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Domaine : Sciences et Technologie
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Option : Réseaux Electriques

Par

Khaled Ben Oualid MEDANI

Contribution à l'Optimisation du Fonctionnement des Réseaux Electriques

Soutenue le: 10/04/2019 devant un jury composé de:

GHERBI Ahmed	Pr	Univ. Ferhat Abbas - Sétif 1	Président
SAYAH Samir	Pr	Univ. Ferhat Abbas - Sétif 1	Directeur
HAMOUDA Abdellatif	Pr	Univ. Ferhat Abbas - Sétif 1	Examinateur
DIB Djalel	Pr	Univ. L'Arbi Tbessi - Tébessa	Examinateur
MESSALTI Sabir	Pr	Univ. Mohamed boudiaf- M'Sila	Examinateur

Dedication

I dedicate this thesis to my

Mother and my Father

To my Brother and my Sisters

To my colleagues and friends in my social and academic life

MEDANI Khaled Ben Oualid

Acknowledgement

Above all, I would like to thank The Almighty ***God*** *ALLAH for the wisdom and perseverance that he has been bestowed upon me during this research work, and indeed, throughout my life.*

It has been a pleasure for me to work on this thesis. I hope the reader will find it not only interesting and useful, but also comfortable to read.

First and foremost, I would like to express my sense of gratitude and indebtedness to my supervisor ***Pr. SAYAH Samir*** *for his inspiring guidance, encouragement, and untiring effort throughout the course of this work. His timely help and painstaking efforts made it possible to present the work contained in this thesis. I consider myself fortunate to have worked under his guidance during four years (2014- 2018).*

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ملخص:

يعتبر توزيع الطاقة التفاعلي الأمثل (OPRD) مشكلة فرعية لتدفق الطاقة الأمثل (OPF) الذي يسعى إلى إدارة موارد الطاقة التفاعلية للنظام بشكل صحيح. يقدم هذا العمل مقاربة لحل مشكلة توزيع القدرة التفاعلي الأمثل (ORPD) في سياق تشغيل النظام الكهربائي في الظروف العادية وفي مجموعة من الحالات الطارئة. تم حل مشكلة التوزيع الأمثل للطاقة التفاعلية (ORPD) باستخدام خوارزميات عشوائية، مثل استمثال عناصر السرب (PSO) ، و هي واحدة من التقنيات الشائعة في حل مشاكل التحسين في الهندسة ، و ايضا تقنية حديثة ، وهي خوارزمية تحسين تعتمد سلوك الحوت المحدب في الصيد (WOA). علاوة على ذلك تم اقتراح نظام تصحيحي قائم على أساس اجهزة FACT للتخفيف من الانتهاكات التي تحدث في ظل ظروف الطوارئ. من أجل التحقق من صحة الخوارزميات التي تم تطويرها، تم فحص واختبار التقنيات المقترحة على نظام IEEE 14عقدة و 30 عقدة ونظام تزويد الطاقة الجزائري 114 عقدة. أخيرا، تم تطبيق اختبار ANOVA للتحقق من أداء الخوارزمية المقترحة.

الكلمات المفتاحية: التوزيع الأمثل للقدرة التفاعلية ، ميتاهيروستيك ، حالة طوارئ ، تحليل التباين WOA,PSO,ANOVA.

Abstract:

The optimal reactive power dispatch (OPRD) is a sub-problem of the optimal power flow (OPF) that Seeks to properly manage the reactive power resources of the system. This work presents an approach which aims to solve the problem of optimal reactive power dispatch (ORPD) in power system operation under normal and under a set of contingency conditions. The optimal reactive power dispatch (ORPD) problem was solved using a population meta-heuristic methods such as Partical Swarm Optimization (PSO) which is one of the popular techniques, and a recent technique namely Wale Optimization Algorithm WOA. Corrective action scheme based on FACT devises was proposed to mitigate the violations caused in contingency conditions. In order to validate the elaborated algorithms for the various combinations, the proposed techniques were examined and tested on the IEEE 14-bus, 30-bus, and a practical equivalent Algerian electric 114-bus power system. Afterwards, an analysis of variance study (ANOVA) F-test has been applied in order to verify the performance of our proposed algorithm in solving the ORPD.

Keywords: Optimal reactive power dispatch, meta-heuristic techniques, Contingency analysis, analysis of variance ANOVA F-test, PSO, WOA.

Résumé:

La répartition optimale de la puissance réactive (OPRD) est un sous-problème du transit optimal de puissance (OPF) dont l'objectif est de rationaliser des ressources de puissance réactive disponibles. Ce travail présente une approche visant à résoudre le problème de la répartition optimale de la puissance réactive (ORPD) dans le cadre du fonctionnement d'un réseau électrique dans des conditions normales et dans un ensemble de conditions d'urgence. Le problème de répartition optimale de la puissance réactive (ORPD) a été résolu à l'aide d'une méthode métaheuristique de population, telle que l'optimisation par essaims de particules (PSO), qui est une technique populaire, et une technique récente, à savoir l'algorithme d'optimisation des Baleines (WOA). Une stratégie de mesure corrective basée sur les dispositifs FACT a été proposée pour atténuer les violations causées dans des conditions d'urgence. Afin de valider les algorithmes élaborés pour les différentes combinaisons, les techniques proposées ont été examinées et testées sur le système IEEE à 14 nœuds, à 30 nœuds et dans le réseau de transport Algérien HT ayant 114 bus. Finalement, une analyse de variance par l'approche ANOVA été menée afin de vérifier les performances de notre algorithme proposé pour la résolution des problèmes traitées.

Mots-clés: Répartition optimale de la puissance réactive, Techniques métaheuristiques, Analyse de contingence, Analyse de variance ANOVA test, PSO, WOA.

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List of Abreviations:

