA
RECHERCHE SCIENTIFIQUE

UNIVERSITÉ FERHAT ABBAS - SÉTIF



FACULTÉ DE TECHNOLOGIE
THÈSE

Présentée au Département d'Électrotechnique

Pour l'obtention du diplôme de

DOCTORAT

Filière : Electrotechnique / Option : Automatique et Systèmes

Par **MESSASMA Chaouki**

THÈME

Contrôle avancé de la fréquence des réseaux avec une forte pénétration des systèmes à énergie renouvelable

Jury :

Président	SID Mohamed Amine	Professeur	Univ. Sétif 1
Directeur de thèse	CHOUABA Seif Eddine	Professeur	Univ. Sétif 1
Co-Directeur	SARI Bilal	Professeur	Univ. Sétif 1
Examineur	HASSAINE Said	Professeur	Univ. Tiaret
Examineur	DAILI Yacine	M.C.A	Univ. Sétif 1
Examineur	BOURAHALA Fayçal	M.C.A	Univ. Skikda
Invité	BARAKAT Abdallah	Maitre de conférences	Univ. Nantes (France)

PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
UNIVERSITY FERHAT ABBAS -SÉTIF-



Faculty of Technology

Submitted in fulfillment of the requirements for :

Ph.D degree

Department of Electrical Engineering / Option : **Automatic and Systems**

Presented by **MESSASMA Chaouki**

Theme

**Advanced grid frequency control with high penetration
of renewable energy systems**

Jury :

President	SID Mohamed Amine	Professor	Univ. Setif1
Director	CHOUABA Seif Eddine	Professor	Univ. Setif1
Co-Director	SARI Bilal	Professor	Univ. Setif1
Examiner	HASSAINE Said	Professor	Univ. Tiaret
Examiner	DAILI Yacine	M.C.A	Univ. Setif1
Examiner	BOURAHALA Fayçal	M.C.A	Univ. Skikda
invited	BARAKAT Abdallah	Associate Prof.	Univ. Nantes (France)

Acknowledgements

In the name of Allah, the Most Gracious, the Most Merciful.

I begin by expressing my deepest gratitude to Allah, the Almighty, who bestowed upon me the faith, courage, and patience necessary to navigate the challenges and triumphs of this PhD thesis journey.

I sincerely thank Professor SID Mohamed Amine, president of the jury ; Professor HAS-SAINE Said ; Dr. DAILI Yacine ; and Dr. BOURAHALA Fayçal for their valuable time, remarks, and constructive feedback on this work.

I express my heartfelt appreciation to my thesis director, Professor CHOUABA Seif Ed-dine, and co-director, Professor SARI Bilal, whose unwavering guidance, mentorship, and support have illuminated my path throughout this work. Their wisdom and encouragement have been a true blessing.

I am deeply indebted to Dr. Abdalah Barakat from Nante University, who joined me as a co-supervisor on this sacred journey. His dedicated guidance, approachability, compassionate listening, and steadfast patience have been instrumental in shaping this work.

To my beloved family, my parents, my wife, my devoted sons, supportive brothers, and caring sisters—and all my cherished friends, I express my deepest gratitude for your constant presence and unwavering faith in my journey of knowledge. Your steadfast support has been both my inspiration and my strength.

I wish to acknowledge and express gratitude to all individuals, regardless of their roles, who have contributed to the development of this thesis. Your assistance, whether through insightful discussions, constructive feedback, or acts of encouragement, has significantly enriched the outcome of this research.

Completing this Ph.D. thesis has been a transformative journey, and the support I have received from all quarters has made this achievement possible. I am truly thankful for the collective impact of each person who has contributed to this endeavour.

Dedication

I dedicate this work to my parents:

*May they find here the testimony of my deep gratitude and
acknowledgment*

For my incredible wife and sons:

*Your unwavering encouragement and endless patience have been
my greatest blessings. Thank you for being the heart of my world,
even during times when I've felt distant and overwhelmed*

*To my brothers and my sisters, my grandparents and my family
who give love and liveliness.*

*To all my friends, both near and far, who've offered their direct
and indirect support, shared in the emotional moments of this
journey, and provided warm encouragement along the way, I'm
profoundly grateful for your presence and unwavering backing*

Thanks!

MESSASMA Chaouki

ملخص

تقدم هذه الدراسة استراتيجيات متقدمة للتحكم في التردد بهدف تعزيز استقرار الشبكات الكهربائية ذات الاختراق العالي لمصادر الطاقة المتجددة (RES)، وخاصة محطات الطاقة الشمسية الكهروضوئية (PV) وتوربينات الرياح. نظراً لطبيعتها المتغيرة، تفرض هذه المصادر تحديات كبيرة على استقرار الشبكة. تقدم استراتيجيات جديدة للتحكم في التردد، تمتاز بالبساطة والكفاءة والدقة. وعلى عكس الأساليب التقليدية، تعمل هذه الاستراتيجيات بشكل مستقل دون الحاجة إلى معدات مساندة مثل البطاريات، مما يقلل التكاليف والتعقيد مع ضمان أداء موثوق للشبكة. تم تصميمها في البداية للشبكات المتكاملة مع أنظمة الطاقة الشمسية، حيث يتم التحقق من فعاليتها باستخدام وحدات التحكم التناسبية-التكاملية (PI). كما يتم دمج آلية تخفيض الحمل مع القصور الذاتي الحقيقي المستمد من المولدات التزامنية (SGs) المعطلة لتكوين قصور ذاتي هجين (HI)، مما يعزز استقرار الشبكة. لتحسين الأداء، يتم دمج تقنيات تحكم متقدمة تشمل المنطق الضبابي والخوارزميات الجينية، مما يتيح التكيف الديناميكي مع تغيرات إنتاج الطاقة الشمسية، وبالتالي تحسين استقرار الشبكة وتمكين زيادة اختراق مصادر الطاقة المتجددة. بعد ذلك، يتم توسيع هذه الاستراتيجيات لتشمل تكامل طاقة الرياح، من خلال تطوير نهج تحكم قوي للحفاظ على استقرار التردد في ظل تقلبات سرعة الرياح. كما يتم تحسين استراتيجيات تخفيض حمل توربينات الرياح (WT) باستخدام تقنيات الذكاء الاصطناعي وأساليب التحكم المتقدمة، مما يؤدي إلى تطوير حل شامل لإدارة التردد قابل للتكيف مع سيناريوهات الطاقة المتجددة المختلفة.

أخيراً، تبحث الدراسة في أداء الأنظمة الهجينة التي تجمع بين الطاقة الشمسية وطاقة الرياح، بالإضافة إلى استراتيجيات فك الارتباط بينهما باستخدام آليات تخفيض الحمل. يتم تعزيز هذا النظام باستخدام تقنيات تحكم قوية لضمان الاستقرار والموثوقية. تخضع جميع الاستراتيجيات المقترحة لاختبارات صارمة في بيئة MATLAB Simulink، مع محاكاة في كل من شبكات الحافلة اللانهائية والشبكات المعزولة، مما يضمن متانتها وموثوقيتها وقابليتها للتطبيق في شبكات الطاقة الفعلية. **الكلمات المفتاحية:** الطاقة الشمسية الكهروضوئية (PV)، توربينات الرياح (WT)، تخفيض الحمل، التحكم الأولي في التردد (PFC)، القصور الذاتي الافتراضي (VI)، القصور الذاتي الحقيقي (RI)، القصور الذاتي الهجين (HI)، المولد التزامني (SG)، الشبكات اللانهائية والمعزولة.

Abstract

This study develops advanced frequency control strategies to enhance the stability of electrical grids with high penetration of renewable energy sources (RES), specifically photovoltaic (PV) solar plants and wind turbines. Due to their intermittent nature, these RES introduce significant challenges to grid stability. A novel frequency control strategy is introduced, characterized by simplicity, efficiency, and precision. Unlike conventional methods, it operates independently of auxiliary equipment such as batteries, reducing costs and complexity while ensuring reliable grid performance. Initially designed for PV-integrated grids, its effectiveness is validated using proportional-integral (PI) controllers. A deloading mechanism is combined with real inertia from decommissioned synchronous generators (SGs) to form hybrid inertia (HI), enhancing overall stability. To further improve performance, advanced control techniques, including fuzzy logic and genetic algorithms, are incorporated. These AI-driven enhancements enable dynamic adaptation to PV variability, improving grid stability and facilitating higher RES penetration. The study then extends this strategy to wind energy integration, developing a robust control approach to maintain frequency stability under fluctuating wind conditions. A wind turbine (WT) deloading strategy is further refined through AI-based techniques and advanced control methodologies, creating a comprehensive frequency management solution adaptable to diverse renewable energy scenarios.

Finally, the research investigates hybrid PV-wind systems and their decoupling strategies with deloading mechanisms. Robust control techniques are employed to ensure stability and reliability in these multi-source configurations. All proposed strategies undergo rigorous testing and validation in MATLAB Simulink under infinite bus and isolated network conditions, demonstrating their robustness, reliability, and practical feasibility for real-world power grids.

Keywords: photovoltaic (PV), wind turbine (WT), deloading, primary frequency control (PFC), virtual inertia (VI), real inertia (RI), hybrid inertia (HI), synchronous generator (SG), infinite and isolated grid.

Résumé

Cette étude développe des stratégies avancées de contrôle de fréquence afin d'améliorer la stabilité des réseaux électriques à forte pénétration des sources d'énergie renouvelable (RES), notamment les centrales solaires photovoltaïques (PV) et les éoliennes. En raison de leur nature intermittente, ces sources posent des défis importants pour la stabilité du réseau. Une nouvelle stratégie de contrôle de fréquence est proposée, caractérisée par sa simplicité, son efficacité et sa précision. Contrairement aux approches conventionnelles, elle fonctionne indépendamment des équipements auxiliaires tels que les batteries, réduisant ainsi les coûts et la complexité tout en assurant des performances fiables du réseau. Initialement conçue pour les réseaux intégrant le photovoltaïque, son efficacité est validée à l'aide de régulateurs proportionnel-intégral (PI). Un mécanisme de réduction de charge est combiné à l'inertie réelle provenant des générateurs synchrones (SG) mis hors service pour former une inertie hybride (HI), renforçant ainsi la stabilité globale du réseau. Afin d'améliorer encore les performances, des techniques de contrôle avancées, notamment la logique floue et les algorithmes génétiques, sont intégrées. Ces améliorations basées sur l'intelligence artificielle permettent une adaptation dynamique à la variabilité de la production photovoltaïque, renforçant ainsi la stabilité du réseau et facilitant une plus grande pénétration des énergies renouvelables. L'étude étend ensuite cette stratégie à l'intégration de l'énergie éolienne, en développant une approche de contrôle robuste pour maintenir la stabilité de fréquence face aux variations de vitesse du vent. Une stratégie de réduction de charge pour les éoliennes (WT) est ensuite optimisée à l'aide de techniques d'intelligence artificielle et de méthodes de contrôle avancées, aboutissant à une solution globale de gestion de fréquence adaptée à divers scénarios d'énergie renouvelable.

Enfin, la recherche examine la performance des systèmes hybrides PV-éolien et leurs stratégies de découplage avec des mécanismes de réduction de charge. Ces configurations sont renforcées par des techniques de contrôle robustes afin de garantir leur stabilité et leur fiabilité. Toutes les stratégies proposées font l'objet de tests rigoureux et de validations dans MATLAB Simulink, avec des simulations réalisées dans des conditions de réseau infini et de réseau isolé, garantissant leur robustesse, leur fiabilité et leur applicabilité aux réseaux électriques réels.

Mots clés : photovoltaïque (PV), éolienne (WT), diminution de la puissance (deloading), contrôle primaire de fréquence (PFC), inertie virtuelle (VI), inertie réelle (RI), inertie hybride (HI), générateur synchrone (SG), réseau infini et isolé.

JOURNAL PAPERS:

1. MESSASMA, Chaouki, BARAKAT, Abdallah, CHOUABA, Seif eddine, and SARI, Bilal. ***PV system frequency regulation employing a new power reserve control approach and a hybrid inertial response***. Electric Power Systems Research, 2023, vol. 223, p. 109556, <https://doi.org/10.1016/j.epsr.2023.109556>.
2. MESSASMA, Chaouki, CHOUABA, Seif eddine, BARAKAT, Abdallah, and SARI, Bilal. ***Innovative real-time deloading approach to wind systems with applications in primary frequency control***. Electric Power Systems Research, 2024, Vol. 237, p. 110983, <https://doi.org/10.1016/j.epsr.2024.110983>.
3. MESSASMA, Chaouki, CHOUABA, Seif eddine, SARI, Bilal, BARAKAT, Abdallah, and LUIS C. Félix-Herrán. ***Improving primary frequency response in photovoltaic systems using hybrid inertia and intelligent control techniques***. Journal of Electrical Engineering, 2024, Vol. 75.
4. MESSASMA, Chaouki, CHOUABA, Seif eddine, SARI, Bilal, and BARAKAT, Abdallah. ***Improving real-time wind turbine deloading using advanced control strategy***. Electr Eng (2024). <https://doi.org/10.1007/s00202-024-02883-x>.

INTERNATIONAL CONFERENCES:

1. MESSASMA, Chaouki, CHOUABA, Seif Eddine, and SARI, Bilal. ***The primary frequency control techniques for grid-connected PV systems: A review***. In the 5th International Conference on Artificial Intelligence in Renewable Energetic Systems IC-AIRES2021, held on November 22-24, 2021 in ESC-Koléa-Tipasa, Algeria.
2. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal, and BARAKAT, Abdallah. ***Modeling and Simulation of 10 MW PV array with ARV MPPT based on ANN model***. In : 2022 19th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, 2022. p. 165-170.
3. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal, and BARAKAT, Abdallah. ***Power reserve control (PRC) of PV systems techniques overview***. In : 2022 19th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, 2022. p. 1466-1470.
4. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal, and BARAKAT, Abdallah. ***Power reserve generation in 100 KW PV central connected to***

grid using ANN strategy. In the 6th International Conference on Artificial Intelligence in Renewable Energetic Systems, IC-AIRES2022, held on November 20-22, 2022 at the University of Tamanrasset, Tamanrasset, Algeria.

NATIONAL CONFERENCES:

1. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal. ***Simulation and command of a three-phase double-stage PV grid using AVR MPPT based on ANN model and a simple DQ current controller.*** In 1st National Conference of Thermal Engineering on Renewable and Conventional Processes (NCTE 22), on October 25-26, 2022, held at the University of Batna 3, Algeria.
2. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal et al. ***Adaptive Deloading Technique for PV Systems Using Regression-Based APR Approach.*** In the National Conference of Applied Sciences and Engineering NCASE'24, held on November 17 and 18, 2024, and organized by the Applied Sciences Laboratory (LSA) of the National Higher School of Advanced Technologies (ENSTA).
3. MESSASMA, Chaouki, CHOUABA, Seif Eddine, and SARI, Bilal. ***FLC-Based Deloading Technique for Direct-Driven Wind Turbine PMSG.*** In the National Conference of Applied Sciences and Engineering NCASE'24, held on November 17 and 18, 2024, and organized by the Applied Sciences Laboratory (LSA) of the National Higher School of Advanced Technologies (ENSTA).

CHAPTERS:

1. MESSASMA, Chaouki, CHOUABA, Seif Eddine, and SARI, Bilal. ***The primary frequency control techniques for grid-connected PV systems: a review.*** Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities: Case Study: Tipasa, Algeria, 2022, p. 220-229.
2. MESSASMA, Chaouki, CHOUABA, Seif Eddine, SARI, Bilal, and BARAKAT, Abdallah. ***An approach for power reserve control (PRC) strategy based on a novel ANN model.*** In International Conference on Artificial Intelligence in Renewable Energetic Systems. Cham: Springer International Publishing, 2022. p. 594-601.

Contents

List of Figures

List of Tables

List of Abbreviations

List of Symbols

General introduction	1
1 Chapter 1 : Review of Frequency Control Systems and Deloading Techniques in Electrical Power Grids	3
1.1 Introduction	3
1.2 Renewable energy sources	7
1.3 Impact of RES integration on electrical power systems	9
1.4 Grid frequency	10
1.5 PV and Wind Turbine (WT) Primary Frequency Control (PFC) techniques .	12
1.5.1 PFC techniques in PV system	14
1.5.2 PFC techniques in Wind system	17
1.6 PFC techniques comparison	21
1.7 Conclusion	24
2 Chapter 2 : Advanced Real-Time Deloading Techniques for Frequency Regulation in PV Systems	26
2.1 Introduction	26
2.2 Description and modeling of PV systems	27
2.2.1 PV modelling	27
2.2.2 PV grid system	29

2.3	Deloading technique and hybrid inertia	30
2.3.1	PRC modes	32
2.3.2	Switching control block	34
2.3.3	Deloading region	35
2.4	Primary frequency control and inertial response	36
2.4.1	Primary frequency control	36
2.4.2	Inertial control strategy	37
2.5	Proposed PV PRC system configurations	38
2.6	Simulation tests and results	39
2.6.1	PRC validation	40
2.6.2	PFC test	41
2.6.3	PFC and VIC in isolated grid	44
2.6.4	Real and hybrid inertia integration	45
2.7	Integration of advanced techniques	49
2.7.1	Governor controller update :	50
2.7.2	DC-DC controller update :	51
2.7.3	PFC and VIC integration loop update :	52
2.8	Tests and discussion	53
2.9	Conclusion	59
3	Chapter 3 : Advanced Control Strategies for Improving Real-Time Wind Turbine Deloading	61
3.1	Introduction	61
3.2	Description and modeling of Wind Energy Systems	62
3.2.1	Main components of WES	63
3.2.2	WT modelling	66
3.3	Wind systems proposed deloading approach	68
3.3.1	Maximum power measurement and power reserve modes	70
3.3.2	Trigger signal	71
3.3.3	Power control regions and MPPT PAC	73
3.3.4	Frequency and blade control	75
3.4	Validation strategy	75
3.4.1	System description	75
3.4.2	Validation tests and scenarios	77
3.5	Results and discussion	78

3.5.1	Wind variation tests	78
3.5.2	PFC integration tests	80
3.6	Advanced and robust controller implementation	83
3.6.1	PI-FLC application	83
3.6.2	Grid side control (GSC)	84
3.7	Simulation tests	87
3.7.1	Tests	87
3.7.2	Results	88
3.8	Conclusion	93
4	Chapter 4 : Deloading and Advanced Control Techniques for Hybrid PV-Wind System	95
4.1	Introduction	95
4.2	Description of the Hybrid PV-Wind System	96
4.2.1	Hybrid RES	96
4.2.2	Hybrid deloading	97
4.2.3	Hybrid PV WT grid-tied system	97
4.3	Testing and validation of the hybrid deloading system	99
4.4	Integration and implementation of the $\mathcal{H}_\infty$ controller	103
4.4.1	Hybrid system $\mathcal{H}_\infty$ implementation	103
4.4.2	Test and results	104
4.5	Hybrid system with frequency service	105
4.5.1	PFC integration	105
4.5.2	Test and results	105
4.6	Conclusion	107
	General conclusion	108
	Bibliography	110
A	Annex 1	122
B	Annex 2	123
C	Annex 3	124

List of Figures

1.1	State-of-the-art diagram	4
2.1	Single diode electrical model : (a) PV cell model (b) PV array model	27
2.2	PV system characteristics	28
2.3	Irradiation and temperature influence	29
2.5	DC-DC Converter types	30
2.6	Single-stage DC-AC inverter circuit	30
2.7	Three-phase inverter with RLC filter	31
2.8	Proposed PRC strategy	32
2.9	Proposed PRC strategy	33
2.10	PV linearization for the operation in the right region (100 kW PV)	35
2.11	Frequency regulation diagram : PRC, PFC, and VIC	36
2.12	Bloc diagram of the complete system implemented in Matlab	39
2.13	Proposed PRC under climates changes	41
2.14	PRC integration into Primary frequency response	42
2.15	Proposed PRC under typical waveform of frequency variation	43
2.16	Grid frequency and PV plant power with different scenarios of frequency re- gulation control	44
2.17	Grid frequency and PVSG active power for different H_{PVSG} value	46
2.18	Grid frequency with hybrid inertia	47
2.19	PV power and PVSG active power with hybrid inertia	48
2.20	Governor control loop.	50
2.21	$PI_{governorGA}$ tuning diagram.	51
2.22	$PI_{boostGA}$ tuning diagram and DC-DC control using FLC_{boost}	51
2.23	FLC_{boost} membership functions : inputs members : (a) error (e) and (b) change of error (Δe), and output member : (c) Duty (U)	52

2.24	PFC loop methods : (a) classical (b) FLC_{PFC}	53
2.25	FLC_{PFC} membership functions : inputs members : (a) frequency variation (Δf) and (b) speed of frequency deviation (df), and output member : (c) injected power reserve (ΔP_{PFC})	53
2.26	Grid frequency and PV plant power using $PI_{governor}$ and $PI_{governorGA}$	55
2.27	Grid frequency, PV plant power and compensator power using PI_{boost} , $PI_{boostGA}$ and FLC_{boost}	56
2.28	Grid frequency and PV plant power using $FLC - PI_{boost}$, $FLC - PI_{boostGA}$ and $FLC - FLC_{boost}$	57
2.29	Grid frequency : without HI, with HI, and with AHI	58
3.8	Diagram of the proposed power reserve strategy	69
3.9	Trigger signal (Trig-Sig) configurations diagram	70
3.10	Presentation of the extracted power in PR mode	74
3.11	Frequency regulation and blade control	75
3.12	System configuration and proposed strategy	76
3.13	10 MW WT characteristic	77
3.14	Power reserve generation using TTS and CTS modes	79
3.15	C_p and β Variation in MPPT, TTS and CTS modes	79
3.16	Generating power reserve with real wind speed data	80
3.17	Droop regulation validation	81
3.18	VIC, Droop and PFC integration in isolated grid	82
3.19	PI-FLC structure	84
3.20	PI-FLC membership functions : inputs members : (a) error (e) and (b) change of error (Δe), and outputs members : (c) K_P and (d) K_I	84
3.21	Conventional grid-side control	85
3.22	$\mathcal{H}_\infty$ grid side control	86
3.23	The configuration of $\mathcal{H}_\infty$ control incorporating weighting function	86
3.24	Wind speed variation scenario	88
3.25	Comparison of WT power, C_p , and β : deloading strategies	89
3.26	Comparison of WT power, V_{dc} , C_p , and β : without parameter variations . .	89
3.27	Comparison of WT power and V_{dc} : with low resistance variation	91
3.28	Comparison of I_{abc} and V_{abc} : with low resistance variation	91
3.29	Comparison of WT power and V_{dc} : with low inductance variation	92
3.30	Comparison of I_{abc} and V_{abc} : with low inductance variation	92

3.31	Comparison of WT power and V_{dc} : with high parameter variations	93
4.1	AC common hybrid deloading strategies	97
4.2	Hybrid PV WT-tied grid configurations	98
4.3	Climatic change scenario	100
4.4	PV deloading without WT contribution	100
4.5	PV 15% reserve and WT 5% reserve	101
4.6	PV and WT with 10% reserve each	101
4.7	PV 5% reserve and WT 15% reserve	102
4.8	WT deloading without PV contribution	102
4.9	H_{∞} -based hybrid PV-WT system implementation	103
4.10	PV and WT systems in deloading mode during variations in grid parameters	104
4.11	PV and WT power response : without vs. with PFC Integration	106
4.12	Grid frequency : without vs. with PFC Integration	106

List of Tables

1.1	Comparison of Deloading and Energy Storage Systems	21
1.2	Summary of AI-based deloading techniques in PV and WT systems, highlighting the role and necessity of AI	24
2.1	Realised tests	40
2.2	PRC tests results	42
2.3	Results of PFC and VIC tests	46
2.4	Results of RI and HIC tests	49
2.5	Fuzzy rules of FLC_{boost}	53
2.6	Fuzzy rules of FLC_{PFC}	54
2.7	Summary of controllers and subjected tests	54
2.8	Global test results.	58
3.1	Fuzzy rules of K_P	84
3.2	Fuzzy rules of K_I	84
3.3	Strategy test	90
3.4	Low variations test	92
4.1	Deloading scenarios for PV and WT systems	100
A.1	100 kW PV grid parameters : infinite and isolated configuration	122
B.1	Parameters of 10 MW Direct-Driven PMSG System	123
C.1	Parameters of Hybrid PV-WT Grid in Isolated Configuration	124

List of Abbreviations

AC:	Alternative Current
AGC:	Automatic Generation Control
AHI:	Advances Hybrid Inertia
ANN:	Artificial Neural Networks
AV:	Alternative Voltage
CPGC:	Constant Power Generation Control
CTS:	Conditional Trigger Signal
DC:	Direct Current
DV:	Direct Voltage
DEL PAC:	Deloading Pitch Angle Controller
ESS:	Energy Storage Systems
FLC:	Fuzzy Logic Controller
GA:	Genetics Algorithmic
G:	Irradiation
GSC:	Grid Side Control
HAWT:	Horizontal-Axis Wind Turbines
HIC:	Hybrid Inertial Control
HTS:	Hybrid Trigger Signal
IGBT:	Insulated Gate Bipolar Transistors
ITAE:	Time Multiplied Absolute Error
MIMO:	Multi-input Multi-Output
MPM:	Maximum Power Measurement
MPPT:	Maximum Power Point Tricker
PAC:	Pitch Angle Control
P&O:	Perturb and Observe
PFC:	Primary Frequency Control
PI:	Proportional Integrator

PI-FLC:	Proportional Integrator Fuzzy Logic Controller
PMSG:	Permanent Magnet Synchronous Generator
PRC:	Power Reserve Control
PV:	PhotoVoltaic
PVSG:	PV Synchronous Generator
RES:	Renewable Energy Source
RIC:	Real Inertial Control
RoCoF:	Rate of Change of Frequency
RSC:	Rotor Speed Control
SG:	Synchronous Generators
T:	Temperature
TTS:	Temporal Trigger Signal
VAWT:	Vertical-Axis Wind Turbines
VIC:	Virtual Inertia Control
VIR:	Virtual Inertial Response
VSWTs:	Variable-Speed Wind Turbines
WECS:	Wind Energy Conversion System
WT:	Wind Turbine

List of Symbols

β ($^{\circ}$):	Blade pitch angle
β_{Del} ($^{\circ}$):	Deloading blade pitch angle
β_{MPP} ($^{\circ}$):	MPP blade pitch angle
C_p :	Power coefficient
C_{pDel} :	Deloading power coefficient
Δf (Hz):	Frequency variation
ΔP_{Droop} (W):	Droop additional power
ΔP_{PFC} (W):	Injected power reserve
ΔP_{VIC} (W):	Virtual inertial additional power
ΔV_w (m/s):	Wind speed variation
$Ev(t)$:	PV voltage instantaneous relative error
FLC_{boost} :	Boost converter FLC controller
FLC_{PFC} :	PFC FLC controller
f_0 (Hz):	Nominal frequency
G_{del} :	Deloading gain
H :	Inertia constant
H_{PVSG} :	PVSG Inertia constant
I_d (A):	D axis current transformation
I_q (A):	Q axis current transformation
I_{pv} (A):	PV current
K_{Droop} :	Droop gain
K_I :	The PI integrator gain
K_P :	The PI proportional gain
K_{VIC} :	Virtual inertia gain
L_f (H):	Filter inductance

P_{Del} (W):	Deloading power
P_{mpp} (W):	Maximal power
P_{nom} (W):	WT nominal power
P_{pv} (W):	PV output power
P_{ref} (W):	Reference power
P_{res} (W):	Reserve power
P_w (W):	Wind turbine output power
PI_{boost} :	Boost converter PI controller
$PI_{boostGA}$:	Boost converter PI controller tuned using GA
$PI_{governor}$:	Governor PI controller
$PI_{governorGA}$:	Governor PI controller tuned using GA
R_f (Ω):	Filter resistance
T_1 (s):	MPPT period
T_2 (s):	PRC period
T_{cyc} (s):	Cycle period
$Trig - Sig$:	The trigger signal
T_{sw} (s):	Switching time
V_w (m/s):	Wind speed
V_{w-nom} (m/s):	Nominal wind speed
V_{del} (V):	PV deloading voltage
V_{mpp} (V):	Maximal PV voltage
V_{pv} (V):	PV voltage
W_r (rpm):	Generator rotational speed

General introduction

The global switch towards renewable sources of energy is changing the face of the power sector. Integrating renewable energy sources (RES) with traditional power grid is crucial for ensuring a sustainable energy future. As the world faces the pressing challenges of climate change and the depletion of fossil fuel reserves, harnessing the vast potential of renewable energy is both a necessity and an opportunity.

One of the most significant challenges in this transition is maintaining grid frequency stability, which is essential for a secure and reliable power supply network. RES are inherently intermittent and variable, with no intrinsic inertia, especially in photovoltaic (PV) and wind energy systems, creating specific challenges for grid operators. To effectively address these issues, innovative strategies and sophisticated control methods must be adopted to keep grid frequencies within acceptable limits and enable greater RES integration.

Among renewable energy sources, wind and photovoltaic (PV) energy systems are the most widely used and impactful. Given the increasing penetration of these RES types, enhancing grid frequency control is a key focus of this doctoral research.

This research addresses these challenges by proposing advanced deloading strategies and innovative control techniques to enhance the integration of RES into modern power grids. Initially, an in-depth analysis of RES integration and its impact on frequency stability is conducted, highlighting the challenges posed by these systems. Subsequently, a novel deloading approach is developed and applied to photovoltaic and wind systems, accompanied by advanced control methods such as hybrid inertia and artificial intelligence algorithms.

This thesis also validates these strategies through rigorous simulations and tests under various operating scenarios. Finally, a broader integration of these methods into a hybrid PV-wind system is explored, demonstrating improvements in frequency regulation and grid stability.

The thesis is organized into four main chapters, each addressing a specific aspect of renewable energy integration and control:

Chapter 1 Review of state-of-the-art frequency control systems and deloading techniques

used in power grids with high renewable energy penetration. A review of classical and advanced strategies is conducted, highlighting existing challenges and solutions.

Chapter 2 develops an analytical approach for the advanced control of grid-integrated photovoltaic systems. The concepts of deloading and hybrid inertia are detailed and validated through simulations. Explore enhancements through fuzzy logic control (FLC) and genetic algorithms (GA), critically evaluating their design, testing, and impact on system efficiency.

Chapter 3 focuses on the integration of wind energy systems (WES) and their impact on grid stability. A comprehensive modeling approach and an innovative deloading strategy, supported by an experimental validation methodology based on real installation data, are presented. The study explores advanced control techniques, including $\mathcal{H}_\infty$ control, to enhance system performance. Validation tests using a direct-driven PMSG system assess the effectiveness of these strategies, with simulation results highlighting key improvements.

Chapter 4 examines the integration of photovoltaic and wind systems in a hybrid setup. It proposes an advanced control approach combining robust $\mathcal{H}_\infty$ control and artificial intelligence (AI) algorithms, synthesizes the results, and discusses future improvements for optimizing control strategies to enhance renewable energy integration into power grids

Finally, the general conclusion summarizes all the relevant results of this thesis, highlighting the effectiveness of the proposed deloading strategies and control techniques for enhancing frequency stability in power grids with high renewable energy penetration. The discussions focus on the strengths and limitations of the developed methods, assessing their performance under various operational scenarios.

Additionally, the thesis conclusions outline future research directions for further refining the proposed approaches. Potential future work includes experimental validation on real-world power systems, optimization of control parameters, and integration of hybrid energy storage solutions to complement deloading strategies. These advancements will contribute to the ongoing efforts to enhance grid resilience and facilitate the transition to a more sustainable energy landscape.

Chapter 1: Review of Frequency Control Systems and Deloading Techniques in Electrical Power Grids

This chapter provides an overview of current trends in energy supply and the ongoing transition toward RES. It focuses on the increasing adoption of PV and WT systems, which are among the most widely utilized RES technologies. However, their large-scale integration introduces challenges related to grid stability, particularly in maintaining frequency regulation.

To address these stability concerns, various solutions proposed in the literature are explored, with a particular emphasis on the role of advanced control techniques in enhancing electrical power system resilience in high-penetration scenarios. These methods play a crucial role in ensuring grid reliability while accommodating increasing levels of PV and WT integration. To enhance clarity, the following diagram, figure 1.1, visually represents the key topics covered in this chapter.

1.1 Introduction

The transition from conventional to RES marks a crucial transformation in the energy sector. This significant change is driven by a heightened awareness of the pressing need to combat climate change, as illustrated in figure 1.2, which depicts the alarming upward trajectory of carbon dioxide (CO₂) emissions. Additionally, figure 1.3 showcases the progression in electrical power consumption, highlighting the growing energy demands that must be met [1].

This transition stems from the imperative to fortify energy security in response to escalating electrical power demands and harness the abundant clean and sustainable resources

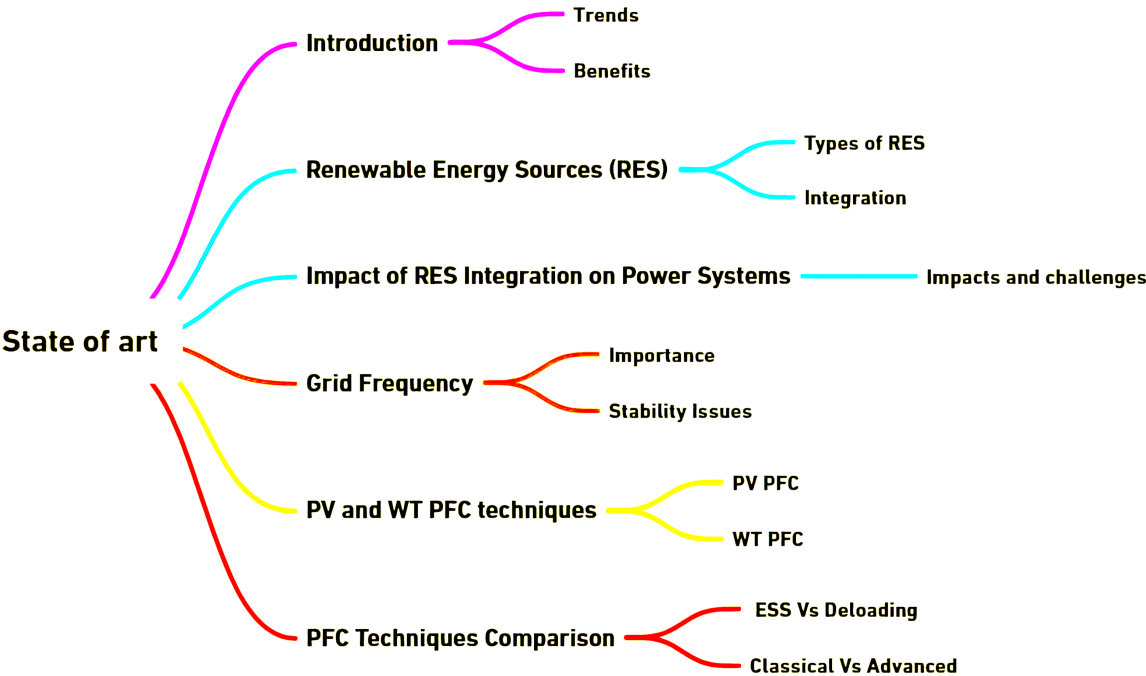


FIGURE 1.1 – State-of-the-art diagram

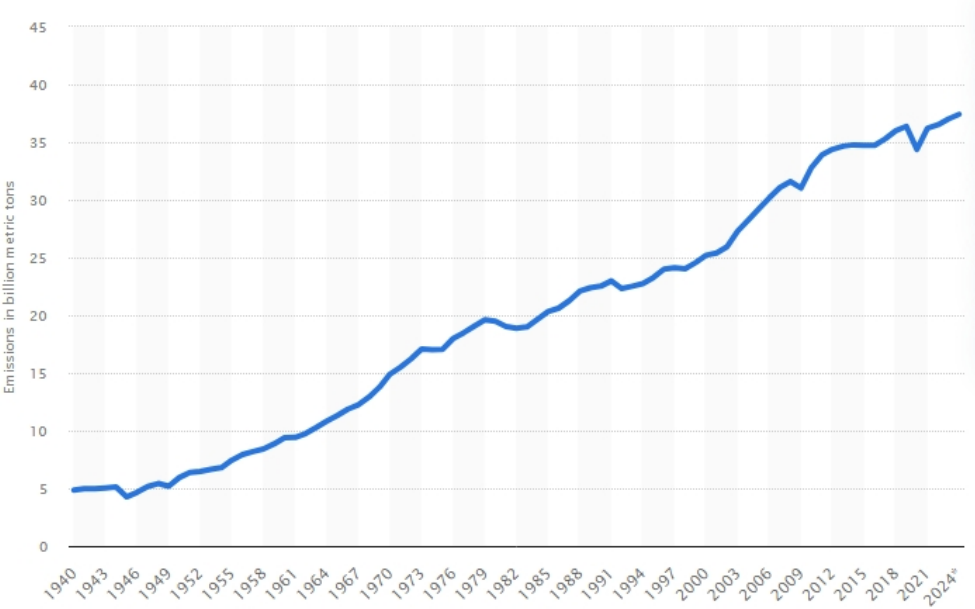


FIGURE 1.2 – The trend in carbon dioxide (CO₂) emissions from 1940 to 2024 [2]

that nature provides. It entails departing from the conventional reliance on fossil fuels like coal, oil, and natural gas, which have held sway as the primary energy sources for several de-

cadences. Instead, it embraces the potential of RES, such as solar, wind, hydro, and geothermal power, which offer environmentally responsible and sustainable alternatives. RES not only reduces the carbon footprint but also contributes to a more resilient and diversified energy landscape. By transitioning to RES, we take a significant step towards a cleaner, greener, and more sustainable energy future while addressing the urgent challenges posed by climate change and ensuring a secure energy supply for future generations [1].

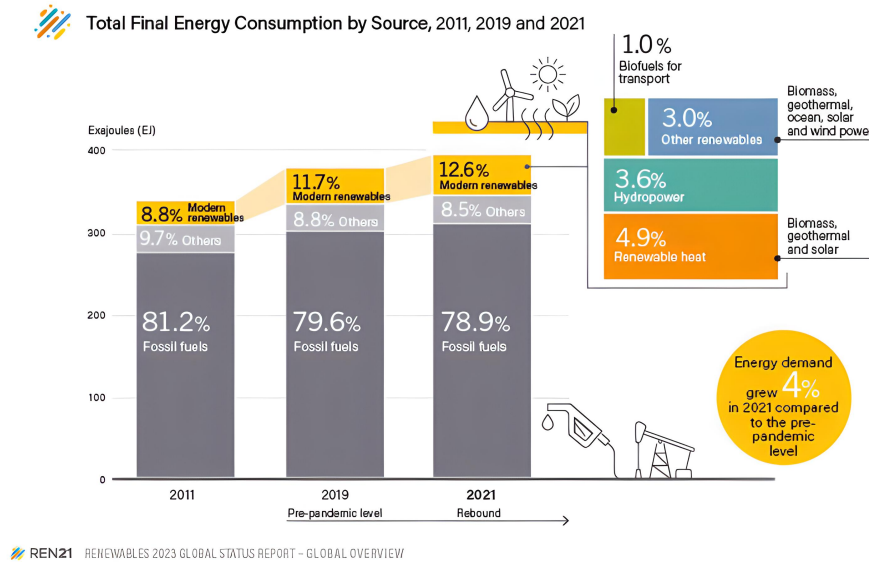


FIGURE 1.3 – The pattern of energy consumption between 2021 and 2022 [2]

At the end of 2023, the global renewable generation capacity reached a remarkable milestone of 3 870 GW, representing a substantial increase compared to the previous year, with a growth of 473 GW (+13.9%). As presented in figure 1.4, Asia played a dominant role in this expansion, contributing nearly 69.3% of the new capacity, which translated to a substantial growth of 327.8 GW. This bolstered Asia's total renewable capacity to 1.961 terawatts (TW), making up 50.7% of the global total. Notably, China played a pivotal role in this surge, adding an impressive 297.6 GW to its renewable capacity [2].

Furthermore, both Europe and North America experienced notable growth, with their capacities expanding by 71.2 GW (+10.0%) and 34.9 GW (+7.0%), respectively. The African continent continued its steady expansion with an increase of 2.7 GW (+4.6%), slightly surpassing the previous year's figures. Oceania continued its impressive double-digit growth trajectory, expanding by 5.5 GW (+9.4%), primarily driven by developments in Australia. South America also maintained its upward trend, achieving a capacity expansion of 22.4 GW

Renewable power capacity by region

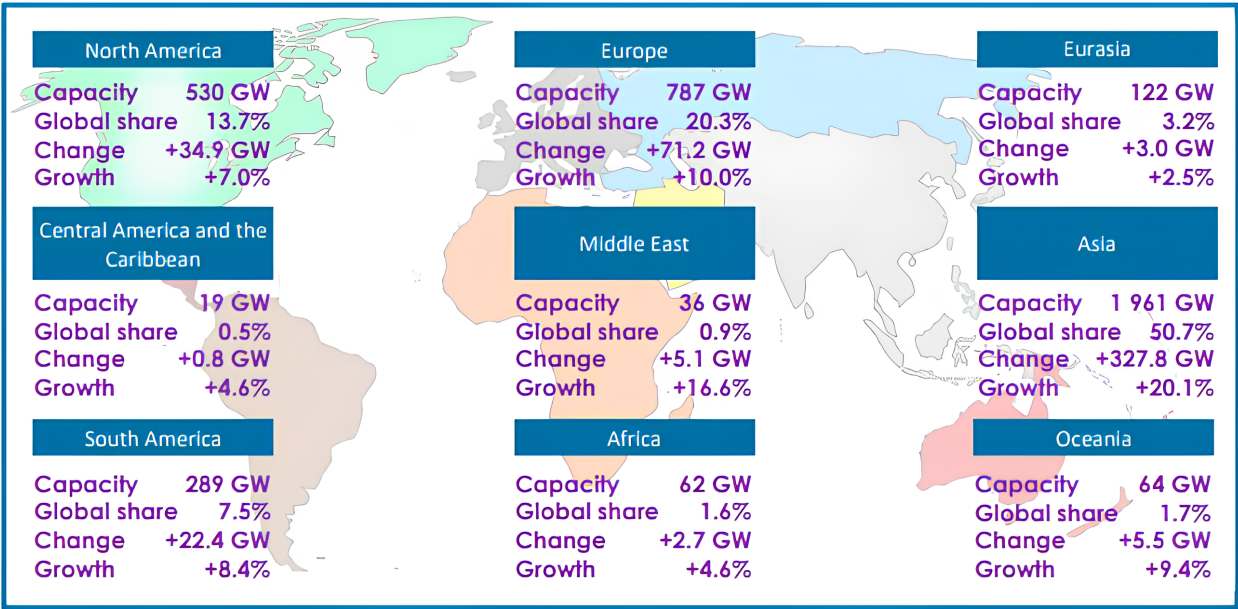


FIGURE 1.4 – Regional distribution of renewable generation capacity [2]

(+8.4%). Additionally, the Middle East set a new record for expansion, commissioning 5.1 GW of new capacity in 2023, marking an impressive growth rate of 16.6% [2].

Looking ahead, the International Energy Agency (IEA) forecasts that over the next five years, several renewable energy milestones are expected to be reached. In 2025, renewables-based electricity generation is set to overtake coal-fired generation. In 2026, wind and solar electrical power generation are each poised to surpass electrical power generation from nuclear. Then, in 2029, electricity generation from PV is set to surpass hydropower, becoming the largest RES globally, with wind-based generation expected to surpass hydropower in 2030 [3].