AGA	*Adaptive genetic algorithm*
DE	*Differential evolution*
PSO-w	*Particle swarm optimization with inertia weight*
PSO-Cf	*Particle swarm optimization with constriction factor*
CLPSO	*Comprehensive learning particle swarm optimizer*
MOAIA	*Multi-objective adaptive immune algorithm*
IGA	*Immune Genetic Algorithm*
CMAES	*covariance matrix adopted evolutionary strategy*
MNSGA-II	*Modified Non-Dominated Sorting Genetic Algorithm-II*
NSGA-II	*Non-Dominated Sorting Genetic Algorithm-II*
RGA	*Real coded Genetic Algorithm*
EP	*Evolutionary Programming*
SOA	*Seeker Optimization Algorithm*
MASRL	*Multi-agent-Based Reinforcement Learning*
MGA	*Multi-objective Genetic Algorithm*
FSGA	*Fast synthetic Genetic Algorithm*
Fuzzy-GA	*Fuzzy Genetic Algorithm*
SQP:	*sequential quadratic programming*
MODE	*Multi-objective Differential Evolution*
SPEA2	*Strength Pareto Evolutionary Algorithm 2*
MTLA-DDE	*Modified teaching learning algorithm and double differential evolution algorithm*
TLA	*Teaching learning algorithm.*
DDE	*Double differential evolution algorithm.*
EPSDE	*Ensemble of Mutation and Crossover Strategies and Parameters in Differential Evolution.*
Sa-DE	*Self-adaptive Differential Evolution.*
SF	*Superiority of feasible solutions.*
SP	*Self-adaptive penalty*
EC	*E-Constraint0*
SR	*Stochastic Ranking.*
ECHT	*Ensemble of Constraint Handling Techniques.*
GPAC	*General Passive Congregation PSO.*
LPAC	*Local Passive Congregation PSO.*
CA	*Coordinated Aggregation.*
IP-OPF	*interior point based OPF.*
PSO-TVAC	*Particle Swarm Optimization with time varying acceleration coefficients.*
MVO	*Multi verse Optimize.*
QEA	*Quantum-inspired evolutionary algorithm.*
2ArchMGWO	*Two-archive multi-objective grey wolf optimizer.*
HTSSA	*Hybridized Tabu Search-Simulated Annealing.*
SA	*Simulated Annealing.*
TS	*Tabu Search.*
OGSA	*opposition-based gravitational search algorithm.*
OSAMGSA	*Novel Opposition-Based Self-Adaptive Modified Gravitational Search Algorithm.*
NGBWCA	*Gaussian Bare-Bones Water Cycle Algorithm.*
GBICA	*Gaussian Bare-bones multi-objective Imperialist Competitive Algorithm.*
JGG	*Jumping Gene Genetic Algorithm.*
NSGA-I	*Non-dominated Sorting GA-II.*
OMOPSO	*Optimized PSO-based Multi-Objective Optimization algorithm.*
VEPSO	*Vector Evaluated Particle Swarm Optimization.*
MOPSO-CD	*algorithm with the use of Crowding Distance mechanism.*
ITDEA	*Interactive Territory Defining Evolutionary Algorithm.*
NEKA	*Neighborhood Knowledge-Based Evolutionary Algorithm.*
GDE3	*Generalized Differential Evolution 3 Algorithm.*
MICA-IWO	*Hybrid Modified Imperialist Competitive Algorithm And Invasive Weed Optimization*
TLBO	*Teaching Learning Based Optimization.*

QOTLBO	*Quasi-Oppositional Teaching Learning Based Optimization.*
GBTLBO	*Gaussian Bare-Bones Teaching Learning Based Optimization.*
HA	*Harmony Search Algorithm.*
BB-BC	*Big Bang-Big Crunch.*
MOAIA	*Multi-Objective Adaptive Immune Algorithm.*
IGA	*Immune Genetic Algorithm.*

List of Acronyms :

$\boldsymbol{F}(\boldsymbol{x}, \boldsymbol{u})$	*Objective function.*
$\boldsymbol{h}\ (\boldsymbol{x}, \boldsymbol{u})$	*Vector of equality constraints.*
$\boldsymbol{g}\ (\boldsymbol{x}, \boldsymbol{u})$	*Sets of inequality constraints.*
$\boldsymbol{P_{loss}}$	*Active power loss.*
$\boldsymbol{V_i}, \boldsymbol{V_j}$	*Voltage of i^{th} and j^{th} buses respectively.*
$\boldsymbol{V_g}, \boldsymbol{V_L}$	*Generation and load bus voltage respectively.*
$\boldsymbol{P_{g1}}$	*Real generation of slack generator.*
$\boldsymbol{p_{gi}}, \boldsymbol{Q_{gi}}$	*Active and reactive power of i^{th} generator.*
$\boldsymbol{p_{di}}, \boldsymbol{Q_{di}}$	*Active and reactive power of i^{th} load bus.*
$\boldsymbol{G_{ij}}, \boldsymbol{B_{ij}}, \boldsymbol{\theta_{ij}}$	*Conductance, admittance and Phase difference of voltages between i^{th}And j^{th} Bus.*
$\boldsymbol{T_k}$	*Tap-setting of transformer of branch k.*
$\boldsymbol{S_L}$	*Apparent power flow through lth transmission line.*
N	*Buses' number.*
NG	*Generators' number.*
NT	*Tap regulating transformers' number.*
NTL	*Transmission lines' number.*
NC	*Shunt VAR compensators' number.*
NPQ	*Number of PQ buses.*
$\boldsymbol{r_{gi}}$	*Penalty factor related to generators.*
$\boldsymbol{r_{Qi}}$	*Penalty factor related to generators reactive.*
t	*Current iteration.*
A, C	*Coefficient vector.*
X*	*Position vectorof the best solution obtained.*
X	*Position vector.*
| |	*Absolute value.*
.	*Element-by-element multiplication.*
a	*Vector linearly decreased from 2 to 0.*
r	*Random vector limited into [0, 1].*
b	*Constant for defining the shape of the logarithmic spiral.*
l	*Random number uniformly distributed in the range of [-1, 1].*
p	*Probability for each encircling way.*
X_rand	*Chosen randomly from whales in the current trial run.*

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Chapter 0

General Introduction

Abstract:

In this chapter, a brief general introduction based on analyzing and studying of the well-known optimal reactive power dispatch ORPD problem in normal and under contingency conditions is presented. There will also be some arguments that reflect the main proposed contributions in this manuscript. Then, the organization and structure of thesis takes a place in this chapter. Finally, the scientific contributions involving conference papers and journal papers that were published during this thesis are provided.

0.1 General introduction

Along with the development of the economic, the scale of the power grid also keeps growing. In some areas, however, the construction and upgrading of the power grid did not keep pace with the growth of the loads. Then a severe shortage of the reactive power would appear. For the purpose of minimizing the real power loss, utility companies can either change the structure of the power grid or replace the old wiring with lower impedance lines. However, both of these methods require investing large amounts of money. So, the simplest and most economical way remains the optimal allocation of reactive power dispatch and adapts the electrical power system to operate close to its permissible operating limits.

The advantage of this solution is the efficient operation of already installed electrical networks, however it requires the use of very sophisticated control means to ensure a healthy and secure conduct of charged electrical networks. FACTS technology is a means to fulfill this function. It is based on power electronics to control different power grid parameters, namely active power, reactive power, and voltage. Several types of FACTS exist in the industry and the choice of the appropriate device depends on the objectives.

In the early days, the starting point of reactive power dispatch is to improve the power factor at each end user by installing reactive power compensators. This approach, of course, can reduce the total power loss. But in order to get the maximum profit, electricity grid designers have to take a more holistic view and calculate the power flow.

In large power grids, efficient distribution of reactive power is required to maintain the voltage within acceptable operating limits and to control transmission losses. Reactive power is critical to the operation of the power networks on both safety aspects and economic aspects. Rational reactive power dispatch scheme can improve the power quality as well as reduce the real power loss. On the contrary, if the reactive power is unreasonably allocated, then it will bring great economic losses and might even threaten the security of the power grid.

One of the essential goals of reactive energy dispatch is to ensure the viability and continuity of operation of the electrical energy system in the many different states. Dy Liacco in [1] introduced the concept of the preventive (normal), emergency, and restorative operating states and their associated controls, which mean that power system, may be identified to be operating in a number of states.

While operating power system, it is necessary to consider a factor which relates to the system security and involves the design of the system to maintain the system security in normal conditions and under various contingencies. In the modern days, the power system is becoming wide and complex. Contingency analysis of a power system is a major activity in power system planning and operation. In general, line outage, transformer outage and generator outage are most common type of outages; they may lead to over loads in other branches and/or sudden system voltage rise or drop **[2].** So for this reason, optimal reactive power dispatch has to be studied in normal conditions and under contingencies.

The problem of reactive energy planning has already been tackled by several approaches, as the literature shows; based on conventional optimization methods as well as metaheuristic techniques. In recent years, and to overcome this problem, meta-heuristic techniques are more and more applied. These methods in general do not require the convexity of the objective function and have a high probability to converge towards the minimum global.

0.2 Objectives and contributions

This doctoral thesis focused on improving the performance of electrical networks through the optimal allocation of reactive power. The performance of the power grid is evaluated in terms of active losses and voltage profile regulation.

The core contributions of this thesis are as follow:

- Original holistic review of several possible objective functions, constraints and meth heuristics applied to solve the optimal reactive power dispatch ORPD in the last 10 years.
- A novel approach based on the Whale Optimization Algorithm (WOA) has been proposed for ORPD in normal and under contingency conditions in standard IEEE power systems with (14 and 30 buses) and the large scale Algerian 114-bus electric test system in order to evaluate the performance of the power grid in terms of voltage profile, and active power losses with satisfying the power system constraints.
- Statistical analysis has been achieved in this study using One-way ANOVA test system, to give a certain level of confidence to our study and evaluate which algorithms are most suitable in solving the ORPD problem.

0.3 Organization of the Thesis

After a general introduction to the undertaken work, the main body of the thesis is structured as follows:

In the first chapter, reactive power compensation technologies are presented in the first part. Then, the second part is devoted to a general presentation and modeling of the FACTS technology. Models are proposed for stationary operating states.

The second chapter presents the general background, objective functions, constraints, and algorithm techniques of Optimal Reactive Power Dispatch (ORPD). Several mathematical models of ORPD in the literature are summarized. The mathematical formulation of the objective and performance functions commonly used in the (ORPD) was presented in this chapter, the proposed solution techniques were classified and some comparisons between methods were reported.

In the third chapter, problem formulation of (ORPD) is detailed. In addition, different metaheuristic algorithms namely, particle swarm optimization (PSO), particle swarm optimization with time varying acceleration coefficients (PSO-TVAC) and a recent metaheuristic technique namely, whale optimization algorithm (WOA) will be successfully applied to solve the optimal reactive power dispatch ORPD problem in normal conditions (without outages). The proposed methods have been examined and tested on the IEEE 14-bus system and IEEE 30-bus system. Furthermore, a comparison study of the cited algorithms has been made to show the potential of these optimization methods, and prove their robustness and effectiveness in solving the ORPD problem.

In the chapter 04, the ORPD under contingency conditions is discussed. The IEEE 30 bus test system is considered using WOA algorithm. Four different case studies are considered in this chapter to assess the ability of the proposed method for solving complex problems under contingency conditions. Moreover, an approach which is based on FACT devices is proposed as a corrective action scheme in order to withstand the violations caused by the different outages.

In the chapter 05, the ORPD for several scenarios presented previously in chapter 03 and 04, is carried out on a real and practical equivalent 114 bus Algerian power system to give a more practical aspect to our work.

Conclusions and future works are discussed in chapter 06.

0.4 Scientific production

0.4.1 Conference papers

- **MEDANI Khaled ben Oualid** and **SAYAH Samir**, ''*Using a particle swarm optimization for solving reactive power dispatch problem*'', The 9th international conference CEE 2016, Batna, ALGERIA.

- **MEDANI Khaled ben Oualid** and **SAYAH Samir**, ''*Optimal Reactive Power Dispatch using Particle Swarm Optimization with time varying acceleration coefficients*'', The 8th International Conference on Modelling, Identification and Control ICMIC-2016, 2016 , Algiers, ALGERIA.

- **MEDANI Khaled ben Oualid** and **SAYAH Samir**, '' *Optimal VAR control under various contingency conditions using whale optimization algorithm*, The 2th international conference IC-AIRES 2018, Tipaza, ALGERIA.

0.4.2 Journal papers

- **MEDANI Khaled ben Oualid, SAYAH Samir,** and **Abdelghani Bekrar**, "*Whale optimization algorithm based optimal reactive power dispatch: A case study of the Algerian power system*", *Electric Power Systems Research,* Vol: 163, Part B, October 2018, Pages 696-705

0.5 References

[1] Dy Liacco et al., Dy Lia. *'The Adaptive Reliability Control System''* IEEE Transactions on Power Apparatus and Systems, PAS-86 (1967), pp. 517- 531.

[2] S.Sakthivel, et al *"Optimal Location of SVC for Voltage Stability Enhancement under Contingency Condition through PSO Algorithm",* International Journal of Computer Applications (0975 – 8887) Vol. 20–,No.1, April 2011.

Chapter 1

Reactive Power Compensation Technologies and FACT Devices

Abstract:

A general introduction to the Var compensation technologies is presented in this chapter. There are two types of Var generators: traditional devices such as (capacitors, inductors, generators, synchronous compensators, and static compensators), and Flexible Alternating Current Transmission System (FACT) devices which are a combination of power electronics components with traditional power system components. Moreover, tow FACT devices (SVC and TCSC) that were used in this project have been modeled and detailed.

1.1 Introduction

Var compensation is defined as the management of reactive power to improve the performance of AC power systems. The concept of Var compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most power quality problems can be attenuated or solved with an adequate control of reactive power **[1].** Reactive power compensation in transmission systems improves the stability of the AC systems by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, and can avoid disastrous blackouts **[2].**

Series and shunt Var compensation are used to modify the natural electrical characteristics of AC power systems, while shunt compensation changes the equivalent impedance of the load **[1].** In both cases, the reactive power that flows through the system can be effectively controlled improving the performance of the overall ac power system.