Algeria renewable energy acceleration in 2024: In 2024, Algeria is making notable progress in its shift toward renewable energy with the launch of a 2,000 MW solar PV project led by Sonelgaz, scheduled for completion by mid-2025. This development marks a significant increase from the 589.7 MW installed between 2011 and 2022. The project encompasses 14 solar plants spread across 11 provinces, with nine facilities constructed by Chinese companies and five by Algerian firms, demonstrating both international cooperation and local involvement [4].

Algeria also prioritizes domestic solar panel production, supported by ENIE and the Firmer Algeria joint venture, to strengthen its renewable energy sector. Alongside this major

initiative, additional projects are in progress, including the Solar 1,000 MW program and a 3,000 MW plan, all contributing to the country's goal of reaching 15,000 MW of installed capacity by 2035. Moreover, Algeria is positioning itself as a significant player in green hydrogen production, with a pilot project in partnership with Germany's VNG AG, aiming for large-scale commercial production by 2030 [4].

The subsequent paragraph will delve into the specific categories and types of RES contributing to this remarkable rise in clean energy capacity to provide a more detailed breakdown of this progression.

1.2 Renewable energy sources

The global increase in renewable energy capacity for each RES technology presented in figure 1.5 is highlighted by:

Hydropower: Hydropower continued to grow steadily, representing the largest proportion of global renewable energy capacity (GREC). It reached a substantial capacity of 1 268 GW, constituting 33% of the total GREC [5].

Solar energy: Solar PV technology has emerged as a prominent player, accounting for 37% of the GREC, with an increase of 346 GW and a total capacity of 1 419 GW. Concentrated solar electrical power, on the other hand, experienced a more modest growth of 0.3 GW [5].

Wind energy: Wind energy represented 26% of the GREC, totalling 1 017 GW. Although there was an additional 116 GW of wind electrical power capacity in 2023, the growth rate in this sector continued to decelerate compared to the preceding two years [6].

Constitutes: The remaining sources of renewable energy, which include 150 GW of bioenergy, 15 GW of geothermal, and 0.5 GW of marine energy, collectively constitute approximately 4% of the global electrical power capacity within the renewable energy sector. While these sources may have a smaller capacity compared to some other renewables, they still contribute significantly to the overall renewable energy landscape, adding to the diversity and sustainability of global energy production [6].

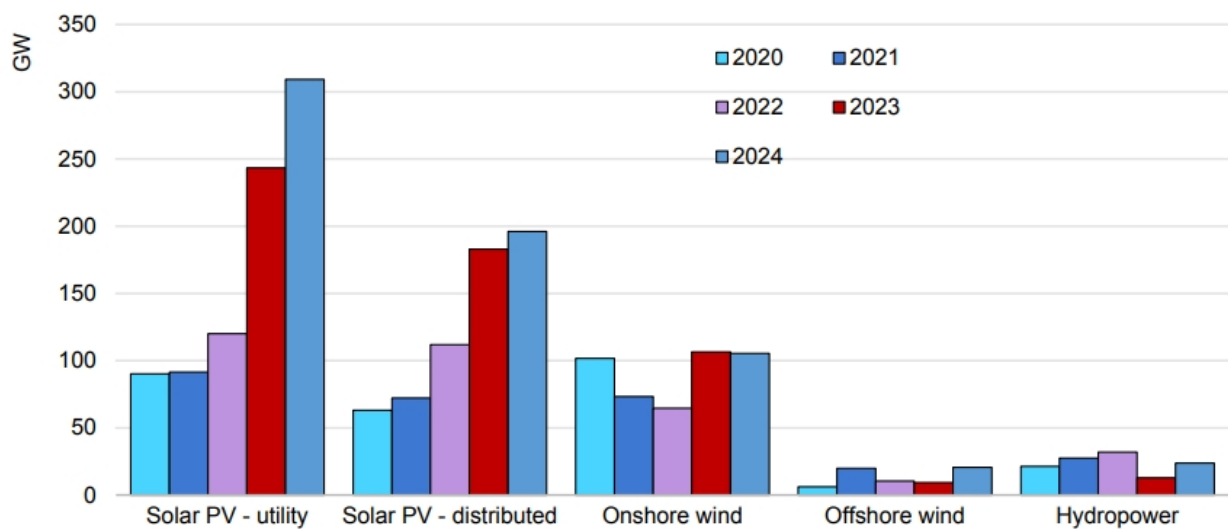
These highlights underscore the continued expansion and diversification of renewable energy sources, with varying growth rates among different technologies and regions, reflecting the ongoing global transition towards cleaner and more sustainable energy options.

In 2023, the renewable energy sector continued to be characterized by the sustained predominance of solar and wind energy in terms of capacity expansion. Solar electrical power

witnessed a significant increase of 346 GW, while wind energy contributed an additional 116 GW. These two renewable sources combined to make up an impressive 90% of all new renewable capacity installations, totaling 462 GW for the year. Figure 1.5 visually depicts this trend and highlights the noteworthy emergence of these renewable energy sources compared to conventional electricity generation. This data emphasizes the pivotal role solar and wind technologies play in driving the expansion of clean and sustainable energy globally [7].

Given their paramount significance in the renewable energy sector, this study focuses primarily on solar and wind energy sources, acknowledging their central role in shaping the future of sustainable energy production.

Renewable electricity capacity additions by technology, 2020-2024



Global electricity generation by technology, 2000-2030

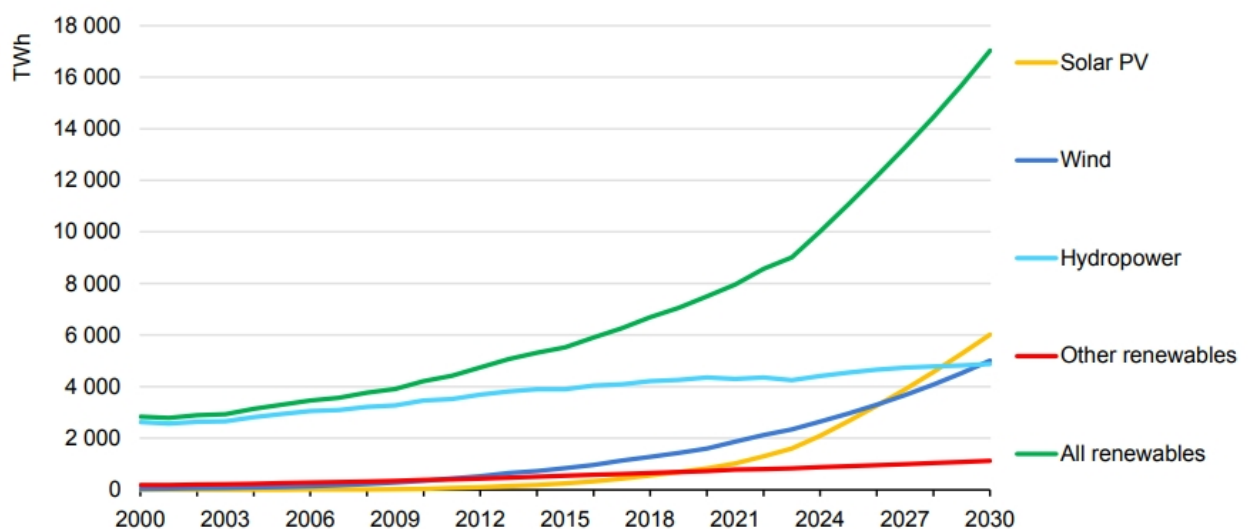


FIGURE 1.5 – RES emergency and distribution [5]

1.3 Impact of RES integration on electrical power systems

As previously mentioned, the integration of RES presents challenges due to its impact on the quality of the electrical power system. In this section, the principal challenges and influences of PV and wind systems on electrical grid quality are summarized as follows [8–10]:

Voltage stability: PV and wind systems, often connected at various electrical grid points, can cause voltage fluctuations because of their intermittent nature. These fluctuations can affect the ability of the electrical grid to maintain a stable voltage level, potentially leading to voltage deviations that could harm sensitive equipment and disrupt the electrical power supply.

Transient stability: Rapid and unpredictable changes in PV and wind generation can cause transient disturbances in the electrical grid. Transient stability refers to the electrical grid's capacity to remain stable during sudden and temporary disturbances. The variability of these renewable sources can challenge the electrical grid's resilience in responding to such disturbances.

Small-signal stability: Intermittent electrical power injections from PV and wind sources can introduce subtle, continuous oscillations into the electrical grid, known as small-signal stability issues. Although these oscillations may not be immediately disruptive, they can accumulate over time, potentially affecting overall electrical grid performance.

Frequency stability: Conventional electrical power plants provide inherent rotational inertia, which stabilizes electrical grid frequency. In contrast, RES like PV and wind systems lack this inertia, making electrical grid frequency more susceptible to fluctuations due to rapid changes in RES output. These fluctuations, if not managed properly, can disrupt the stable operation of electrical grid-connected devices.

Reserve requirement increase: PV and wind electrical power's intermittent nature can necessitate an increase in the required reserves. These reserves are essential to compensate for the sudden and unpredictable drops in renewable electrical power output, ensuring the electrical grid's reliability during such events.

Reactive power support: The capacity of PV and wind systems to generate or consume reactive power can influence electrical grid voltage stability. Reactive power support is vital for voltage regulation and electrical grid stability. Fluctuations in reactive power support can lead to voltage deviations that may affect electrical power quality.

Rotor angle stability: Large-scale of PV and wind farms can have an impact on the

dynamics of synchronous generators in the electrical grid due to their intermittent electrical power output. Rotor angle stability ensures that these generators' rotor angles remain within acceptable bounds to prevent electrical grid instability and protect connected equipment.

Dynamic performance: PV and wind integration introduce dynamic challenges due to the variability and unpredictability of these sources. Dynamic performance assesses the electrical grid's ability to respond effectively to rapid changes in electrical power generation or load without compromising overall stability and performance.

Load condition response: Electrical grid operators must adapt to changing load conditions driven by fluctuations in PV and wind generation. This involves monitoring and adjusting grid parameters, including voltage and frequency, to ensure consistent and reliable electrical power delivery as load conditions vary.

These impacts underscore the intricate interplay between PV and wind power systems and power system stability, emphasizing the necessity for meticulous planning and control strategies to ensure the reliable integration of PV and wind energy into the electrical grid. This study places a specific focus on the impact of electrical grid frequency or grid frequency stability, a paramount concern in electrical power systems. Prolonged deviations in frequency can lead to severe consequences, including blackouts with substantial economic and operational repercussions. Ensuring a consistent and stable electrical grid frequency within a narrow range is of utmost importance to prevent damage to electrical equipment, mitigate electrical power quality issues, avoid load shedding, and avert widespread blackouts.

The upcoming section will delve into a comprehensive exploration of electrical grid frequency, its various phases, and the influence of RES integration on frequency stability. It will scrutinize the significance of maintaining electrical grid frequency stability and shed light on the challenges introduced by the variability of RES generation.

1.4 Grid frequency

Grid frequency, also known as electrical grid frequency or mains frequency, is a fundamental parameter governing the operation of electrical power systems. It measures the number of complete alternating current (AC) cycles per second within an electrical grid and is typically expressed in hertz (Hz). This frequency characterizes the periodicity of the AC voltage waveform [11–13].

In most parts of the world, grid frequency adheres to either 50 Hz or 60 Hz standardized values. In regions with a 50 Hz standard, the voltage waveform completes 50 cycles per

second, whereas those adhering to a 60 Hz standard complete 60 cycles per second.

The precise control and maintenance of grid frequency fall under the responsibility of electrical grid operators. Deviations from the standard or nominal frequency (f_0) can have substantial repercussions for electrical equipment and the stability of the electrical power grid. Grid frequency is pivotal in ensuring that generators, motors, and other electrical devices operate at their designed speeds and execute their functions accurately [11–13].

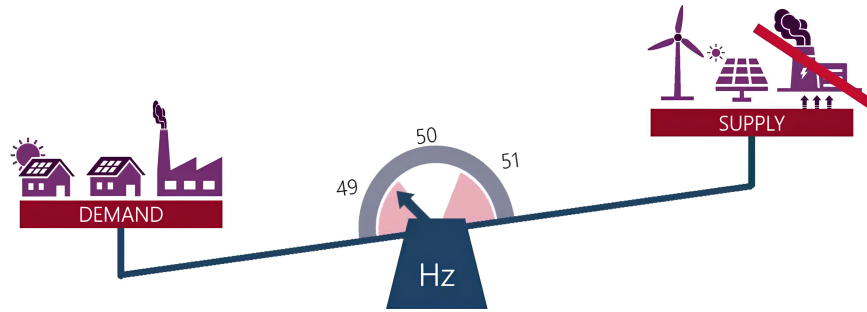


FIGURE 1.6 – Frequency balance [12]

The equilibrium between electricity generation and consumption influences grid frequency, as illustrated in figure 1.6. When generation exceeds consumption, the frequency tends to rise, while excessive consumption results in a lower frequency. Electrical grid operators employ various control mechanisms, such as adjusting generator output and load shedding, to uphold grid frequency within a narrow and specified range. This meticulous management is essential for the dependable and efficient operation of the electrical grid.

Figure 1.7 illustrates the standard grid frequency response, composed of three crucial phases essential for maintaining the electrical grid’s stability and reliability. The primary frequency control (PFC) phase, lasting approximately 30 seconds, includes the inertial response and governor response. The inertial response acts as the first line of defense against frequency deviations by using the inertia of rotating machinery to momentarily stabilize the frequency. The governor’s response then adjusts the generator’s electrical power output to correct frequency deviations. Secondary control, also known as automatic generation control (AGC), operates over minutes, optimizing the electrical power output of multiple generators across a larger area to maintain the system’s frequency around its nominal value while considering economic and operational constraints. Tertiary control, or delistage control, operates on the longest timescale (hours to days) and focuses on optimizing generation resources, considering factors such as fuel costs, maintenance schedules, and unit commitment to ensure the most efficient and cost-effective generators are dispatched to meet the expected load while

maintaining system stability [11–13].

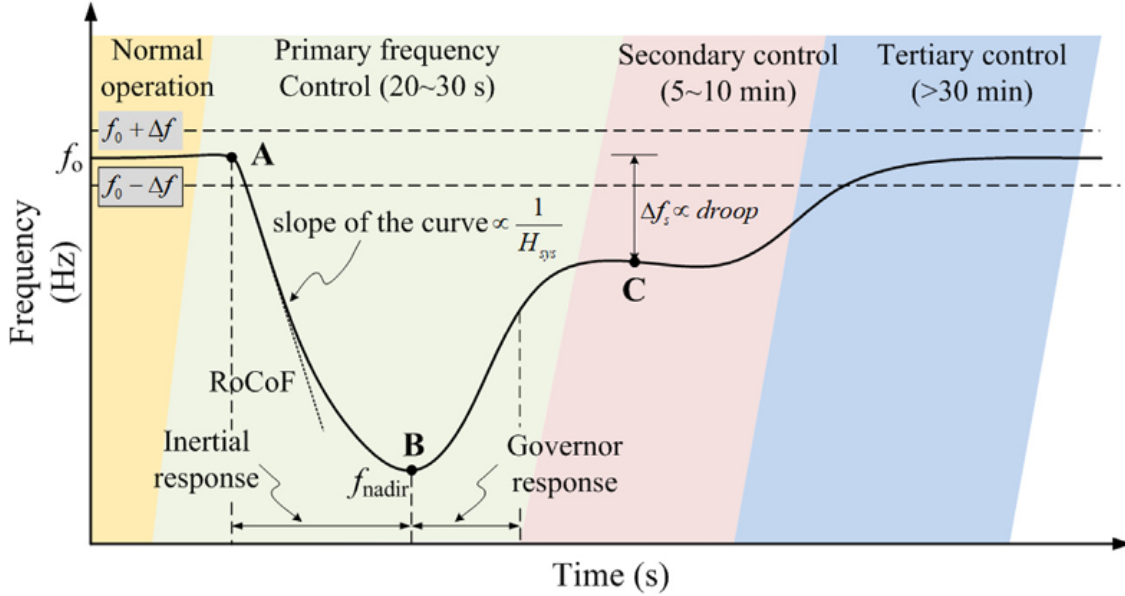


FIGURE 1.7 – Typical frequency control response to electrical power distribution [13]

Inertial and governor responses are key for frequency stability. Figure 1.7 shows a typical frequency response with nominal frequency (f_0) and acceptable limits (Δf). A disturbance, often from load changes at point A, leads to the lowest frequency point (f_{nadir}) at B. The slope between A and B represents the rate of change of frequency (RoCoF), inversely related to system inertia. Governor control at C restores stability. The crucial elements pertain to where the frequency reaches stability and the initial RoCoF. In this context, the RoCoF is notably influenced by the system's inertia, with H_i representing the inertia of each electrical power source. This relationship is expressed mathematically in the following equation:

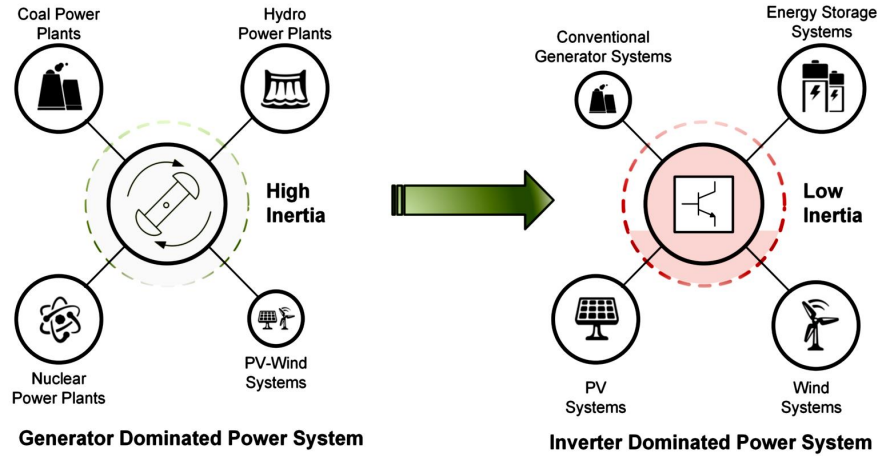
$$RoCoF \propto \frac{1}{H_{sys}} \quad (1.1)$$

Here H_{sys} signifies the system's overall inertia ($\sum H_i$).

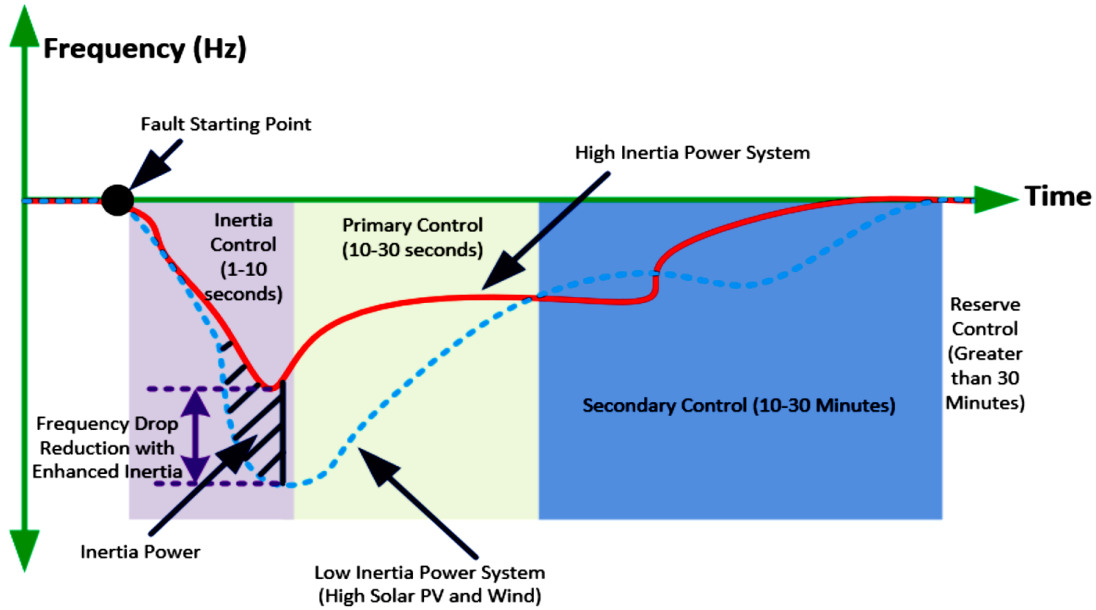
1.5 PV and Wind Turbine (WT) Primary Frequency Control (PFC) techniques

The integration of RES, such as solar PV and wind, reduces overall system inertia by replacing conventional synchronous generators. Since wind turbines and PV systems are interfaced through power electronic converters, they inherently lack internal inertia and offer

limited contribution to frequency response (figure 1.7(a)). This reduction in inertia increases the RoCoF, triggering load-shedding even with minor load-generation mismatches and reducing electrical power reserve, leading to frequency deviations (figure 1.8(b)). Therefore, new controllers must be designed for RES to emulate synchronous generators' behavior, improving system frequency response. In the upcoming subsection, we will discuss the main techniques,



(a) The transition to an inverter-based power system



(b) Low inertia impact on frequency control response

FIGURE 1.8 – Integrating RES and its impact on grid frequency [14]

control approaches, and strategies employed in solar PV and wind systems, depicted in figure 1.9, to enhance frequency response and maintain stable grid frequency.

1.5.1 PFC techniques in PV system

The main approaches for controlling primary frequency in PV-integrated electrical power systems are roughly classified into two categories: the first with an energy storage system (ESS) and the second without (figure 1.9). Each option presents its own set of advantages and disadvantages, and the decision between them is influenced by a variety of factors, including the cost of storage devices, the availability of sunlight, and the specific requirements of the electrical grid [15–19].

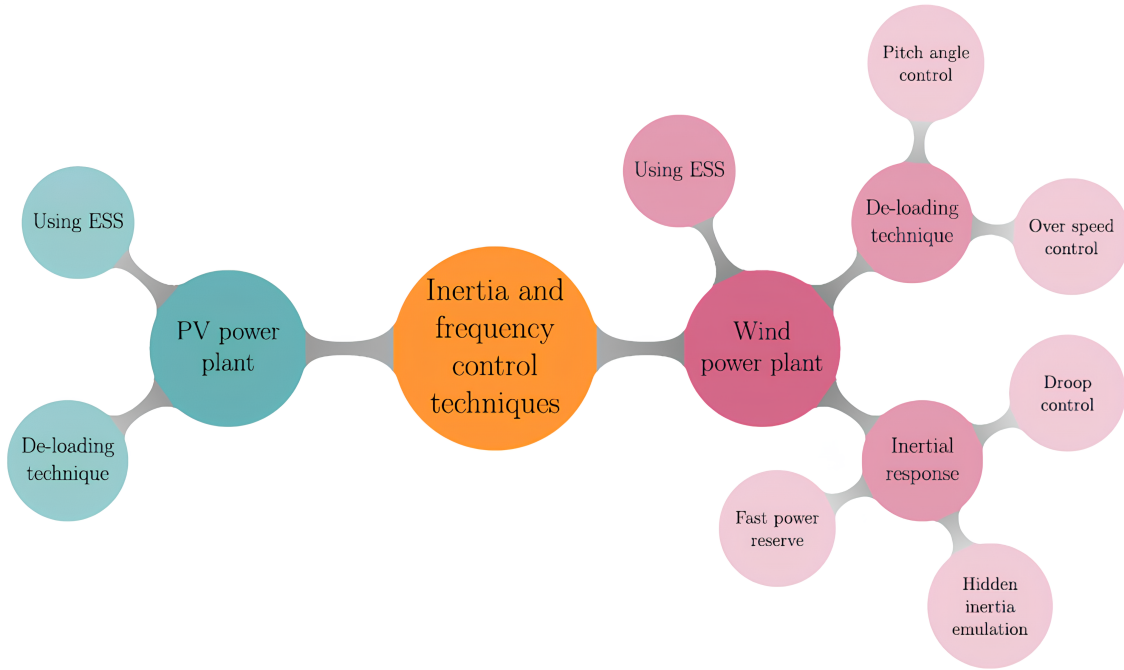


FIGURE 1.9 – PV and wind system inertia and frequency control methods [15]

1.5.1.1 Using energy storage systems

To address this challenge, researchers and engineers have explored the integration of energy storage systems (ESS) into the PFC loop. Various ESS technologies are utilized to provide an additional electrical power reserve, achieved by temporarily storing excess energy generated by solar panels , as illustrated in figure 1.10. These ESS systems are managed both centrally and locally through a power electronic converter system, which effectively replicates the inertia response of traditional electrical power generation. The emulation of inertial response is achieved by adjusting the active output of the storage device in inverse

proportion to the rate of change of the grid frequency, thereby enhancing the system's primary frequency response.

Among the diverse range of ESS options under investigation, including superconducting magnetic energy storage (SMES), supercapacitors, electric batteries (BESS), fuel cells, and flywheel energy storage, SMES technology emerges as the most promising choice for emulating inertia. SMES holds advantages in terms of its rapid response time and capability to deliver high electrical power outputs, making it a valuable asset for bolstering frequency stability and electrical grid resilience.

In summary, the integration of ESS, particularly leveraging SMES technology, within the PFC loop proves to be an effective strategy for improving the stability and reliability of the electrical power grid in the presence of high PV penetration. However, implementing this technique involves higher costs and increased grid infrastructure complexity.

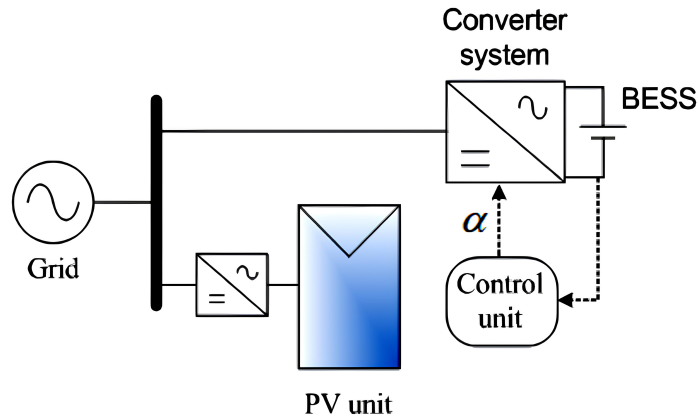


FIGURE 1.10 – Primary frequency control in PV integrated electrical power system using BESS [16]

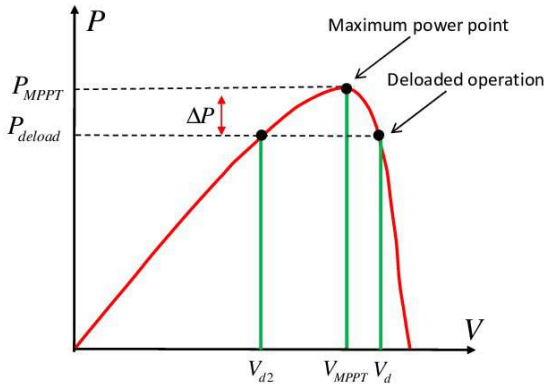
1.5.1.2 Deloading techniques

Several strategies integrate PV systems into the PFC loop without needing additional devices like ESS. One innovative approach involves a unique PV power curtailment control method aimed at providing auxiliary services during electrical grid disturbances. Diverging from traditional methods, this technique employs a virtual frequency droop-based control system to adjust the active power output of PV units, thereby contributing to crucial frequency regulation services. This method operates in two modes, one bolstering inertial response and the other preventing frequency collapse. Additionally, recent advancements have emphasized delta power control, where a portion of the PV power output is reserved to bolster electri-

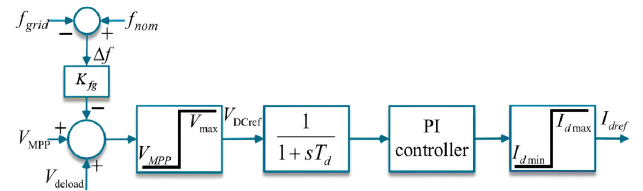
cal grid stability. Another novel concept involves using the electromagnetic energy stored in DC-link capacitors to simulate virtual inertia, thereby enhancing system stability during disturbances.

Nonetheless, the predominant approach garnering significant attention is the application of power reduction or deloading techniques. In these methods, the MPPT can be configured to operate outside the MPP to maintain a designated electrical power reserve, as illustrated in figure 1.11(a). This approach is particularly advantageous because it is more cost-effective and doesn't necessitate additional equipment.

The electrical power plant operator may regulate how much reserve power is generated using the deloading technique by setting a deloading gain, which displays the ratio of the reserve power to the maximum available power. An in-depth discussion of the different power reserve calculation techniques is provided in [17], along with a method for estimating the minimum amount of power reserve required to ensure frequency stability, which is closely related to the frequency nadir.



(a) Deloading procedure in PV plants



(b) Power control in deloaded PV system

FIGURE 1.11 – Primary frequency control in PV integrated electrical power system using deloading approach [17]

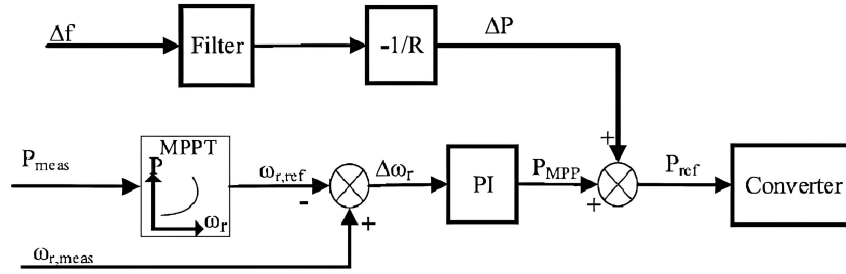
The deloading technique can generally be divided into two approaches:

- ★ **Power reserve control (PRC):** In the PRC approach, the MPP is continuously monitored to determine the reference power value, ensuring that the desired power reserve is generated under all conditions [18].
- ★ **Constant power generation control (CPGC):** in the CPGC approach, the system follows a predefined power value (P_{limit}), as stipulated by the grid operator, which is lower than the maximum power value (P_{mppt}). The goal is to generate the desired power

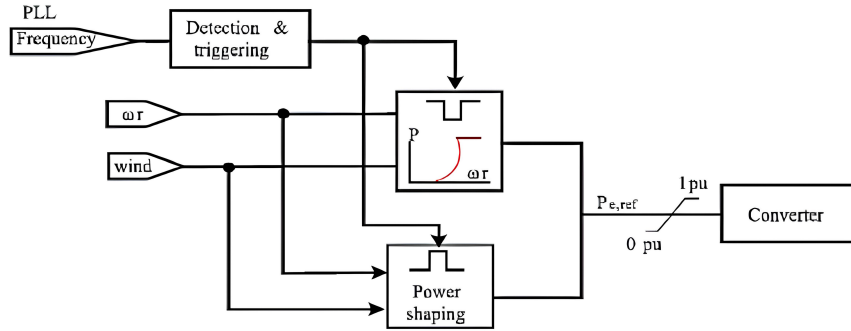
reserve. However, if the power output of the PV system falls below P_{limit} , it operates in MPP mode without providing any power reserve [18].

1.5.2 PFC techniques in Wind system

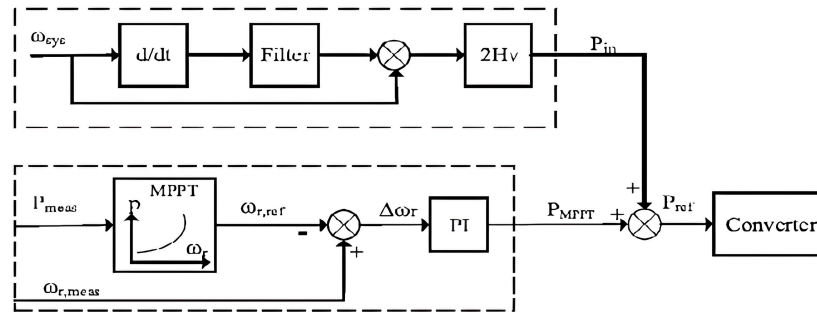
Recent literature surveys have highlighted three predominant methods for supporting grid frequency: operating variable speed wind turbines (VSWTs) in a deloaded state, integrating embedded ESS, and emulating an inertial response (see figure 1.12) [20–26].



(a) Droop speed



(b) Fast power reserve



(c) Inertia emulation

FIGURE 1.12 – Inertia response control techniques for variable-speed wind turbines [21]

1.5.2.1 Inertial response

The inertial response technique in wind turbine systems leverages three key approaches:

1. **Droop control:** This approach mimics the behavior of a governor in a conventional synchronous generator by responding to changes in system frequency. It regulates the active power output from the wind turbines in proportion to frequency deviations (Δf). By adjusting the power output based on frequency changes, droop control helps maintain electrical grid stability, significantly enhancing the frequency nadir (the lowest point of frequency during a disturbance) and the overall frequency recovery process.
2. **Fast power reserve:** This approach involves quickly supplying additional active power to the electrical grid by utilizing the kinetic energy stored in the rotating masses of the wind turbines. When a sudden frequency deviation occurs, the wind turbines temporarily decrease their rotor speed to provide this additional power, helping to stabilize the electrical grid. After the disturbance, the wind turbines enter a recovery phase, gradually restoring the rotor speed and power output to their normal operating levels.
3. **Hidden inertia emulation:** This technique replicates the inertia response of traditional generators, providing immediate support to counteract frequency fluctuations. Inertial emulation enhances the wind turbines' ability to contribute to electrical grid stability by delivering a rapid response to frequency changes, similar to the inertial response provided by conventional generators. This is achieved through advanced control algorithms that simulate the effect of physical inertia, allowing wind turbines to support the electrical grid more effectively during transient events.

1.5.2.2 Using ESS

Energy storage systems (ESSs) are among the most reliable control strategies implemented to mitigate low inertia and frequency issues (figure 1.13). ESSs can be integrated into the electrical grid with wind energy electrical power systems, providing a dependable solution adaptable to the varying nature of wind. Various ESSs, such as BESS, superconducting magnetic energy storage systems (SMES), flywheel energy storage systems (FESS), supercapacitors, and combinations like BESS with automatic generation control (AGC), are crucial for delivering improved frequency response during faults. Since ESSs differ in energy and electrical power density, hybrid techniques based on ESS have been suggested as an effective frequency response solution. For instance, SMES can enhance the frequency response of permanent magnet synchronous generators (PMSG) due to its fast response characteristics.

In PMSG wind energy systems, an artificial inertia controller provides duties to the boost converter in the DC link, controlling power output and torque by managing the current through the reactor, thereby improving frequency response. Doubly-fed induction generator (DFIG) wind energy systems employ flywheel energy storage to provide primary frequency response by appropriately distributing the reserve active power between the turbine and the flywheel. This power reserve is activated by local controls when the RoCoF deviates from the set value, with these local controls being further activated by the central control situated within the operator's premises.

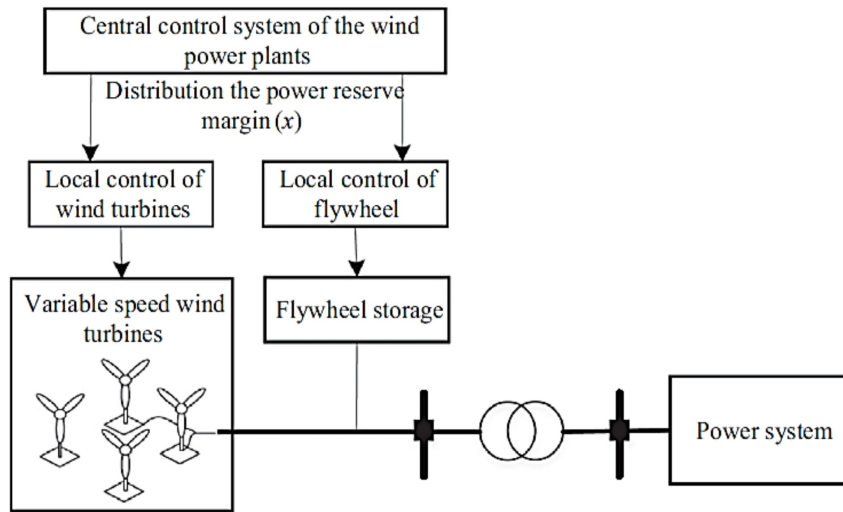


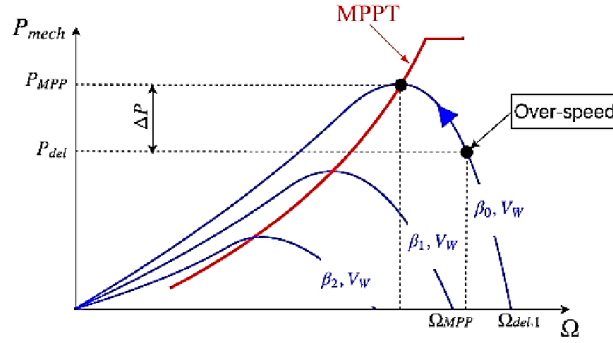
FIGURE 1.13 – Flywheel energy storage systems control techniques for variable-speed wind turbines [23]

1.5.2.3 Deloading techniques

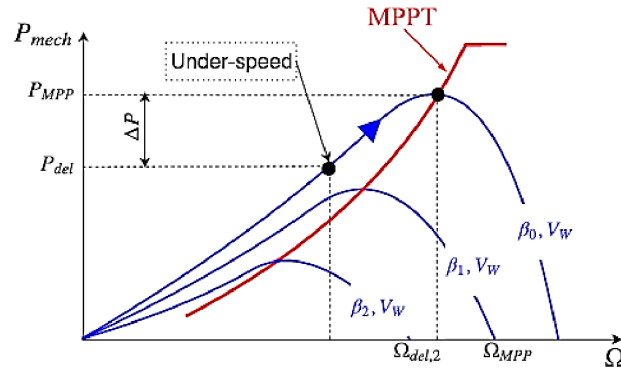
In general, the deloading technique in wind turbine systems involves two types of control systems: speed control and pitch angle control.

1. **Deloading by speed control (SC):** Speed control adjusts the value of the tip speed ratio (λ) by shifting the operating point to the left or right of the maximum power point, as illustrated in figures 1.14(a) and 1.14(b). When the wind turbine operates at point A, deloading can be achieved through under-speed or over-speed control. In under-speed control, the operating point moves towards point C, while in over-speed control, the operating point shifts towards point B, which is the preferred method.
2. **Deloading by pitch angle control (PAC):** Pitch angle control is used to deload the wind turbine by increasing the blade's pitch angle (figure 1.14(c)). This controller is

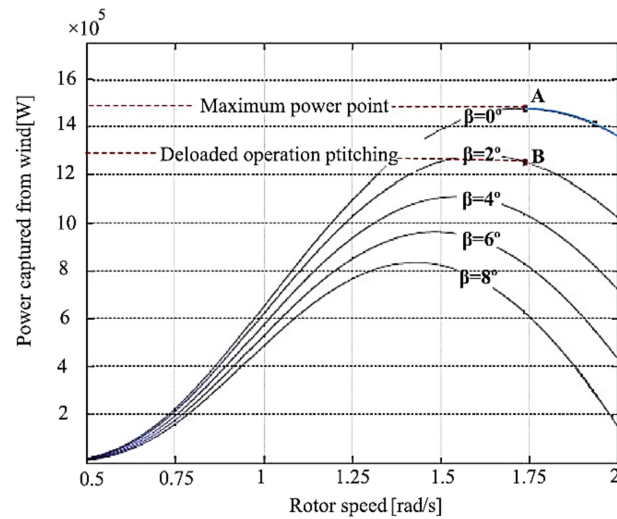
typically activated when the wind turbine generator reaches its rated speed and when the over-speed controller is unable to perform the deloading operation.



(a) Over-speed control



(b) Under-speed control



(c) Pitch angle control

FIGURE 1.14 – Deloading techniques for variable-speed wind turbines [25]

1.6 PFC techniques comparison

Both deloading and energy storage systems (ESS) contribute to maintaining frequency stability in grids with high renewable energy penetration. However, deloading stands out due to its cost-effectiveness, efficiency, and long-term reliability. By reducing the output of PV and wind systems below their maximum capacity, deloading enables rapid frequency response without requiring additional infrastructure investments. It provides a stable, long-lasting solution without suffering from capacity degradation, unlike ESS.

Conversely, ESS offers flexible energy storage and release, enhancing electrical grid stability. However, its high capital costs, operational expenses, and battery degradation limit its long-term viability. While ESS can effectively manage short-term fluctuations, its dependency on storage capacity and frequent cycling makes it a more complex and costly option. Given its real-time adaptability, lower cost, and minimal operational requirements, deloading

Technique	Advantages	Disadvantages
Deloading	- Cost-effective - No conversion losses - Long lifespan	- Reduces generation revenue - Wastes potential energy - Limited scalability
Energy Storage Systems	- Generates revenue - Fast response time - Prevents curtailment	- High capital and maintenance costs - Battery degradation - Complex setup

TABLE 1.1 – Comparison of Deloading and Energy Storage Systems

proves to be a more scalable and sustainable PFC solution. It optimizes power generation while maintaining electrical grid stability, making it a technically and economically favorable alternative to ESS [27].

Table 1.1 summarises the key differences between these PFC techniques.

Traditional and advanced deloading methods for PV and WT systems Advanced control techniques, particularly AI-based methods, have significantly improved the effectiveness of deloading strategies in PV and wind turbine systems. While traditional control methods, such as proportional (P), integral (I), and derivative (D) controllers, have been widely used for managing electrical power extraction uncertainties, their performance is often limited by fixed tuning parameters and difficulty in adapting to dynamic fluctuations. Hybrid

controllers like PI, PD, and PID enhance reliability by balancing system response, but they still struggle with handling complex nonlinearities and unpredictable disturbances [28].

In contrast, AI-driven techniques such as artificial neural networks (ANNs), fuzzy logic (FL), genetic algorithms (GA), particle swarm optimization (PSO), and reinforcement learning (RL) introduce adaptive and predictive capabilities that significantly enhance system performance. These approaches excel in managing uncertainties, optimizing energy production, and ensuring real-time adjustments to electrical grid conditions. For instance, ANNs improve forecasting accuracy, FL effectively handles nonlinearities, and GA optimizes control parameters. Moreover, reinforcement learning (RL) and model predictive control (MPC) enable proactive decision-making, further boosting system efficiency and resilience [29].

The main distinctions between classical and advanced techniques are:

- ★ Handling uncertainties: Traditional methods struggle with nonlinearities and fluctuations, while AI-based methods effectively manage uncertainties and optimize responses.
- ★ Response time: Traditional methods have a moderate response and adapt slowly, whereas AI-based methods provide fast, real-time adaptation to sudden changes.
- ★ Performance: Traditional methods perform poorly in high renewable energy systems, while AI-based methods efficiently handle dynamic fluctuations.
- ★ Scalability: Traditional methods degrade in performance as system complexity increases, while AI-based methods scale effectively to large and complex systems.

Several research studies have explored AI-driven deloading techniques for PV and WT systems, integrating machine learning, fuzzy logic, and optimisation methods to enhance power reserve management, frequency control, and system adaptability. Table 1.2 below summarises key AI-based deloading techniques from the literature, highlighting their specific methods and contributions for both PV and WT systems:

Reference	AI-Based Deloading Technique and Contribution
[29]	Implements adaptive power-voltage matching (APVM) to optimize PV power extraction while ensuring a power reserve without MPPT. AI enables dynamic power regulation and enhances the system's responsiveness to fluctuating environmental conditions.
[30]	Uses an artificial neural network (ANN) for accurate real-time power reserve estimation in PV systems. By leveraging AI-driven predictive analytics, it minimizes reliance on static models and improves energy management through adaptive learning and dynamic adjustment to varying conditions.
[31]	Proposes a linear regression-based AI model for estimating maximum PV power output under fluctuating environmental conditions. By continuously refining power predictions, AI enhances adaptability, optimizes energy utilization, and improves overall system reliability.
[32]	Combines ANN and fuzzy logic to optimize PV deloading and power reserve management. AI-driven predictive modeling and rule-based control enhance decision-making, ensuring optimal power allocation and system performance.
[33]	Introduces a deep learning-assisted adaptive nonlinear deloading (DL-AND) method for wind turbine load frequency control. By leveraging AI-driven deep learning techniques, the proposed approach enhances adaptability to frequency fluctuations, ensuring faster response times and more efficient energy regulation.