Based on the use of reliable high-speed power electronics, powerful analytical tools, advanced control and microcomputer technologies, flexible AC transmission systems FACT have been developed which represent a new concept for the operation of power transmission systems **[3].** In order to observe the impact of FACT devices in an electric power system, it is necessary to represent them by models. FACT modeling is carried out on the basis of the elements used in power flow calculations. They are more particularly: generators, loads, shunt elements as well as the lines and the transformers. FACT devices are considered ideal elements and their active losses are not taken into account.

In this chapter a general introduction to reactive power compensation technologies is presented and several models of FACT devices have been detailed.

1.2 Reactive power compensation

The analysis of the variations in the demand of reactive power shows that the problem of supply-demand adaptation has two aspects that require the use of devices whose characteristics are very different **[4]:**

- The first is to follow the periodic fluctuations for loads to a large extent predictable. A large part of the adjustment can therefore be made to Var generators whose action is discontinuous and with a relatively long response time. This category includes capacitor banks and inductors installed on the grid.

➢ The second is to manage with abrupt and random variations. This requires the implementation of Var generators whose response time is very short. This category includes production units, synchronous compensators, static compensators and flexible alternating current transmission systems FACT.

1.3 Var generator technologies

1.3.1. Traditional Var generators

1.3.1.1. Capacitors

Their role is to provide some of the reactive energy consumed by the loads in the network. There are two types:

➢ Bank Capacitor connected to the high voltage load buses of the transmission substations. They are mainly intended to compensate reactive losses on the high voltage grid.

➢ Bank Capacitor connected to medium voltage load buses of distribution substations. These batteries are used to offset the global call for reactive energy from distribution networks to transmission networks. They are localized and sized individually according to the voltage setting.

1.3.1.2. Inductances

They are used to compensate the reactive energy supplied in off-peak hours by very high voltage lines or cables. They are either directly connected to the grid or connected to the tertiaries of the transformers. Therefore, they allow a limitation of over voltages in the network.

1. 3.1.3. Generators

The generators are well located to meet the reactive energy needs. Their dynamic performance allows them to handle with sudden fluctuations in demand. On the other hand, they can only provide partial compensation for the reactive loads, because of the significant voltage drops that reactive energy transits create on the networks.

1. 3.1.4. Synchronous compensators

Synchronous compensators are rotating machines that provide no active power. Reactive power provided or absorbed depending on whether they are under or over excited.

1.3.1.5. Static compensators

They consist of the set of thyristors-controlled capacitors and inductors, mounted upside-down in each phase. Each of them thus being a driver for half a period. The reactive power absorbed by the inductance varies by controlling the RMS value of the current flowing through it by action on the thyristor firing angle.

1.3.2. FACT devices technology

1.3.2.1. Definition

Flexible Alternating Current Transmission System (FACT) simply refers to a combination of power electronics components with traditional power system components. They are intended to improve power system reliability, power transfer capability, transient and dynamic stability improvements, and voltage regulation.

The important advantages of these FACT controllers include [5]:

- Improving power transfer capability
- Confining power flow to designated routes
- Transient and dynamic stability improvement
- Damping of power system oscillations
- Better voltage regulation
- Flexible operation and control of the system
- Secure loading of the transmission lines close to their thermal limits
- Prevention of cascading outages by contributing to emergency control

1.3.2.2. Role of FACT devices

Based on power electronics converters and digital control schemes, reactive power compensators implemented with self-commutated converters have been developed to compensate not only reactive power, but also voltage regulation, flicker, harmonics, real and reactive power, transmission line impedance, and phase-shift angle. It is important to note, that even though the final effect is to improve power system performance, the control variable in all cases is basically the reactive power.

In an electrical network, the FACT make it possible to perform functions in both steady-state and transient modes. They generally act by absorbing or supplying reactive power, controlling the impedance of the lines or changing the angles of the voltages. In permanent regimes, FACT devices are used primarily in two contexts:

- Maintaining the voltage at an acceptable level by supplying reactive power when the load is high and the voltage is too low, however, they absorb it if the voltage is too high.

- Control of the power transits so as to reduce or even eliminate the overloads in the lines or the transformers as well as to avoid looping flows in the network. They then act by controlling the reactance of the lines and adjusting the phase shifts.

1.3.2.3. General classification of these FACT devices

FACT devices are classified depending on the technology used in their implementation and the way they are connected to the power system (shunt or series).

They can be classified as follow **[6]**:

A. Series Controllers

Series controllers are being connected in series with the line as they are meant for injecting voltage in series with the line. These devices could be variable impedances like capacitor, reactor or power electronics based variable source of main frequency, sub synchronous or harmonic frequency, or can be a combination of these, to meet the requirements. If the injected voltage is in phase quadrature with the line current, then only supply or consumption of variable reactive power is possible. These types of controllers include:

- SSSC: Static synchronous series compensator
- TCSC: Thyristor controlled series capacitor
- TCSR: Thyristor controlled series reactor
- TSSC: Thyristor switched series capacitor
- TSSR: Thyristor switched series reactor

B. Shunt controllers

Shunt controllers will be connected in shunt with the line so as to inject current into the system at the point of connection. They can also be variable impedance, variable source, or a combination of these.

If the injected line current is in quadrature with the line voltage, variable reactive power supply or consumption could be achieved. But any other phase relationship could involve real power handling as well. This category includes STATCOM (Static synchronous compensator) and SVC (Static Var compensator).

The common Static VAR compensators are:

- TCR: Thyristor controlled reactor
- TSR: Thyristor switched reactor
- TSC: Thyristor switched capacitor

C. Combined Series-Series Controllers

This category comprises of separate series controllers controlled in a coordinated manner in the case of a multiline transmission system. It can be also unified controller in which the series controllers perform the reactive power compensation in each line independently whereas they facilitates real power exchange between the lines via the common DC link because, in unified series-series controllers like Interline Power Flow Controller (IPFC), the DC terminals of the controller converters are all connected together.

D. Combined Series-Shunt Controllers

It is a combination of separate series and shunt controllers, being operated in a coordinated manner. Hence, they are capable of injecting current into the line using the shunt part and injecting series voltage with the series part of the respective controller.

If they are unified, there can be real power exchange between the shunt and series controllers via the common DC power link, as in the case of Unified Power Flow Controllers (UPFC).

1.4 FACT devices modeling

FACT modeling consists of representing devices under certain assumptions and in a selected frequency domain. The developed models are then integrated into calculation programs so that they can simulate their effects throughout the system.

Different ways of modeling FACT devices have been developed for the study of stationary regimes. They are differentiated mainly by the method used to integrate the FACT in the calculation of the load flow. The three novelizations encountered most often in the literature are respectively based on the injection of equivalent power, the creation of a fictitious bus or the modification of the admittance matrix. These three techniques are presented in the following paragraphs.