Reference	AI-Based Deloading Technique and Contribution
[34]	Presents a heuristic fuzzy logic controller (FLC) designed for frequency regulation in hybrid wind power systems. Utilizing AI-driven real-time adjustments, the proposed approach dynamically optimizes fuzzy rules to enhance electrical grid stability, ensuring effective adaptation to fluctuating power demand.
[35]	Employs artificial bee colony (ABC) optimization to autonomously tune a fuzzy-based PID droop control system for wind turbines. The AI-driven self-tuning mechanism dynamically selects optimal control parameters, enhancing turbine performance across diverse operating conditions and improving overall system stability.
[36]	Presents a game theory-based AI model for distributed control of rotor speed and kinetic energy storage in variable-speed wind turbines (VSWTs). The AI-driven approach optimizes cooperative decision-making among turbines, enhancing power regulation efficiency and maximizing energy storage utilization for improved system performance.
[37]	Optimizes fuzzy droop control in wind turbines through artificial bee colony (ABC) optimization, enabling self-tuning capabilities. By dynamically adjusting droop parameters in real-time based on electrical grid conditions, the AI-driven approach enhances frequency regulation.

TABLE 1.2 – Summary of AI-based deloading techniques in PV and WT systems, highlighting the role and necessity of AI

1.7 Conclusion

This chapter has examined recent advancements in RES integration, with particular attention to the breakthroughs achieved in 2023. Among RES technologies, PV and WT systems have emerged as the most dominant, reflecting their widespread adoption and critical role in the evolving energy sector.

The integration of WT and PV systems into electrical grids has significantly enhanced overall grid performance. However, as the penetration of RES continues to grow, challenges related to grid regulation and stability are becoming increasingly critical. This chapter has provided an in-depth analysis of the impact of RES integration on grid quality with a parti-

cular emphasis on frequency regulation. It includes a clear definition of grid frequency and its various phases, highlighting the crucial role of stable frequency in grid operations. Additionally, the chapter recognizes that the integration of RES can lead to frequency disturbances and system instability, both of which pose significant concerns for grid operators.

A major focus of this chapter was on PFC techniques used in PV and wind energy systems. An overview of widely utilized PFC methods was presented, along with an assessment of their effectiveness in maintaining electrical grid stability. A comparative analysis between two key PFC techniques, deloading and ESS, was conducted. The findings demonstrated that deloading techniques outperform ESS in maintaining frequency stability due to their ability to directly regulate power output and manage electrical grid fluctuations more effectively.

Additionally, the chapter explored advancements in AI applications for deloading control strategies. A comparison between conventional deloading techniques and AI-driven approaches revealed that AI-enhanced methods offer significant improvements. Advanced techniques such as ANN, FLC, and other AI-based models provide enhanced adaptability, predictive capabilities, and real-time response, leading to more efficient and effective electrical grid management. Key examples of AI-based deloading strategies in both PV and wind systems were presented, demonstrating their potential to mitigate RES integration challenges and optimize electrical grid performance.

In conclusion, this chapter underscores the importance of both traditional and advanced control methods in managing the effects of RES integration. It highlights the continuous evolution of these technologies and their pivotal role in ensuring a stable and reliable electrical grid. As RES penetration increases, the development and implementation of sophisticated control strategies, particularly AI-driven solutions, will be essential in maintaining grid resilience and sustainability.

Chapter 2: Advanced Real-Time Deloading Techniques for Frequency Regulation in PV Systems

This second chapter explores the integration of PV energy by providing an overview of PV modeling and grid configurations. It then introduces and evaluates a novel deloading technique for PV systems, which is further optimized by incorporating a real inertia configuration to enhance frequency stability. Finally, the chapter concludes by discussing the implementation of an advanced control mechanism within the proposed PV deloading system, highlighting its added benefits and contributions.

2.1 Introduction

Aligned with the study's objectives, this chapter embarks on a comprehensive PV grid systems analysis. A deep understanding of the dynamic behavior of PV systems is crucial for gaining insights into their operation and integration. The chapter begins with a detailed description and modeling of PV systems, focusing on key components and their interactions within the energy conversion process. This foundational groundwork is essential for accurately predicting system behavior and optimizing performance.

A significant contribution of this chapter is the presentation of a novel deloading technique designed to enhance the efficiency and reliability of PV systems. This technique is rigorously tested and validated to ensure its effectiveness in real-world conditions. The chapter also integrates this deloading approach with advanced frequency control mechanisms, demonstrating its potential to improve grid stability and performance.

Furthermore, the chapter explores the application of AI in refining the proposed deloading technique. Specifically, it incorporates FLC and GA to optimize control parameters and

enhance system adaptability. The integration of these AI techniques is validated through a series of tests, showcasing their impact on system performance and their ability to address the challenges associated with variable renewable energy sources.

By presenting both theoretical insights and advanced methodologies in PV system optimization, including innovative deloading strategies and AI-enhanced control techniques, this chapter aims to contribute valuable knowledge to the field of photovoltaic technologies and their integration into modern energy systems.

2.2 Description and modeling of PV systems

This section introduces the fundamental concepts of PV system modeling, including key models and their applications, to better understand and enhance PV system performance under various conditions.

2.2.1 PV modelling

PV cell modeling is essential for optimizing solar energy systems. These models, as presented in figure 2.1, simplify complex physical processes into electrical circuits, helping design and adjust PV systems effectively. Key components include PV current sources, diode junctions, series and shunt resistances, and factors such as temperature and irradiance effects [38]. Various models are used to study PV cells: Single diode model: Includes a PV current

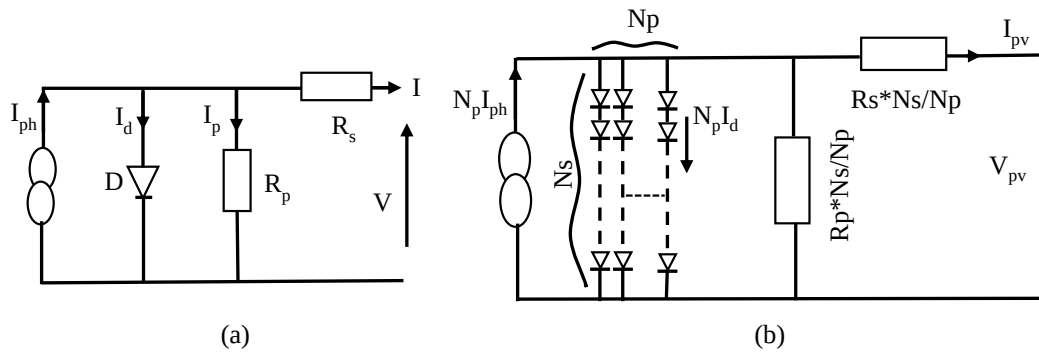


FIGURE 2.1 – Single diode electrical model : (a) PV cell model (b) PV array model

source, diode junction, series resistance, and shunt resistance. Double diode model: Adds an extra diode for improved accuracy in high-efficiency cells. Bishop model: A highly precise model suitable for real-world applications with varying environmental conditions [39, 40].

The electrical model for a PV cell is given by:

$$I = I_{ph} - I_0 \left[e^{\frac{V + IR_s}{nV_t}} - 1 \right] - \frac{V + IR_s}{R_p} \quad (2.1)$$

The mathematical equivalent model for a PV array, consisting of N_s cells in series and N_p cells in parallel, is presented as:

$$I_{PV} = N_p I_{ph} - N_p I_0 \left[e^{\frac{V_{PV} + IR_s(N_s/N_p)}{nV_t N_s}} - 1 \right] - \frac{V_{PV} + IR_s(N_s/N_p)}{R_p(N_s/N_p)} \quad (2.2)$$

The mathematical model that characterizes the electrical behavior of PV cells and arrays introduces a set of critical variables and parameters, which include: I and I_{PV} : The current flowing through the PV cell and array, respectively; V and V_{PV} : The voltage across the PV cell and array, respectively; I_{ph} : Photocurrent corresponds to the current generated by sunlight;

I_0 : Diode saturation current;

V_t : Thermal voltage is influenced by the PV cell's temperature;

n : Diode ideality constant provides insights into diode characteristics;

R_s : Series resistance accounts for internal electrical losses;

R_p : Parallel resistance reflects any parallel paths for current within the cell.

Graphical representations such as the I-V and P-V curves, figure 2.2, illustrate the PV system's performance:

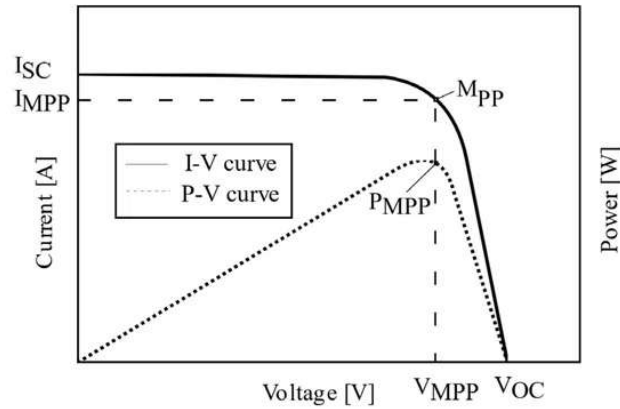


FIGURE 2.2 – PV system characteristics

I-V curve: shows the relationship between current and voltage, including the maximum power point (MPP) [41].

P-V curve: depicts power output relative to voltage, also highlighting the MPP.

Environmental factors like irradiance and temperature significantly affect PV performance, as shown in figure 2.3 :

Irradiance: Higher levels increase power output, while lower levels reduce it. Variations in irradiance shift the MPP [42].

Temperature: Higher temperatures decrease efficiency by lowering voltage and increasing internal resistance [43].

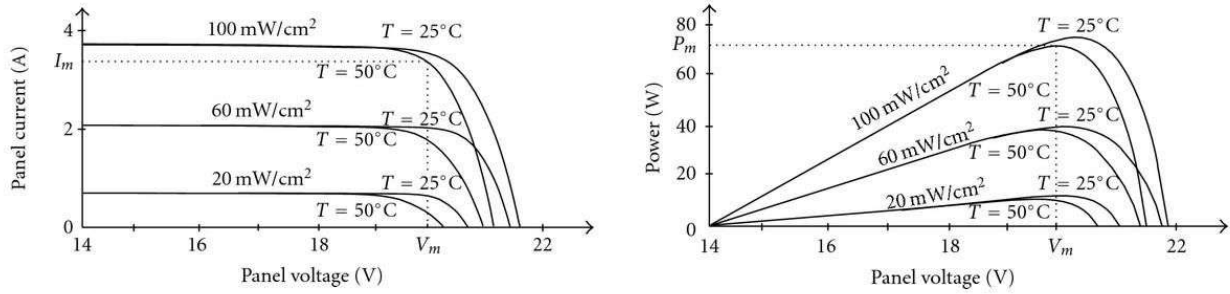


FIGURE 2.3 – Irradiation and temperature influence

2.2.2 PV grid system

PV grid systems come in two main configurations, as illustrated in figure 2.4 :

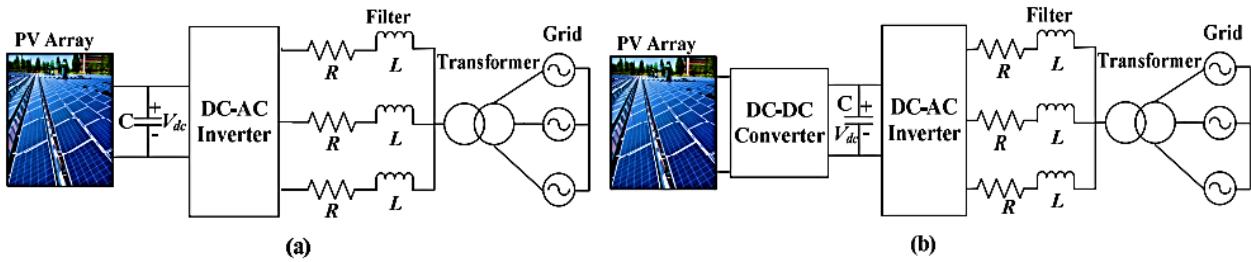


FIGURE 2.4 – PV grid systems: (a) single stage (b) double stage [44]

- ★ Single-stage: simpler but less versatile (figure 2.4(a)).
- ★ Double-stage: more commonly used, includes a DC-DC converter for better control (figure 2.4(b)) [44, 45].

Components of a PV grid system include:

DC-DC converters: optimize energy output by matching voltage or current with load requirements. Types include Buck, Boost, Cuk and Buck-Boost converters (figure 2.5) [46, 47].

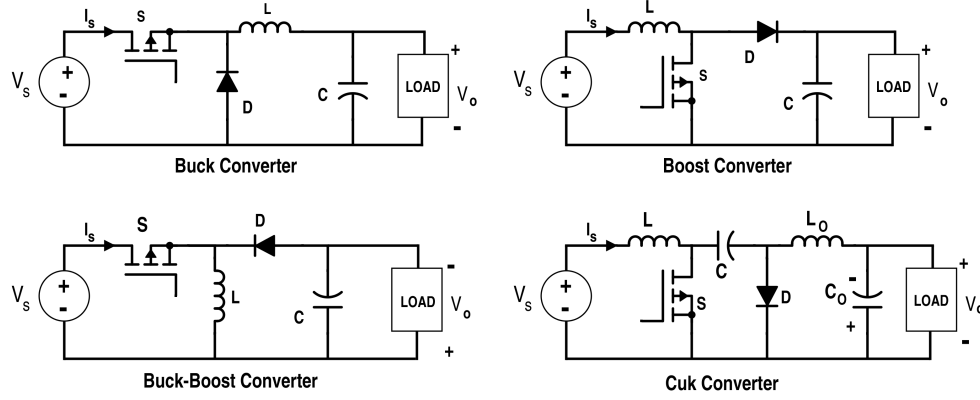


FIGURE 2.5 – DC-DC Converter types

DC-AC inverters: Convert DC power from PV panels into AC power for grid compatibility. Types include string inverters, microinverters, central inverters, hybrid inverters, and grid-tied inverters with backup (figure 2.6) [48–50].

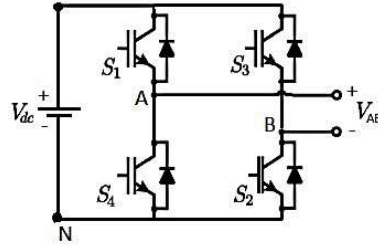


FIGURE 2.6 – Single-stage DC-AC inverter circuit

Three-phase RLC filter: Improves output quality by filtering harmonics, reducing noise, stabilizing voltage, and suppressing transients (figure 2.7) [51, 52].

2.3 Deloading technique and hybrid inertia

The existing literature on deloading techniques presents several limitations. In [17], a method for maintaining power reserves is proposed, utilizing deloading reference power generated through an ANN model to estimate the maximum PV power. Similarly, in [18], a linear

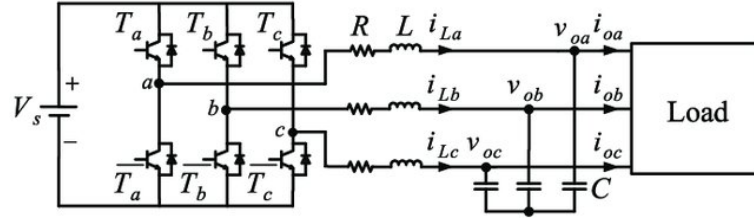


FIGURE 2.7 – Three-phase inverter with RLC filter

regression-based approach is introduced to estimate maximum power under different environmental conditions, ensuring the necessary power reserve. However, both techniques exhibit reduced accuracy in dynamic climatic conditions, as they rely on offline analytical models and training-based assumptions. Furthermore, these methods assume uniform temperature and sunlight distribution across all PV modules, overlooking the impact of partial shading. Additionally, the requirement for temperature and irradiation sensors increases installation and maintenance costs.

A different PRC technique, described in [19], employs periodic switching between two computational blocks—one responsible for estimating the available PV power and the other for calculating deloading power and defining the target power reserve. However, this periodic switching introduces fluctuations, reducing the lifespan of system components and affecting overall stability.

This thesis presents a novel online deloading technique based on a PRC approach. The proposed method is distinguished by its simplicity and independence from complex mathematical models, system parameters, and additional equipment. It operates through a cyclic control mode of the DC-DC converter, utilizing conditional switching to effectively adapt to changing climate conditions, such as temperature and irradiation variations. By eliminating reliance on external sensors and auxiliary systems, such as the DC link conductance mentioned in [53], this approach addresses the limitations of previous PRC methods. The proposed technique streamlines the deloading process, ensuring robust performance in fluctuating environmental conditions without requiring extensive additional infrastructure.

In addition to the novel PRC approach that leverages virtual inertia (VI), this thesis also explores the use of synchronous generators (SGs) to provide real inertial (RI) responses in PV systems. These SGs, which have been relied upon for over a century for their reliable RI responses, can be integrated into the grid using static frequency converters or methods similar to those used in hydrogenerators. Figure 2.8 illustrates our suggested strategies for integrating the hybrid inertia (HI) consisting of VI and RI in frequency regulation.

Moreover, the thesis will analyze the performance of the HI response. This hybrid approach seeks to optimize grid stability by leveraging the strengths of both VI and RI, offering a comprehensive solution to enhance the overall performance and reliability of PV systems in the grid.

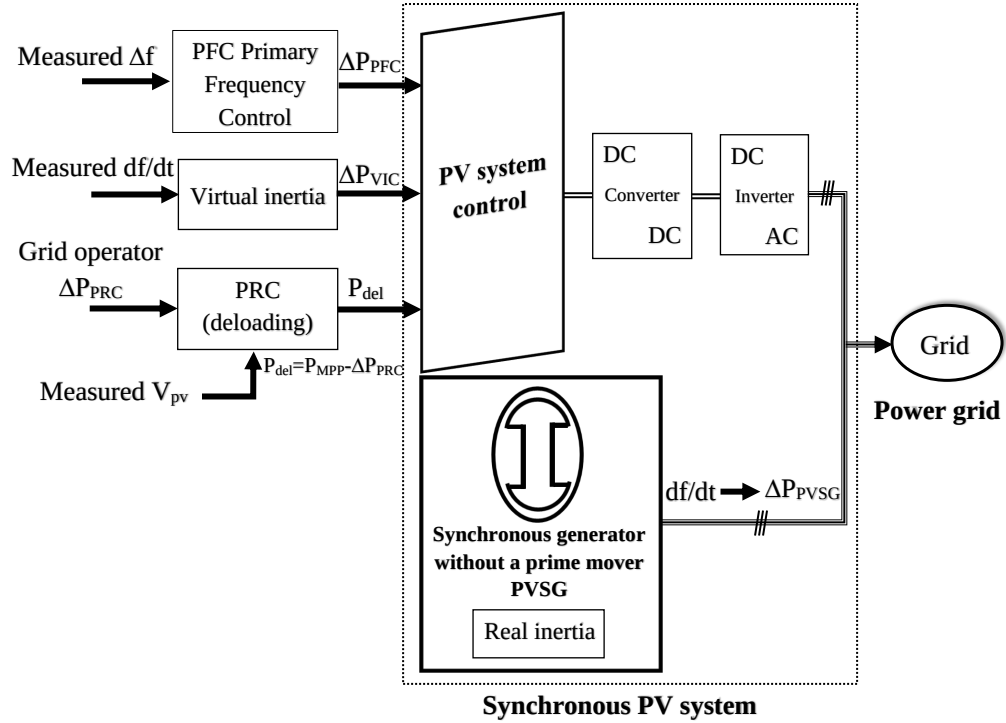


FIGURE 2.8 – Proposed PRC strategy

2.3.1 PRC modes

The PRC method operates in a cyclic manner involving two distinct modes of PV power converter, as illustrated in figure 2.9. The first one, MPPT mode, is used to identify and track the available PV power (P_{mpp}). The duration of this mode, denoted as T_1 , is adjustable based on experimental needs to ensure accurate tracking. Following MPPT, the system switches to PRC mode, which is designed to maintain the PV plant at a deloaded operating point. The duration of PRC mode is set to T_2 , allowing time for the system to stabilize at the deloaded power level.

During the entire cycle period (T_{cyc}), which is the sum of T_1 and T_2 , the switching control signals are not actively considered. Once the cycle is triggered, the MPPT mode operates for T_1 seconds to maximize power output, after which the PRC mode is activated for a minimum

of T_2 seconds.

In MPPT mode, the perturb and observe (P&O) method is employed, which relies on measurements of PV voltage (V_{pv}) and current (I_{pv}). This method enables the PV plant to operate at its maximum power output without requiring additional sensors for irradiation and temperature [54]. Upon completion of MPPT mode, the maximum power value (P_{mpp}) and corresponding PV voltage (V_{mpp}) are recorded and used by the PRC mode.

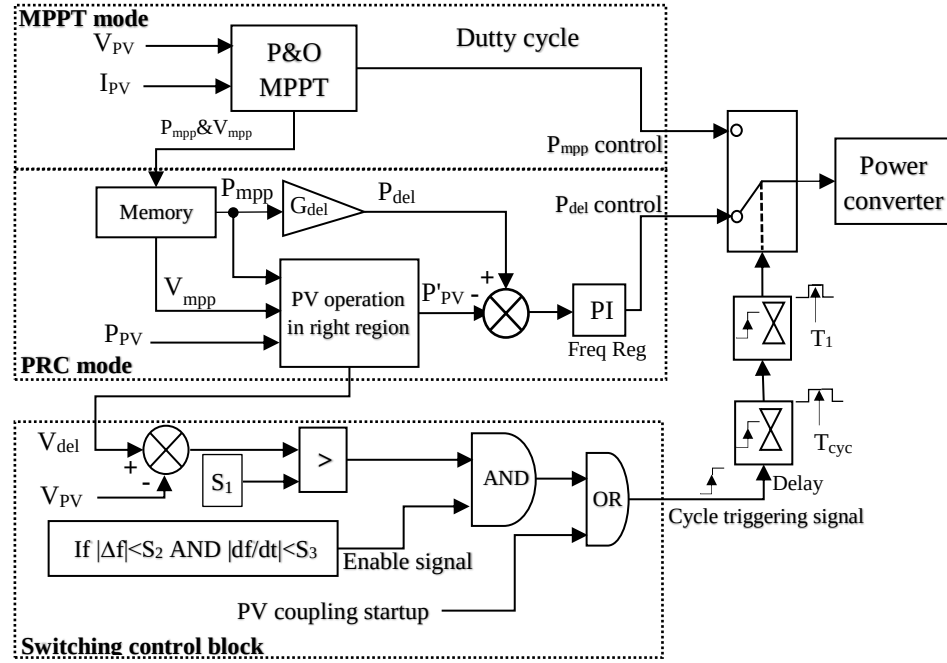


FIGURE 2.9 – Proposed PRC strategy

The PRC mode utilizes a simple PI controller to adjust the PV operation around a deloading power reference (P_{del}). This reference is set to ensure that the PV plant operates in a stable and controlled manner. The power reserve (ΔP_{PRC}) is calculated as the difference between P_{mpp} and P_{del} , as shown in the following equations:

$$\begin{cases} P_{del} = G_{del} \times P_{mpp} \\ \Delta P_{PRC} = P_{mpp} - P_{del} \end{cases} \quad (2.3)$$

Here, G_{del} represents the deloading gain, defined by the operator (e.g., $G_{del} = 0.9$ corresponds to 90% of P_{mpp}). This method ensures a reliable and adjustable power reserve to enhance grid frequency stability.

2.3.2 Switching control block

As shown in figure 2.9, the cycle starts after the coupling of the PV plant with the grid. The MPPT is activated for T_1 seconds, followed by the PRC mode, in which the active power generated by the PV is controlled to the deloaded value P_{del} . During a variation in the solar irradiation or/and temperature, the PV voltage V_{pv} will change due to the regulation loop that regulates the active power to the deloaded one. Consequently, the PV voltage signal is used to identify a change in the available power. Any fluctuation in PV plant voltage V_{pv} is monitored by the switching control block. This detection is accomplished by calculating the instantaneous relative error $Ev(t)$ of the observed V_{pv} as described in equation 2.4 and comparing it to a predetermined threshold S_1 bigger than the voltage sensor error. In our study, S_1 is set to 0.2%. The error $Ev(t)$ is defined as follows:

$$Ev(t) = \frac{V_{del} - V_{pv}}{V_{max}} \quad (2.4)$$

With V_{del} and V_{max} denote the deloading voltage and the maximum voltage measurable by the voltage sensor, respectively.

As presented in figure 2.9, the triggering signal can be inhibited when the enable signal is deactivated. This signal ensures that the PV voltage variation used by the switching control is only related to weather condition changes (temperature and/or irradiation). The following tasks are made possible by the trigger signal:

- ★ Cycle (MPPT mode then PRC mode) activation with each change of G and/or T to supply the operator requested power reserve in real-time with a cycle activation at PV plant coupling;
- ★ The PV voltage variation detection block should be deactivated during the cycle period (T_{cyc}), and at the end of it, the system should be kept in PRC mode until the next activation;
- ★ If a frequency error occurs during a grid perturbation and frequency regulation phase, the voltage variation detection is deactivated. At the end of this phase, the PV voltage variation detection block must be reactivated.
- ★ To identify the end of the frequency regulation phase, a frequency speed signal is charged. When this signal is turned on, the cycle mode is started for that specific operation. In the event that a change in the climate occurs during the frequency regulation cycle, this activity is carried out to update the power reserve.

2.3.3 Deloading region

Figure 2.10 presents the P-V characteristics of a 100 kW PV system. The PV curve shows that each P_{del} value has two possible points on each side with their own voltage, one on the left side with V_{delL} voltage and one on the right side with V_{delR} voltage. The PV panel may fluctuate or swing between V_{delL} and V_{delR} as the PI controller tries to reach the P_{del} value, which could cause momentary instability. To avoid this issue, one deloading zone must be fixed; it is visible that the right region of the PV curve has bigger voltage values than the left region. Higher voltage levels enhance converter efficiency by offering higher voltages and faster dynamic response as a result of a steeper slope [55]. As a result, in our work, we preferred the operation on the right side of the curve using V_{delR} as deloading voltage.

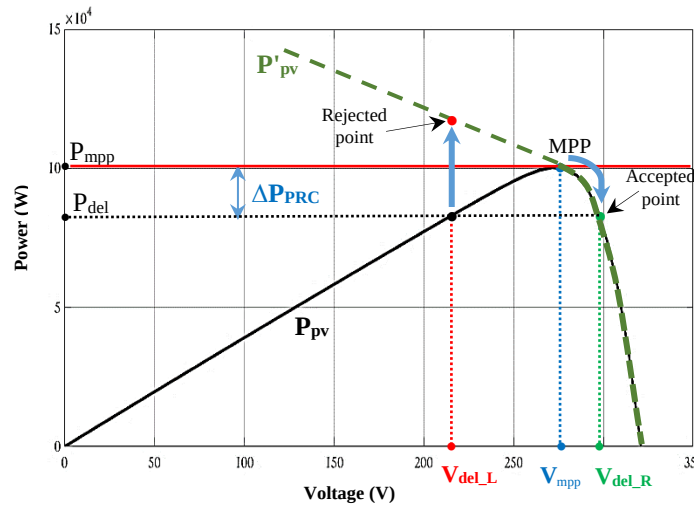


FIGURE 2.10 – PV linearization for the operation in the right region (100 kW PV)

A monotone technique is used to ensure that the deloading process is conducted in the correct region. The principle of this algorithm is to modify the panel's PV curve (solid line) by a curve changing P'_{pv} (dotted line) as shown in figure 2.10. This new curve is identical to the original curve in the right region of the MPP, but in the left region P'_{pv} is a PV curve image created by mirroring based on a horizontal line that passes through the MPP point. The image of deloading voltage in the left region has high power corresponding values above the P_{del} reference value, which will cause a significant negative error at the PI controller ($P'_{pv} - P_{del}$). As a result, the PI controller rejects this region and retains only the V_{delR} values.

The new PV power plant P'_{pv} is calculated as follows:

$$P'_{pv}(t) = \begin{cases} P_{pv} & \text{si } V_{pv} \geq V_{mpp} \\ 2P_{mpp} - P_{pv} & \text{sinon} \end{cases} \quad (2.5)$$

2.4 Primary frequency control and inertial response

2.4.1 Primary frequency control

In this study, we employ the same strategy utilized in hydropower plants and several PFC research studies [56]. It is based on a droop gain (K_{Droop}), which quantifies the plant's participation level in keeping the frequency at the nominal value. Figure 2.11 depicts the frequency regulation loop, which includes the PRC, PFC, and virtual inertia control (VIC) strategies. Regarding the PFC, in a steady state, the PI input must be equal to zero and the power provided by the virtual inertial response is zero. Consequently:

$$\Delta P_{PFC} = P'_{pv} - P_{del} = \Delta f / K_{Droop} \quad (2.6)$$

The frequency variation (Δf) is calculated as:

$$\Delta f = \frac{f_0 - f_m}{f_0} \quad (2.7)$$

f_m and f_0 are the measured frequency and the nominal frequency, respectively.

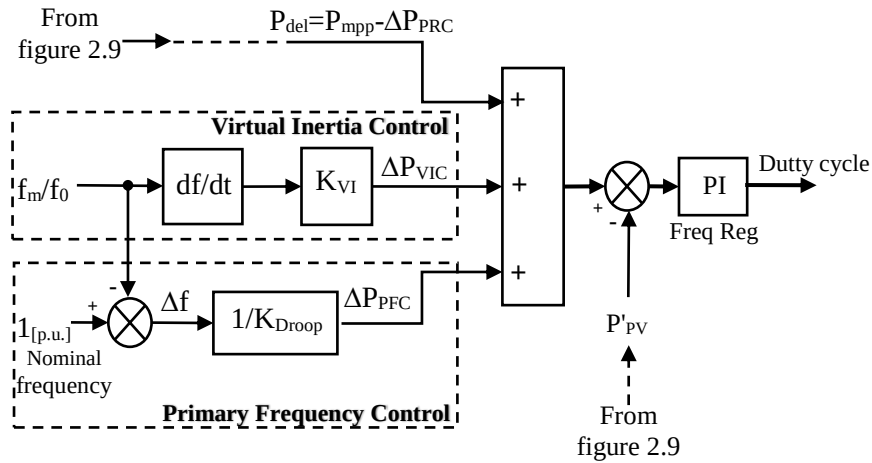


FIGURE 2.11 – Frequency regulation diagram: PRC, PFC, and VIC

For example, for $K_{Droop} = 4\% = 0.04$, if the frequency changes by -0.4% (-200 mHz), the PV plant will increase the injected power by 10% (0.1 p.u.). The maximum power of the PV, which is dependent on temperature and irradiation, can be utilised as the base active power for normalisation. The base or nominal frequency (f_0) is 50 Hz or 60 Hz.

The following formula can be used to adjust K_{Droop} depending on the amount of power required to be injected during a specific fluctuation of the grid frequency:

$$K_{Droop} = \frac{\Delta f_{max}}{1 - G_{del}} \quad (2.8)$$

with Δf_{max} being the highest frequency that causes an increase in injected power equal to the power reserve amount.

2.4.2 Inertial control strategy

The PFC often specified by grid codes allows the injected power to be increased or decreased proportionately to the frequency variation. However, inertial response inherited from synchronous power plants (hydro, thermal, etc.) modifies the injected power based on the RoCoF ($\frac{df}{dt}$) that depends on the intensity of the grid perturbation. The swing equation in synchronous power plants can be expressed as follows:

$$2H \times \frac{d\bar{w}}{dt} = \bar{P}_m - \bar{P}_e - D \times \bar{w} \quad (2.9)$$

$$\bar{P}_e = \bar{P}_m - 2H \times \frac{d\bar{w}}{dt} - D \times \bar{w} \quad (2.10)$$

Where $\bar{P}_e$ and $\bar{P}_m$ are respectively the mechanical power and electromagnetic power of the SG in per unit. H is the inertia constant that is proportional to the rotating component's moment of inertia. $\bar{w}$ is the angular frequency in per unit, and D is a damping coefficient.

To mimic the inertial response provided by a synchronous power plant, we consider an additional power reference ΔP_{VIC} for the PV controller to provide a virtual inertial response. ΔP_{VIC} is proportional to the RoCoF [57].

$$\Delta P_{VIC} = 2H_{PV} \times \frac{df}{dt} \quad (2.11)$$

ΔP_{VIC} is the additional power reference for VIC. H_{PV} is the equivalent virtual inertia constant.

In this work, this quantity of power (ΔP_{VIC}) is obtained using the absolute value of frequency RoCoF multiplied by the sign of frequency deviation, as follows:

$$\Delta P_{VIC} = 2H_{PV} \times sig(\Delta f) \times abs(\frac{df}{dt}) \quad (2.12)$$

where: $\text{sig}(\Delta f)$ is the frequency deviation's sign, which is positive when the frequency reduces and negative when it rises. $\text{abs}(\frac{df}{dt})$ is the absolute value of the RoCoF.

The idea of combining the two control loops, PFC and VIC, into frequency regulation is depicted in figure 2.11. When a frequency fluctuation emerges, the PV power reference is updated to respond to this variation; the new power reference is equal to the total of the previous deloading power and the power requested by both the PFC and the VIC.

Virtual inertia is a good means to provide a fast response during a frequency variation. However, as discussed in the introduction, synchronous generators provide inertial response without any control. The PV synchronous generator (PVSG) proposed in this study is mainly used to provide a real inertial response. It can be equipped with an excitation system to control the reactive power to zero or work as a synchronous compensator. In terms of electrical design, the nominal active power of the PVSG is minimized, and it is equivalent to the power needed from the grid to run the generator as a motor and recover the iron and friction losses. Moreover, synchronous generators used in closed thermal power plants can be used as PVSG. This paper does not consider the PVSG design but its effect on frequency regulation, which is mainly determined by the inertia constant H or the moment of inertia of the rotor part. We will also examine the behavior of the complete system in the presence of a real and a virtual inertial response given by the control system (hybrid response).

2.5 Proposed PV PRC system configurations

As presented in figure 2.12, the proposed PV system includes a 100 kW PV system made up of 66 parallel strings, each of which is made up of 5 SunPower SPR-305E-WHT-D modules in series [56]. A two-stage converter is used to couple the PV with the grid. The DC-DC converter of type boost is controlled by the frequency regulation control block that includes the PRC, PFC, and VIC. The boost converter component values are calculated using the equations cited in [58]. The DC-AC inverter is controlled to achieve a constant DC voltage and zero reactive power ($I_{q-ref}=0$). This last control strategy is very used with double-stage inverters where a park transformation is used and a decoupling between the d-axis and the q-axis is implemented. Details about the inverter control in the d-q axis are explained in multiple papers [59, 60]. The LR filter at the inverter output allows filtering of the injected current. The values of R_f and L_f are also calculated using [61].

The proposed PV system is coupled to the grid under two configurations: an infinite grid and a non-infinite (isolated) grid. In the infinite configuration, the grid is modeled

as a voltage source with constant frequency and voltage. In contrast, the isolated grid is represented in Simulink by a large synchronous generator with variable loads, which can be modified abruptly. In this case, load variations directly influence the grid frequency. The PVSG used in the simulation is connected to the grid via a circuit breaker. The Table in the

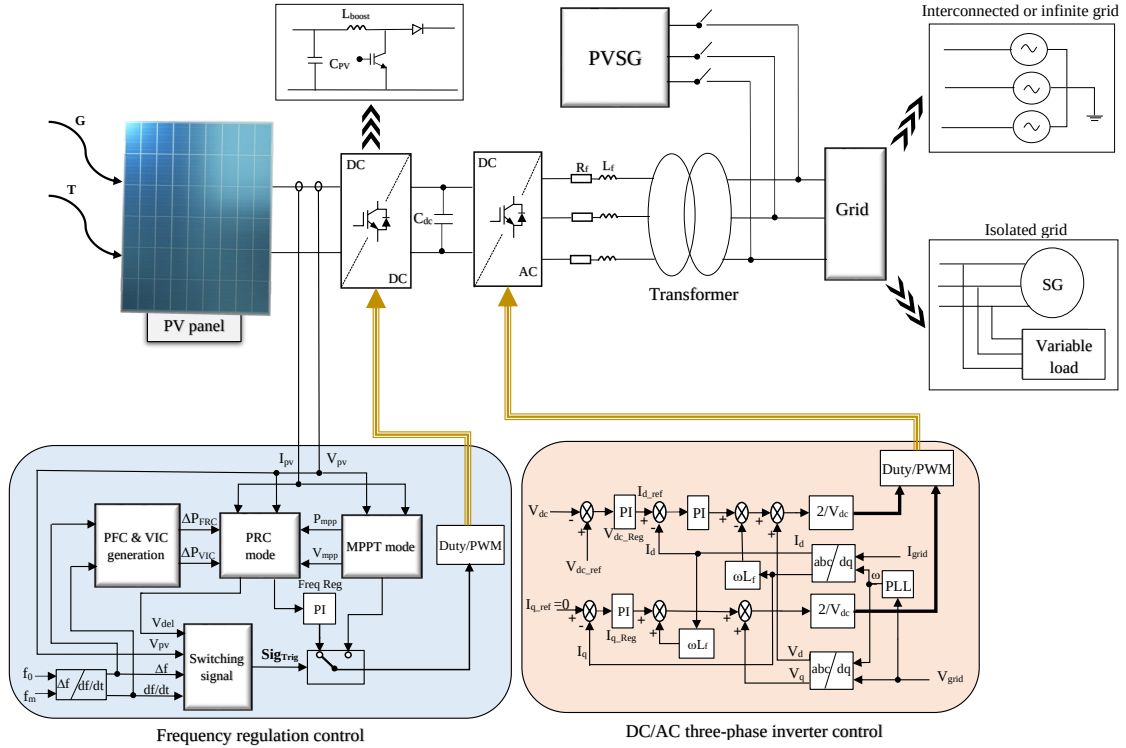


FIGURE 2.12 – Bloc diagram of the complete system implemented in Matlab

appendix lists all component characteristics and controller settings. It should be mentioned that the offered solutions were tested on a double-stage PV system, although they are equally applicable to a single-stage PV system.

The proposed system, under different configurations, is implemented in Matlab Simulink software.

2.6 Simulation tests and results

The experiments conducted to validate the suggested techniques, along with their integration into frequency control and grid frequency stability enhancement, are summarized in Table 2.1. The main objective of the first test, focusing on the PRC, is to validate the correct

operation of the new PRC algorithm under variations in irradiation and/or temperature. The other tests (PFC, VIC, RI, and HIC) demonstrate the contributions of the proposed structures to frequency regulation.

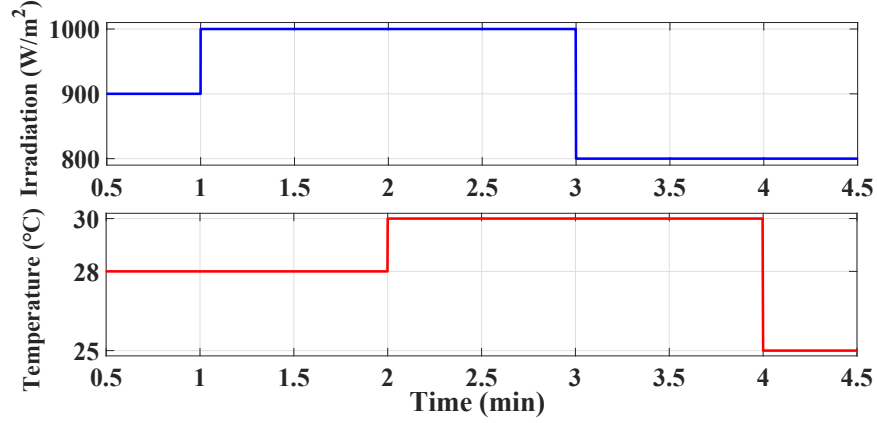
TABLE 2.1 – Realised tests

Tests	Interconnected (infinite grid)	isolated
PRC Climatic change ($\Delta G, \Delta T$)	✓	✓
PFC	✓	✓
VIC	✓	✓
Real inertia (RI)	X	✓
Hybrid inertia control (HIC)	X	✓

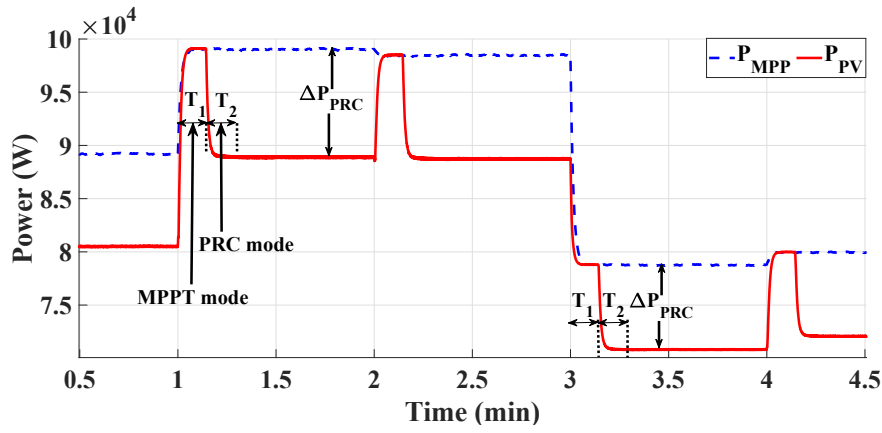
2.6.1 PRC validation

This test shows that the suggested PRC approach produces the desired power reserve under a variety of environmental conditions. Due to this, the PV plant is connected to an infinite grid without coupling the PVSG, then it is applied to the climatic scenario (ΔG and ΔT) depicted in figure 2.13(a). The chosen climatic scenario replicates two changes in radiation: an increase in G from 900 W/m^2 to 1000 W/m^2 at $t = 1$ minute, followed by a decrease to 800 W/m^2 at $t = 3$ minutes, and two changes in temperature: an increase in T from 28°C to 30°C at $t = 2$ minutes, followed by a decrease to 25°C at $t = 4$ minutes. The maximum power generated by the PV plant (P_{mpp}), the power generated (P_{pv}) using PRC technique, and the power reserve (ΔP_{PRC}) are all shown in figure 2.13(b). In this test, the targeted power reserve is 10% of P_{mpp} , for this reason, the deloading gain G_{del} is set to 0.9.

As presented in figure 2.13(a), the increase of the solar irradiation from 900 W/m^2 to 1000 W/m^2 induces a variation of the PV voltage that is fast detected by the PRC algorithm. Consequently, the MPPT mode is activated during 9 seconds ($T_1=9$) where the PV systems work at the maximum power point (99 kW) and the PRC algorithm deduces the resulting deloading power based on the registered maximum power and the deloading gain requested by the operator ($G_{del}=0.9$). After 9 seconds, the PV system is forced to work in PRC mode for 9 seconds ($T_2=9$), where the active power generated by the PV is regulated to the deloading value (89.2 kW). As we can see, the system achieves steady-state operation in less than 0.08 minutes without oscillations in the active power output. The following Table provides the obtained PV power and dynamics during these tests. In a steady state, the PV power equals 90% the maximum power.



(a) Climatic Change scenario



(b) Power reserve generation

FIGURE 2.13 – Proposed PRC under climates changes

This test validates the proper operation, efficiency, and fast response of the suggested PRC technique in generating reserve power. As shown in figure 2.13(b), the suggested PRC provides and generates a desirable power reserve ΔP_{PRC} , which is appropriately fixed in this test at 10% of the power generated by the PV plant, under varying climatic conditions such as changing irradiation or temperature, or both at the same time, at the appropriate time without any power losses and without oscillation.

2.6.2 PFC test

In this test, we examine the performance of the PFC strategy and its interaction with the proposed PRC technique interconnected grid. For this reason, only the PFC part already discussed is integrated into frequency regulation with a power reserve of 10% ($G_{del}=0.9$). To accomplish this, the same PV system described in the previous test is used with $K_{Droop}=4\%$,

TABLE 2.2 – PRC tests results

Time (min)	Variation	P_{mpp} (kW)	P_{del} (kW)	ΔP_{PRC} (kW)(%)	Response time (min)	Power overshot
1	100 W/m ²	9.90	8.92	0.98 (9.9%)	0.057	0
2	2 °C	9.85	8.87	0.98 (9.9%)	0.055	0
3	-200 W/m ²	7.86	7.08	0.78 (9.9%)	0.078	0
4	-5 °C	8.00	7.20	0.80 (10%)	0.076	0

the PVSG and the VIC are not activated. As requested by many grid codes of synchronous power plants, we simulate a sudden variation of the grid frequency and observe the variation of the active power provided by the PV plant. In this test, there are two frequency perturbations at the desired time ($t = 2$ seconds), the first being a 200 mHz (0.4%) step up and the second being a 50 mHz (0.1%) step down in grid frequency. The simulation results of this test are illustrated in figures 2.14(a) and 2.14(b).

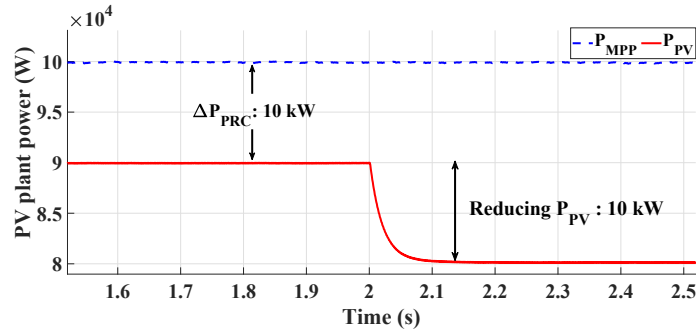
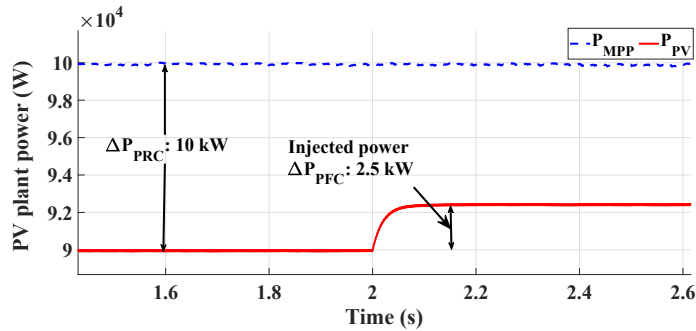
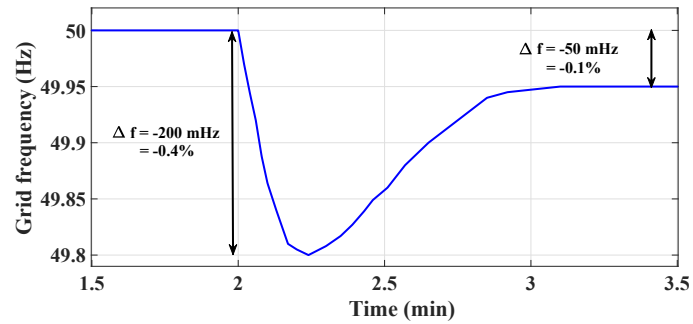

 (a) PV power for $\Delta f = +200$ mHz (+0.4%)

 (b) PV power for $\Delta f = -50$ mHz (-0.1%)

FIGURE 2.14 – PRC integration into Primary frequency response

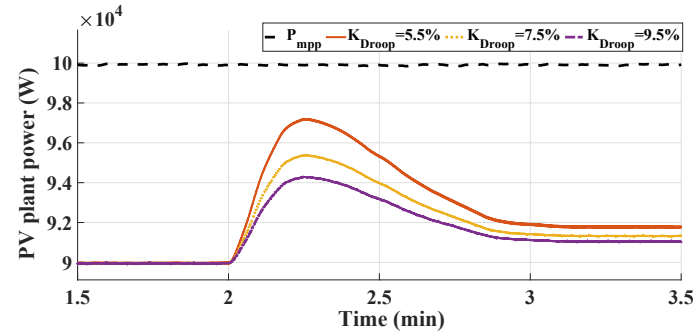
During the sudden increase of the grid frequency by 200 mHz, figure 2.14(a) shows a reduction of the PV active power injected in the grid. The power reduction from 90 kW to

80 kW corresponds to the PFC algorithm based on K_{Droop} a set equal to 4% (0.04 p.u.) and the frequency increase of 200 mHz (0.4%) as given by equation 3.6. The final value of the PV power is reached without any oscillation and with a response time 90% equal to 0.05 s. Figure 2.14(b) shows the use of the power reserve obtained by the PRC strategy by injecting additional active power (2.5 kW) during a sudden decrease of the grid frequency by 50 mHz (0.1%). Here again, the system reaches the stable steady state without any oscillation.

The validation of the PFC is generally realized by simulating a sudden variation of the grid frequency, as presented above. Another scenario is employed to evaluate the PFC performance. It consists of simulating a frequency droop that may be obtained during the loss of a major power plant. Figure 2.15(a) shows a typical waveform of the frequency variation, and figure 2.15(b) presents the PFC response for different values of K_{Droop} . We can see that the participation of the PV system in regulating the grid frequency is inversely proportional, K_{Droop} which is generally based on the request of the grid operator.



(a) Frequency perturbation



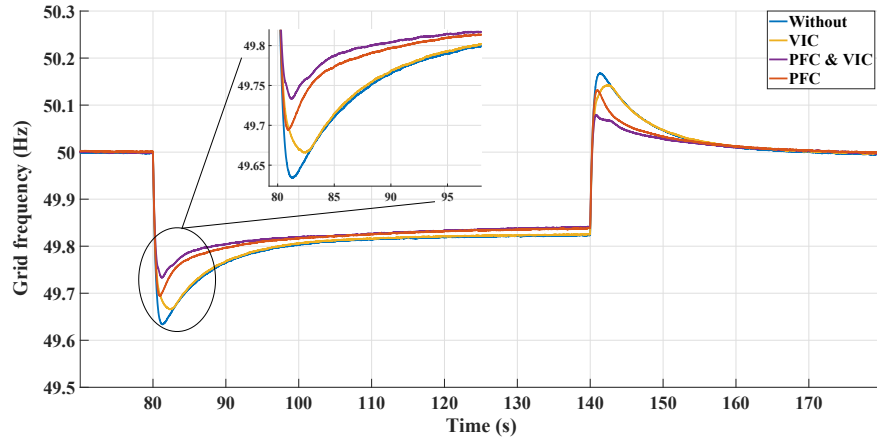
(b) ΔP_{PFC} for different K_{Droop}

FIGURE 2.15 – Proposed PRC under typical waveform of frequency variation

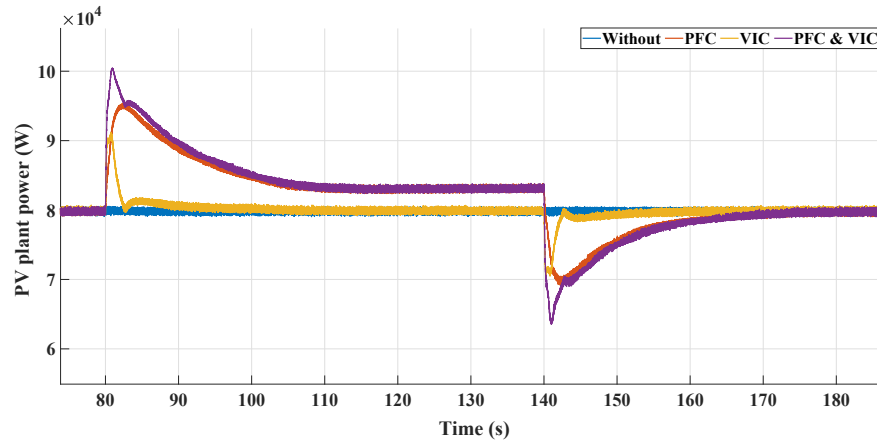
It should be mentioned that the climatic conditions in all of the next tests are set to standard conditions ($G = 1000 \text{ W/m}^2$ and $T = 25^\circ \text{C}$).

2.6.3 PFC and VIC in isolated grid

The validation of the inertia control strategies associated with the PRC technique is realized in isolated mode (not infinite grid), where the grid frequency is perturbed during load variations. The VIC, RI, and HIC are tested under the same conditions. The PV system is connected to a load (200 kW) and a 302.1 kVA synchronous generator representing the isolated grid source equipped with primary frequency control. Suddenly, an additional load of 100 kW is connected to the grid (at $t = 80$ s) and then disconnected (at $t = 140$ s). Figure



(a) Grid frequency



(b) PV plant power

FIGURE 2.16 – Grid frequency and PV plant power with different scenarios of frequency regulation control

2.16(a) presents the grid frequency during the impact of the additional load and the load shedding. The blue curve refers to the system response without the use of the PFC in the PV system and without the VIC. The red curve represents the response obtained when the PFC

in the PV system is only activated. However, the yellow curve shows the frequency variation when the VIC is only activated without the activation of the PFC in the PV system. The last curve, the purple one, gives the obtained frequency variation with a PV frequency regulation based on PFC and VIC. Figure 2.16(b) shows the injected power by the PV system during the sudden load impact and rejection. Without a frequency regulation strategy, the PV power injected and shown by the blue curve is constant (equal to 80 kW) independent of the frequency variation. For this reason, the frequency droop is about 0.74%. The frequency nadir is reached after 1.30 s. The PFC allows the injection of an additional power proportional to the frequency variation. However, the VIC injects an additional power proportional to the speed of the frequency variation to slow down the speed of the frequency decrease. For this reason, the frequency droop obtained with PFC and VIC is reduced to 0.52%. The frequency nadir is reached after 1.20 s. Thanks to the PRC strategy, which reserves the power to be used by the PFC and the VIC. During the load shedding, we observe an increase in the grid frequency. The PFC and the VIC techniques reduce fast the injected PV power. Here again, the frequency control based on PFC and VIC offers a stable control and achieves the best performance.

Table 2.3 summarizes the obtained results.

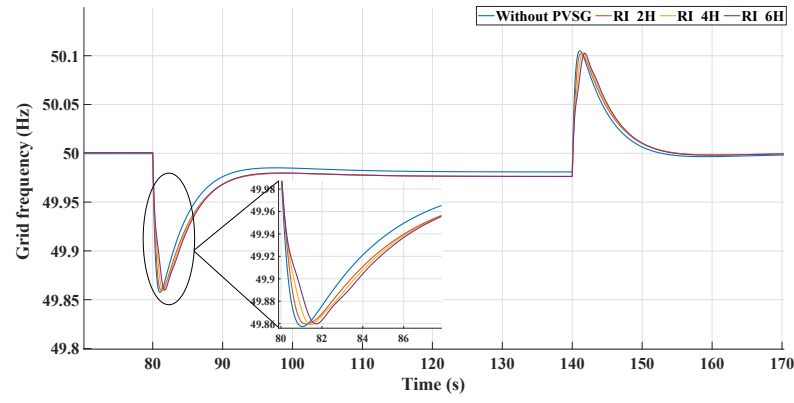
It should be noted that the power reserve in this and subsequent tests are set to 20% of P_{mpp} , therefore the deloading gain G_{del} is modified to 0.8. The gain of the VIC ($2H_{PV}$) is set to 5.

2.6.4 Real and hybrid inertia integration

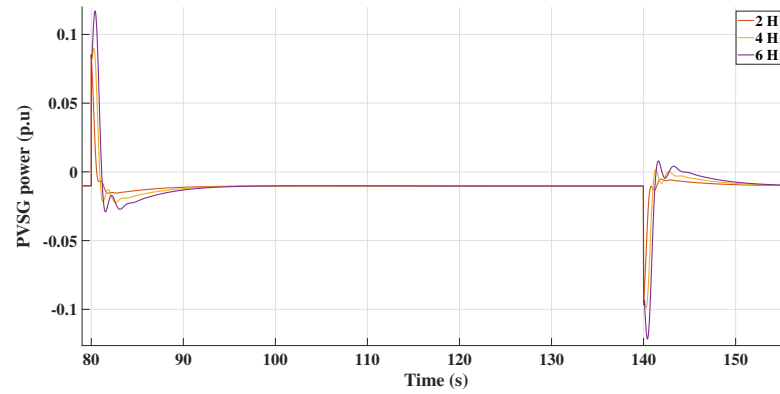
The grid operating in isolated mode is perturbed during a sudden variation of the connected loads. The same scenario of grid frequency perturbation used in the third VIC test is used, this scenario involves increasing power consumption at $t=80$ seconds, followed by a decrease in consumption at $t=140$ seconds by connecting and disconnecting the same additional charge. First, this scenario is applied to a system consisting of PVSG connected to an isolated grid without interconnecting the PV plant. The RI performance is evaluated for various inertia constant values ($H_{PVSG} = 2, 4$ and 6). In figure 2.17(a), the blue curve shows the grid frequency without employing the PVSG and the PV system. The other curves demonstrate the influence of the PVSG inertia on the frequency variation. During a sudden load impact, the frequency nadir, without a PVSG, is reached at $t = 81.05$ s. However, the employing of a PVSG with $H=6$ delays the frequency nadir to 81.75 s. As shown in figure 2.17(b), the frequency decrease induces a physical uncontrolled power injection by the PVSG

TABLE 2.3 – Results of PFC and VIC tests

Test	f droop (Hz), (%)	Max injected power (kW)	Response time (s)
LOAD IMPACT			
Without	0.37 (0.74%)	0	19.50
VIC	0.34 (0.68%)	10.80	17.30
PFC	0.31 (0.62%)	15	11.25
PFC & VIC	0.26 (0.52%)	20	8.20
LOAD SHEDDING			
Without	0.17 (0.34%)	0	16.80
VIC	0.14 (0.28%)	9	17.70
PFC	0.13 (0.26%)	10.50	16.80
PFC & VIC	0.08 (0.16%)	14.10	15.90



(a) Grid frequency



(b) PVSG active power

FIGURE 2.17 – Grid frequency and PVSG active power for different H_{PVSG} value

which helps to reduce the speed of the frequency increase and consequently the frequency stability. A high value of H allows to injection of more power during a frequency droop. During a load rejection (at $t=140$ s), the PVSG absorbs power from the grid because of the frequency increase. The absorbed power is stored as kinetic energy in the PVSG rotor part. As noted previously, the PVSG is integrated without a prime mover. In a steady state, the active power associated with the PVSG is negative which corresponds to the power losses.

The frequency regulation in the presence of the PVSG and the PV plant is also tested with the same scenario type (sudden impact and rejection of an additional load). The blue curve in figure 2.18 shows the frequency without activation of the PFC, VIC, and RI systems. As shown in figure 2.19(a), the injected power by the PV plant is constant and independent of the frequency variation. On the other hand, the yellow curve (PFC and RI) shows the system response in the presence of the PVSG and the PFC control strategy associated with the proposed PRC. The frequency nadir is reduced from 0.37 (Hz) to 0.28 (Hz) (-0.18 %). In addition, the time response (at 90%) of the frequency regulation is reduced from 19.50 s to 18 s. The PV plant associated with the PVSG performs a very good regulation of frequency.

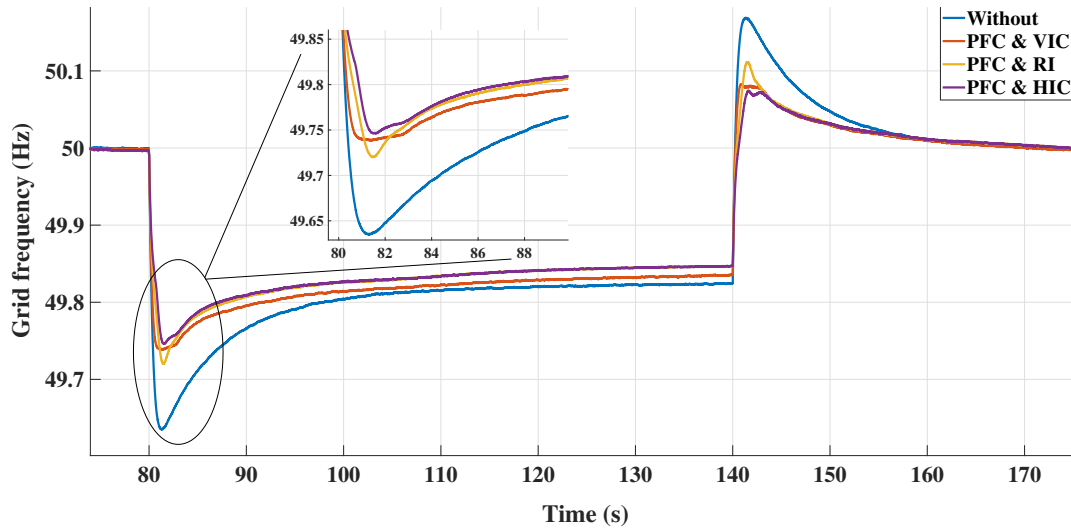
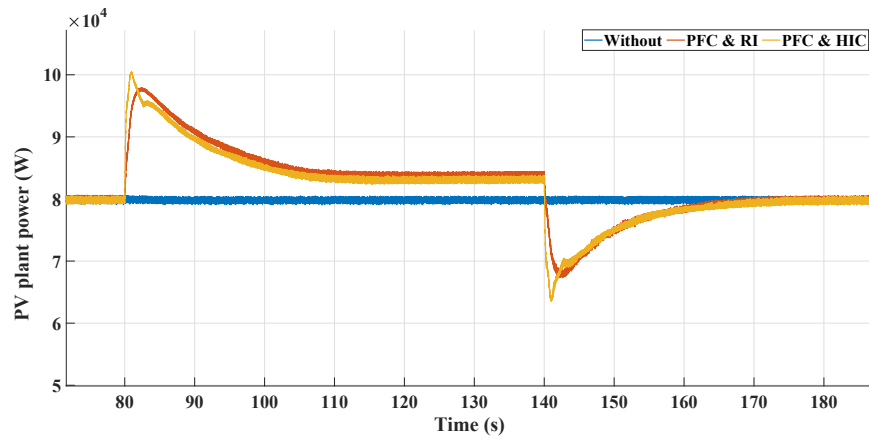


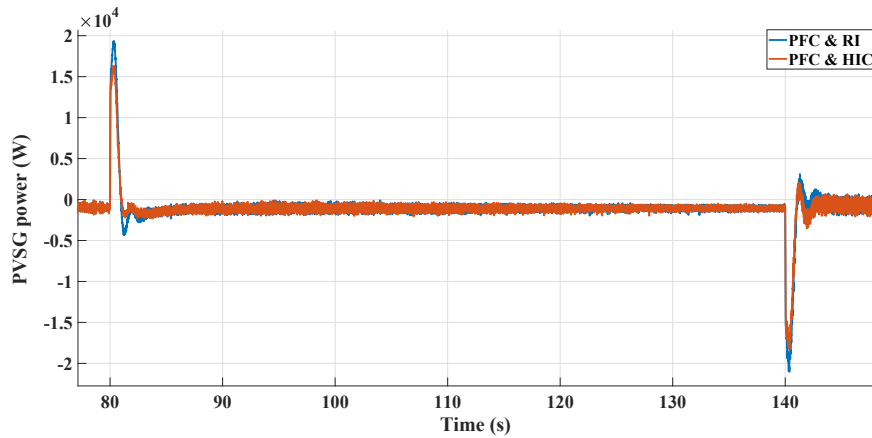
FIGURE 2.18 – Grid frequency with hybrid inertia

To compare the RI with the VI, the red curve (PFC and VIC) shows the response in the presence of the PFC and the VI. However, the PVSG is deactivated. The frequency regulation performance in (PFC and VIC) is nearly similar to that obtained with the PFC associated with the PVSG. However, the structure of the RI allows a physical inertial response without using control or power electronics.

Finally, we tested the hybrid structure where the VIC and RI are activated. This last test is shown by the violet curve (PFC and HIC) in figure 2.18. This strategy performs the best in terms of perturbation rejection. In the hybrid solution, the operator can adjust the level of contribution of the VIC. In addition, the power plant equipped with a PVSG ensures an intrinsic inertial response which represents a not controlled stabilizing element of the grid. The power injected by the PV system and the PVSG is presented in figures 2.19(a) and 2.19(b). This figure shows that the PV systems used, in a transient state, the complete reserve power obtained by the PRC strategy. During the load rejection, we observe again a very good performance of the hybrid solution, thanks to the PRC algorithm which provides the necessary power for the PRC and the VIC strategies. Table 2.4, presents the frequency droop and frequency overshoot in % and the response time.



(a) PV power



(b) PVSG active power

FIGURE 2.19 – PV power and PVSG active power with hybrid inertia

TABLE 2.4 – Results of RI and HIC tests

Test	f droop (Hz), (%)	Response time (s)	f overshoot (Hz), (%)
Without	0.37 (0.74%)	19.50	0.17 (0.34%)
PFC & VIC	0.265 (0.53%)	18.30	0.08 (0.16%)
PFC & RI	0.28 (0.56%)	18.00	0.11 (0.22%)
PFC & HIC	0.25 (0.50%)	17.10	0.07 (0.14%)

2.7 Integration of advanced techniques

Classic control systems require deep knowledge of the controlled system as well as exact mathematical modeling. Due to the intermittent nature of PV systems, fluctuating system parameters, unpredictable fluctuations in load demand, and the presence of grid faults, standard control techniques may perform poorly, adapt inadequately, and become unstable under changing operating situations. These constraints have driven researchers to investigate and use more advanced and adaptive control strategies for highly nonlinear PV grid systems. Adaptive neuro-fuzzy inference systems (ANFIS), FLC, ANN, and evolutionary algorithms are some of the artificial intelligence (AI) techniques that are often employed. An intelligent control technique's main advantage is that it significantly boosts dynamic performance and enhances robustness to disturbances[61–65].

The classical control loops implemented in a PV grid model consist of the DC-DC boost converter controller, the PFC and VIC integration controller, and the governor controller. The first two controllers have already been explained and presented in figures 2.9 and 2.11, both relying on a conventional PI controller.

The governor controller also relies on a conventional PI controller, as shown in figure 2.20. This PI controller is responsible for regulating the main synchronous generator's speed to balance power generation and demand with some power statism. The difference between the nominal and measured frequencies serves as the controller's input, while the rotor speed is the output. The PI controller's proportional (K_P) and integrator (K_I) gains are determined using both trial-and-error and Matlab's tuning method.

Advanced technique integration and simulation tests : The classical loops undergo a transformation using advanced techniques to enhance both high-frequency grid stability and the overall efficiency of hybrid inertia integration. Initially, the parameters of the PI

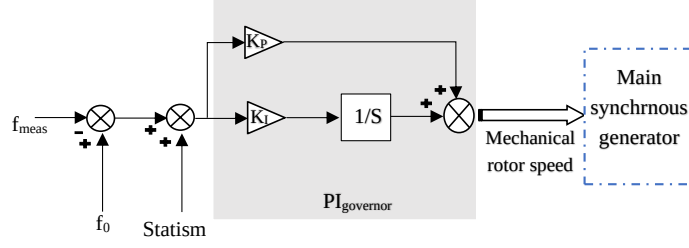


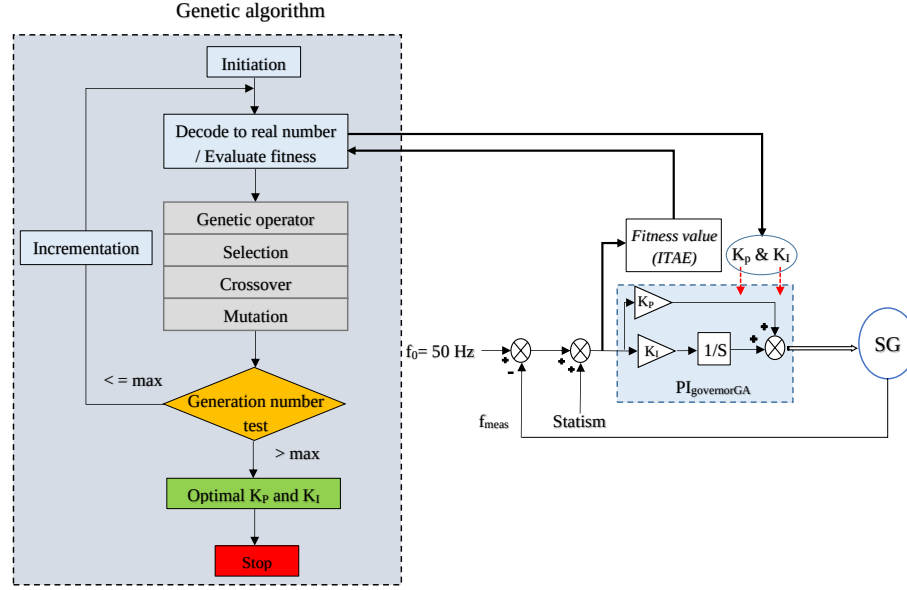
FIGURE 2.20 – Governor control loop.

controllers are fine-tuned using GA to optimize the performance of the governor controllers and the DC-DC converter. Subsequently, an FLC is introduced to replace the PI_{boost} controller and to manage the PR injection, providing greater adaptability to nonlinear dynamic characteristics.

The next paragraphs describe the various controllers utilized, the simulation results for each of them, and a comparison of the controllers used to obtain the best possible one.

2.7.1 Governor controller update:

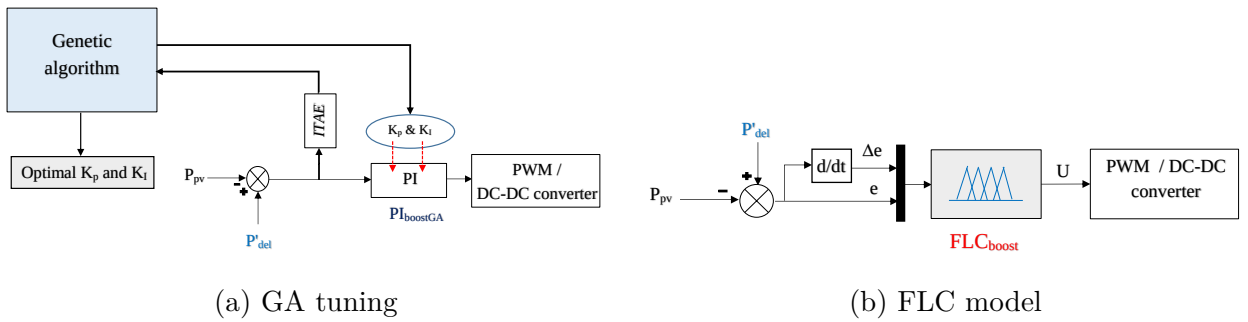
The controller aims to adjust the grid rotor speed based on power demand, as illustrated in figure 2.20. This controller is built on a PI controller, tuned using previously described techniques. It takes the difference between the measured frequency (f_{meas}) and the nominal frequency (f_0 , set at 50 Hz) as inputs and outputs the reference mechanical rotor speed. In this phase, as shown in figure 2.21, the tuning process involves using a GA to determine the PI parameters ($PI_{governorGA}$). The GA is widely used and applied in similar cases [66, 67]. The GA was configured with a population size of 50 individuals to ensure diverse exploration. A moderate mutation rate of 0.1 was chosen to balance exploration and maintain genetic diversity. To prevent premature convergence, the GA ran for 100 generations. A crossover rate of 0.8 was implemented to balance exploration and exploitation. Parent selection utilized tournament selection with a tournament size of 3, maintaining a balance between selection pressure and diversity. The GA aimed to minimize the integral time multiplied absolute error (ITAE) value, described in equation 2.13, serving as the fitness function. These parameter selections were the result of preliminary experiments, aiming to achieve a balance between computational efficiency and tuning effectiveness.


 FIGURE 2.21 – $PI_{governorGA}$ tuning diagram.

$$ITAE = \int_{t=0}^{t=final} |\Delta f| \times t \times dt. \quad (2.13)$$

2.7.2 DC-DC controller update:

The primary objective of this loop is to adjust the PV plant to the desired reference power in two situations: P_{mpp} representing the reference power in MPP mode, denoted as position P_1 , and P'_{del} in PR mode, denoted as position P_2 . This loop focuses on a PI controller tuned using a conventional technique, PI_{boost} , and then further tuned using GA for $PI_{boostGA}$. The GA is applied with the same parameters as previously detailed, as shown in figure 2.22(a).


 FIGURE 2.22 – $PI_{boostGA}$ tuning diagram and DC-DC control using FLC_{boost}

Integrating an FLC offers numerous advantages over traditional controllers like the PI controller, particularly in systems with nonlinearities or complex dynamics, such as renewable energy systems. Its adaptability allows it to adjust to changing operating conditions, making it suitable for systems with varying parameters or environments. The FLC's simple rule base is intuitive and easier to develop compared to complex mathematical models, making it more accessible for implementation and tuning [68, 69]. In this context, as the second phase, the PI controller, PI_{boost} , of this loop is replaced by an FLC model as shown in figure 2.22(b). This FLC has two inputs: the error (e) between PV plant power and targeted power (P'_{del}) and its variation (Δe), and one output, which is the duty cycle of the DC-DC controller.

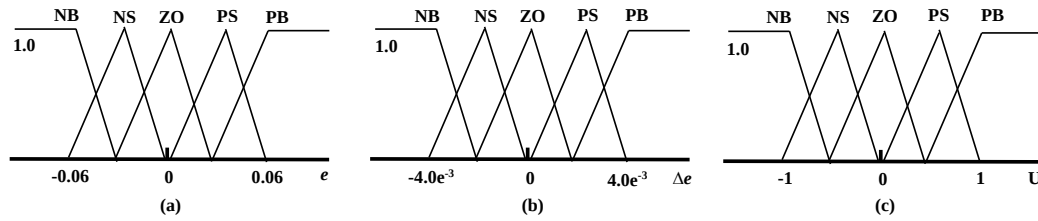


FIGURE 2.23 – FLC_{boost} membership functions: inputs members: (a) error (e) and (b) change of error (Δe), and output member: (c) Duty (U)

Figure 2.23 shows the input membership functions (e and Δe) and the output membership functions (U) of the FLC_{boost} . Table 2.5 outlines the FLC_{boost} guidelines that influence its decision-making process. These rules are developed based on numerous input variable combinations and implemented using the Mandani approach, which leverages a series of fuzzy IF-THEN rules. Each rule describes the proper output for a given set of input variables. FLC_{boost} makes use of linguistic variables including negative big (NB), negative small (NS), zero (ZO), positive big (PB), and positive small (PS).

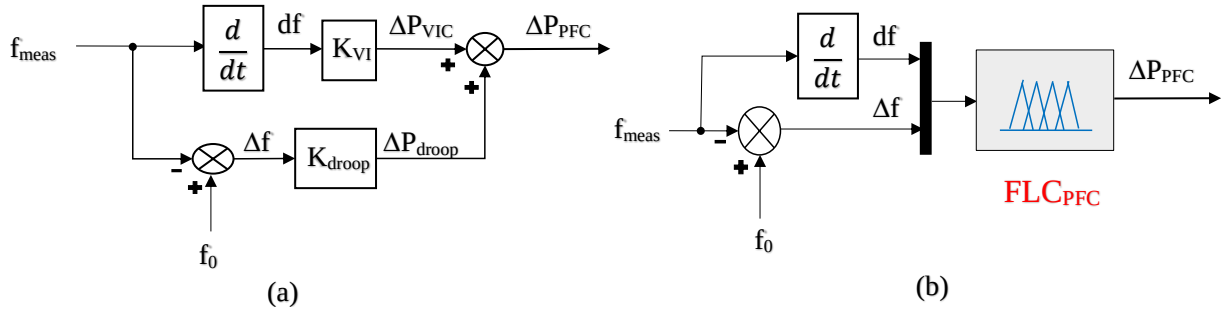
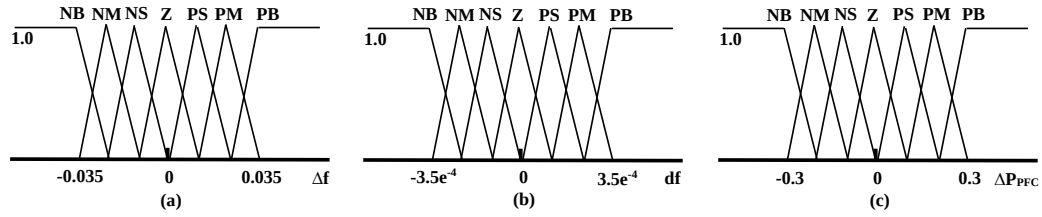
2.7.3 PFC and VIC integration loop update:

The PFC and VIC loops are integrated first using a classical approach, as depicted in figure 2.11 and governed by equations 2.6 and 2.13. To handle the nonlinear dynamics of these loops, an additional FLC is introduced, as illustrated in figure 2.24. The frequency deviation and its rate (Δf and df) serve as inputs to the FLC model, and the extra power (ΔP_{PFC}) is produced at its output. Figure 2.25 presents the input membership functions (Δf and df) and the output membership functions (ΔP_{PFC}) of the PFC_{FLC} .

Table 2.6 outlines the PFC_{FLC} guidelines that influence its decision-making process.

TABLE 2.5 – Fuzzy rules of FLC_{boost} .

$\Delta e/e$	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB


 FIGURE 2.24 – PFC loop methods: (a) classical (b) FLC_{PFC} .

 FIGURE 2.25 – FLC_{PFC} membership functions: inputs members: (a) frequency variation (Δf) and (b) speed of frequency deviation (df), and output member: (c) injected power reserve (ΔP_{PFC})

2.8 Tests and discussion

To demonstrate the superiority of the proposed system using conventional configurations and after applying various intelligent techniques, two main scenarios were applied for different configurations using different developed controllers: $PI_{governor}$, $PI_{governorGA}$, PI_{boost} ,

TABLE 2.6 – Fuzzy rules of FLC_{PFC} .

df/ Δf	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NM	NS	ZO	PS	PM	PB
NM	NB	NM	NS	ZO	PS	PM	PB
NS	NB	NM	NS	ZO	PS	PM	PB
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NB	NB	NB	ZO	PB	PB	PB
PM	NB	NB	NB	ZO	PB	PB	PB
PB	NB	NB	NB	ZO	PB	PB	PB

$PI_{boostGA}$, FLC_{boost} , and FLC_{PFC} . These configurations were tested in various combinations.

In the first scenario, the different configurations were subjected to the already described frequency perturbation scenario. Throughout all tests, the irradiation was set to 1000 W/m^2 , the temperature was maintained at 25°C , and G_{del} was set to 0.8.

In the second scenario, the system underwent frequency fluctuations under two conditions: in the absence of frequency support and with frequency support. The Table below provides a summary of each controller and the corresponding tests conducted.

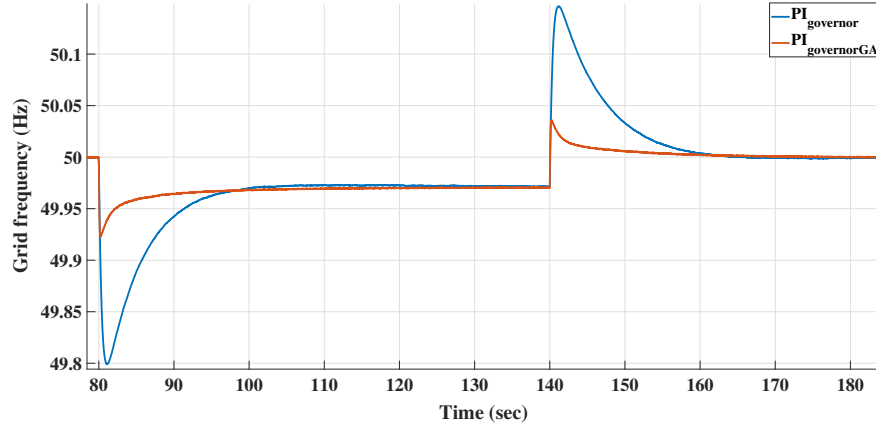
Below is a Table summarizing each controller and the tests they were subjected to:

TABLE 2.7 – Summary of controllers and subjected tests

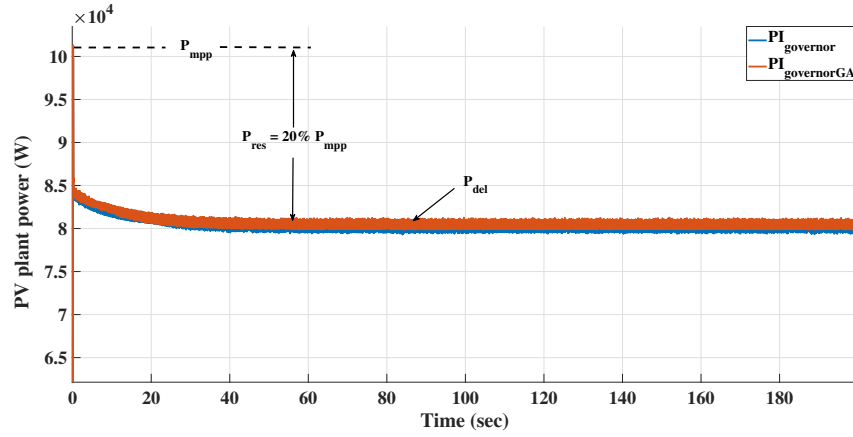
Controller / Test	Frequency perturbation	AHI integration
Governor	✓	X
DC-DC boost	✓	✓
PR integration	✓	✓

Figures 2.26(a) and 2.26(b) depict the simulation results of the first test, which involves subjecting both $PI_{governor}$ and $PI_{governorGA}$ configurations to the described frequency perturbation scenario. The grid frequency and PV plant power illustrated in this figure show that the grid frequency reaches a nadir of 49.799 Hz using $PI_{governor}$ and a nadir of 49.923 Hz using $PI_{governorGA}$. This demonstrates the effectiveness of $PI_{governorGA}$ by improving the frequency nadir by 0.124 Hz and reducing the frequency droop from 0.201 Hz (0.402%) to 0.077 Hz (0.154%). The same figure shows the PV plant power output of 80 kW while maintaining a P_{res} of 20 kW, which is 20% of the maximum power (100 kW), without any PR integration

as previously configured. Additionally, the real or internal inertia is not integrated, resulting in the absence of frequency regulation services in this configuration.



(a) Grid frequency



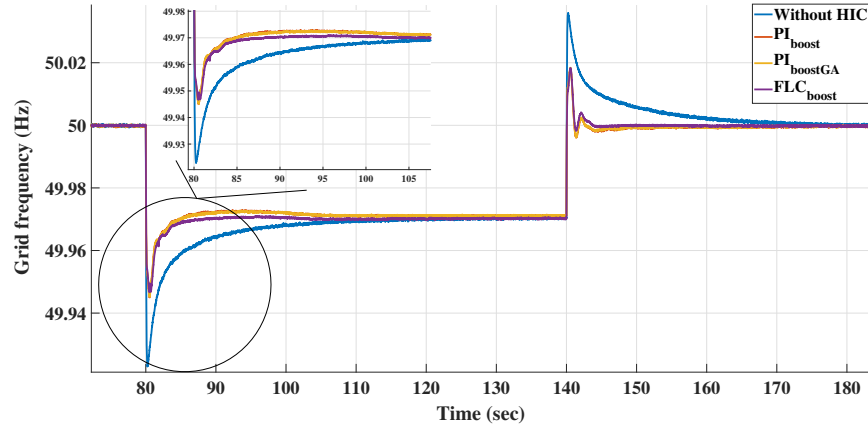
(b) PV plant power

FIGURE 2.26 – Grid frequency and PV plant power using $PI_{governor}$ and $PI_{governorGA}$

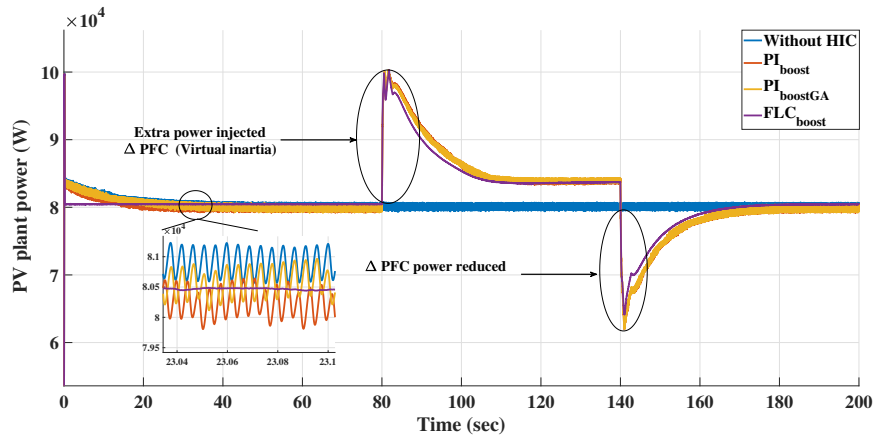
From the first test, $PI_{governorGA}$ demonstrates its superiority over the conventional one. For this reason, it will be kept as the governor controller in the subsequent tests.

Figures 2.27 and 2.28 provide detailed insights into the grid characteristics, grid frequency, PV plant power, and compensator active power results of tests using different configuration combinations. Initially, the benefits of employing conventional HI are evident, showcasing a reduction in the frequency nadir from 49.799 Hz to 49.861 Hz, a decrease in frequency droop from 0.201 Hz (0.402%) to 0.139 Hz (0.278%), but an increase in response time from 14.10 s to 14.85 s in load impact. This effect is also observed in load shedding, with a reduction in the frequency nadir from 50.146 Hz to 50.085 Hz, a decrease in frequency droop from 0.146 Hz (0.293%) to 0.085 Hz (0.175%), and decreases in nadir time from 141.16 s to 140.9 s, but

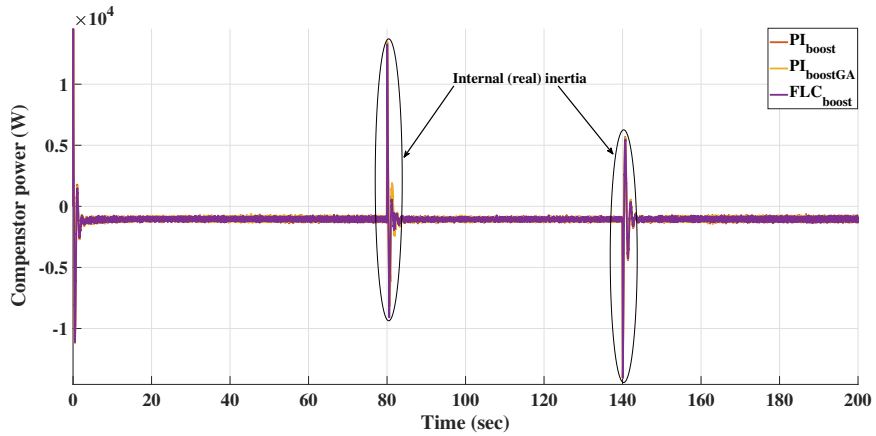
an increase in response time from 16.44 s to 23.10 s.