1.4.1. Power injection at the ends of the line

One of the most common methods is to represent the devices FACT as power injections at the buses as shown in **Figure.1.1.**

The reactive power of FACT device will be injected on the line as shown by **Fig1.1.a**, and by injecting of power to both extremities **Fig1.1.b.** [7]. Active and reactive power Injections at bus i are given by:

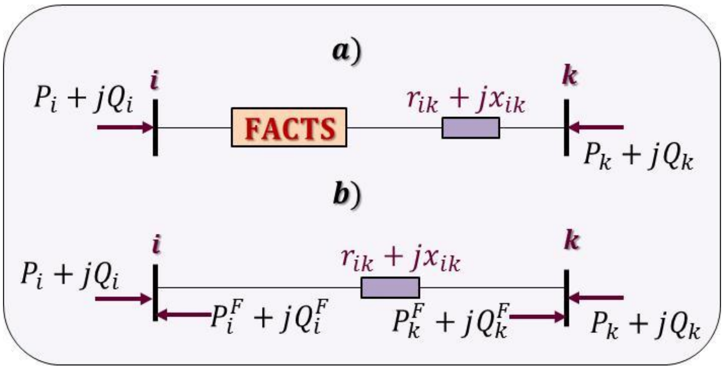

Fig.1.1. *Power injection modeling: a) line with FACT, b) line with equivalent injections.*

$$P_i^F = P_{ik} - P_{ik}^F \quad \textbf{(1.1)}$$

$$Q_i^F = Q_{ik} - Q_{ik}^F \quad \textbf{(1.2)}$$

Where : P_i^F, Q_i^F are active and reactive power of FACT devices injected in bus i, P_{ik}, PQ_{ik} are injected active and reactive power at bus i and , P_{ik}^F, Q_{ik}^F are active and reactive power considering FACT in the line.

The variations of this modeling have been proposed in [8], the model of injecting of decomposed power is proposed. The effects of FACT on the power transits in the lines and those on the control of the voltages at the buses are treated separately.

1.4.2 Creating a fictional bus

FACT modeling based on the creation of a fictional node is presented in [9].The model of UPFC-type device, allowing the control of active and reactive power transits, is shown in **Fig.1.2.**

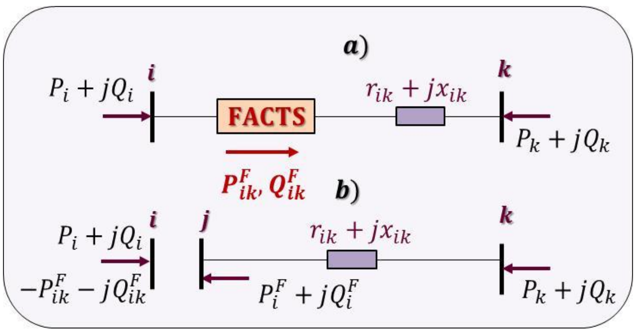

Fig.1.2. *Modeling with fictitious node: a) line with FACT, b) equivalent representation.*

The set points of the devices are directly expressed in terms of power flow in the lines or injected at the buses **Fig.1.2.a**. To maintain the power balance, the power injected at bus j is subtracted from that injected at bus i as shown **Fig.1.2.b.** The new bus is taken into account in the power distribution calculation by modifying the structure of the Jacobian matrix. The corresponding controlled quantities are summarized in **Table 2.1**.

Table 2.1. *FACT types that can be modeled by creating a fictional node*

Types of FACT	*Controlled quantities*
SVC	Reactive power Q_i^F injected at the node
TCPAR	Active power P_{ik}^F transmitted in the line
TCVR	Reactive power Q_{ik}^F transmitted in the line
UPFC	Active P_{ik}^F and Q_{ik}^F reactive powers transmitted in the line

In **[10]**, control of FACT devices is performed by the calculation of optimal power distribution. The FACT set points are calculated to optimize an objective function.

1.4.3 Modification of the admittance matrix

FACT devices are envisaged as elements that directly modify the nodal admittance matrix of the grid **[11]**.They are inserted in the line according to the representation of **Fig.1.3.** Depending on the type of FACT model, the device can be placed in the middle or at the end of the line.

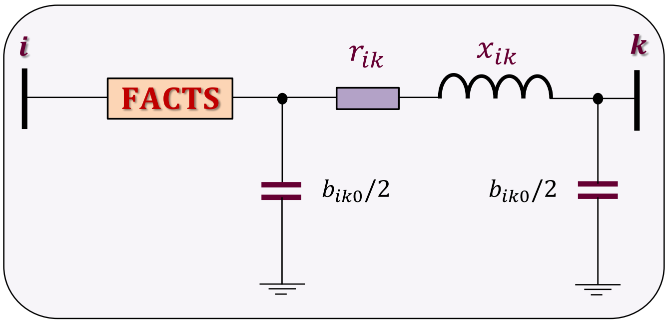

Fig.1.3. *Integration of FACT device in transmission line.*

The parameters of an equivalent transmission line including FACT devices are presented in **(1.3)**

$$Y_{mod} = \begin{pmatrix} Y'_{ii} & Y'_{ik} \\ Y'_{ki} & Y'_{kk} \end{pmatrix} = \begin{pmatrix} Y_{ii} & Y_{ik} \\ Y_{ki} & Y_{kk} \end{pmatrix} + \begin{pmatrix} y_{ii}^{F} & y_{ik}^{F} \\ y_{ki}^{F} & y_{kk}^{F} \end{pmatrix} \qquad \textbf{(1.3)}$$

Where : Y_{mod} is the admittance of line after compensation. Y is the admittance of line before adding FACT. Y' is the admittance of line after adding FACT, Y^F is the admittance of FACT device. i and k are buses.

Depending on the type of FACT and its position in the line, only part of the parameters of the matrix Y gets modifications.

Different methods are possible to process the values of the devices. They can be used as input quantities in a conventional load flow or as variables to be optimized in an optimal power flow calculation **[12]**.

1.4.4. Choice of devices

The FACT devices are chosen so that they can act on the three parameters governing the transits of powers in a network. In this perspective, the modeled FACT devices are as follows:

- *Reactive power compensator*
- *Thyristor series compensators*
- *The unified power transit controller*

In general, FACT devices can be inserted either at the nodes of the network, or in series with the lines. In practice, devices whether shunt or series are often inserted at existing stations. Although sometimes this position is not the best, it is justifiable by reducing costs by avoiding the creation of a new position.

1.4.5 Shunt FACT devices

The modeled shunt FACT devices are static compensators of reactive power such as SVC and other derivatives (TCR, TSC). Although they perform lesser than the synchronous static compensator, they are hardly important in steady state.