(a) Grid frequency

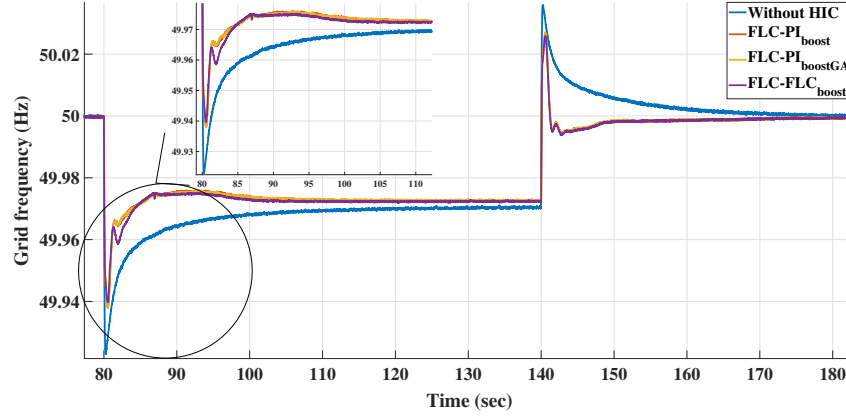


(b) PV plant power

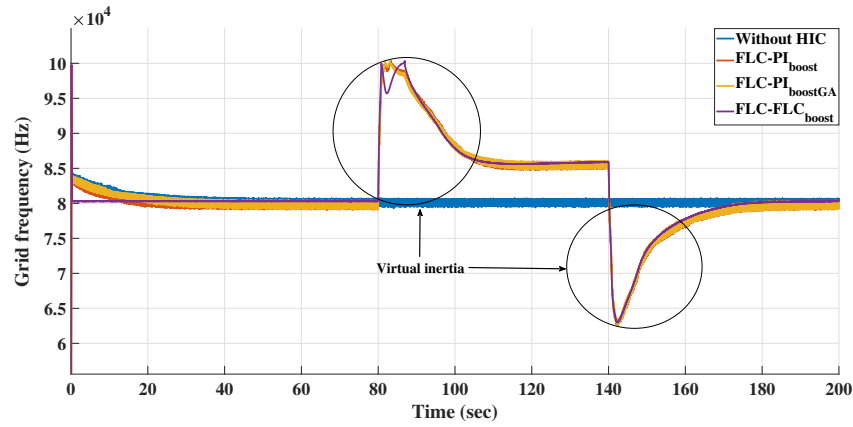


(c) compensator power

FIGURE 2.27 – Grid frequency, PV plant power and compensator power using PI_{boost} , $PI_{boostGA}$ and FLC_{boost}



(a) Grid frequency



(b) PV plant power

 FIGURE 2.28 – Grid frequency and PV plant power using $FLC - PI_{boost}$, $FLC - PI_{boostGA}$ and $FLC - FLC_{boost}$

Subsequently, the efficacy of intelligent control approaches is illustrated by utilizing the AHI, which includes $PI_{governorGA}$ as the governor controller, FLC_{boost} as the DC-DC boost controller, and an FLC model in PFC integration (FLC_{PFC}). This configuration results in a further significant reduction in frequency nadir to 49.940 Hz, a reduction of frequency droop to 0.06 Hz (0.120%), a decrease in nadir time to 80.53 s, and a significant reduction in response time to 4.47 s in load impact. Moreover, better results are achieved in load shedding, with a reduction in frequency nadir to 50.026 Hz, a reduction of frequency droop to 0.026 Hz (0.05%), a decrease in nadir time to 140.059 s, and a significant reduction in response time to 0.59 s.

Figure 2.29 illustrates the outcomes obtained with AHI compared to conventional HI and without HI incorporation. This visualization highlights the significant contributions made by

AHI in both disturbance power scenarios, as well as improvements in the DC-DC converter's response time. Furthermore, it ensures excellent response quality devoid of oscillations and maintains high system stability.

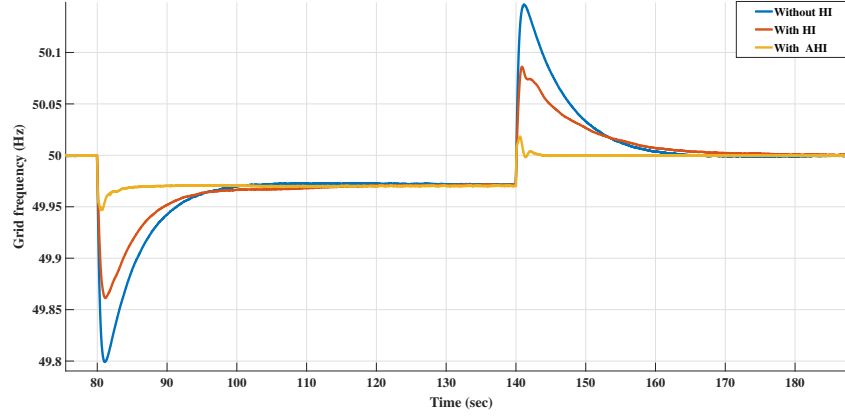


FIGURE 2.29 – Grid frequency: without HI, with HI, and with AHI

TABLE 2.8 – Global test results.

LOAD IMPACT						
Governor	Boost	HIC	f_{nadir} (Hz)	Δf (Hz & %)	T_{nadir} (s)	$T_{response}$ (s)
$PI_{governor}$	PI_{boost}	without	49.799	0.201 (0.402%)	81.10	14.10
$PI_{governorGA}$	PI_{boost}	without	49.923	0.077 (0.154%)	80.23	15.27
$PI_{governor}$	PI_{boost}	classical PFC	49.861	0.139 (0.278%)	81.15	14.85
$PI_{governorGA}$	PI_{boost}	classical PFC	49.945	0.055 (0.110%)	80.54	3.26
$PI_{governorGA}$	$PI_{boostGA}$	classical PFC	49.945	0.055 (0.110%)	80.54	3.26
$PI_{governorGA}$	FLC_{boost}	classical PFC	49.947	0.053 (0.106%)	80.51	3.29
$PI_{governorGA}$	PI_{boost}	FLC_{PFC}	49.938	0.062 (0.123%)	80.54	5.03
$PI_{governorGA}$	$PI_{boostGA}$	FLC_{PFC}	49.938	0.062 (0.124%)	80.56	5.03
$PI_{governorGA}$	FLC_{boost}	FLC_{PFC}	49.940	0.060 (0.120%)	80.53	4.47
LOAD SHEDDING						
$PI_{governor}$	PI_{boost}	without	50.146	0.146 (0.293%)	141.16	16.44
$PI_{governorGA}$	PI_{boost}	without	50.035	0.035 (0.071%)	140.25	19.75
$PI_{governor}$	PI_{boost}	classical PFC	50.085	0.085 (0.175%)	140.90	23.10
$PI_{governorGA}$	PI_{boost}	classical PFC	50.183	0.183 (0.366%)	140.59	0.29
$PI_{governorGA}$	$PI_{boostGA}$	classical PFC	50.184	0.184 (0.368%)	140.55	0.34
$PI_{governorGA}$	FLC_{boost}	classical PFC	50.183	0.183 (0.366%)	140.56	0.35
$PI_{governorGA}$	PI_{boost}	FLC_{PFC}	50.027	0.027 (0.053%)	140.59	0.62
$PI_{governorGA}$	$PI_{boostGA}$	FLC_{PFC}	50.027	0.027 (0.054%)	140.58	0.62
$PI_{governorGA}$	FLC_{boost}	FLC_{PFC}	50.026	0.026 (0.051%)	140.59	0.59

As previously discussed, internal inertia is a natural reaction and is not linked to any controller. This justifies that the compensator does not generate any active power until a frequency perturbation appears. At $t = 80$ seconds, the compensator provides a constant quantity of power as internal inertia, injecting 12.98 kW proportional to the frequency deviation direction under all configurations, as shown in figure 2.27(c).

Where $f_{variation}$ is the minimum or highest frequency value registered when frequency deviation appears; $T_{variation}$ is the time of the $f_{variation}$; and $T_{response}$ is the duration required to restore the frequency from the $f_{variation}$ to 95% of its final value.

The illustrated results of tests in various figures and Table 2.8 underscore the substantial improvement afforded by a real-time deloading technique integrated with diverse intelligent techniques. This enhancement is evidenced by the notable reduction in frequency nadir and response time, both of which play critical roles in bolstering grid frequency stability. The decrease in frequency nadir reflects the system's enhanced ability to manage sudden disturbances and fluctuations, thereby ensuring that grid frequency remains within acceptable limits. Moreover, the observed reduction in response time signifies a more agile and responsive system, capable of swiftly adapting to changes in operating conditions and mitigating the adverse effects of frequency deviations. Collectively, these findings highlight the pivotal role of intelligent techniques in fortifying the stability and reliability of power systems, offering operators a robust framework to navigate the complexities of modern grid operations and enhance overall system performance.

2.9 Conclusion

This chapter provided a detailed examination of PV grid operations, including mathematical modeling, dynamic behavior, and the critical challenge of frequency stability in fluctuating grid conditions. A major contribution was the introduction of an innovative deloading strategy that leverages the virtual inertia of PV systems and the real inertia of offline synchronous generators (SGs) to create a hybrid inertia solution. This approach, supported by power reserve (PR) through PFC loops, effectively compensates for the inertia deficit in conventional PV systems. Validation results demonstrated a significant reduction in frequency fluctuations and enhanced grid stability, emphasizing its suitability for power networks with high renewable energy penetration.

Building on this foundation, the study also explored advanced control strategies to further optimize the deloading mechanism. The integration of fuzzy logic control (FLC) improved

real-time decision-making under dynamic and uncertain conditions, while genetic algorithms (GA) optimized controller tuning for enhanced performance. The AI-enhanced deloading strategy yielded notable improvements, including faster frequency stabilization, improved system resilience, and better adaptability to grid variations.

Looking ahead, the findings highlight the transformative role of AI-assisted control strategies in addressing the stability challenges of modern power grids. Future research should focus on expanding AI-driven optimization techniques, integrating predictive analytics for real-time grid adaptation, and exploring multi-agent systems for decentralized control. Additionally, the potential of hybrid inertia solutions in large-scale energy networks warrants further investigation, particularly in multi-source renewable grids where wind, battery storage, and demand-side management can work in synergy. By advancing these approaches, the next generation of PV-based power systems can achieve greater reliability, scalability, and resilience, paving the way for a more adaptive and robust renewable energy future.

Chapter 3: Advanced Control Strategies for Improving Real-Time Wind Turbine Deloading

This chapter focuses on the integration of wind turbine (WT) systems. It begins with a literature review covering various configurations and WT modeling. This is followed by the introduction of a novel deloading technique, which is subsequently enhanced using advanced and robust control methods.

3.1 Introduction

Wind energy systems (WES) have emerged as a critical component of modern power generation, offering a sustainable alternative to conventional energy sources. However, their integration into power grids presents significant challenges due to the inherent variability of wind and its impact on system stability. Addressing these challenges requires advanced modeling techniques, innovative control strategies, and effective deloading approaches to enhance the reliability and performance of WES.

This chapter provides a comprehensive study of WES, focusing on advanced control strategies and their role in improving system stability and efficiency. Building upon foundational concepts, it begins with an in-depth description and modeling of WES, covering key components such as WT configurations, generator types, and electronic converters. These elements are analyzed in the context of their interactions within the system, supported by detailed modeling approaches that enable accurate simulation and performance assessment under various operational conditions.

Following this, the chapter introduces a novel deloading technique designed to enhance the stability and efficiency of WES. The proposed approach is validated through a series

of dynamic response tests, demonstrating its ability to support frequency regulation and improve grid stability. By enabling controlled power reserve management, this deloading strategy contributes to a more resilient integration of wind energy into power networks.

The discussion then shifts to the application of advanced control techniques, with a particular emphasis on $\mathcal{H}_\infty$ robust control. This section explores the advantages of $\mathcal{H}_\infty$ control in improving the robustness and adaptability of WES, particularly in addressing system uncertainties and parameter variations. Extensive test scenarios and validation results are presented, showcasing the enhancements achieved through these sophisticated control methods.

By addressing critical aspects such as system modeling, deloading strategies, and advanced control applications, this chapter aims to contribute to the development of more efficient and resilient wind energy systems, further advancing the role of wind power in modern electricity generation.

3.2 Description and modeling of Wind Energy Systems

Wind energy systems, often referred to as wind power or WTs, harness the natural force of the wind to generate clean and sustainable electricity. These systems consist of towering WTs equipped with rotating blades that capture the wind's kinetic energy and convert it into a valuable source of power [70].

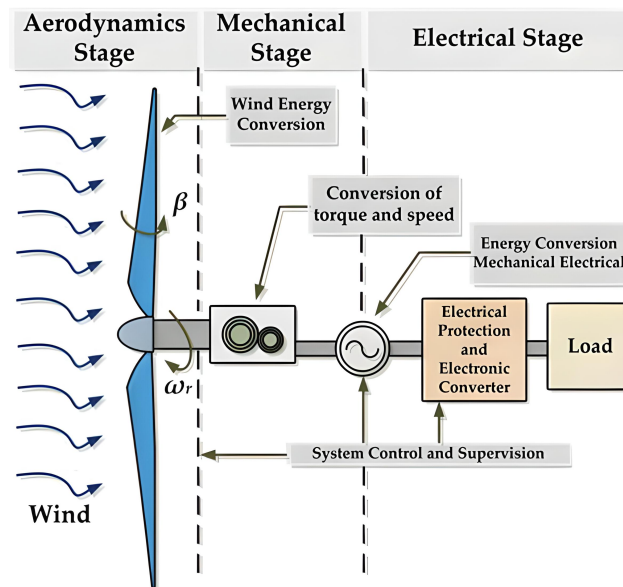


FIGURE 3.1 – Wind system stages [71]

A complete wind energy system, such as a wind farm, encompasses various components, including individual WTs with rotor blades, hubs, nacelles, and generators, as well as towers to elevate them to optimal heights. These turbines are connected to the electrical grid via transformers and distribution equipment, integrating the electricity produced into the grid. A centralized control system monitors and optimizes the performance of each turbine, while infrastructure like access roads, foundations, and maintenance systems support their operation. Additionally, as presented in figure 3.1, within each wind system, there are distinct stages: the aerodynamic stage, involving the rotor blades and hub, which capture wind energy; the mechanical stage, within the nacelle, where mechanical components convert kinetic energy to rotational energy; and the electrical stage, where generators transform this mechanical energy into electrical power. Sometimes, energy storage and remote monitoring systems are added for improved wind energy production management [72].

3.2.1 Main components of WES

3.2.1.1 Wind Turbine

Wind turbines are central to WES, converting wind energy into electricity. Key components, as shown in figure 3.2, include rotor blades, nacelle (housing the generator and gearbox), and the tower, all designed for efficient energy capture and conversion. Additionally, the yaw drive ensures the turbine faces the wind, and the pitch system adjusts blade angles for optimal power generation [73].

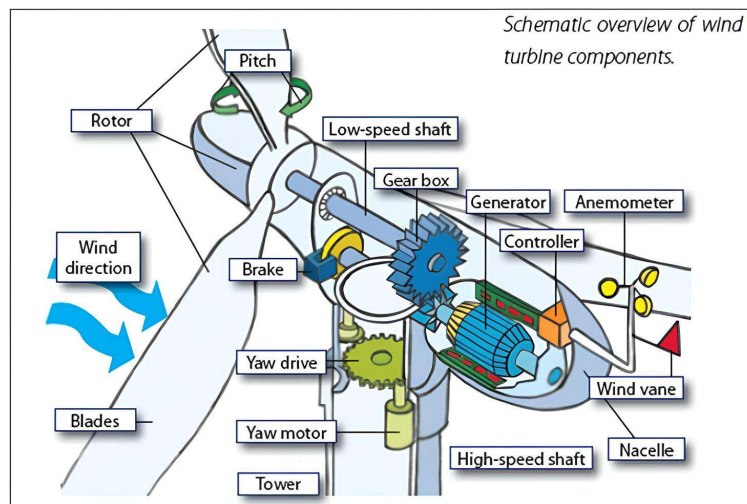


FIGURE 3.2 – Primary components of a WT [71]

Types of WTs : The two main types are Horizontal-Axis (HAWT) and Vertical-Axis (VAWT) as depicted in figure 3.3 [74]. HAWTs align with wind direction and are widely used, while VAWTs capture wind from any direction, making them ideal for turbulent environments. Turbines can also be classified into fixed and variable-speed models, with variable-speed turbines being more efficient but complex [75].

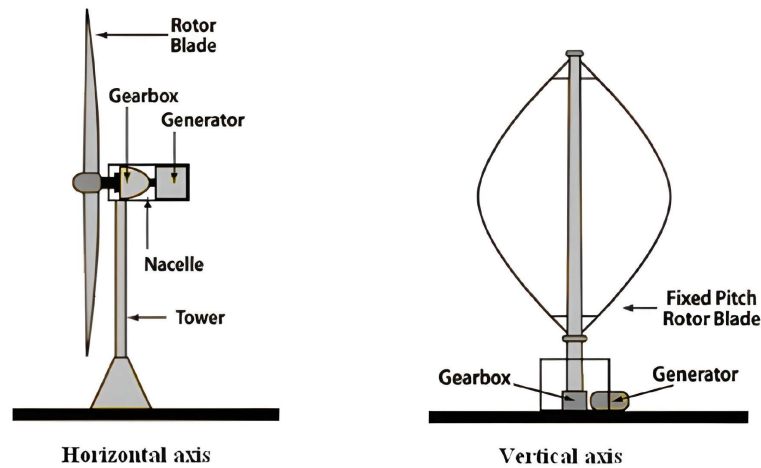


FIGURE 3.3 – Horizontal axis WT (HAWT) and vertical axis WT (VAWT) [76]

Control systems : Control systems, like pitch angle and rotor speed control, regulate turbine operation for safety and efficiency. Other systems include yaw control, SCADA for remote monitoring, and brake systems for emergency shutdowns [77].

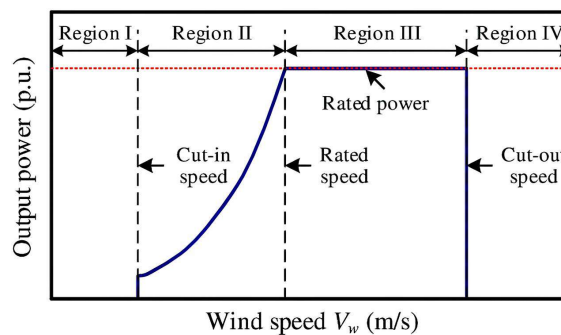


FIGURE 3.4 – WT operational region [78]

Operating regions : Turbines operate, as presented in figure 3.4, across cut-in (starting generation), cut-out (protection during high winds), and maximum power tracking regions, ensuring optimal energy capture under varying wind conditions [78].

3.2.1.2 Generator

WT generators, synchronous or asynchronous, convert mechanical energy into electrical energy. Synchronous generators offer higher efficiency but are more complex, while asynchronous generators (induction generators) are cost-effective and widely used [79]. Figures 3.5 and 3.6 depict these generator types.

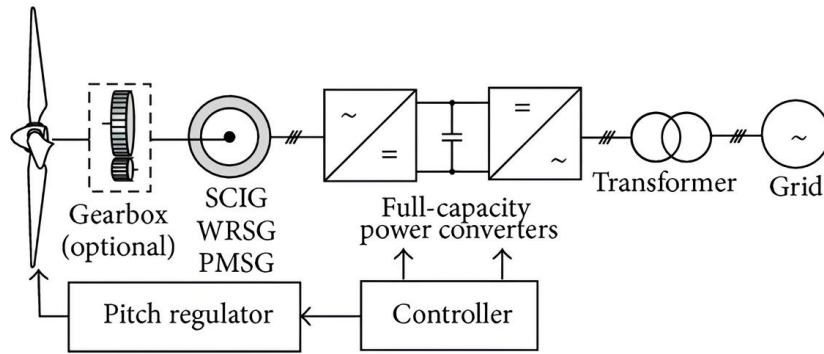


FIGURE 3.5 – Synchronous generator configurations [79]

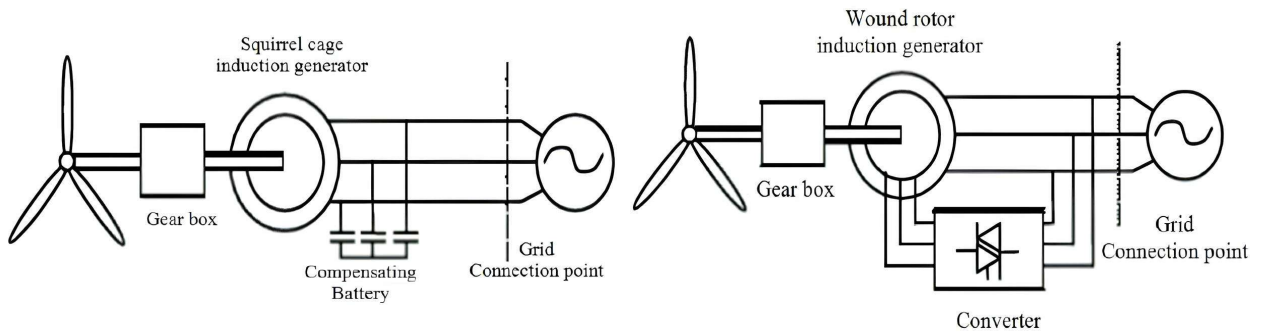


FIGURE 3.6 – Asynchronous generator configurations [79]

3.2.1.3 Electronic converter and protection

The electronic converter, as illustrated in figure 3.7, consisting of AC-DC and DC-AC components, ensures stable power conversion for grid compatibility. Protection systems, including mechanical brakes, temperature monitoring, and lightning protection, safeguard turbine operation and prevent damage [80–82].

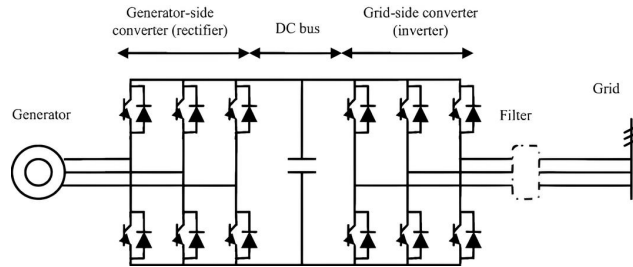


FIGURE 3.7 – WT electronic converter [82]

3.2.2 WT modelling

WT modeling encompasses the creation of mathematical, computational, or physical representations of WTs to predict their behavior and performance. It involves defining blade geometry, considering aerodynamics and structural integrity, incorporating wind resource data, modeling electrical systems, assessing environmental and economic impacts, and optimizing design and control strategies. WT models aid in maximizing energy production, ensuring safety and reliability, and evaluating the environmental and economic feasibility of wind energy projects, making them essential tools in the design and analysis of WTs for sustainable energy generation [83].

3.2.2.1 Blade aerodynamics modeling

As previously mentioned, the initial phase of WT operation is dedicated to the aerodynamic process, which aims to convert kinetic energy into mechanical energy. This mechanical energy results from the rotation of the turbine blades. The Betz limit, also referred to as Betz's law, establishes a fundamental boundary for WT efficiency, stating that no WT can capture more than 59.3% of the wind's kinetic energy. To characterize the aerodynamic performance of WTs, a power coefficient (C_p) is commonly used. Subsequently, a simplified aerodynamic model is often applied to analyze the static behavior of mechanical torque (T_m), allowing us to understand the relationship between turbine rotational speed, wind speed, and the power

coefficient [83].

$$T_m = \frac{1}{2\lambda} \rho \pi R^3 U_w^2 C_p(\lambda, \beta) \quad (3.1)$$

with: ρ denotes air density measured in Kg/m^3 ; R signifies the blade radius in meters; U_w corresponds to wind speed in meters per second (m/s); β stands for the blade pitch angle, measured in degrees; and (λ) represents the tip speed ratio.

The calculation of mechanical power extracted from the wind by the WT, denoted as P_W , can be precisely described by the following equation:

$$P_W = \frac{T_m}{W_m} = \frac{1}{2} \rho \pi R^2 U_w^3 C_p(\lambda, \beta) \quad (3.2)$$

Where W_m is the rotational speed of the WT rotor expressed as follows:

$$W_m = \frac{\lambda U_w}{R} \quad (3.3)$$

The calculation of aerodynamic power efficiency (C_p) often relies on empirical equations tailored to the specific characteristics of individual WT designs and operational conditions. These equations incorporate a set of constants denoted as C_1 , C_2 , C_3 , C_4 , C_5 , and C_6 , which are determined through empirical data or modeling. As an example, the specific equation for C_p applicable to a three-bladed WT with variable speed is referenced as follows:

$$C_p = C_1(C_2/\lambda_i - C_3\beta - C_4)e^{(C_5/\lambda_i)} + C_6\lambda \quad (3.4)$$

The constant λ_i depends on β and other constants (C_7 , and C_8) as:

$$\lambda_i = \frac{1}{\frac{1}{\lambda + C_7\beta} - \frac{C_8}{\beta^3 + 1}} \quad (3.5)$$

3.2.2.2 Mechanical drive train model

The gearbox and drive train within a WT play a critical role in harnessing the kinetic energy of the wind and converting it into usable electrical power. These components act as an intermediary between the turbine's rotating blades and the electrical generator. Their primary function is to ensure that the rotational motion generated by the blades is transmitted efficiently and at the optimal speed to the generator, where electricity is produced. This process involves adapting to varying wind speeds while maintaining a consistent generator rotational speed, resulting in a stable and reliable electrical output. Additionally, the gearbox and drive train can also enhance the rotational speed relative to the incoming wind speed, contributing to the overall efficiency of the WT system. In essence, they are essential components that facilitate the effective energy conversion from wind into electricity [84].

The drive train model relies on an array of parameters and WT characteristics, encompassing rotor and generator inertia, gear ratios, torque, friction, bearing properties, damping coefficients, stiffness, electromagnetic features, and wind conditions. Together, these parameters intricately shape the drive train system's behavior and its adaptability to fluctuating wind conditions. Their collective importance lies in facilitating simulations that elucidate the transformation of wind's kinetic energy into mechanical power within the WT. Subsequently, this mechanical energy is further converted into electrical energy. The incorporation of these parameters plays a pivotal role in optimizing and conducting in-depth analyses of WT performance [84].

The mathematical model describing the mechanical transmission mechanism can be expressed as follows:

$$\frac{d}{dt}W_m = \frac{1}{J_{eq}}(T_m - T_e - B_m W_m) \quad (3.6)$$

Where:

- ★ T_e represents the electromagnetic torque.
- ★ B_m denotes the rotational friction (in units of kg^2/s).
- ★ J_{eq} represents the equivalent rotational inertia, expressed in kg^2 , and is given by :

$$J_{eq} = \frac{J_m}{n_m^2} + J_g \quad (3.7)$$

Where: J_m and J_g are the turbine inertia and generator inertia, respectively; n_m^2 is the speed ratio of the gearbox.

3.3 Wind systems proposed deloading approach

Various deloading approaches have been proposed in the literature [85–98], primarily relying on estimating the available WT power to determine the appropriate deloading power level. This estimation is typically based on the calculation of mechanical power extracted from the wind (P_W), which is influenced by multiple factors, including air density, rotor sweep area, wind speed, rotor speed, blade pitch angle, and tip speed ratio. The aerodynamic power coefficient (C_P) is computed using empirical equations tailored to specific WT designs and operational scenarios.

However, a key drawback of these techniques is their dependence on power estimation, which may introduce inaccuracies due to variations in environmental conditions and turbine

parameters. These uncertainties can affect the reliability and effectiveness of the deloading process, potentially limiting its ability to provide precise power reserves for grid support.

The second deloading principle involves more complex calculations using mathematical models to directly determine the deloading power (P_{Del}). This approach considers key parameters such as deloading rotor speed and aerodynamic power coefficients, enabling a more precise estimation of the required power reduction [85, 91, 93].

The third principle leverages graphical models to estimate MPPT and deloading values, simplifying the computation process while facilitating effective power reserve generation [97, 98]. This method provides a more intuitive approach, reducing computational demands compared to purely mathematical models.

Despite their advantages, these methods face challenges due to their reliance on theoretical estimates, sophisticated control systems, and sensor technology. Effective implementation requires precise measurements and prior knowledge of the WT parameters, increasing both cost and system complexity. In addition, maintenance becomes more demanding, necessitating specialized expertise to fine-tune control systems and ensure optimal performance under varying wind conditions.

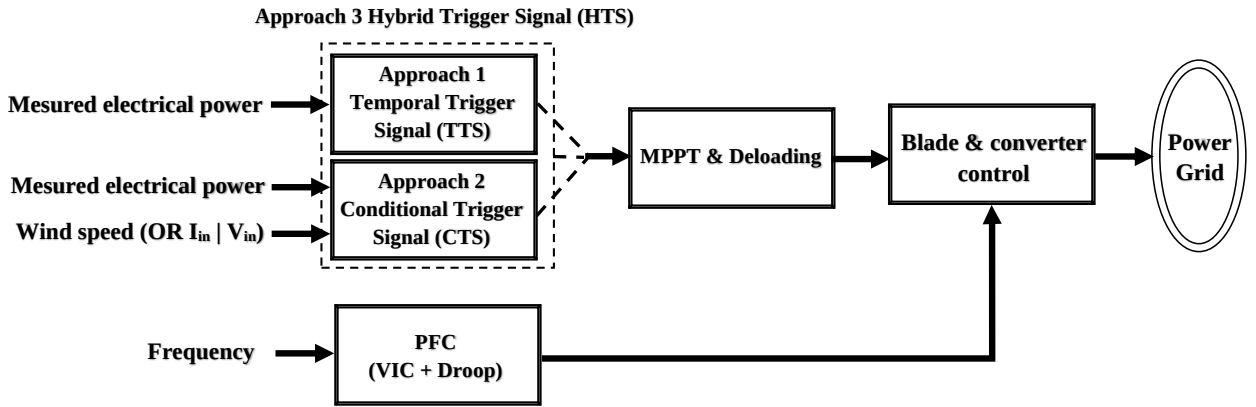


FIGURE 3.8 – Diagram of the proposed power reserve strategy

This thesis proposes a novel real-time approach that avoids the need for complex models, prior WT knowledge, or additional sensors. This method rates in a continuous cycle, starting at maximum power production and transitioning to deloading to generate power reserves, offering flexible configuration options as shown in figure 3.8. Its simplicity reduces costs, sensor requirements, and maintenance demands, making it an efficient solution for primary frequency regulation. Validation tests confirm its effectiveness in improving grid stability

and optimizing the performance of the WT power system. In the following sections, a detailed presentation and implementation configurations of the proposed deloading approach are examined.

3.3.1 Maximum power measurement and power reserve modes

The technique started with the maximum power measurement (MPM) mode; in this mode, the WT runs at its maximum power and measures this power. This mode employs two controllers to achieve this: the MPPT PAC and the P&O MPPT algorithm controller. The MPPT PAC determines the blade pitch angle (β_{MPP}) required to extract the maximum mechanical power for a given wind speed. In the coming section, a detailed explanation of the MPPT PAC and the reference pitch angle (β_{MPP}).

Once β_{MPP} is defined, a second controller based on the P&O MPPT algorithm takes over to manage the WT at its MPPT, ensuring that it operates at the point where maximum power is attained. This algorithm takes DC current (I_{in}) and DC voltage (V_{in}) measurements at the output of the rectifier as inputs. By continuously adjusting the duty cycle of a DC-DC boost converter that controls the energy flow from the WT to the grid, the algorithm perturbs the operating point and observes the corresponding changes in power output. It fine-tunes the duty cycle based on whether the power output increases or decreases with each perturbation. This process continues until the MPP is reached, at which point the system stabilizes, and the corresponding P_{MPP} is recorded for future reference [99]. It is important to note that WT power is restricted to its nominal power, which is the highest level of power that the WT can supply.

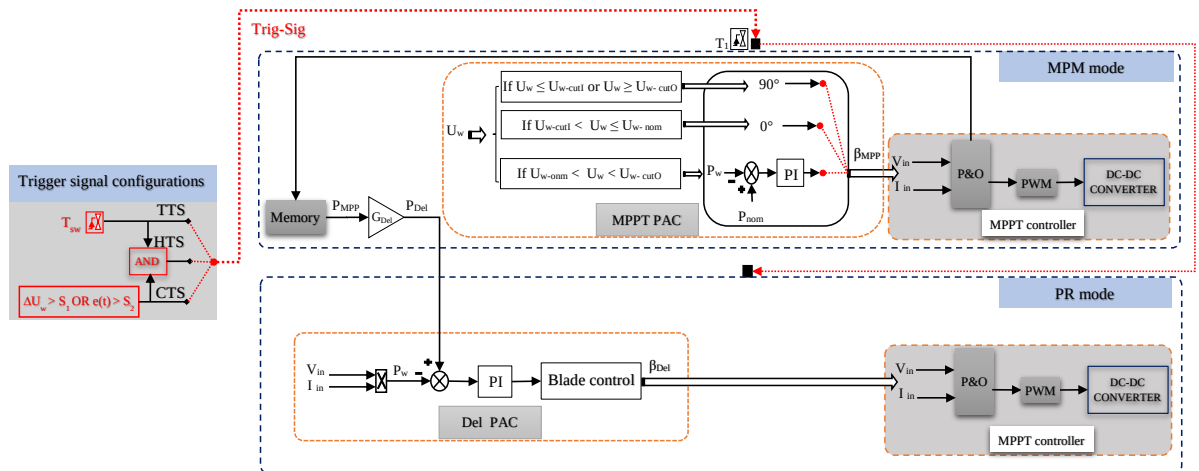


FIGURE 3.9 – Trigger signal (Trig-Sig) configurations diagram

In the first operating mode of the proposed approach, the duration is set to T_1 . This duration is adjusted to allow for a correct measurement of the available power of the energy source. The appropriate setting of T_1 is crucial to ensuring the accuracy and efficiency of the MPM mode.

Once the available power (P_{MPP}) is determined, the system transitions into its second operating mode, referred to as the power reserve (PR) mode. In this mode, the WT operates at the reference deloading power to generate a specified power reserve.

This process is achieved by computing the deloading pitch angle (β_{Del}) using a dedicated deloading pitch angle controller (DEL PAC). The DEL PAC employs a PI controller, which takes the current wind power (P_W) and the desired deloading reference power as inputs. Once the optimal (β_{Del}) is determined, the DC-DC boost converter is again controlled by the previously used P&O MPPT algorithm. This ensures that the WT operates at its maximum power point, which, in this case, corresponds to the required deloading power (P_{Del}).

3.3.2 Trigger signal

Following the completion of this cycle, the system remains in PR mode until a new activation is initiated to start a new cycle, during which it calculates the new MPP and PR. The trigger signal ($Trig - Sig$), which initiates cycle activation, may be configured in two manners, allowing for flexibility in system implementation options as presented in figure 3.9. These two configurations include:

- ★ Temporal trigger signal (TTS);
- ★ Conditional trigger signal (CTS).

The next subsections will explain and comprehensively define the trigger signal concept for each configuration shown in figure 3.9.

3.3.2.1 Temporal trigger signal (TTS)

The core concept of the TTS configuration hinges on temporal switching activation, as illustrated in figure 3.9. This entails the utilization of a predetermined switching time (T_{sw}), which is a periodically recurring signal that triggers cycles at specific intervals. To ensure the effective functioning of this configuration, it T_{sw} must satisfy several critical criteria:

- ★ **Completion of the cycle:** The switching time must be greater than the system's cycle time ($T_{sw} > T_{cyc}$) to provide ample time for each cycle to fully execute. This ensures

that all necessary tasks and operations within a cycle are completed before the next cycle begins.

- ★ **Switching time adjustment:** The choice of T_{sw} should be made with careful consideration, aiming to strike a balance between minimizing its impact on the system's stability and maximizing its effectiveness in capturing variations in wind conditions (U_w). A shorter T_{sw} allowed the control system to capture the majority of wind variations while increasing system oscillations, whereas a longer T_{sw} can give stability while missing considerable wind fluctuations.

Meeting these criteria guarantees that the TTS configuration allows the switching mechanism to function effectively within the context of wind energy generation while also ensuring the desired power reserve without compromising system stability.

3.3.2.2 Conditional trigger signal (CTS)

The second configuration's fundamental notion is a modified cycle initiation process with conditional activation or switching. After the initial cycle is automatically activated when the WT is connected to the grid, a monitoring signal is employed to initiate the next cycle by detecting any changes in WT maximum power. The monitoring signal provides flexibility through a range of implementation methods, including:

- ★ **Wind speed variation:** In this configuration, the monitoring signal relies on the detection of wind speed variations, denoted as ΔU_w . A crucial component in this process is the U_w sensor, which assumes a pivotal role by continuously monitoring the wind speed and collecting real-time data concerning the current wind conditions within the system's environment. When the U_w sensor registers any changes in wind speed (ΔU_w), it triggers the initiation of the next cycle. It's worth noting that the detected ΔU_w must exceed a predefined threshold denoted as S_1 . This threshold is set to prevent erroneous signals and false variations from prematurely initiating cycles, ensuring the reliability of the cycle initiation process.
- ★ **DC current (I_{in}) or DC voltage (V_{in}) variation:** In this configuration, the CTS is predicated on the detection of variations in DC current or DC voltage at the output of the rectifier, which serves as indicators of wind speed change. This detection process involves the calculation of the instantaneous relative error denoted as $e(t)$, derived from the observed values of I_{in} or V_{in} , as detailed in equation 3.8. The calculated value $e(t)$ is then compared to a predetermined threshold represented as S_2 , which is set to a value

exceeding the inherent error margin of the current or voltage sensors. The formulation for the instantaneous relative error $e(t)$ is defined as follows:

$$e(t) = \frac{I_{Del} - I_{in}}{I_{max}} \quad OR \quad e(t) = \frac{V_{Del} - V_{in}}{V_{max}} \quad (3.8)$$

Here I_{Del} and V_{Del} represent the deloading current and voltage, respectively. I_{max} and V_{max} denote the maximum current and maximum voltage that the sensor can measure, respectively.

In this configuration, CTS based on I_{in} or V_{in} variation, it is important to include a duration for the PR mode, denoted as T_2 . This duration represents the time needed to stabilize the WT at the desired deloading operating point (P_{Del}) and to stabilize both I_{in} and V_{in} , ensuring a correct capture of their variations.

By harnessing wind variation detection through the analysis of wind speed, I_{in} , or V_{in} , this configuration principle guarantees the system's adeptness in responding to real-time environmental changes efficiently.

A hybrid trigger signal (HTS) is an extra configuration, presented in figure 3.9, that may be used to avoid the risk of not capturing changes in wind speed due to the sensor sensitivity in the CTS configuration or the switching time in the TTS configuration. By integrating the two configurations, the HTS signal is created, which uses the TTS as an extra trigger signal and the CTS as the primary cycle initiation signal.

3.3.3 Power control regions and MPPT PAC

In addition to the deloading operation assured by the described cycle, the MPPT PAC is designed to ensure the WT safe and efficient operation across a range of operational conditions, as presented in figure 3.10. The controller accomplishes the following tasks:

1. **Cut_in and Cut_out Regions:** In the cut-in and cut-out regions, characterized by wind speeds either falling below the cut-in threshold (U_{w-cutI}) or surpassing the cut-out threshold (U_{w-cutO}), the WT pitch angle (β_{MPP}) is set to 90° . This configuration is implemented to safeguard the turbine: it prevents operation at low wind speeds and shields the turbine from potential damage during high-wind conditions. It's important to note that within these two regions, the WT does not generate any power, and no deloading operation occurs.
2. **Maximum power region without limitation:** In this region, which covers the specified range of wind speeds greater than U_{w-cutI} but less than or equal to the nominal

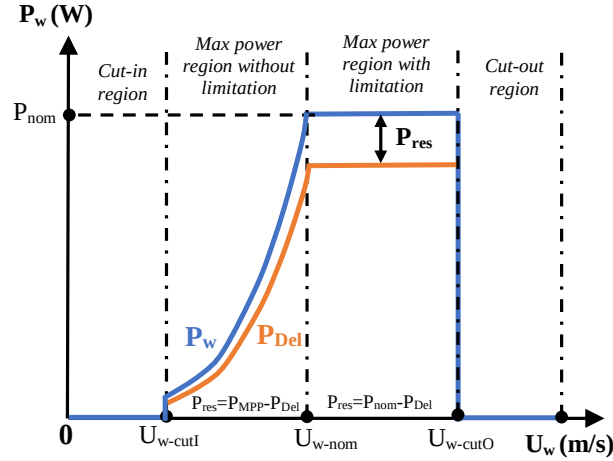


FIGURE 3.10 – Presentation of the extracted power in PR mode

wind speed (U_{w-nom}) corresponding to nominal power denoted as P_{nom} . The angle β_{MPP} is set to 0° , enabling the turbine's blades to efficiently extract the maximum mechanical power from the wind. Achieving MPPT is then accomplished by employing the P&O MPPT algorithm to regulate the output of the DC-DC boost converter. In this region, the deloading power reference P_{Del} is calculated using the available maximum power P_{MPP}

3. **Maximum power region with limitation:** When U_w exceeds U_{w-nom} but remains below U_{w-cutO} , the WT tends to accelerate its rotation speed, resulting in an increase in power output beyond the WT nominal power (P_{nom}). To ensure safe and reliable operation while preventing overloading of the blades, it is crucial to limit the available power to P_{nom} . In this operating region, the controller maintains a constant generator rotational speed (W_r) and increases β_{MPP} to a value greater than 0° . By adjusting the pitch angle, the WT effectively controls the power output to match P_{nom} , ensuring efficient operation and avoiding potential mechanical stresses caused by excessive power production. The P_{Del} is calculated based on P_{nom} in this region.

The equation 3.9 establishes the values of P_{Del} and P_{res} across different operational regions of the WT, as illustrated in figure 3.10.

$$\begin{cases} P_{res} = P_{MPP}(1 - G_{Del}) ; & \text{without limitation} \\ P_{res} = P_{nom}(1 - G_{Del}) ; & \text{with limitation} \end{cases} \quad (3.9)$$

3.3.4 Frequency and blade control

The total supplemental power provided by the WT in deloading mode ΔP_{PFC} , as presented in figure 3.11, is the sum of the contributions from the Droop and VIC phases:

$$\Delta P_{PFC} = \Delta P_{Droop} + \Delta P_{VIC} \quad (3.10)$$

The new power reference P_{ref} , incorporating the WT power with frequency regulation, is calculated as:

$$P_{ref} = P_{Del} + \Delta P_{PFC} \quad (3.11)$$

This power reference dynamically adjusts the WT blade pitch angle β and rotor speed W_r via PI controllers to precisely control the generated power output, ensuring additional power is injected into the grid to proactively compensate for detected frequency deviations.

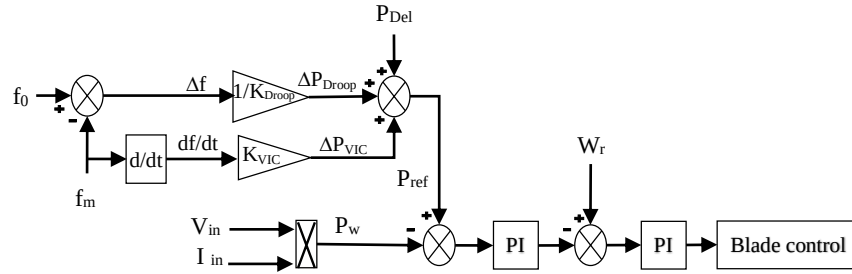


FIGURE 3.11 – Frequency regulation and blade control

3.4 Validation strategy

To validate and demonstrate the accuracy and efficiency of the proposed strategy, it is applied to a driven direct-wind permanent magnet synchronous generator (PMSG) grid system under various scenario tests. The entire system and different simulation tests are implemented in the Matlab Simulink environment. The following sections offer a comprehensive overview of the employed system and the different tests and scenarios applied.

3.4.1 System description

The proposed system presented in figure 3.12 comprises a 10 MW WT, with its specifications outlined in figure 3.13. This turbine is connected directly to a PMSG and operates

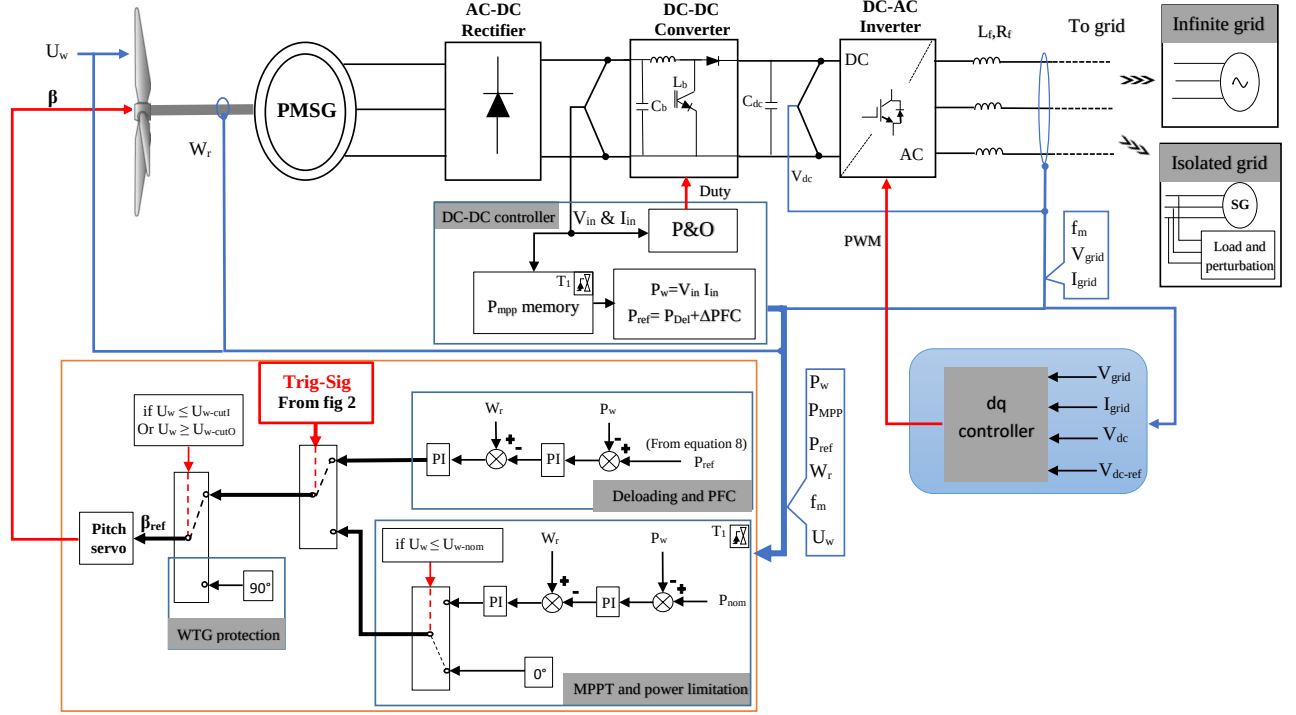


FIGURE 3.12 – System configuration and proposed strategy

without the need for a gearbox or multiplier, utilizing a direct-drive approach [100]. The generator is then coupled to a three-phase rectifier to produce a DC output.

For grid integration, a two-stage converter is used, as detailed in Chapter 2. The first stage, a DC-DC boost converter controlled by a P&O MPPT algorithm, regulates power extraction [101]. The second stage, a DC-AC three-level inverter with IGBTs, ensures DC-AC conversion, constant DC voltage, and zero reactive power, applying d-q axis decoupling [102]. An LR filter at the inverter output enables current filtering, with component values determined using [103]. The grid is simulated in two configurations. In the first configuration, it is represented as an infinite grid, achieved by connecting a three-phase voltage source in series with an RL circuit. The second approach involves simulating an isolated grid by employing a large SG connected to a main load, which represents electrical consumption, with varying load profiles that allow for sudden changes. Consequently, alterations in the load directly influence the frequency of the isolated grid. This approach considers the dynamic characteristics of a real-world isolated grid, where frequency deviations are a consequence of load fluctuations.

All the characteristics of the components and settings of the controllers are listed in the appendix (Table B.1).

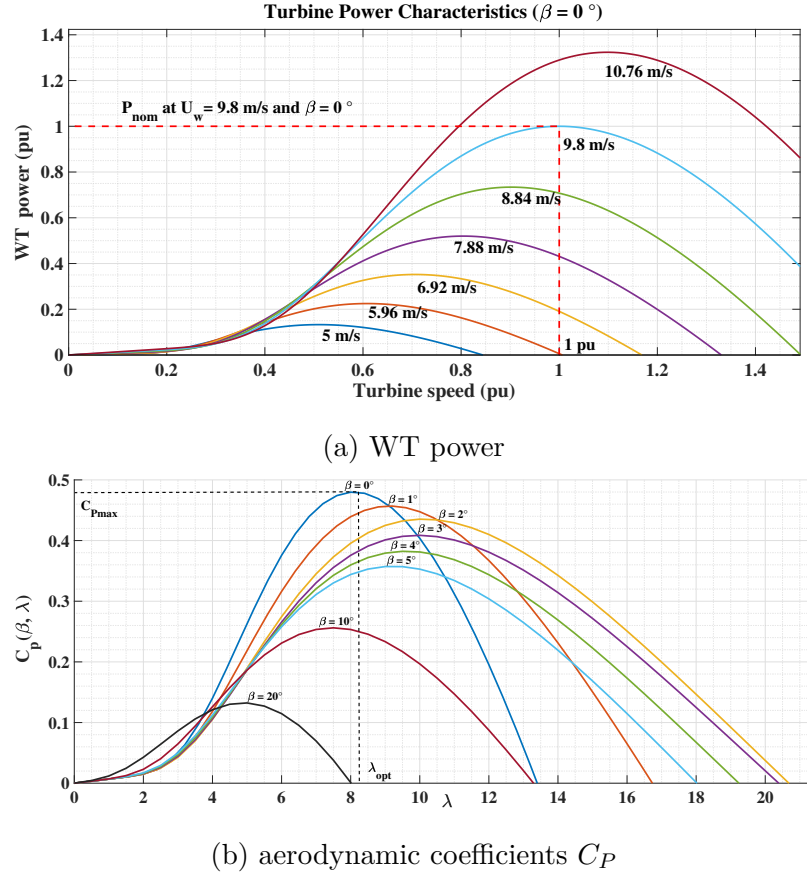


FIGURE 3.13 – 10 MW WT characteristic

3.4.2 Validation tests and scenarios

The proposed deloading strategy has undergone rigorous testing across various grid configurations, including infinite and isolated grids, to evaluate its performance under diverse operating conditions and climate variations. These tests are crucial for assessing the strategy's robustness and adaptability in real-world applications. Initial conditions such as turbine cut-in (4 m/s), cut-out (25 m/s), and nominal wind speeds (9.8 m/s), along with parameters like temporal switching time ($T_{sw} = 25$ s), MPM mode duration ($T_1 = 5$ s) and deloading gain ($G_{Del} = 0.8$), ensure the turbine maintains optimal power reserve ($P_{res} = 2$ MW) at nominal power (P_{nom}).

Wind speed variability tests simulate conditions from 8 m/s to 11 m/s, as illustrated in figure 3.14, mimicking fluctuating wind speeds with durations of 25 s to 40 s. Real-world wind data validation from ADA Municipal Airport over 24 hours on March 15, 2023, visualized in figure 3.16(a), further verifies the strategy's efficacy in practical scenarios [104].

Integration into frequency regulation systems involves two key tests: first, validating droop

regulation through simulations of power generation fluctuations in an infinite grid configuration and second, assessing overall frequency regulation capability under sudden power imbalance scenarios in an isolated grid setup. These tests highlight the strategy's ability to respond dynamically to changes in power demand, ensuring grid stability and effective power management in varying operating environments.

3.5 Results and discussion

3.5.1 Wind variation tests

In the initial test, the WT was operated in two distinct regions capable of generating power reserves. These tests were conducted under varying wind speeds, including both increases and decreases. The test results, visually depicted in figure 3.14, illustrate that the proposed strategy, with different configurations of the trigger signal (TTS and CTS), effectively achieves the desired power reserve. However, it is important to acknowledge the specific limitations associated with each configuration.

The TTS configuration does not rely on any sensors, which eliminates the risk of sensor errors. However, it depends on the setting of T_{sw} (the switching time interval). This can sometimes lead to gaps in capturing wind speed variations. For instance, as shown in figure 3.15 at $t = 85$ s, there is a change in U_w that occurs just before the activation of the cycle, indicating a delay in response. This issue can be mitigated by reducing T_{sw} to ensure a more timely capture of wind speed changes.

On the other hand, the CTS configuration continuously monitors climatic changes without any capturing gaps. It relies on various sensors, such as wind speed sensors, current sensors, or voltage sensors. The performance of the CTS configuration is therefore highly dependent on the reliability and accuracy of these sensors. If the sensors are precise and dependable, the CTS configuration can provide real-time adjustments to wind speed variations, offering a more responsive and accurate system compared to the TTS configuration.

In the second phase, dedicated to maximizing power while adhering to nominal power limitations, spanning time intervals from $t = 85$ s to $t = 150$ s, the system follows a distinct set of operations. In the MPM mode, the MPPT PAC adjusts β to β_{MPP2} (greater than 0°) to maintain the power output (P_w) at the nominal power level, denoted as P_{nom} . Additionally, the MPPT P&O algorithm maintains C_P at its new maximum value, C_{Pmax2} . After another duration of T_1 s, the PR mode is once again initiated. During this PR mode, β is increased to β_{Del2} by the Del PAC, surpassing the initial β_{MPP2} , while the MPPT P&O algorithm reduces

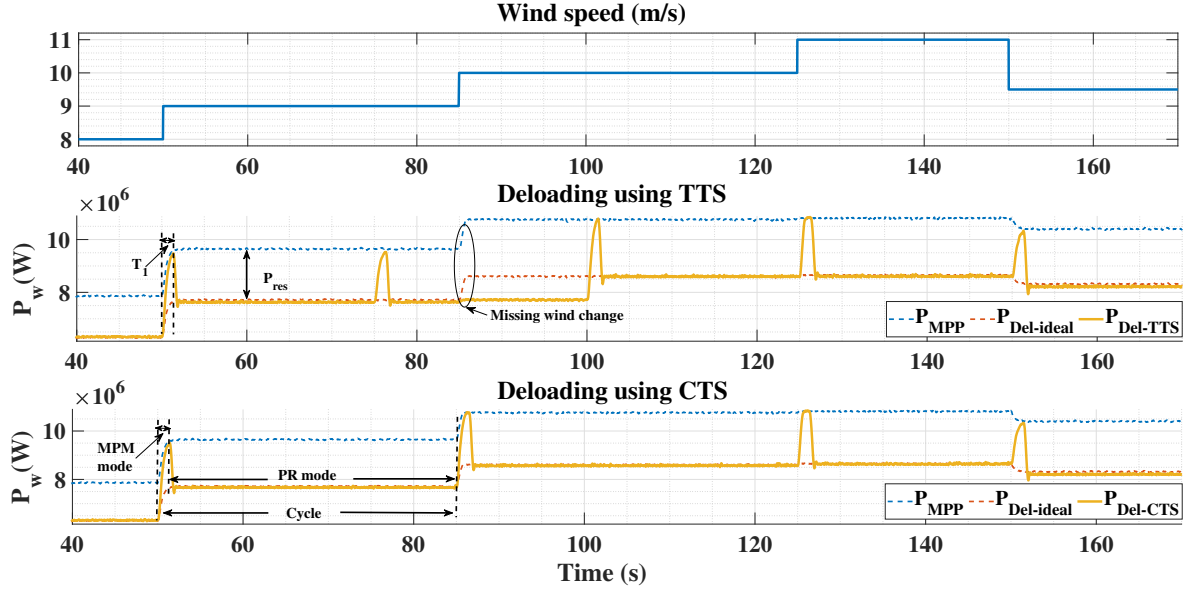
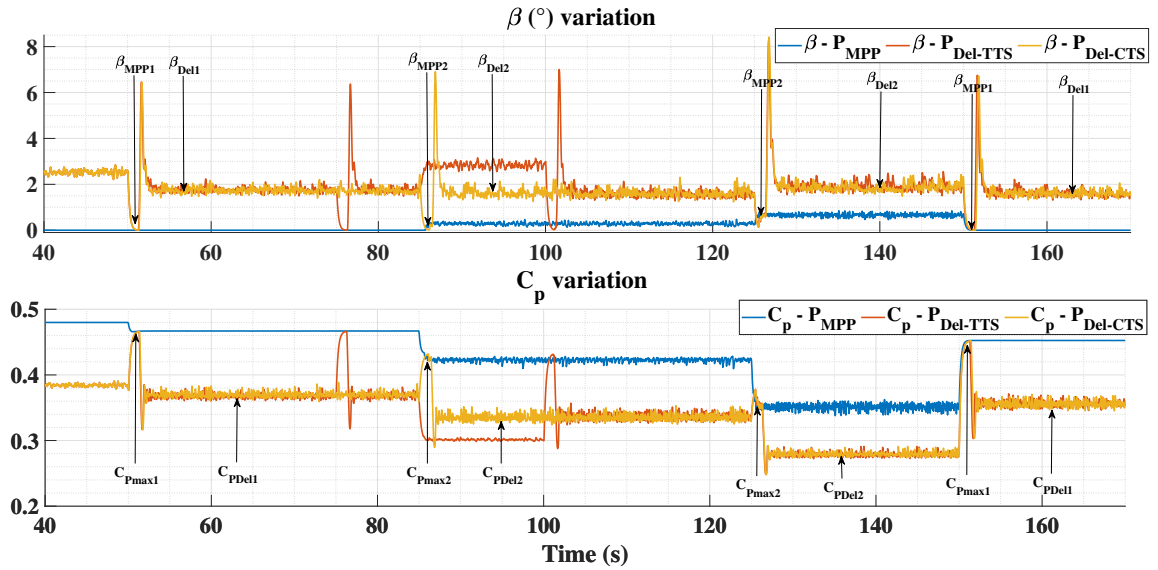


FIGURE 3.14 – Power reserve generation using TTS and CTS modes


 FIGURE 3.15 – C_p and β Variation in MPPT, TTS and CTS modes

C_P to $C_{P_{Del2}}$, enabling the WT to operate at the deloading point. This figure effectively communicates the dynamic adjustments in blade pitch and aerodynamic power coefficient as the system transitions between modes to optimize power generation, both within and constrained by power limitations.

Figure 3.16(b) displays the power of the WT controlled using the proposed strategy with TTS configuration during a recording of data of real wind speed variations. In power generated during this test. As depicted, the proposed strategy successfully achieves the desired

power reserve throughout the entire testing period. This outcome demonstrates that the strategy effectively adapts to real-world wind conditions, ensuring consistent and reliable power reserve generation during the test period.

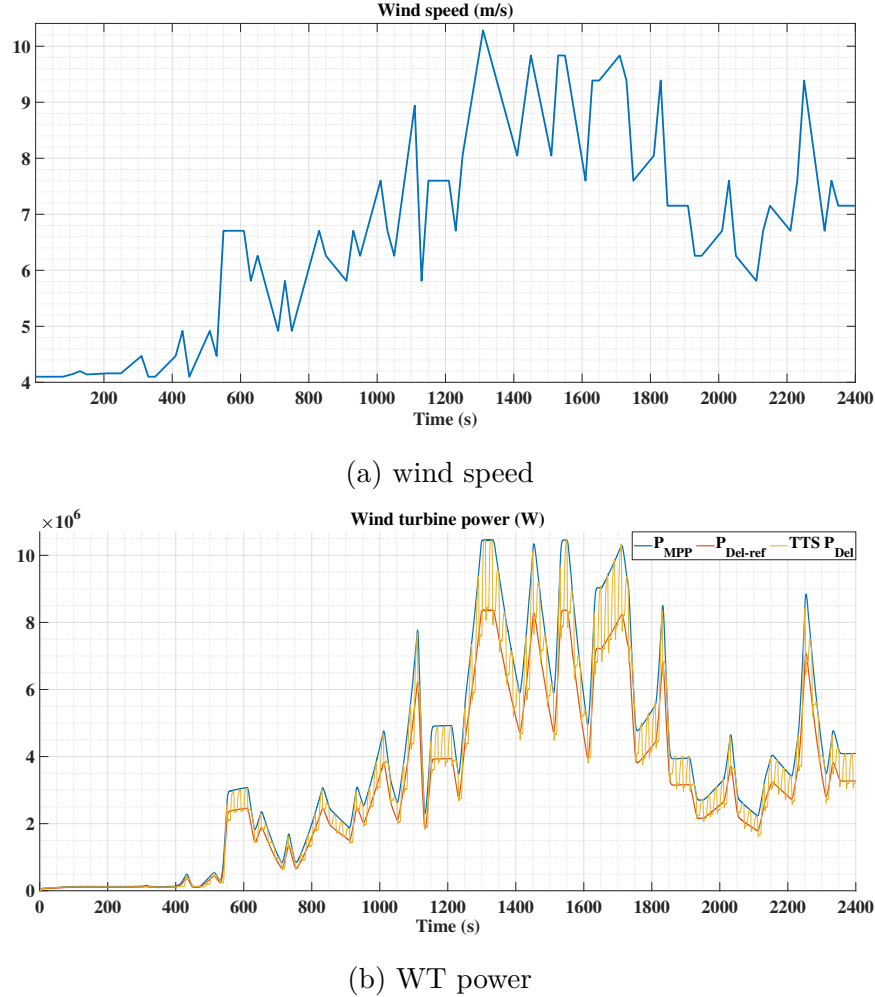


FIGURE 3.16 – Generating power reserve with real wind speed data

3.5.2 PFC integration tests

In this section, the primary focus is to validate and demonstrate the successful integration of the proposed strategy with PFC and its associated benefits. The validation process is divided into two parts, each addressing specific aspects of the strategy's performance. The first part aims to showcase the droop regulation behavior of the proposed strategy. In the second part of the validation, the complete integration of the proposed strategy with PFC is thoroughly examined.

3.5.2.1 Droop regulation

Figure 3.17 illustrates the application of a power reserve obtained through the deloading strategy, which involves injecting an additional 2 MW of active power when the grid frequency experiences a sudden 200 mHz (0.4%) decrease. The increase in power from 8 MW to 10 MW is attributed to the droop algorithm part, which relies on parameters such as K_{Droop} set to 2% (0.02 p.u.) and a 200 mHz (0.4%) reduction in frequency. Notably, the system smoothly attains the final value of (P_w) without exhibiting oscillations, achieving a 90% response time of just 4 s.

In a subsequent frequency disturbance, specifically a sudden 200 mHz increase in the grid frequency, figure 3.17 demonstrates a reduction of 2 MW in the WT active power injected into the grid, again corresponding to the droop integration. Notably, the system returns to a stable, steady state without exhibiting any oscillations.

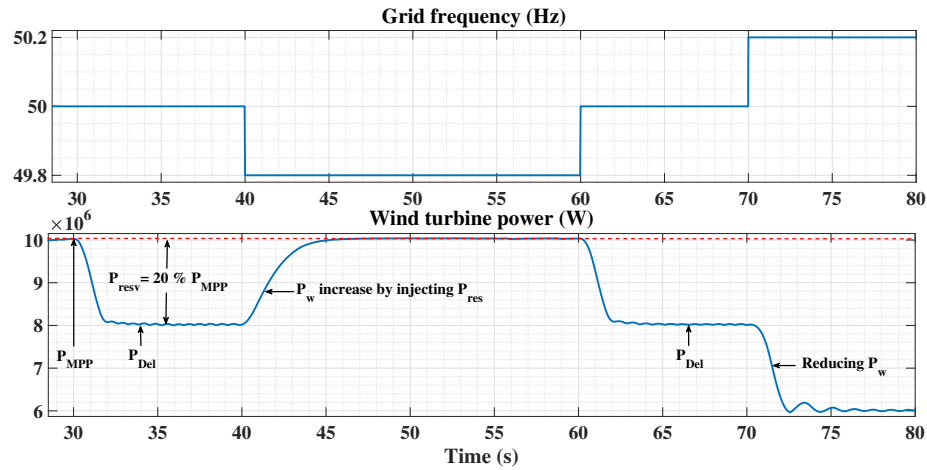


FIGURE 3.17 – Droop regulation validation

These simulation tests validate the correct and precise functioning of the Droop regulation part in maintaining power equilibrium. The system effectively responds to changes in power demand, ensuring stability by adjusting power generation without oscillations and with a convenient response time.

3.5.2.2 Droop and VIC

In this phase, the goal is to validate two main aspects of the PFC command: the Droop part and the VIC part. To achieve this, another frequency scenario is employed to evaluate the PFC system's performance. This scenario involves simulating a frequency signal that could occur when a major power plant experiences an outage.

Figure 3.18 illustrates a standard frequency waveform, demonstrating a notable increase in power demand at $t = 120$ s, followed by a subsequent decrease at $t = 160$ s. This depiction also showcases the pivotal role of the PFC loop in responding to these changes, including its two parts, the Droop part and the VIC part. When faced with heightened power demand at $t = 120$ s, the PFC system promptly signals the WT to inject additional power into the grid, ensuring grid stability. Conversely, when power demand decreases at $t = 160$ s, the PFC system directs the WT to reduce its power output, effectively balancing the supply and demand of electricity and maintaining the grid's frequency within acceptable limits.

The noteworthy aspect here is the system's effective response to these changes in power demand, ensuring power balance within the grid. It achieves this with remarkable stability, without undesirable oscillations, and demonstrates a rapid response to these fluctuations. This control and stability are critical for maintaining the reliability and efficiency of the power grid, particularly during unexpected events like power plant outages.

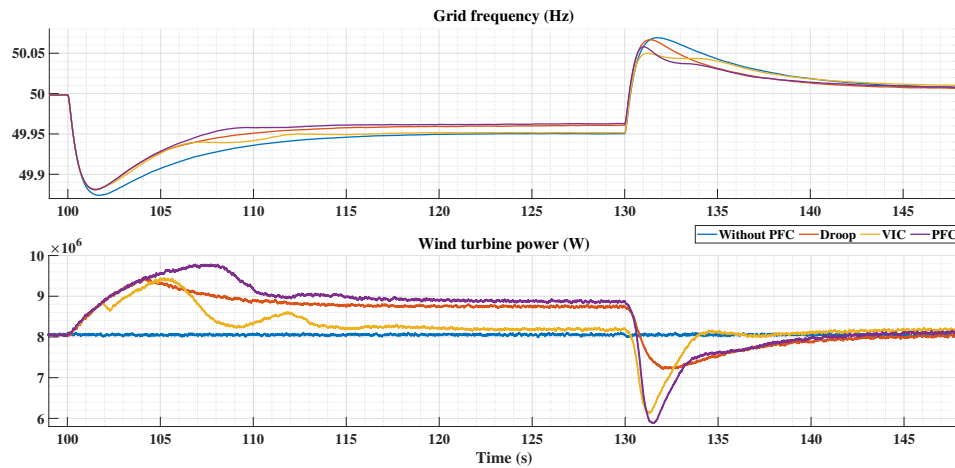


FIGURE 3.18 – VIC, Droop and PFC integration in isolated grid

In summary, after conducting comprehensive tests on the proposed deloading strategy, which has consistently validated its accuracy, ensured high system stability, and demonstrated its ability to respond swiftly without undesirable oscillations, it is clear that this strategy offers an optimal solution. Notably, its key qualities include its simplicity of implementation, devoid of additional sensors or the need for intricate mathematical models or prior knowledge of system parameters. These qualities, coupled with the successful validation results, position this strategy as a comprehensive and suitable approach for real-world grid implementations.

3.6 Advanced and robust controller implementation

The first proposed deloading strategies focus on conventional Proportional-Integral (PI) controllers, which are commonly employed. However, these methods often fall short in handling the dynamic and unpredictable nature of wind energy. By integrating advanced control techniques, the efficiency and stability of the system can be significantly enhanced. In this work, an FLC and $\mathcal{H}_\infty$ controller are integrated. The FLC provides adaptive control capabilities, allowing for better handling of nonlinearities and uncertainties, while the $\mathcal{H}_\infty$ controller offers robust performance against disturbances and model inaccuracies [105]. This combination ensures more reliable and efficient deloading, thereby improving overall grid stability.

3.6.1 PI-FLC application

The proposed deloading approach initially utilizes a conventional $PI_{Del-PAC}$ controller in PR mode to maintain WT operation around the target P_{Del} under varying conditions. However, PI controllers face tuning challenges and may lose accuracy with certain V_w changes. To address this, a PI-FLC is implemented to ensure precise tuning in response to climate changes. Unlike conventional controllers, PI-FLC effectively manages uncertainties and imprecise inputs, enhancing adaptability to dynamic conditions and improving the overall performance and robustness of the deloading strategy.

The main objective of the conventional PI controller in the PAC system is to adjust P_{W-nor} to match reference $P_{Del-nor}$ by controlling the β , typically transitioning from the MPP β_{MPP} to the desired deloading point β_{Del} . However, this controller often struggles with parameter tuning and may lose accuracy in certain climate conditions.

The nonlinear characteristics of power systems, encompassing components like the WT, PMSG, and rectifier, pose challenges for linearization, complicating traditional PI controller methods for regulating variable-speed WECS. In response, PI-FLC emerges as a rule-based nonlinear control approach, offering advantages by effectively handling system model uncertainties. The transition from conventional PI control to PI-FLC is depicted in figure 3.19. This system functions as a multi-input multi-output (MIMO) FLC setup with two inputs: the error between actual and desired per unit power output (P_W and P_{Del}) (e) and its rate of change (Δe). Its outputs are the PI parameters (K_P and K_I), and then a reference signal consisting of β_{Del} is generated.

Figure 3.20 shows the input membership functions (e and Δe) and the output membership functions (K_P and K_I) of the PI-FLC. Tables 3.1 and 3.2 outline the PI-FLC guidelines that

influence its decision-making process.

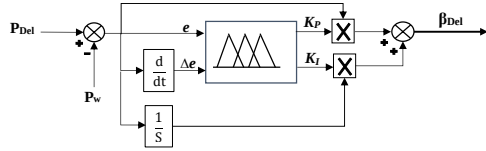


FIGURE 3.19 – PI-FLC structure

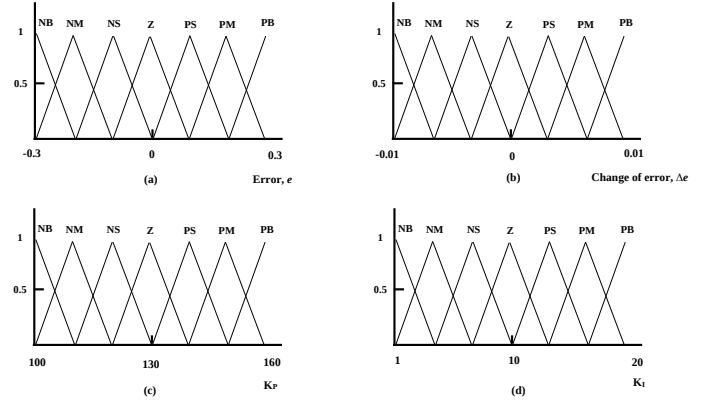


FIGURE 3.20 – PI-FLC membership functions: inputs members: (a) error (e) and (b) change of error (Δe), and outputs members: (c) K_P and (d) K_I

TABLE 3.1 – Fuzzy rules of K_P

$\Delta e/e$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	PS
NS	NM	NM	NM	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	Z	PM	PM	PM	PB	PB

TABLE 3.2 – Fuzzy rules of K_I

$\Delta e/e$	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

3.6.2 Grid side control (GSC)

3.6.2.1 Conventional GSC

The grid-side control loop monitors the inverter to regulate both the DC link voltage (V_{dc}) and the grid voltage (V_{abc}) to enable the transfer of active power without reactive power. In the GSC system illustrated in figure 3.21, the AC signals' active and reactive power components are separated by transforming them into the dq reference frame. The amplitude of the current in the d-axis is adjusted to maximize active power transfer, while the amplitude in the q-axis is adjusted to minimize reactive power. This control approach is widely employed with double-stage inverters in renewable energy systems, with further

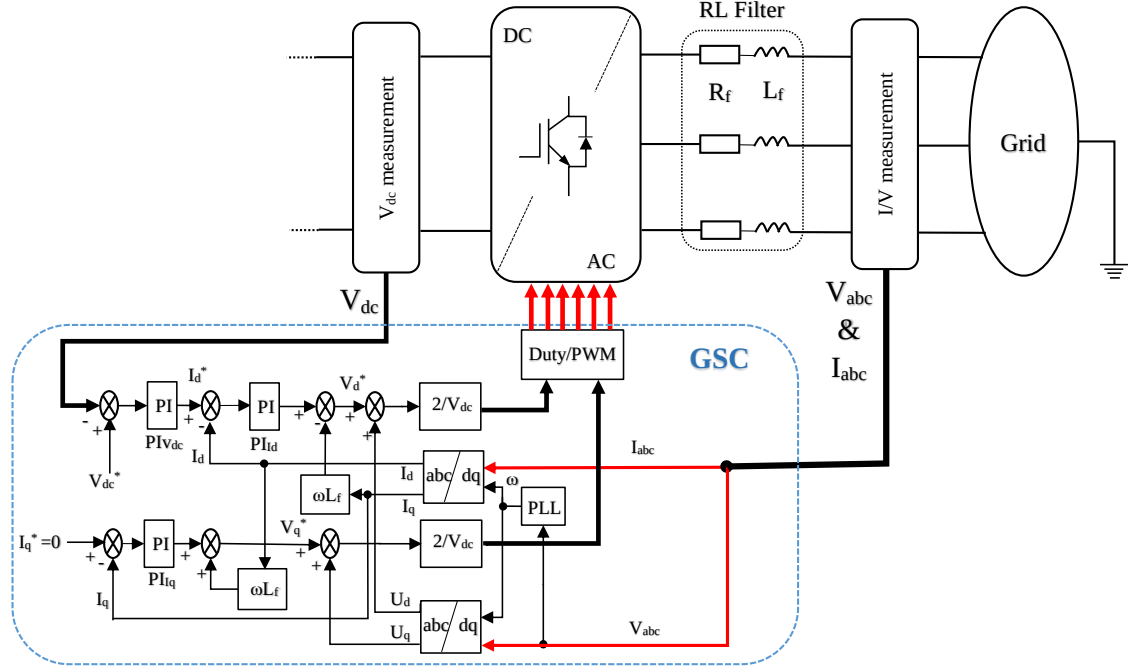


FIGURE 3.21 – Conventional grid-side control

details provided in [106, 107]. The grid-side dynamic model, incorporating the dynamics of the inverter and filter, is given by :

$$\begin{cases} dI_d/dt = 1/L_f(v_d^* - R_f I_d + \omega L_f I_q) + U_d + 2/V_{dc} \\ dI_q/dt = 1/L_f(v_q^* - R_f I_q - \omega L_f I_d) + U_q + 2/V_{dc} \end{cases} \quad (3.12)$$

where R_f denotes the grid resistance and L_f represents the grid inductance.

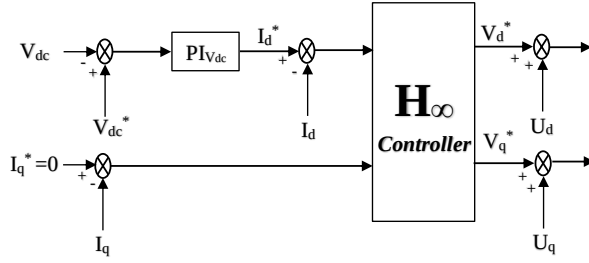
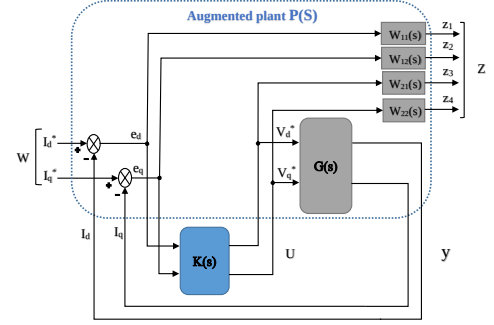
3.6.2.2 $\mathcal{H}_\infty$ implementation

The digital $\mathcal{H}_\infty$ robust control, replacing the I_d PI controller (PI_{Id}) and the I_q PI controller (PI_{Iq}), is depicted in figure 3.22 with a feedback configuration. The augmented system, labeled P, is presented in figure 3.23 and described as follows:

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \quad (3.13)$$

and $G(s)$ is the matrix of transfer function equal to $C_2(SI - A)^{-1}B_2 + D_{22}$

In this context, the digital $\mathcal{H}_\infty$ robust control aims to design a controller $K(s)$ to minimize the induced norm of the input-output operator $T_{zw}(w \rightarrow z)$, where x represents the state


 FIGURE 3.22 – $\mathcal{H}_\infty$ grid side control

 FIGURE 3.23 – The configuration of $\mathcal{H}_\infty$ control incorporating weighting function

vector, w is the exogenous input vector (including external inputs and disturbances), u is the control input vector, z is the error (output) vector, and y is the measurement vector.

The robustness objective encompasses two main characteristics. Firstly, it aims to achieve robust disturbance rejection from exogenous signals in the low-frequency region. This translates to ensuring that the sensitivity function ($S(s) = 1 / (1 + G(s)K(s))$) approaches zero as the frequency w approaches zero. Secondly, the controller must guard against instability arising from parameter variations. This is typically achieved by minimizing the control effort ($R(s) = K(s) / (1 + G(s)K(s))$).

The $\mathcal{H}_\infty$ control algorithm addresses these challenges by solving a suboptimal controller design problem. The algorithm aims to synthesize a stabilizing controller that ensures the closed-loop gain from the disturbance w to the controlled output z is less than a specified level of optimality, denoted by γ (where $\gamma > 0$).

$$\|T_{wz}\|_\infty \left\| \begin{pmatrix} W_{11}S, W_{12}S \\ W_{21}R, W_{22}R \end{pmatrix} \right\|_\infty < \gamma. \quad (3.14)$$

By tacking the following assumptions:

$$z = \begin{bmatrix} e_d \\ e_q \\ V_d^* \\ V_q^* \end{bmatrix} = \begin{bmatrix} I_d^* - I_d \\ I_q^* - I_q \\ V_d^* \\ V_q^* \end{bmatrix}, \quad (3.15)$$

$$x = \begin{bmatrix} I_d \\ I_q \end{bmatrix}, \quad w = \begin{bmatrix} I_d^* \\ I_q^* \\ I_d \\ I_q \end{bmatrix}, \quad u = \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix}.$$

The augmented system P derived from the equation (3.11) equal to:

$$\begin{aligned}
 \dot{x} &= \begin{bmatrix} \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \begin{bmatrix} -R_f/L_f & -100\pi L_f \\ 100\pi L_f & -R_f/L_f \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} + \begin{bmatrix} 1/L_f & 0 \\ 0 & 1/L_f \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \\
 z &= \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \\
 y &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \quad (3.16)
 \end{aligned}$$

A crucial aspect of $\mathcal{H}_\infty$ controller design involves determining proper weighting functions. The importance of selecting these functions is widely discussed in the literature. Many studies, including this one, opt for first-order weighting functions, even for second-order systems, due to their simplicity [108–110]. W_{11} and W_{12} are designed as low-pass filters, as described:

$$W_{11} = \frac{s/m_1 + \epsilon_1}{s + \epsilon_1 r_1}, W_{12} = \frac{s/m_2 + \epsilon_2}{s + \epsilon_2 r_2} \quad (3.17)$$

where m_1 , ϵ_1 , and r_1 represent the tuning parameters for W_{11} , while m_2 , ϵ_2 , and r_2 denote the tuning parameters for W_{12} .

The second weighting functions, denoted as W_{21} and W_{22} , are set to avoid controller saturation and are defined as $W_{21} = W_{22} = \frac{V_{dc}}{2}$.

3.7 Simulation tests

3.7.1 Tests

The proposed testing process consists of two distinct phases. The initial phase is sacred to evaluate the performance and precision of the proposed real-time strategy, leveraging PI-FLC as opposed to a conventional PI controller. This stage entails subjecting the configuration to fluctuating V_w to gauge its effectiveness in system regulation. It is important to note that the G_{Del} is set to 0.8 to generate a P_{res} of 20%.

Specifically, the V_w variation scenario, presented in figure 3.24, follows a theoretical framework encompassing four V_w changes. Initially, V_w is set at 7 m/s; at $t = 30$ seconds, V_w increases to 8 m/s, followed by another increment to 10 m/s at $t = 40$ seconds. Subsequently, V_w surges to 11 m/s at $t = 50$ seconds, concluding with a decrease back to 9 m/s at $t = 60$ seconds. This scenario simulates a range of V_w fluctuations occurring within different operational regions of the WT: 7 m/s, 8 m/s, and 9 m/s within the MPPT region, and 10 m/s

and 11 m/s within the power limitation region. Such variability comprehensively assesses the configuration's performance across diverse operating conditions and effectiveness in different WT operating regions.

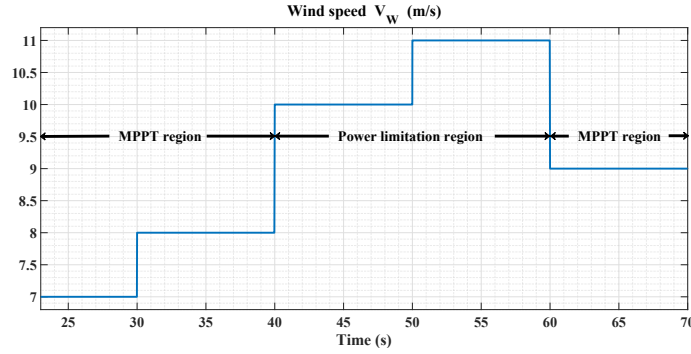


FIGURE 3.24 – Wind speed variation scenario

In the second phase, the focus shifts to evaluating and validating the superiority of the $\mathcal{H}_\infty$ controller in maintaining grid stability. Initially, the $\mathcal{H}_\infty$ controller is validated by demonstrating its ability to provide the desired P_{res} without any changes to the grid parameters (L_f and R_f), which remain at their nominal values. Then the grid parameters are subjected to variations at $t = 3.5$ minutes. The first change involves a low variation of up to 20% in both parameters from their nominal values. The second change involves a significant variation, with R_f varying by more than 50% from its nominal value. The changes in grid parameters are simulated by connecting additional resistance or inductance components in series with the main circuit. A circuit breaker is used to integrate these components at specific times to mimic increases in grid parameters.

3.7.2 Results

Figure 3.25 presents a comprehensive analysis of WT behavior, encompassing key parameters such as output power, C_p , and β , in response to varying V_w . This examination includes the implementation of two distinct control strategies: PI controller and PI-FLC controller, operating in both MPM and PR modes.

The test results, depicted in Table 3.3, show that a strategy based on the PI controller yielded an accuracy error of -15% (-0.15 MW in P_{res}) during the period from $t = 25$ s to $t = 30$ s with $V_w = 7$ m/s, and an error of -10.7% (-0.15 MW in P_{res}) during the period from $t = 30$ s to $t = 40$ s with $V_w = 8$ m/s. In contrast, the strategy based on PI-FLC presented a unique error of +2.5% (-0.05 MW in P_{res}). These results demonstrate the high accuracy of the PI-FLC strategy, providing a more precise P_{res} .

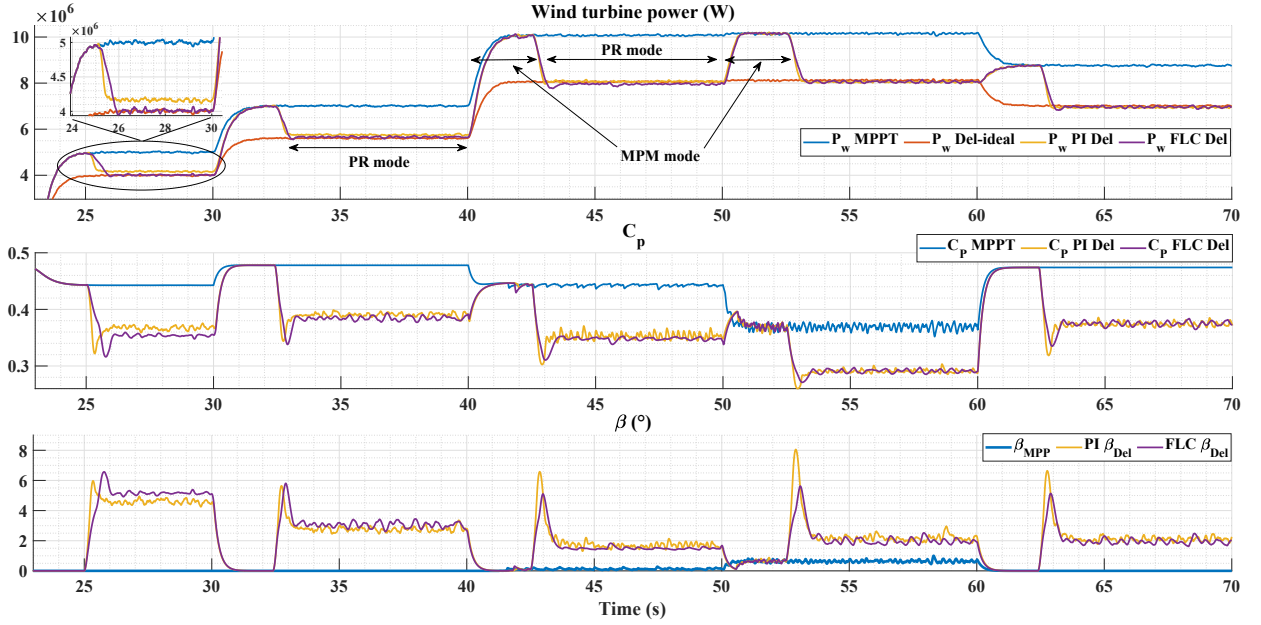


FIGURE 3.25 – Comparison of WT power, C_p , and β : deloading strategies

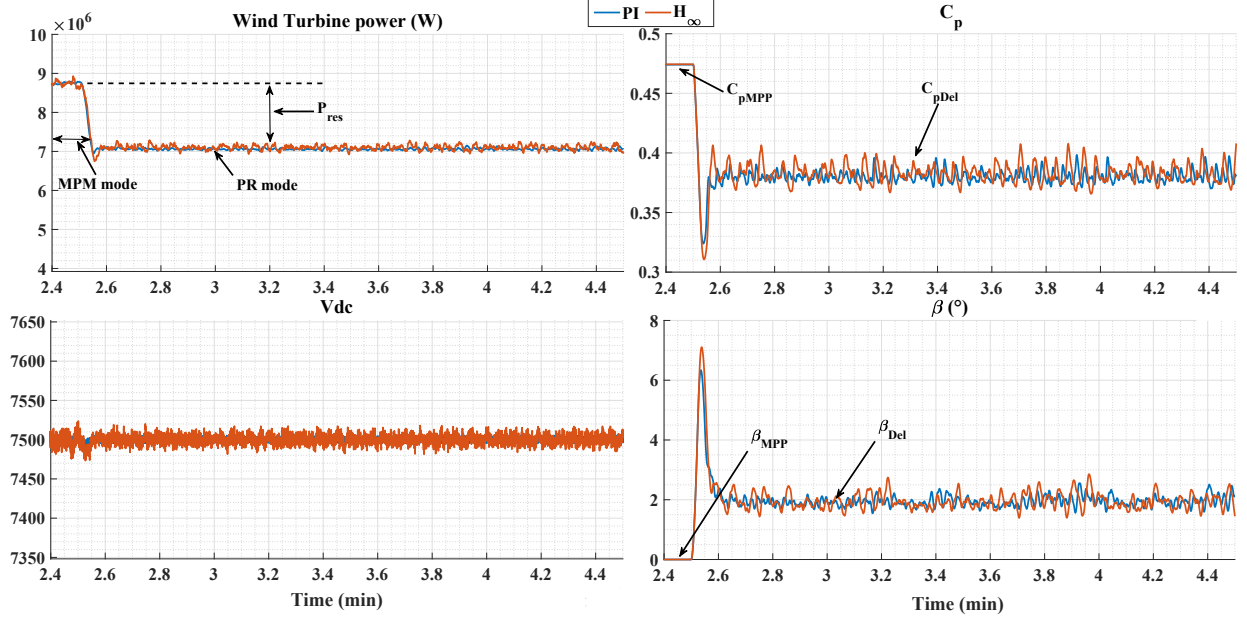


FIGURE 3.26 – Comparison of WT power, V_{dc} , C_p , and β : without parameter variations

The same figure also depicts the C_p and β dynamics using both strategies; this dynamic shows fewer oscillations with the PI-FLC strategy, which provides more stability to the proposed system. The findings demonstrate that employing the deloading approach based on PI-FLC yields notably superior performance, accuracy, and mitigation of oscillations. This is particularly evident compared to the deloading approach with a PI controller.