1.4.5.1. Model of the reactive power static compensator

The static reactive power compensator is modeled by Y_{SVC} as shunt variable admittance **Fig.1.4.a.** Since the power loss of SVC is assumed negligible, so the admittance is assumed purely imaginary:

$$Y_{SVC} = jb_{SVC} \quad \textbf{(1.4)}$$

Where: Y_{svc} is the admittance of the devices SVC. b_{svc} in the susceptance of SVC.

The susceptance b_{SVC}may be capacitive or inductive in nature to provide, or to absorb the reactive power Q_{SVC} **Fig.1.4.b.** The SVC values are expressed as the reactive power Q_{SVC} absorbed at the nominal voltageU_{in} is given by the equation:

$$Q_{SVC} = -U_n^2 . b_{SVC} \quad \textbf{(1.5)}$$

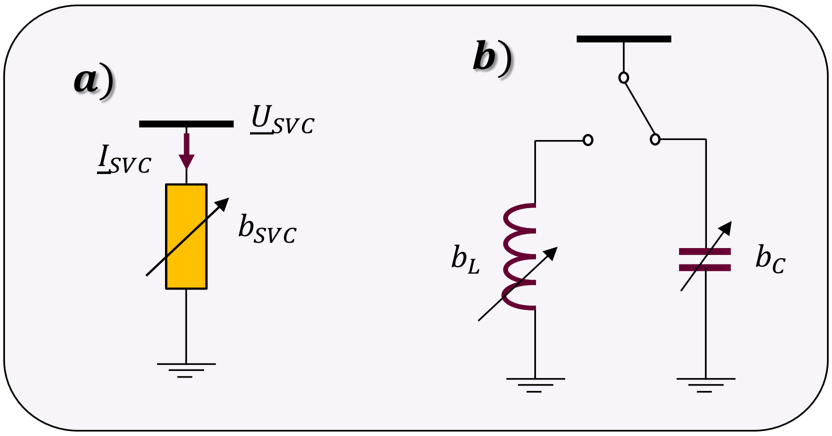

Fig.1.4 *Modeling of SVC: a) symbol, b) model.*

The negative sign indicates that SVC provides reactive power to the system when it is capacitive, and consumes it, when it is inductive. The variation of the reactive power injected as a function of voltage is shown in **Fig.1.5** for multiple compensation values.

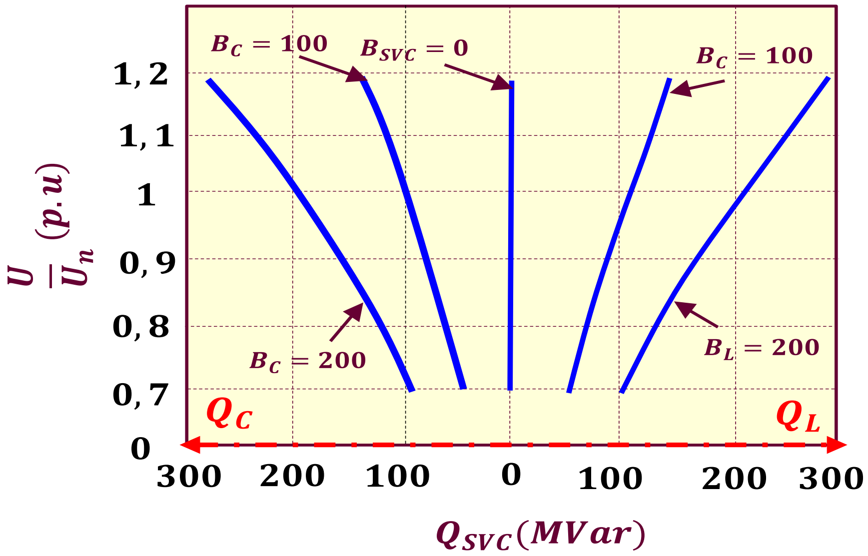

Fig.1.5 *Variation of the reactive power absorbed by a SVC versus the voltage at bus i.*

As already mentioned, FACT facilities are generally located in already existing stations. However, both cases are taken into consideration; namely when the SVC is placed at the end of the line and when it is located in the middle of the line.

1.4.5.2. SVC placed at the end of line (bus)

When connected to buses in the grid, SVCs are typically placed where there are large or highly variable loads. They can also be positioned at buses where the generator fails to provide or absorb enough reactive power to maintain the desired voltage level. **Fig.1.6** illustrates the case of a SVC placed at bus i.

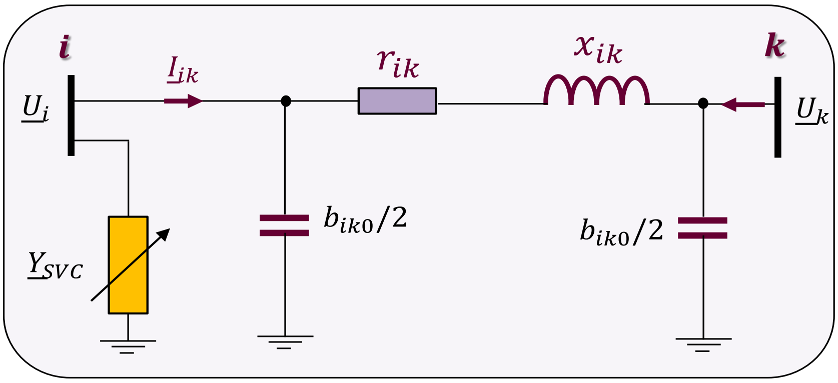

Fig.1.6 *SVC placed at bus.*

When SVC is present at the bus i, only the element Y_{ii} of the nodal admittance matrix is modified, the admittance of the SVC is as follow:

$$\underline{Y}' = \begin{pmatrix} \underline{y}_{ik} + \frac{\underline{y}_{ik0}}{2} + \underline{y}_{SVC} & -\underline{y}_{ik} \\ -\underline{y}_{ik} & \underline{y}_{ik} + \frac{\underline{y}_{ik0}}{2} \end{pmatrix} \tag{1.6}$$

1.4.5.3 SVC placed in the middle of the line

When the static compensator is inserted in the middle of a line, the line is divided into two identical sections. The SVC is connected to the additional median bus m, as shown in **Fig1.7.** In order to accommodate this new bus, an additional row and column should be added to the nodal admittance matrix. To avoid having to change the number of buses of the grid and thus the size of the admittance matrix, a star-delta transformation makes it possible to reduce the system by removing the bus *m* and by calculating the parameters of an equivalent line. Fig1.8 illustrates the steps to obtain this equivalent line.

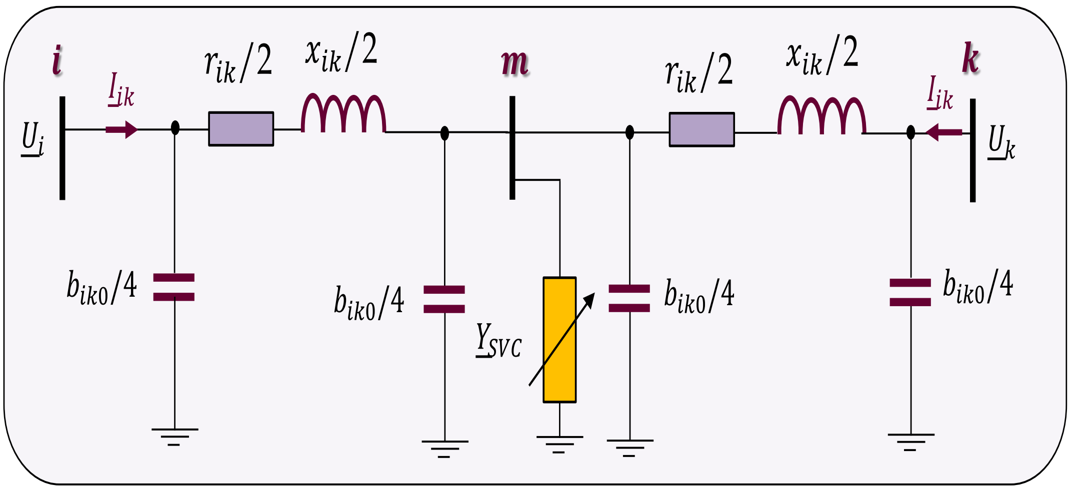

Fig.1.7 *SVC placed in the middle of the line*

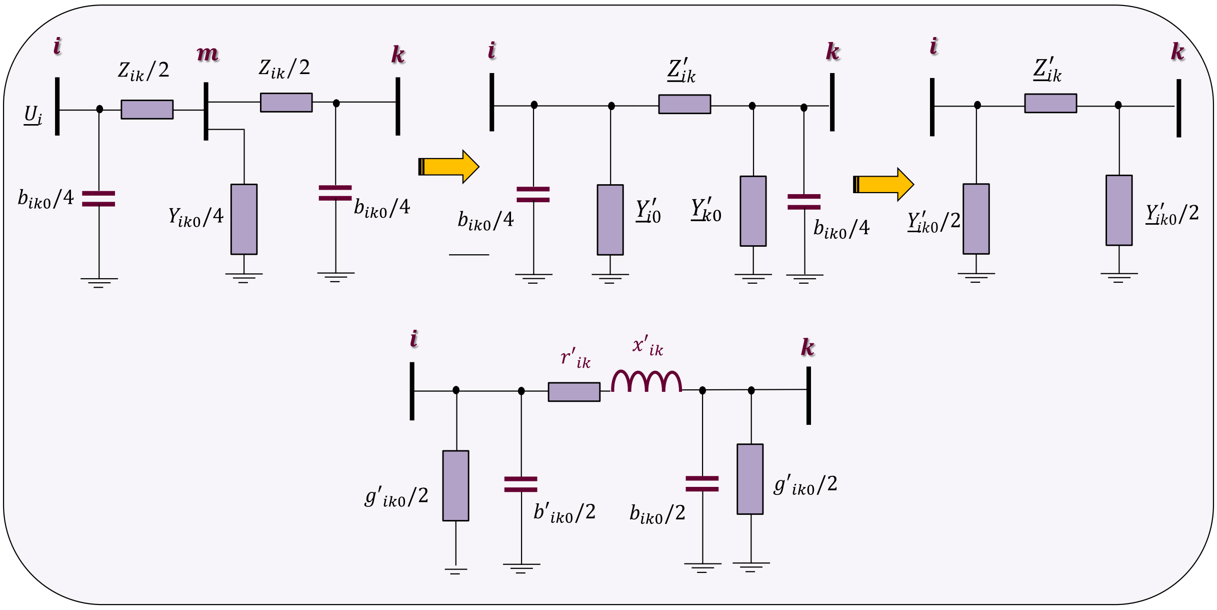

Fig.1.8 *Transformation into an equivalent line with a SVC in the middle*

All elements of the admittance matrix of a line with an SVC in its middle are modified:

$$\underline{Y}_{mod} = \begin{pmatrix} \underline{y'}_{ik} + \frac{\underline{y'}_{ik0}}{2} & -\underline{y'}_{ik} \\ -\underline{y'}_{ik} & \underline{y'}_{ik} + \frac{\underline{y'}_{ik0}}{2} \end{pmatrix} \tag{1.7}$$

The actual values of the elements of the equivalent line are obtained imposing:

$$\underline{y}_{m0} = \frac{\underline{y}_{ik0}}{2} + \underline{y}_{SVC} \tag{1.8}$$

It then comes for longitudinal impedance:

$$\underline{z'}_{ik} = \frac{4\underline{y}_{ik} + \underline{y}_{m0}}{4\underline{y}_{ik}^2} = \frac{1}{\underline{y}_{ik}} + \frac{\underline{y}_{m0}}{4\underline{y}_{ik}^2} = \underline{z}_{ik} + \frac{1}{4}\underline{z}_{ik}^2\left(\frac{\underline{y}_{ik0}}{2} + \underline{y}_{SVC}\right) \tag{1.9}$$

$$r'_{ik} = r_{ik} - \frac{1}{2}.r_{ik}.x_{ik}.\left(\frac{b_{ik0}}{2} + b_{SVC}\right) \tag{1.10}$$

$$x'_{ik} = x_{ik} + \frac{1}{4}.(r_{ik}^2 - x_{ik}^2).\left(\frac{b_{ik0}}{2} + b_{SVC}\right) \tag{1.11}$$

It then comes for longitudinal impedance:

$$\frac{\underline{y'}_{ik0}}{2} = \frac{\underline{y}_{ik0}}{4} + \frac{2\underline{y}_{ik}.\underline{y}_{m0}}{4\underline{y}_{ik} + \underline{y}_{m0}} = \frac{\underline{y}_{ik0}}{4} + \frac{\frac{\underline{y}_{ik0}}{2} + \underline{y}_{SVC}}{2 + \frac{1}{2}\underline{z}_{ik}\left(\frac{\underline{y}_{ik0}}{2} + \underline{y}_{SVC}\right)} \tag{1.12}$$

$$\frac{g'_{ik0}}{2} = \frac{\frac{1}{2} r_{ik} \left(\frac{b_{ik0}}{2} + b_{SVC}\right)^2}{4 - 2.x_{ik}.\left(\frac{b_{ik0}}{2} + b_{SVC}\right) + \frac{1}{4}(r_{ik}^2 + x_{ik}^2).\left(\frac{b_{ik0}}{2} + b_{SVC}\right)^2} \qquad \textbf{(1.13)}$$

$$\frac{b'_{ik0}}{2} = \frac{b_{ik0}}{4} + \frac{2.\left(\frac{b_{ik0}}{2} + b_{SVC}\right) - \frac{1}{2} x_{ik} \left(\frac{b_{ik0}}{2} + b_{SVC}\right)^2}{4 - 2.x_{ik}.\left(\frac{b_{ik0}}{2} + b_{SVC}\right) + \frac{1}{4}(r_{ik}^2 + x_{ik}^2).\left(\frac{b_{ik0}}{2} + b_{SVC}\right)^2} \qquad \textbf{(1.14)}$$

Fig1.9 illustrates the variation of the parameters of an equivalent line with an SVC in the middle of line. It highlights that the shunt susceptance b_{ik0} is the element that is most affected by the presence of the compensator. Its value, expressed in p.u, is practically equal to that of the SVC. In other words, a mid-line SVC has almost the same effect as two SVCs positioned at both ends of the line.