TABLE 3.3 – Strategy test

Strategy based on PI				
V_w (m/s)	P_{mpp} (MW)	P_{Del} (MW)	P_{res} (MW)	error (%)
7	5	4.15	0.85	-15
8	7	5.75	1.25	-10.7
10	10.05	8.05	2	0
11	10.05	8.05	2	0
9	8.75	7	1.75	0
Strategy based on PI-FLC				
V_w (m/s)	P_{mpp} (MW)	P_{Del} (MW)	P_{res} (MW)	error (%)
7	5	4	1	0
8	7	5.6	1.4	0
10	10.05	8	2.05	+2.5
11	10.05	8.05	2	0
9	8.75	7	1.75	0

Figure 3.26 illustrates the configuration characteristics, WT power, C_p , β and V_{dc} , using both controllers, with V_w set to 9 m/s, G_{Del} at 0.8, the grid parameters remain unchanged at their nominal values. Notably, both controllers maintain a P_{res} of 1.8 MW, representing 80% of the WT's maximum power (8.85 MW), while ensuring stable V_{dc} . Particularly noteworthy is the superior performance of the PI controller, evident in its ability to exhibit fewer oscillations, as observed in the behavior of C_p and β .

Figures 3.27, 3.29, and Table 3.4 illustrate the WT output power during deloading mode with low variation in grid impedance parameters introduced at $t = 3.5$ minutes, as previously described. The comparison between controllers shows the impact of these variations on grid characteristics. For R_f variations, the $\mathcal{H}_\infty$ controller reduces WT power fluctuations to 6.4%, compared to 13.6% with the PI controller, achieving a net improvement of about 52.94%. Similarly, V_{dc} fluctuations are reduced to 0.6% with the $\mathcal{H}_\infty$ controller, compared to 0.9% with the PI controller, reflecting a net improvement of approximately 33.33%. For L_f variations, the $\mathcal{H}_\infty$ controller reduces WT power fluctuations to 13.6%, versus 23.5% with the PI controller, yielding a net improvement of around 42.55%. Additionally, V_{dc} fluctuations are reduced to 1.06% with the $\mathcal{H}_\infty$ controller, compared to 1.6% with the PI controller, resulting in a net improvement of about 33.75%.

In addition, figures 3.28, and 3.30 show that the $\mathcal{H}_\infty$ controller reduces fluctuations in I_{abc} and V_{abc} compared to the conventional PI controller, even under low variations in grid impedance parameters. This indicates the superior stability of the $\mathcal{H}_\infty$ controller, which maintains smoother operation and minimizes oscillations in critical grid characteristics such

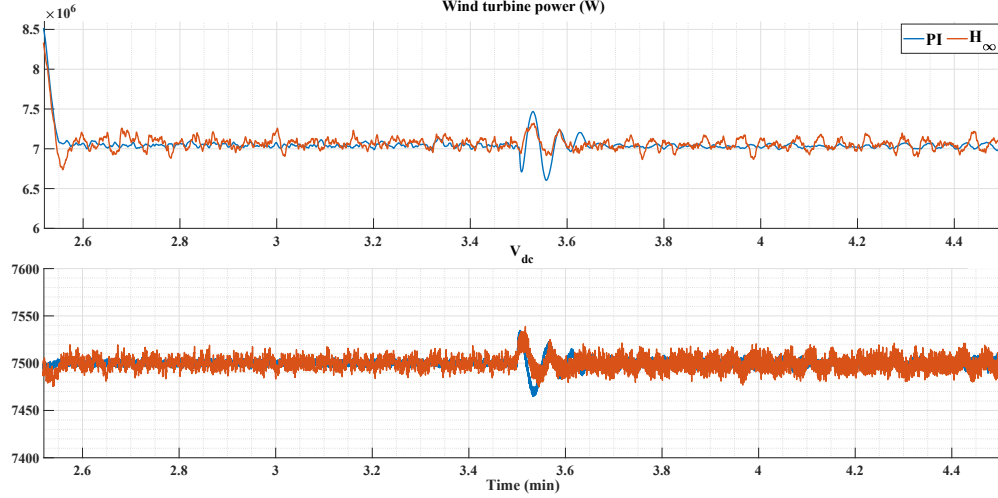


FIGURE 3.27 – Comparison of WT power and V_{dc} : with low resistance variation

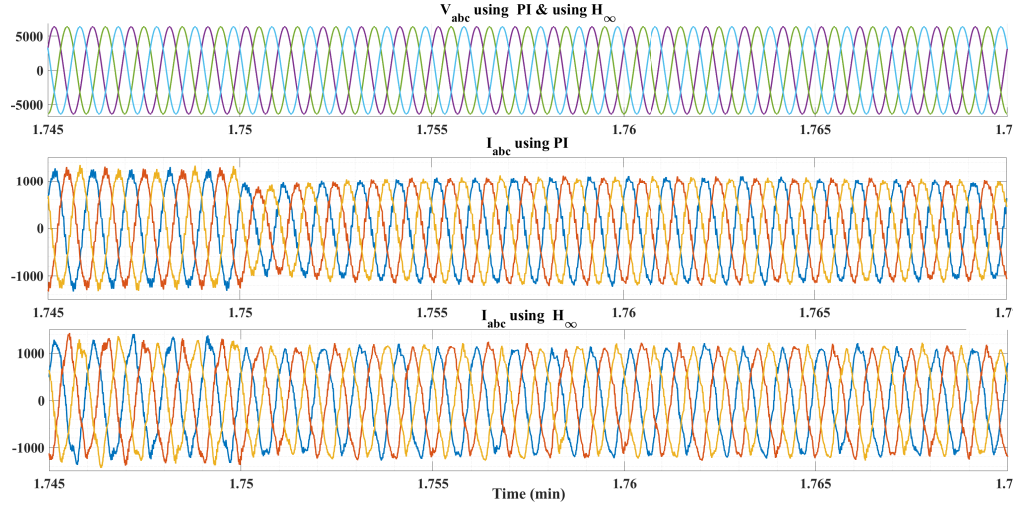


FIGURE 3.28 – Comparison of I_{abc} and V_{abc} : with low resistance variation

as WT power output, V_{dc} , I_{abc} , and V_{abc} . By effectively managing minor parameter variations, the $\mathcal{H}_\infty$ controller ensures more consistent and reliable performance.

Figure 3.31 illustrates the system characteristics under high parameter variations, specifically when R_f is increased by more than 50% from its initial value. The figure shows that the $\mathcal{H}_\infty$ controller adeptly manages these significant variations, maintaining grid stability and effective management throughout. In contrast, the PI controller struggles to cope with such substantial changes, leading to divergence and an inability to maintain grid stability.

All of these test results underscore the significant improvements achieved by integrating advanced control techniques into the proposed deloading processes. The PI-FLC excels in

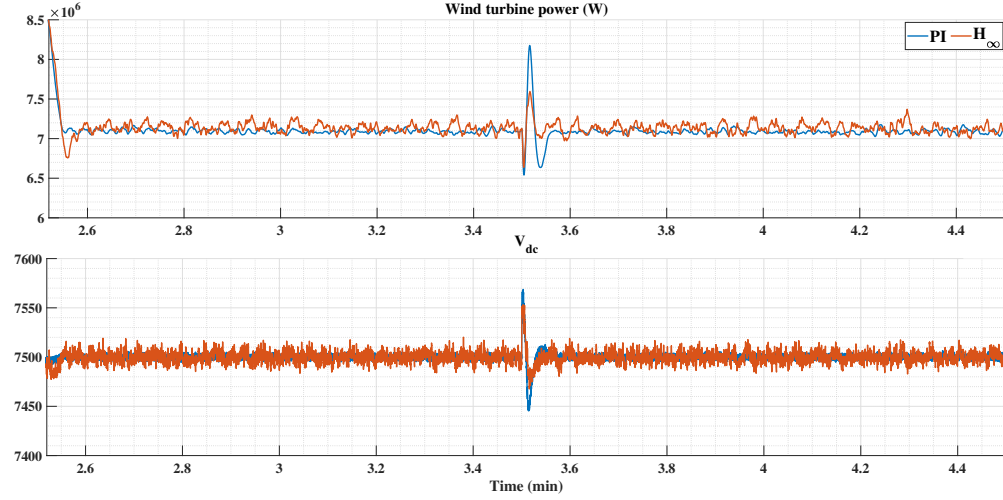


FIGURE 3.29 – Comparison of WT power and V_{dc} : with low inductance variation

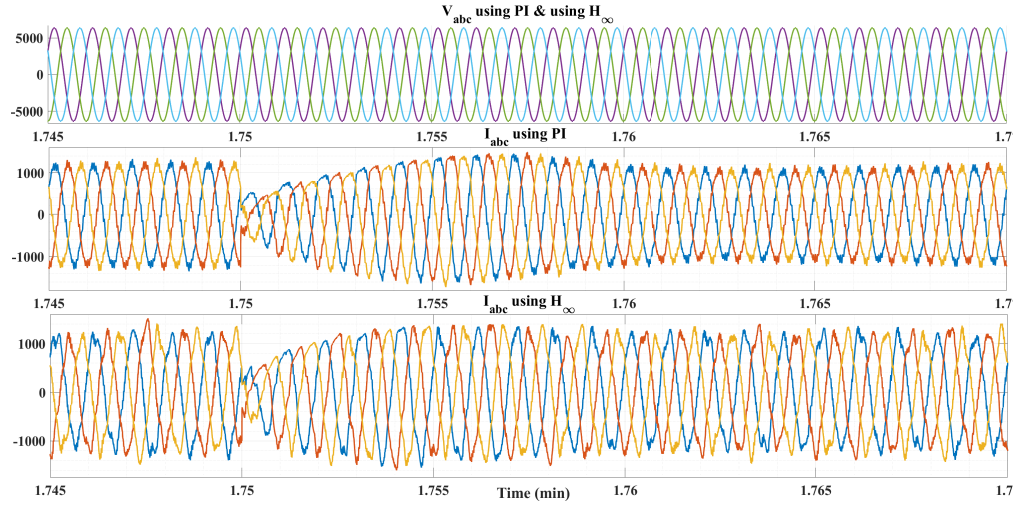


FIGURE 3.30 – Comparison of I_{abc} and V_{abc} : with low inductance variation

TABLE 3.4 – Low variations test

Conventional GSC		
Parameter	ΔP_{Del} (MW)	ΔV_{dc} (V)
R_f	0.9 (13.6%)	70 (0.9%)
L_f	1.6 (23.5%)	125 (1.6%)
$\mathcal{H}_\infty$ controller		
Parameter	ΔP_{Del} (MW)	ΔV_{dc} (V)
R_f	0.4 (6.4%)	50 (0.6%)
L_f	0.9 (13.6%)	80 (1.06%)

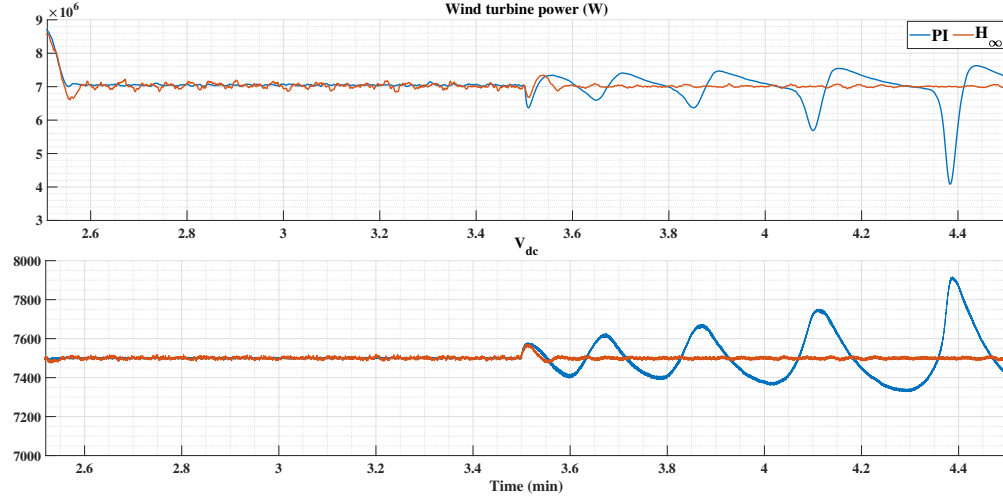


FIGURE 3.31 – Comparison of WT power and V_{dc} : with high parameter variations

adapting to changing climatic conditions, such as wind speed fluctuations. This adaptability ensures more precise and efficient power reserve generation, allowing the system to effectively respond to varying environmental conditions.

Conversely, the $\mathcal{H}_\infty$ controller demonstrates exceptional stability across a wide range of grid parameter variations, both low and high. It maintains consistent system operation even amidst significant variations in grid parameters. The $\mathcal{H}_\infty$ controller's robust performance in managing severe variations helps to minimize the impact of such disturbances, which is essential for sustaining grid stability.

Overall, the advanced control adaptations (PI-FLC) and $\mathcal{H}_\infty$, significantly enhance both the efficiency and stability of WT systems. The PI-FLC improves adaptability to environmental changes, while the $\mathcal{H}_\infty$ controller provides robust performance under varying grid conditions, contributing to the more reliable and stable operation of WT systems.

3.8 Conclusion

This chapter introduced an innovative real-time deloading strategy for wind energy systems (WES), designed for simplicity, efficiency, and adaptability. Unlike conventional approaches, this method eliminates the need for complex computations, prior WT parameter knowledge, or additional sensors. By operating in cyclic modes triggered by a signal mechanism, the proposed strategy dynamically adjusts to changing climate conditions, ensuring effective frequency regulation. Validation tests under various theoretical and real wind speed scenarios confirmed its reliability and practical effectiveness, making it a promising alterna-

tive for grid stability enhancement in wind-integrated power systems.

To further improve adaptability and robustness, the study explored the integration of advanced control strategies. The proportional-integral fuzzy logic controller (PI-FLC) enhanced system adaptability by refining response precision, while the $\mathcal{H}_\infty$ controller bolstered grid stability by minimizing the effects of parameter variations and uncertainties. These improvements reinforce system resilience, enabling WES to operate more efficiently under dynamic grid conditions.

Looking forward, future research directions should explore AI-driven control mechanisms, such as reinforcement learning for self-optimizing deloading strategies, and hybrid AI-fuzzy systems for enhanced real-time decision-making. Additionally, expanding predictive modeling techniques could further improve wind power forecasting and grid interaction, enabling more proactive control adjustments. Investigating multi-objective optimization methods that balance grid stability, economic efficiency, and energy storage integration will be crucial for the next generation of highly adaptive wind energy systems. These advancements can pave the way for a more intelligent, resilient, and sustainable wind-powered energy grid, effectively supporting the global transition toward renewable-dominated power systems.

Chapter 4: Deloading and Advanced Control Techniques for Hybrid PV-Wind System

To address the integration of hybrid RES, specifically PV and WT, this chapter examines the implementation of a hybrid deloading approach. The proposed method is validated under diverse climatic conditions, various system configurations, and different power reserve targets for each source, ensuring its adaptability to real-world scenarios. Additionally, the chapter explores the impact of these configurations on system performance and frequency regulation. Finally, a robust controller is integrated into the hybrid system to enhance its stability, ensuring reliable operation against parameter variations and grid uncertainties.

4.1 Introduction

This chapter focuses on hybridising PV and WT energy systems to enhance their overall performance and maximise power extraction and injection into the grid under varying climate conditions and operational scenarios. Building on the deloading techniques developed for individual PV and wind systems, it explores the integration of these approaches in a hybrid PV-wind configuration. A robust control strategy, employing the $\mathcal{H}_\infty$ controller, is then introduced to adapt the system to maintain stability. The strategy ensures optimal performance by leveraging deloading techniques to compensate for variations in system parameters.

The first section of this chapter provides a comprehensive description of the hybrid PV-wind system, detailing the integration of the proposed deloading techniques for both PV and wind components. This section elucidates the design and operational principles of the hybrid system, demonstrating how the combined approach enhances overall system performance.

Following the description, the second section is dedicated to testing and validating the

hybrid deloading system under varying climate conditions. This evaluation is critical for understanding the system's robustness and adaptability in real-world scenarios, ensuring that the proposed techniques perform effectively across different environmental contexts.

The third section focuses on the integration of the $\mathcal{H}_\infty$ controller within the hybrid system. This section details the implementation of the controller, followed by a thorough validation process that assesses its performance under varying grid impedance conditions. The $\mathcal{H}_\infty$ controller's role in maintaining system stability and optimising grid integration is a key aspect of this section.

The final section of the chapter presents an isolated grid hybrid system analysis. This section aims to validate and illustrate the impact of the deloading approaches on frequency improvement within an isolated grid scenario. The analysis highlights how the integration of advanced deloading techniques and control strategies contributes to enhanced frequency stability and overall grid reliability.

By examining the hybrid PV-wind system through these detailed sections, this chapter provides valuable insights into the effective integration and optimisation of renewable energy technologies, contributing to advancements in grid stability and performance.

4.2 Description of the Hybrid PV-Wind System

4.2.1 Hybrid RES

Hybrid Renewable Energy Systems (HRES) are becoming increasingly popular for power generation due to continuous advancements in renewable energy technologies. By integrating various renewable sources, such as solar and wind, HRES provides a more reliable and stable energy supply. The primary advantages of this combination are improved system balance, enhanced reliability, and greater overall stability. By utilising multiple energy sources, HRES reduces dependence on seasonal variations and optimises the use of available renewable resources [111]. Furthermore, hybrid systems tend to be more reliable and cost-effective compared to systems that rely solely on a single energy source [112].

There are two primary topologies for grid-connected PV and wind hybrid systems. The first configuration integrates the DC outputs from PV panels and WT through DC/DC and AC/DC converters into a common DC/AC inverter, which interfaces with the grid. This setup enables power delivery even if only one source is available, with each unit utilizing MPPT to optimize energy extraction. The second configuration allows renewable sources to inject power directly into the grid through separate DC/AC and AC/DC-DC/AC converters.

This design simplifies the connection process while facilitating efficient power transfer to the grid [113].

4.2.2 Hybrid deloading

The hybrid deloading approach, as shown in figure 4.1, combines the deloading strategies of both PV systems and WT, which were thoroughly explained in the preceding chapters. This method integrates the two strategies into a unified framework designed for an alternating current (AC) hybrid configuration. By operating within this shared AC structure, the approach ensures coordinated implementation of the deloading techniques, enabling efficient control and improved frequency stability under varying operational and environmental conditions.

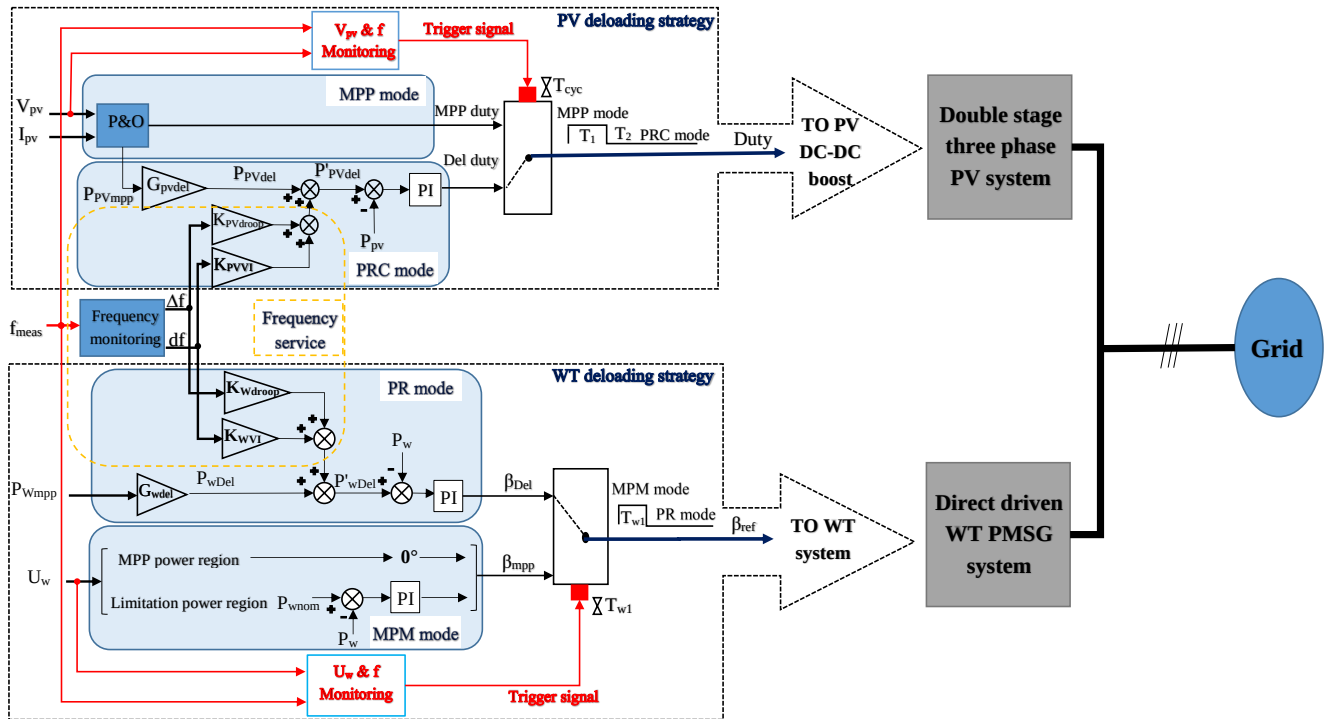


FIGURE 4.1 – AC common hybrid deloading strategies

4.2.3 Hybrid PV WT grid-tied system

The second topology is implemented in the proposed hybrid configuration of this thesis, which integrates a 10 MW PV plant and a 10 MW WT system. This hybrid system is examined under two different operational configurations: an infinite grid and an isolated grid,

as depicted in figure 4.2. Each of these configurations aims to optimize power generation while ensuring stable grid interaction under varying operational conditions.

The 10 MW PV plant uses SunPower SPR-305-WHT modules, a high-efficiency PV technology. It is configured with 50 modules in series and 660 parallel strings, forming a robust power generation system [113]. The plant is connected using a double-stage configuration, as described in chapter 2. The WT system is the same PMSG direct-drive wind turbine system outlined in chapter 3.

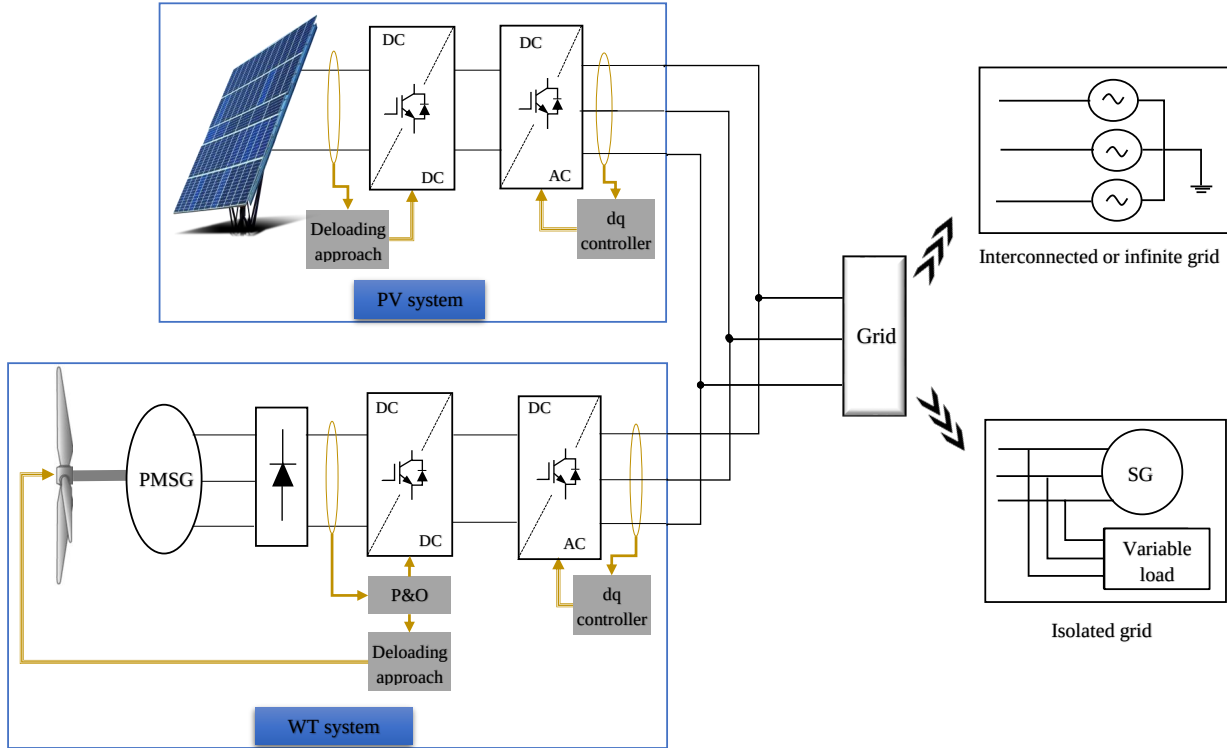


FIGURE 4.2 – Hybrid PV WT-tied grid configurations

Infinite grid configuration In the infinite grid configuration, both the PV and WT systems are connected to a common AC coupling point, which acts as a central interface with the large, stable grid. This setup allows the hybrid system to operate efficiently, regardless of the fluctuating power generation from individual sources, as the infinite grid can absorb surplus power and stabilize frequency and voltage levels. The PV and WT systems both utilize independent MPPT algorithms to maximize energy extraction. The common AC/DC point consolidates the power from both sources before it is fed into the grid, ensuring efficient power flow and grid support. This configuration is particularly effective in environments where grid stability is not a concern, as the large grid compensates for the variability of renewable sources.

Isolated grid configuration In the isolated grid configuration, the PV and WT systems are connected to a common AC point, similar to the infinite grid configuration, but instead of interfacing with a large grid, the system is connected to a SG through a transformer. The SG operates as the primary power stabilizer in the isolated grid, providing inertia and maintaining grid frequency. In this setup, the hybrid system's ability to balance power generation and consumption becomes more critical, as there is no external grid to absorb fluctuations in generation. The transformer ensures the correct voltage levels are maintained between the hybrid system and the SG, allowing for smooth power transfer. Both systems are capable of operating autonomously or in conjunction with each other to ensure a consistent energy supply to the isolated grid. This configuration is commonly used in remote areas where grid extension is not feasible, and system reliability is paramount.

The detailed modeling, simulation, and validation of both configurations are realized using Matlab Simulink software.

4.3 Testing and validation of the hybrid deloading system

To comprehensively evaluate and validate the proposed deloading techniques for both PV and WT systems within the hybrid configuration, the system, as depicted in figure 4.2, was connected to an infinite grid and subjected to various simulated climatic conditions.

For the PV system, these conditions were modelled as changes in solar irradiation and temperature, which directly influence the power generation and efficiency of the PV modules. Similarly, for the WT system, climatic variations were represented by fluctuations in wind speed, affecting the turbine's power output and overall performance.

The climate change scenarios, illustrated in figure 4.3, were carefully designed to emulate real-world variability in energy production, providing a robust test environment for the deloading strategies. These scenarios allowed the system's response to be analysed under dynamic environmental conditions.

The proposed hybrid configuration was tested under a range of deloading conditions to simulate different operational scenarios. These included:

Deloading of the PV system alone with no contribution from the WT system. Deloading of the WT system alone with no contribution from the PV system. Simultaneous deloading of both systems, with varying levels of deloading applied. A detailed summary of these deloading scenarios is provided in the following Table, offering an overview of the test conditions and

their relevance to practical applications.

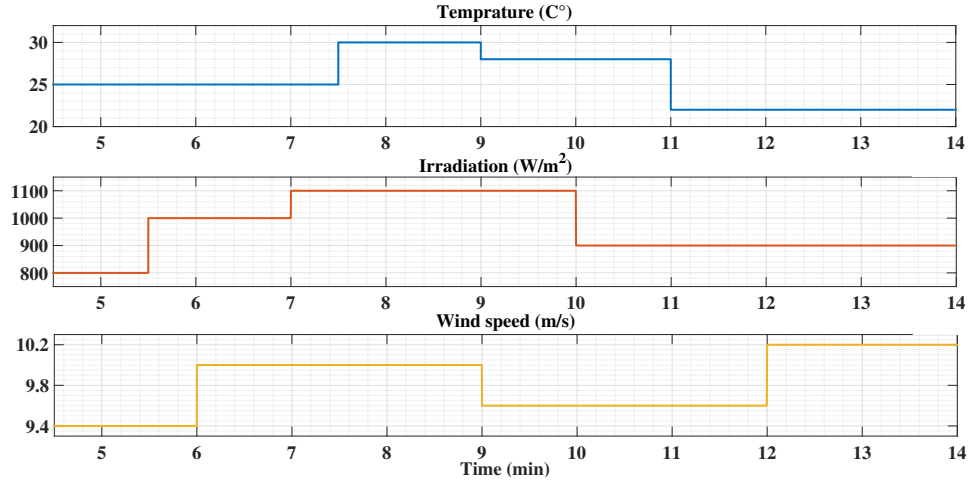


FIGURE 4.3 – Climatic change scenario

TABLE 4.1 – Deloading scenarios for PV and WT systems

Power source	Power reserve percentage (%)				
PV	20	15	10	5	0 (No deloading)
WT	0 (No deloading)	5	10	15	20

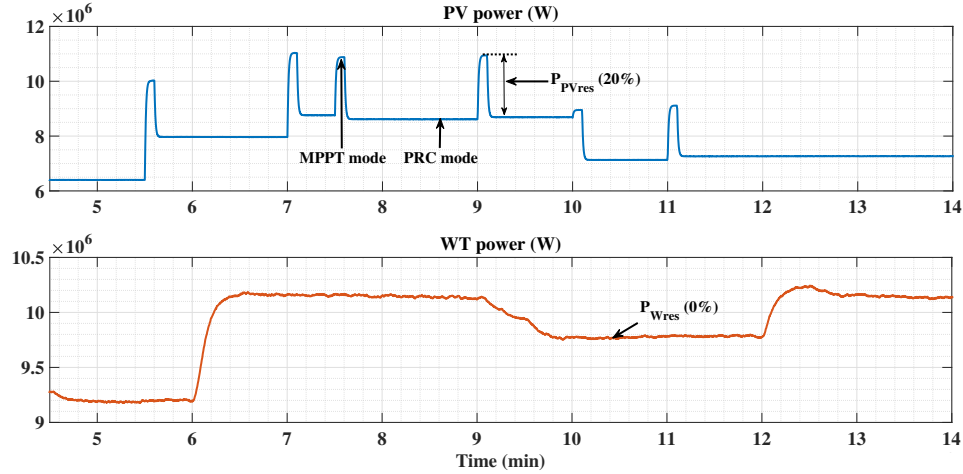


FIGURE 4.4 – PV deloading without WT contribution

Figures 4.4 to 4.8 showcase the output power of the PV and WT systems, both managed using the proposed deloading approach to maintain a predefined power reserve. As detailed in Table 4.1, this power reserve corresponds to varying deloading gain levels, ranging from

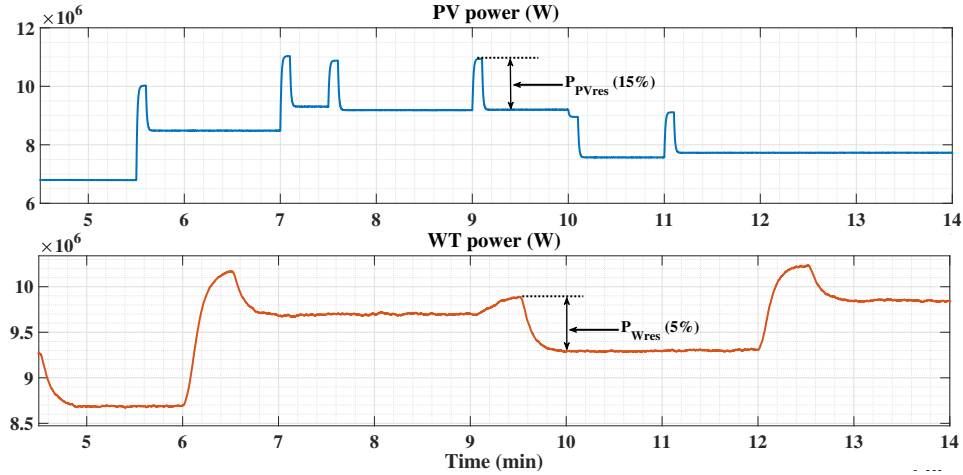


FIGURE 4.5 – PV 15% reserve and WT 5% reserve

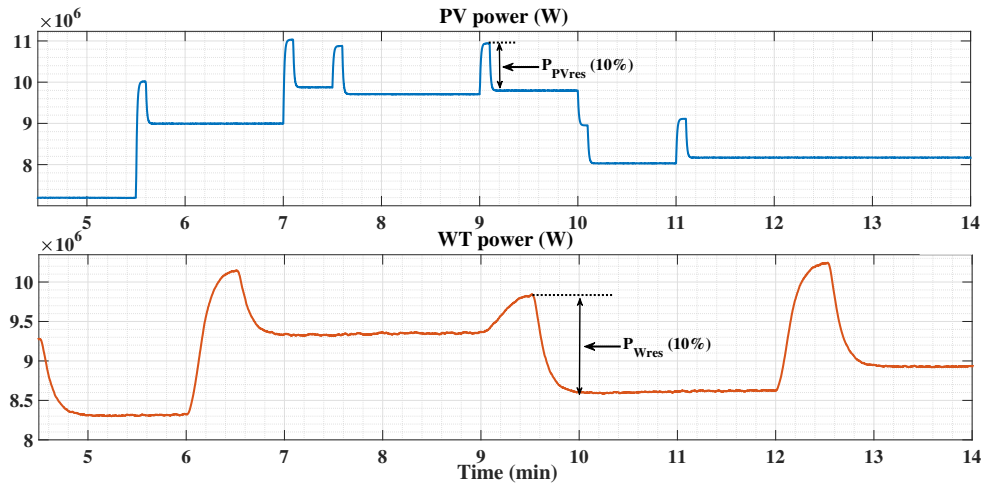


FIGURE 4.6 – PV and WT with 10% reserve each

0% (indicating no reserve power) to 20% (representing the maximum desired reserve). The deloading gain serves as a critical parameter, determining the amount of surplus power retained beyond the immediate demand, thereby enabling the system to respond effectively to unforeseen fluctuations or sudden demand surges.

Figures 4.4 and 4.8 depict scenarios where one system operates in deloading mode (either PV or WT), while the other operates in MPP mode. In these cases, deloading mode is employed strategically to maintain the necessary power reserve, while the MPP mode system continues generating power at peak efficiency. Conversely, figures 4.5 to 4.7 illustrate scenarios where both the PV and WT systems operate simultaneously in deloading mode under varying climatic conditions.

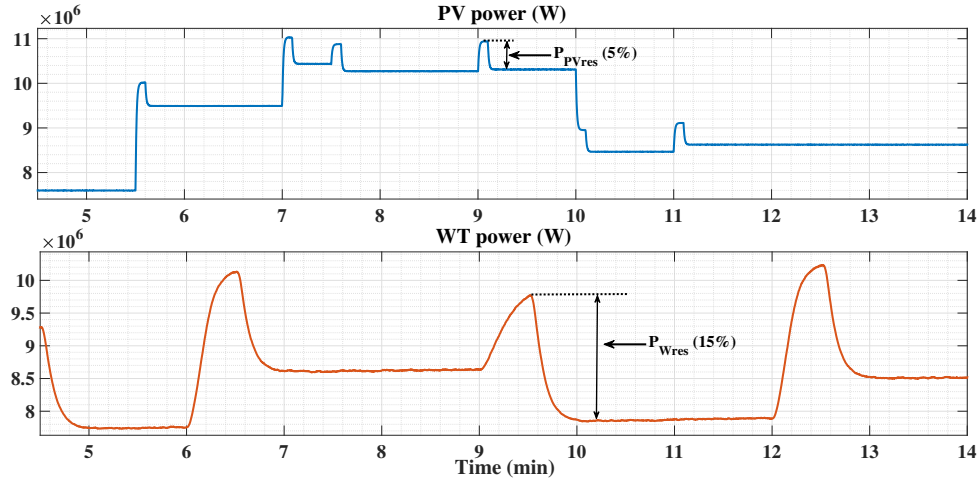


FIGURE 4.7 – PV 5% reserve and WT 15% reserve

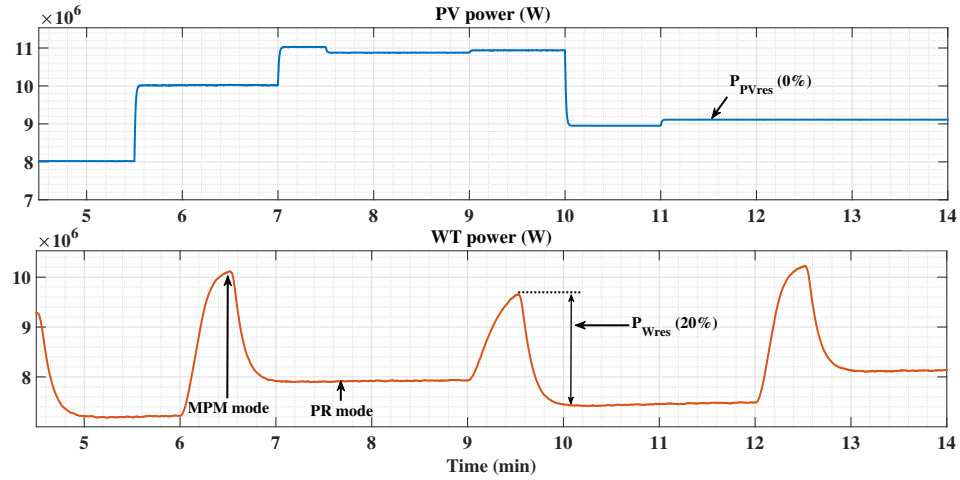


FIGURE 4.8 – WT deloading without PV contribution

The deloading approach dynamically adjusts in response to environmental factors such as solar irradiation, ambient temperature, and wind speed. For instance, when unfavorable conditions reduce PV system productivity, the power reserve of the PV system is lowered, and the WT system compensates by increasing its reserve. Similarly, when PV productivity improves, the WT system reduces its reserve accordingly. This coordinated interaction ensures seamless power reserve management, enabling the hybrid system to adapt to real-time environmental fluctuations without compromising system stability or power availability.

The figures demonstrate the effectiveness of the proposed approach in actively managing the output of both systems. By responding to variations in environmental conditions, the control system dynamically adjusts the generated power, either increasing or decreasing it, to meet reserve power requirements.

In conclusion, the proposed deloading strategy provides a flexible, adaptive, and reliable method for managing power reserves. It enables the system to handle real-time environmental variations while maintaining the desired power reserve.

4.4 Integration and implementation of the $\mathcal{H}_\infty$ controller

4.4.1 Hybrid system $\mathcal{H}_\infty$ implementation

In this section, the conventional dq controller used for the GSC is replaced with a $\mathcal{H}_\infty$ controller to ensure grid stability amidst variations in grid parameters, as presented in figure 4.9. The $\mathcal{H}_\infty$ control architecture and the associated weighting functions have been described in detail in chapter 3. This upgrade aims to enhance the system's robustness by providing better performance under changing conditions, thereby safeguarding against potential instabilities that may arise from fluctuations in grid characteristics.

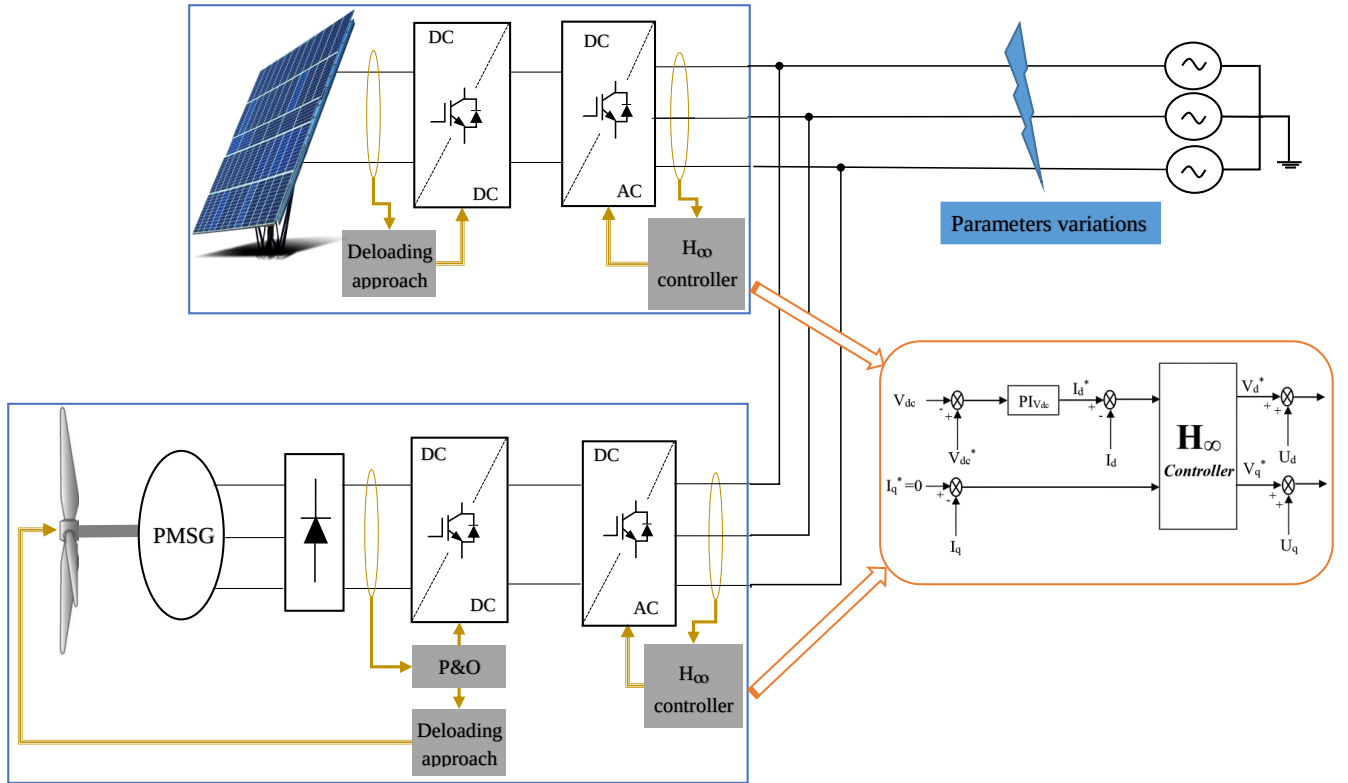


FIGURE 4.9 – H_∞ -based hybrid PV-WT system implementation

4.4.2 Test and results

To assess the performance of the $\mathcal{H}_\infty$ controller relative to the conventional controller, the proposed configuration depicted in figure 4.9 was tested with an infinite grid connection. This setup was subjected to deliberate variations in grid parameters, specifically grid resistance and inductance (L_G and R_G), which were modified by 20% from their nominal values at $t=6$ minutes.

To create these variations in a controlled manner, a circuit breaker was used to integrate the additional components at specified intervals, effectively simulating increases in grid parameters. This experimental design thoroughly evaluates each controller's ability to maintain system stability and performance in response to significant changes in grid conditions, highlighting the advantages of the $\mathcal{H}_\infty$ controller in managing such disturbances.

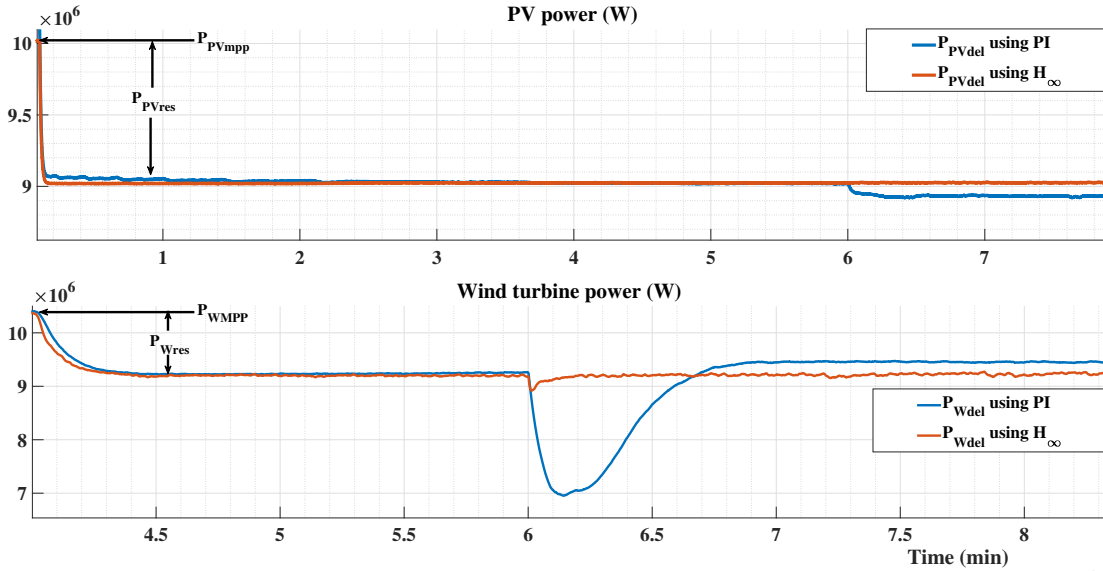


FIGURE 4.10 – PV and WT systems in deloading mode during variations in grid parameters

Figure 4.10 presents the simulation results of the test involving the PV and WT systems operating in deloading mode, demonstrating the $\mathcal{H}_\infty$ controller's capability to maintain and generate the desired power reserve despite the introduced variations in grid parameters. In both the PV and wind systems, the conventional dq controller is adversely affected by these variations, resulting in an inability to maintain a constant power reserve. In contrast, the $\mathcal{H}_\infty$ controller exhibits remarkable stability, effectively providing a consistent power reserve even under fluctuating grid conditions. This highlights the superior performance of the $\mathcal{H}_\infty$ approach in ensuring reliable operation amidst dynamic challenges.

4.5 Hybrid system with frequency service

4.5.1 PFC integration

To validate the improvement of PFC integration, the proposed hybrid PV-WT system is connected to an isolated grid. In this configuration, the PV and WT systems are connected via a transformer to an AC common bus, which is also connected to an SG. This setup is linked to a load representing power consumption.

To simulate power imbalances, an additional load is introduced at $t = 0.8$ min, creating a power deficit, and then removed at $t = 1.1$ min, restoring balance. These load changes result in frequency fluctuations. The deloading gain for both the PV and WT systems is set to 0.8, corresponding to a 20% power reserve for frequency regulation. Detailed system parameters are provided in the annex.

The validation process involves two tests:

Without PFC integration: In the first test, the system operates without any frequency control support from the PV or WT systems. This serves as a baseline to assess how the system responds to load changes and frequency deviations without PFC.

With PFC Integration: In the second test, both the PV and WT systems are enabled with PFC, utilizing the reserved 20% power to help stabilize frequency during load changes.

The comparison between these tests will demonstrate the impact of PFC integration on grid stability and frequency control during power imbalances.

4.5.2 Test and results

Figure 4.11 illustrates the power response of the PV and WT systems in two scenarios: without PFC integration and with PFC integration, under both load conditions—load introduction (impact) and load removal (shedding).

In the without PFC scenario, the PV and WT systems remain in deloading mode during both load situations, meaning they do not supply any additional power to the grid in response to the frequency changes caused by the load variations. This results in no active participation in frequency stabilization.

Conversely, in the PFC scenario, both the PV and WT systems dynamically adjust their power output in response to frequency deviations. During load introduction, they inject additional power to counteract the frequency drop, and during load shedding, they reduce their power output to mitigate frequency overshoot. These adjustments follow the PFC strategy,

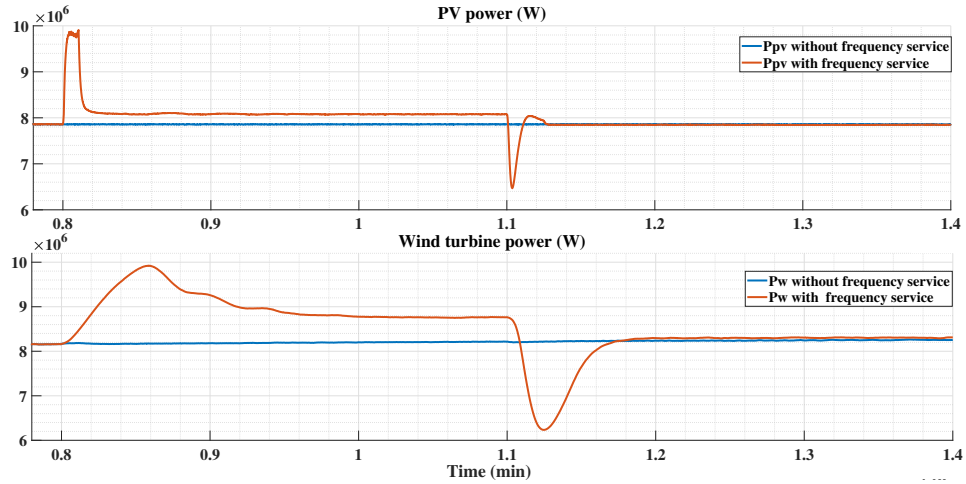


FIGURE 4.11 – PV and WT power response: without vs. with PFC Integration

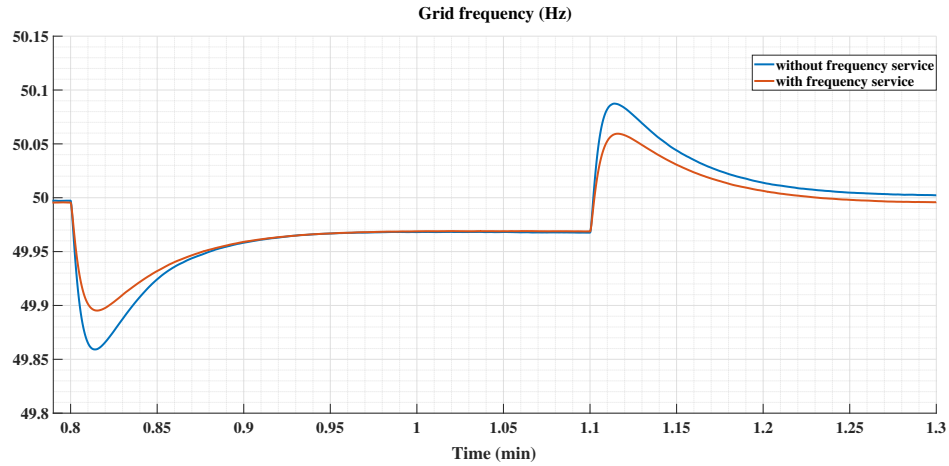


FIGURE 4.12 – Grid frequency: without vs. with PFC Integration

both droop control and VIC to stabilize the grid frequency in real time.

Figure 4.12 illustrates the grid frequency under both PFC scenarios across different load conditions. This figure emphasizes the enhancements in grid frequency resulting from PFC integration. Specifically, the integration of PFC mechanisms significantly reduces frequency deviations and shortens response times during load changes. As a result, the system demonstrates improved stability and responsiveness, allowing for more effective management of frequency fluctuations during load impacts and load-shedding events. This leads to a more resilient grid capable of maintaining frequency within acceptable limits.

4.6 Conclusion

This study demonstrated the critical role of deloading strategies in ensuring power reserve availability and grid stability within a hybrid PV-WT AC system, particularly under fluctuating climatic conditions. By analyzing various power reserve configurations for PV and WT sources, the findings confirmed that adaptive deloading mechanisms effectively mitigate the impacts of irradiation, temperature, and wind speed variations, ensuring a stable and reliable energy supply. Additionally, the integration of robust control mechanisms, such as the $\mathcal{H}_\infty$ controller, significantly enhanced system resilience by counteracting grid parameter variations and improving overall operational robustness. Furthermore, the study highlighted the importance of primary frequency control (PFC) in isolated grid environments, where it was shown to reduce frequency droop, minimize response times, and improve generation-demand balancing, ultimately reinforcing grid reliability and efficiency.

Building on these findings, future research should focus on advancing AI-driven control strategies to further optimize deloading methodologies and enhance grid adaptability. The application of machine learning, reinforcement learning, and model predictive control (MPC) could enable intelligent, data-driven decision-making, facilitating real-time adaptive energy management. These approaches would allow hybrid systems to anticipate and respond to dynamic grid conditions.

Another key area for further investigation lies in the integration of energy storage systems (ESS) and demand-side management. Incorporating advanced storage solutions, such as battery energy storage, supercapacitors, and hybrid storage architectures, can significantly enhance grid flexibility, power quality, and system resilience. Additionally, optimizing demand response strategies through AI-driven analytics can further align generation with consumption patterns, improving overall grid efficiency and reliability.

Moreover, the development of decentralized and multi-agent control frameworks represents a promising research avenue for enhancing system scalability and robustness. The implementation of distributed optimization techniques can facilitate coordinated decision-making in large-scale hybrid renewable networks, enabling faster and more resilient responses to grid disturbances.

By integrating these advanced control methodologies and optimization techniques, hybrid renewable energy systems can transition towards greater automation, intelligence, and resilience, ensuring their long-term viability in future high-renewable power grids.

General conclusion

This thesis has explored and developed advanced deloading approaches to enhance the integration of photovoltaic (PV) and wind energy sources into modern power grids. The research has focused on overcoming critical challenges associated with renewable energy integration, particularly in maintaining grid frequency stability and optimizing power system performance.

One of the primary contributions of this work is the development of novel deloading strategies tailored for both PV and wind energy systems. These approaches are designed to address the inherent intermittency and variability of renewable energy sources while ensuring that power generation remains stable and reliable. By leveraging sophisticated control methodologies, including artificial intelligence (AI)-based controllers, hybrid inertia techniques, and $\mathcal{H}_\infty$ robust control, the study has demonstrated significant improvements in grid stability and renewable energy penetration.

Throughout the research, several key methodologies have been introduced and rigorously tested. The proposed deloading strategies have been validated through comprehensive simulation studies and verification under various operating conditions. The findings have confirmed that integrating deloading techniques with advanced control strategies leads to enhanced system performance, better frequency regulation, and improved adaptability of renewable energy sources in dynamic grid environments.

While the thesis presents substantial advancements in the field of renewable energy control, it also acknowledges certain limitations. Some challenges remain, such as the complexity of real-time implementation, scalability to large-scale power systems, and the need for further optimization of control parameters. Additionally, the study highlights the importance of continued research into hybrid energy storage solutions and AI-driven predictive control to further enhance the efficiency of deloading mechanisms.

Building on the findings of this thesis, several promising research directions can be pursued:

Experimental Validation: Implementing the proposed deloading strategies in real-world

microgrid or pilot-scale setups to assess their practical feasibility and effectiveness.

Adaptive AI-Based Control: Developing more advanced AI-driven control algorithms that dynamically adjust to real-time grid conditions for improved performance.

Scalability Analysis: Investigating the application of deloading strategies in large-scale power systems, ensuring their robustness under different network configurations and load conditions.

Hybrid Energy Storage Integration: Exploring the potential of integrating battery energy storage systems (BESS) and supercapacitors to complement deloading mechanisms and enhance grid resilience.

Economic and Policy Assessment: Evaluating the cost-effectiveness of deloading techniques and their implications on regulatory frameworks to support broader adoption in power grids.

Advanced Forecasting Models: Enhancing predictive models for renewable energy generation to improve the anticipation of grid fluctuations and optimize deloading responses.

These future directions will help bridge the gap between theoretical advancements and practical deployment, further contributing to the development of sustainable and resilient energy systems.

In summary, this thesis underscores the crucial role of advanced control strategies in supporting the transition to a more sustainable energy landscape. By addressing both theoretical and practical aspects of renewable energy integration, it contributes valuable insights into improving grid stability and optimizing renewable energy utilization. The research findings not only enhance the technical understanding of deloading techniques but also offer actionable solutions for policymakers and industry stakeholders to drive the future of clean energy systems.

Bibliography

- [1] Vaclav Smil. *Energy Transitions: Global and National Perspectives*. Bloomsbury Publishing USA, 2016.
- [2] Abu Dhabi International Renewable Energy Agency. Renewable capacity highlights, 20.03.2023.
- [3] International Energy Agency. Global overview, 2024.
- [4] La Nouvelle République. 2024, année des énergies renouvelables et de la transition énergétique en algérie, 2024.
- [5] Abu Dhabi International Renewable Energy Agency. World energy transitions outlook 2023: 1.5°c pathway, 2023.
- [6] Abu Dhabi International Renewable Energy Agency. Renewables 2023 global status report collection, global overview, 2024.
- [7] International Energy Agency. Renewable energy market update outlook for 2023 and 2024, 2024.
- [8] Xiaodong Liang. Emerging power quality challenges due to integration of renewable energy sources. *IEEE Transactions on Industry Applications*, 53(2):855–866, 2016.
- [9] Ahmed Sharique Anees. Grid integration of renewable energy sources: Challenges, issues and possible solutions. In *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*, pages 1–6. IEEE, 2012.
- [10] Oktoviano Gandhi, Dhivya Sampath Kumar, Carlos D Rodríguez-Gallegos, and Dipti Srinivasan. Review of power system impacts at high pv penetration part i: Factors limiting pv penetration. *Solar Energy*, 210:181–201, 2020.

- [11] Mohammad Dreidy, Hazlie Mokhlis, and Saad Mekhilef. Inertia response and frequency control techniques for renewable energy sources: A review. *Renewable and sustainable energy reviews*, 69:144–155, 2017.
- [12] Hassan Bevrani. *Robust power system frequency control*, volume 4. Springer, 2014.
- [13] Rijo Rajan, Francis M Fernandez, and Yongheng Yang. Primary frequency control techniques for large-scale pv-integrated power systems: A review. *Renewable and Sustainable Energy Reviews*, 144:110998, 2021.
- [14] Ujjwol Tamrakar, Dipesh Shrestha, Manisha Maharjan, Bishnu P Bhattarai, Timothy M Hansen, and Reinaldo Tonkoski. Virtual inertia: Current trends and future directions. *Applied sciences*, 7(7):654, 2017.
- [15] Ana Fernández-Guillamón, Emilio Gómez-Lázaro, Eduard Muljadi, and Ángel Molina-García. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renewable and Sustainable Energy Reviews*, 115:109369, 2019.
- [16] Hassan Bevrani, Hemin Golpira, Arturo Roman Messina, Nikos Hatziaargyriou, Federico Milano, and Toshifumi Ise. Power system frequency control: An updated review of current solutions and new challenges. *Electric Power Systems Research*, 194:107114, 2021.
- [17] Tomislav Baškarad, Igor Kuzle, and Ninoslav Holjevac. Photovoltaic system power reserve determination using parabolic approximation of frequency response. *IEEE Transactions on Smart Grid*, 12(4):3175–3184, 2021.
- [18] Pankaj Verma, Tarlochan Kaur, and Raminder Kaur. Power control strategy of an integrated pv system for active power reserve under dynamic operating conditions. *Sustainable Energy Technologies and Assessments*, 45:101066, 2021.
- [19] Mohammad Dreidy, H Mokhlis, and Saad Mekhilef. Inertia response and frequency control techniques for renewable energy sources: A review. *Renewable and sustainable energy reviews*, 69:144–155, 2017.
- [20] Ana Fernández-Guillamón, Emilio Gómez-Lázaro, Eduard Muljadi, and Ángel Molina-García. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renewable and Sustainable Energy Reviews*, 115:109369, 2019.

- [21] Ali Q Al-Shetwi, MA Hannan, Ker Pin Jern, Mahammad Mansur, and Teuku Meurah Indra Mahlia. Grid-connected renewable energy sources: Review of the recent integration requirements and control methods. *Journal of Cleaner Production*, 253:119831, 2020.
- [22] Mohit Bajaj and Amit Kumar Singh. Grid integrated renewable dg systems: A review of power quality challenges and state-of-the-art mitigation techniques. *International Journal of Energy Research*, 44(1):26–69, 2020.
- [23] Kamala Sarojini Ratnam, K Palanisamy, and Guangya Yang. Future low-inertia power systems: Requirements, issues, and solutions-a review. *Renewable and Sustainable Energy Reviews*, 124:109773, 2020.
- [24] Hassan Bevrani, Hêmin Golpîra, Arturo Román Messina, Nikos Hatziargyriou, Federico Milano, and Toshifumi Ise. Power system frequency control: An updated review of current solutions and new challenges. *Electric Power Systems Research*, 194:107114, 2021.
- [25] Ziping Wu, Wenzhong Gao, Tianqi Gao, Weihang Yan, Huaguang Zhang, Shijie Yan, and Xiao Wang. State-of-the-art review on frequency response of wind power plants in power systems. *Journal of Modern Power Systems and Clean Energy*, 6(1):1–16, 2018.
- [26] Aksher Bhowon, Khaled M Abo-Al-Ez, and Marco Adonis. Variable-speed wind turbines for grid frequency support: A systematic literature review. *Mathematics*, 10(19):3586, 2022.
- [27] Ishtiak Mahmud, Nahid-Al Masood, and Atik Jawad. Optimal deloading of pv power plants for frequency control: A techno-economic assessment. *Electric Power Systems Research*, 221:109457, 2023.
- [28] Guo Shu-Feng, Zhang Jie-Tan, Asaah Philip, Hao Li-Li, and Ji Jing. A review of wind turbine deloaded operation techniques for primary frequency control in power system. In *2018 China International Conference on Electricity Distribution (CICED)*, pages 63–71. IEEE, 2018.
- [29] Prakash Pawar, Mudige TarunKumar, et al. An iot based intelligent smart energy management system with accurate forecasting and load strategy for renewable generation. *Measurement*, 152:107187, 2020.

- [30] Gangui Yan, Shuai Liang, Qi Jia, and Yuru Cai. Novel adapted de-loading control strategy for pv generation participating in grid frequency regulation. *The Journal of Engineering*, 2019(16):3383–3387, 2019.
- [31] Pankaj Verma, Tarlochan Kaur, and Raminder Kaur. Power control strategy of an integrated pv system for active power reserve under dynamic operating conditions. *Sustainable Energy Technologies and Assessments*, 45:101066, 2021.
- [32] Pankaj Verma, Tarlochan Kaur, and Raminder Kaur. Power control strategy of an integrated pv system for active power reserve under dynamic operating conditions. *Sustainable Energy Technologies and Assessments*, 45:101066, 2021.
- [33] Akhilesh Kumar Mishra, Puneet Mishra, and HD Mathur. A deep learning assisted adaptive nonlinear deloading strategy for wind turbine generator integrated with an interconnected power system for enhanced load frequency control. *Electric Power Systems Research*, 214:108960, 2023.
- [34] K Sukanya and P Vijayakumar. Frequency control approach and load forecasting assessment for wind systems. *Intelligent Automation & Soft Computing*, 35(1), 2023.
- [35] Ahmadreza Abazari, Hassan Monsef, and Bin Wu. Load frequency control by de-loaded wind farm using the optimal fuzzy-based pid droop controller. *IET Renewable Power Generation*, 13(1):180–190, 2019.
- [36] Jianliang Zhang, Yujun Li, Zhao Xu, Donglian Qi, and Chaoyong Li. Game theory-based optimal deloading control of wind turbines under scalable structures of wind farm. *IET Cyber-Physical Systems: Theory & Applications*, 3(4):224–231, 2018.
- [37] Ahmadreza Abazari, Mehdi Ghazavi Dozein, Hassan Monsef, and Bin Wu. Wind turbine participation in micro-grid frequency control through self-tuning, adaptive fuzzy droop in de-loaded area. *IET Smart Grid*, 2(2):301–308, 2019.
- [38] Natarajan Pandiarajan and Ranganath Muthu. Mathematical modeling of photovoltaic module with simulink. In *2011 1st International Conference on Electrical Energy Systems*, pages 258–263. IEEE, 2011.
- [39] JSurya Kumari and Ch Sai Babu. Mathematical modeling and simulation of photovoltaic cell using matlab-simulink environment. *International Journal of Electrical and Computer Engineering*, 2(1):26, 2012.

- [40] Xuan Hieu Nguyen and Minh Phuong Nguyen. Mathematical modeling of photovoltaic cell/module/arrays with tags in matlab/simulink. *Environmental Systems Research*, 4:1–13, 2015.
- [41] E Duran, M Piliouline, M Sidrach-de Cardona, J Galan, and JM Andujar. Different methods to obtain the i–v curve of pv modules: A review. In *2008 33rd IEEE Photovoltaic Specialists Conference*, pages 1–6. IEEE, 2008.
- [42] Julia A Crook, Laura A Jones, Piers M Forster, and Rolf Crook. Climate change impacts on future photovoltaic and concentrated solar power energy output. *Energy & Environmental Science*, 4(9):3101–3109, 2011.
- [43] Thomas R Karl, Jerry M Melillo, and Thomas C Peterson. *Global climate change impacts in the United States: a state of knowledge report from the US Global Change Research Program*. Cambridge University Press, 2009.
- [44] Samir Kouro, Jose I Leon, Dimitri Vinnikov, and Leopoldo G Franquelo. Grid-connected photovoltaic systems: An overview of recent research and emerging pv converter technology. *IEEE Industrial Electronics Magazine*, 9(1):47–61, 2015.
- [45] K Padmanathan, Uma Govindarajan, Vigna K Ramachandaramurthy, Baskaran Jeevarathinam, et al. Integrating solar photovoltaic energy conversion systems into industrial and commercial electrical energy utilization—a survey. *Journal of Industrial Information Integration*, 10:39–54, 2018.
- [46] Kummara Venkat Guru Raghavendra, Kamran Zeb, Anand Muthusamy, TNV Krishna, SVS V Prabhudeva Kumar, Do-Hyun Kim, Min-Soo Kim, Hwan-Gyu Cho, and Hee-Je Kim. A comprehensive review of dc–dc converter topologies and modulation strategies with recent advances in solar photovoltaic systems. *Electronics*, 9(1):31, 2019.
- [47] Nor Hanisah Baharudin, TMNT Mansur, Fairuz Abdul Hamid, Rosnazri Ali, and Muhammad Irwanto Misrun. Topologies of dc-dc converter in solar pv applications. *Indonesian Journal of Electrical Engineering and Computer Science*, 8(2):368–374, 2017.
- [48] H Haeberlin. Evolution of inverters for grid connected pv-systems from 1989 to 2000. *measurement*, 2(1), 2001.
- [49] Sarat Kumar Sahoo, Sukruedee Sukchai, Franco Fernando Yanine, et al. Review and comparative study of single-stage inverters for a pv system. *Renewable and Sustainable Energy Reviews*, 91:962–986, 2018.

- [50] Ali Bughneda, Mohamed Salem, Anna Richelli, Dahaman Ishak, and Salah Alatai. Review of multilevel inverters for pv energy system applications. *Energies*, 14(6):1585, 2021.
- [51] Zainal Salam, Perng Cheng Tan, and Awang Jusoh. Harmonics mitigation using active power filter: A technological review. *Elektrika Journal of Electrical Engineering*, 8(2):17–26, 2006.
- [52] Muhammad Hafeez Mohamed Hariri, Mohd Khairunaz Mat Desa, Syafrudin Masri, and Muhammad Ammirul Atiqi Mohd Zainuri. grid-connected pv generation system—components and challenges: A review. *Energies*, 13(17):4279, 2020.
- [53] Qiao Peng, Yongheng Yang, Tianqi Liu, and Frede Blaabjerg. Coordination of virtual inertia control and frequency damping in pv systems for optimal frequency support. *CPSS Transactions on Power Electronics and Applications*, 5(4):305–316, 2020.
- [54] Tomislav Baškarad, Ninoslav Holjevac, and Igor Kuzle. Photovoltaic system control for power system frequency support in case of cascading events. *IEEE Transactions on Sustainable Energy*, 2022.
- [55] S Saravanan and N Ramesh Babu. Maximum power point tracking algorithms for photovoltaic system—a review. *Renewable and Sustainable Energy Reviews*, 57:192–204, 2016.
- [56] Dominique Bonkougou, Zacharie Koalaga, and Donatien Njomo. Modelling and simulation of photovoltaic module considering single-diode equivalent circuit model in matlab. *International Journal of Emerging Technology and Advanced Engineering*, 3(3):493–502, 2013.
- [57] Mohammad Dreidy, H Mokhlis, and Saad Mekhilef. Inertia response and frequency control techniques for renewable energy sources: A review. *Renewable and sustainable energy reviews*, 69:144–155, 2017.
- [58] Om Prakash Mahela and Abdul Gafoor Shaik. Comprehensive overview of grid interfaced solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 68:316–332, 2017.
- [59] Vinit Kumar and Mukesh Singh. Reactive power compensation using derated power generation mode of modified p&o algorithm in grid-interfaced pv system. *Renewable Energy*, 178:108–117, 2021.

- [60] Lucas S Xavier, Allan F Cupertino, and Heverton A Pereira. Ancillary services provided by photovoltaic inverters: Single and three phase control strategies. *Computers & Electrical Engineering*, 70:102–121, 2018.
- [61] Mohammad Hossein Mahlooji, Hamid Reza Mohammadi, and Mohsen Rahimi. A review on modeling and control of grid-connected photovoltaic inverters with lcl filter. *Renewable and Sustainable Energy Reviews*, 81:563–578, 2018.
- [62] Assia Mahrouch and Mohammed Ouassaid. Primary frequency regulation based on deloaded control, ann, and 3d-fuzzy logic controller for hybrid autonomous microgrid. *Technology and Economics of Smart Grids and Sustainable Energy*, 7(1):1, 2022.
- [63] Moetasem Ali, Hossam Kotb, M Kareem AboRas, and H Nabil Abbasy. Frequency regulation of hybrid multi-area power system using wild horse optimizer based new combined fuzzy fractional-order pi and tid controllers. *Alexandria Engineering Journal*, 61(12):12187–12210, 2022.
- [64] Mojtaba Moeti and Mehdi Asadi. Robust model reference adaptive pi controller based sliding mode control for three-phase grid connected photovoltaic inverter. *Turkish Journal of Electrical Engineering and Computer Sciences*, 29(1):257–275, 2021.
- [65] Ahmadreza Abazari, Masoud Babaei, SM Muyeen, and Innocent Kamwa. Learning adaptive fuzzy droop of pv contribution to frequency excursion of hybrid micro-grid during parameters uncertainties. *International Journal of Electrical Power & Energy Systems*, 123:106305, 2020.
- [66] Naruttam Kumar Roy, Sayemul Islam, Amit Kumer Podder, Tushar Kanti Roy, and SM Muyeen. Virtual inertia support in power systems for high penetration of renewables—overview of categorization, comparison, and evaluation of control techniques. *IEEE Access*, 10:129190–129216, 2022.
- [67] Mohd Sazli Saad, Hishamuddin Jamaluddin, and Intan Zaurah Mat Darus. Implementation of pid controller tuning using differential evolution and genetic algorithms. *International Journal of Innovative Computing, Information and Control*, 8(11):7761–7779, 2012.
- [68] Brammanayagam Nagarani and JOTHISWAROOPAN NESAMONY. Performance enhancement of photovoltaic system using genetic algorithm-based maximum power point

- tracking. *Turkish Journal of Electrical Engineering and Computer Sciences*, 27(4):3015–3025, 2019.
- [69] MS Omar, Amgad El-Deib, AL El Shafei, ME Abdallah, et al. Comparative study between pi and fuzzy-logic controllers for three-phase grid-connected photovoltaic systems. In *2016 Eighteenth International Middle East Power Systems Conference (MEPCON)*, pages 380–386. IEEE, 2016.
- [70] GM Joselin Herbert, Selvaraj Iniyan, Emer Sreevalsan, and Svonny Rajapandian. A review of wind energy technologies. *Renewable and sustainable energy Reviews*, 11(6):1117–1145, 2007.
- [71] Diana Martinello, Emerson G Carati, Jean P da Costa, Rafael Cardoso, and Carlos MO Stein. Emulation of wind turbines. *Wind Turbines-Design, Control and Applications*, 2016.
- [72] Diana Martinello, Emerson G Carati, Jean P da Costa, Rafael Cardoso, and Carlos MO Stein. Emulation of wind turbines. *Wind Turbines-Design, Control and Applications*, 2016.
- [73] U.S. Department of Energy Federal Energy Management Program (FEMP). Wind technology. 2016.
- [74] Apurb Das, Kudzai B Chimonyo, T Rohith Kumar, S Gourishankar, and C Rani. Vertical axis and horizontal axis wind turbine-a comprehensive review. In *2017 international conference on energy, communication, data analytics and soft computing (ICECDS)*, pages 2660–2669. IEEE, 2017.
- [75] H Li and Zhe Chen. Overview of different wind generator systems and their comparisons. *IET Renewable power generation*, 2(2):123–138, 2008.
- [76] Mohamed Ebeed Hussein Al-Kharbasy, AA Ebrahim, and ON Soliman. Enhancement protection and operation of the doubly fed induction generator during grid fault. *South Valley University-Qena-Egypt*, 2012.
- [77] Eduardo José Novaes Menezes, Alex Maurício Araújo, and Nadège Sophie Bouchonneau Da Silva. A review on wind turbine control and its associated methods. *Journal of cleaner production*, 174:945–953, 2018.

- [78] Jackson G Njiri and Dirk Söffker. State-of-the-art in wind turbine control: Trends and challenges. *Renewable and Sustainable Energy Reviews*, 60:377–393, 2016.
- [79] M Abdelateef Mostafa, Enas A El-Hay, and Mahmoud M ELkholy. Recent trends in wind energy conversion system with grid integration based on soft computing methods: Comprehensive review, comparisons and insights. *Archives of Computational Methods in Engineering*, 30(3):1439–1478, 2023.
- [80] Jamal A Baroudi, Venkata Dinavahi, and Andrew M Knight. A review of power converter topologies for wind generators. *Renewable energy*, 32(14):2369–2385, 2007.
- [81] Rosario Llorente Iglesias, Roberto Lacal Arantegui, and Mónica Aguado Alonso. Power electronics evolution in wind turbines—a market-based analysis. *Renewable and Sustainable Energy Reviews*, 15(9):4982–4993, 2011.
- [82] Remus Teodorescu, Marco Liserre, and Pedro Rodriguez. *Grid converters for photovoltaic and wind power systems*. John Wiley & Sons, 2011.
- [83] M Lydia, S Suresh Kumar, A Immanuel Selvakumar, and G Edwin Prem Kumar. A comprehensive review on wind turbine power curve modeling techniques. *Renewable and Sustainable Energy Reviews*, 30:452–460, 2014.
- [84] Abram Perdana. *Dynamic models of wind turbines*. Chalmers University of Technology, 2008.
- [85] Xiaolian Zhang, Baocong Lin, Ke Xu, Yangfei Zhang, Sipeng Hao, and Qi Hu. An improved over-speed deloading control of wind power systems for primary frequency regulation considering turbulence characteristics. *Energies*, 16(6):2813, 2023.
- [86] Yi Cheng, Rasoul Azizipanah-Abarghooee, Sadegh Azizi, Lei Ding, and Vladimir Terzija. Smart frequency control in low inertia energy systems based on frequency response techniques: A review. *Applied Energy*, 279:115798, 2020.
- [87] Hui Liu, Peng Wang, Teyang Zhao, Zhenggang Fan, and Houlin Pan. A group-based droop control strategy considering pitch angle protection to deloaded wind farms. *Energies*, 15(8):2722, 2022.
- [88] KV Vidyanandan and Nilanjan Senroy. Primary frequency regulation by deloaded wind turbines using variable droop. *IEEE transactions on Power Systems*, 28(2):837–846, 2012.

- [89] Jiaxin Hu, Chong Shao, Weizhou Wang, Guoyi Xu, Caihong Dong, and Tianshu Bi. A fast frequency control strategy for deloaded wtg in the power system with high penetration of renewable energy. In *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, pages 4036–4041. IEEE, 2019.
- [90] Abdullah Bubshait and Marcelo G. Simões. Optimal power reserve of a wind turbine system participating in primary frequency control. *Applied Sciences*, 8(11):2022, 2018.
- [91] Xiaolian Zhang, Baocong Lin, Ke Xu, Yangfei Zhang, Sipeng Hao, and Qi Hu. An improved over-speed deloading control of wind power systems for primary frequency regulation considering turbulence characteristics. *Energies*, 16(6):2813, 2023.
- [92] Zhetong Ding, Jiping Wu, Ying Wang, Shuo Shan, Kun Yuan, and Kaifeng Zhang. Drl-based frequency response of wind turbine generators adapting their variable regulation capabilities. *IET Renewable Power Generation*, 17(3):495–506, 2023.
- [93] Said I Abouzeid, Yufeng Guo, and Hao-Chun Zhang. Dynamic control strategy for the participation of variable speed wind turbine generators in primary frequency regulation. *Journal of Renewable and Sustainable Energy*, 11(1), 2019.
- [94] Xu Zhang, Xiaobing Zha, Shuai Yue, and Yunlong Chen. A frequency regulation strategy for wind power based on limited over-speed de-loading curve partitioning. *Ieee Access*, 6:22938–22951, 2018.
- [95] Xue Lyu and Dominic Groß. Grid forming fast frequency response for pmsg-based wind turbines. *IEEE Transactions on Sustainable Energy*, 2023.
- [96] Haocheng Luo, Zechun Hu, Hongcai Zhang, and Huimiao Chen. Coordinated active power control strategy for deloaded wind turbines to improve regulation performance in agc. *IEEE Transactions on Power Systems*, 34(1):98–108, 2018.
- [97] Jinxin Ouyang, Mingyu Pang, Mengyang Li, Di Zheng, Ting Tang, and Wei Wang. Frequency control method based on the dynamic deloading of dfigs for power systems with high-proportion wind energy. *International Journal of Electrical Power & Energy Systems*, 128:106764, 2021.
- [98] Jianfeng Dai, Cangbi Ding, Xia Zhou, and Yi Tang. Adaptive frequency control strategy for pmsg-based wind power plant considering releasable reserve power. *Sustainability*, 14(3):1247, 2022.

- [99] Hossam HH Mousa, Abdel-Raheem Youssef, and Essam EM Mohamed. State of the art perturb and observe mppt algorithms based wind energy conversion systems: A technology review. *International Journal of Electrical Power & Energy Systems*, 126:106598, 2021.
- [100] Leandro BK Fisch and Marcelo L Heldwein. Modeling, control and operation of a 10 mw direct-drive wind energy conversion system. In *2021 Brazilian Power Electronics Conference (COBEP)*, pages 1–8. IEEE, 2021.
- [101] Hugues Renaudineau, Jean-Philippe Martin, Babak Nahid-Mobarakeh, and Serge Pierfederici. Dc–dc converters dynamic modeling with state observer-based parameter estimation. *IEEE Transactions on Power Electronics*, 30(6):3356–3363, 2014.
- [102] Mohammad Ebrahimi, Sayed Ali Khajehoddin, and Masoud Karimi-Ghartemani. Fast and robust single-phase dq current controller for smart inverter applications. *IEEE transactions on power electronics*, 31(5):3968–3976, 2015.
- [103] Xing Wei, Lan Xiao, Zhilei Yao, and Chunying Gong. Design of lcl filter for wind power inverter. In *2010 World Non-Grid-Connected Wind Power and Energy Conference*, pages 1–6. IEEE, 2010.
- [104] Ada municipal airport, ok us wban: 72204453930 (kadh), hourly observations on the 15th of march 2023. <https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/>.
- [105] Nezihe Yıldıran and Emin Tacer. A new approach to h-infinity control for grid-connected inverters in photovoltaic generation systems. *Electric Power Components and Systems*, 47(14-15):1413–1422, 2019.
- [106] Nagwa F Ibrahim, Karar Mahmoud, Matti Lehtonen, and Mohamed MF Darwish. Comparative analysis of three-phase pv grid connected inverter current control schemes in unbalanced grid conditions. *IEEE Access*, 2023.
- [107] Moshammed Nishat Tasnim, Tofael Ahmed, Monjila Afrin Dorothei, Shameem Ahmad, GM Shafiullah, SM Ferdous, and Saad Mekhilef. Voltage-oriented control-based three-phase, three-leg bidirectional ac–dc converter with improved power quality for micro-grids. *Energies*, 16(17):6188, 2023.
- [108] Yun Wang, Qiuwei Wu, Wenming Gong, and Mikkel Peter Sidoroff Gryning. h_∞ robust current control for dfig-based wind turbine subject to grid voltage distortions. *IEEE Transactions on Sustainable Energy*, 8(2):816–825, 2016.

- [109] Gerasimos Rigatos, Pierluigi Siano, Alexey Melkikh, and Nikolaos Zervos. A nonlinear h -infinity control approach to stabilization of distributed synchronous generators. *IEEE Systems Journal*, 12(3):2654–2663, 2017.
- [110] bilal Khelloufi, abdeslem ans Sari and seif eddine Chouaba. Structured h_∞ control based robust power system stabilizer for stability of multi-machine system. *Revue romaine des sciences techniques série électrotechnique et énergétique*, 69(1):91–96, 2024.
- [111] Molla Shahadat Hossain Lipu, Md Shazib Uddin, and Muhammad Ahad Rahman Miah. A feasibility study of solar-wind-diesel hybrid system in rural and remote areas of bangladesh. *International journal of Renewable energy research*, 3(4):892–900, 2013.
- [112] Orhan Ekren and Banu Y Ekren. Size optimization of a pv/wind hybrid energy conversion system with battery storage using simulated annealing. *Applied energy*, 87(2):592–598, 2010.
- [113] Rashid Al Badwawi, Mohammad Abusara, and Tapas Mallick. A review of hybrid solar pv and wind energy system. *Smart Science*, 3(3):127–138, 2015.

Annex 1

TABLE A.1 – 100 kW PV grid parameters: infinite and isolated configuration

Symbol	Component	Value
Configuration parameters		
Grid	Main synchronous generator	302.1 (kW)
Compensator	Secondary synchronous generator	100.7 (kW)
PV	PV plant	100.7 (kW)
Consumption	Principal load	200 (kW)
Perturbation	Additional load	100 (kW)
Boost parameters		
L_{boost}	Boost converter's inductance	0.54 mH
C_{pv}	PV plant capacitance	1400 μ F
C_{dc}	DC link capacitance	6000 μ F
V_{ref}	DC-link voltage reference	600 V
f_b	Converter switching frequency	5 kHz
(K_{Pb}, K_{Ib})	Converter PI parameters	(62 , 8)
Filter and grid parameters		
f_{inv}	Inverter switching frequency	25 kHz
f_0	Rated grid frequency	50 Hz
L_f	Filter inductance	0.85 mH
R_f	Filter resistance	1 m Ω
C_f	Filter capacitance	6000 μ F
(K_{Pdc}, K_{Idc})	DC voltage PI parameters	(10 , 0.1)

Annex 2

TABLE B.1 – Parameters of 10 MW Direct-Driven PMSG System

Parameters	Description	Value
WT parameters		
P_{RM}	Rated Mechanical Power	10 MW
R	Blade Radius	90 m
U_{w-cutI}	Minimum Wind Speed	4 m/s
U_{w-cutO}	Maximum Wind Speed	25 m/s
U_{w-nom}	Rated Wind Speed	9.8 m/s
λ_{opt}	Optimal Tip Speed Ratio	8.2
PMSG parameters		
P_{nom}	Rated Apparent Power	10.7 MVA
V_{ll}	Rated Line Voltage	4000 V
n	Number of Pole	320
L_d	d-Axis Stator Inductance	1.8 mH
L_q	q-Axis Stator Inductance	1.8 mH
R_s	Stator Resistance	64 mΩ
Boost parameters		
L_b	Inductance of boost converter	0.54 mH
C_b	Capacitance of of boost converter	955.85 μF
C_{dc}	DC link capacitance	6000 μF
V_{dc-ref}	DC-link voltage reference	6500 V
f_b	Converter switching frequency	5 kHz
Filter and grid parameters		
f_{inv}	Inverter switching frequency	25 kHz
f_0	Rated grid frequency	50 Hz
L_f	Inductance of filter	1.5 mH
R_f	Resistance of filter	1.4 mΩ
Configuration Parameters		
Grid	Main synchronous generator	30 MW
Charge	Additional charge	19 MW

Annex 3

TABLE C.1 – Parameters of Hybrid PV-WT Grid in Isolated Configuration

Symbol	Component	Value
Grid	Main synchronous generator	40 (MW)
PV	PV plant	10 (MW)
WT	WT	10 (MW)
Consumption	Principal load	20 (MW)
Perturbation	Additional load	10 (MW)