The value of g'_{ik0} being very low, it can be negligible, and the model of the equivalent line is similar to that used for lines without SVC.

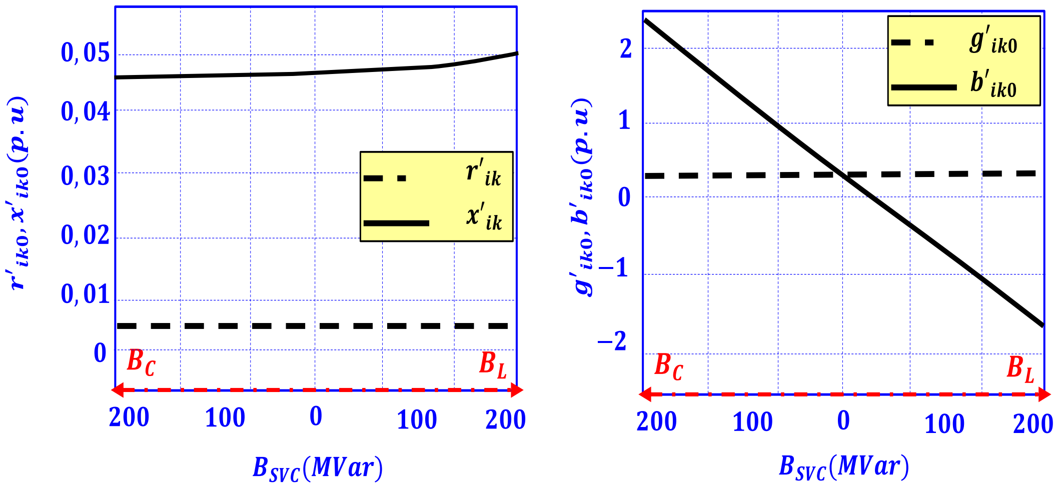

Fig.1.9. *Parameters of an equivalent line with SVC in the middle*

1.4.6. Series compensation devices

The modeled series compensation devices are Thyristor series compensators (TCSC, GCSC or TSSC). They modify the apparent impedance of the line by inserting reactive elements in series.

The SSSC has higher performance than the devices mentioned above. However, its representation does not seem possible with the methodology adopted to model the FACT devices. Indeed, the compensation achieved by this element is done by inserting a voltage in series in the line which is in quadrature with the current flowing there. It is therefore necessary to know the value of the current to be able to adjust the phase of the voltage to be inserted. This requires an iterative process.

1.4.6.1. Model of the Thyristor series compensator

The Thyristor series compensators used may be capacitive or inductive in nature. They are therefore similar to TCSC devices type. They are modeled by variable impedances inserted in series with the line as shown in **Fig.1.10.a.** Since the devices are considered ideal, only the reactive part of the impedance is taken into account. The model is formed of two parallel branches formed respectively of an inductance and a variable capacitance. To avoid resonance phenomena, the branches are exclusively engaged by means of a switch as illustrated **Fig1.10.b.** The value of the reactance of the TCSC is therefore given by:

$$x_{TCSC} = k_{TCSC} . x_{ligne} \tag{1.15}$$

The maximum compensation degrees are 80% in capacitive mode and 20% in inductive mode [13]:

$$-0.8 \le k_{TCSC} \le 0.2 \tag{1.16}$$

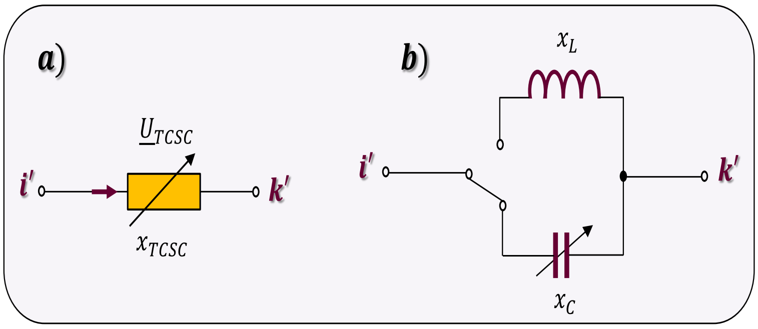

Fig.1.10 *TCSC modeling: a) general model b) model.*

1.4.6.2. Integration of the TCSC into the system

When a TCSC is placed in a line connecting the nodes i and k, it is directly integrated in the π diagram of the line according to the model of **Fig.1.11.**

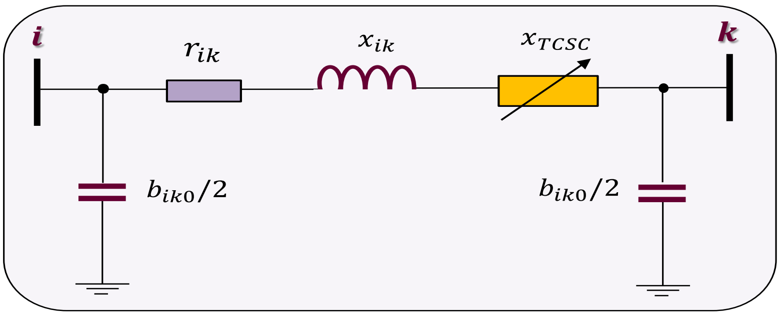

Fig.1.11 *TCSC inserted in a line.*

The effective reactance of the line is:

$$x'_{ik} = x_{ik} + x_{TCSC} \tag{1.17}$$

The matrix admittance of the line is modified as follows:

$$\underline{Y} = \begin{pmatrix} \underline{y}'_{ik} + \frac{\underline{y}_{ik0}}{2} & -\underline{y}'_{ik} \\ -\underline{y}'_{ik} & \underline{y}'_{ik} + \frac{\underline{y}'_{ik0}}{2} \end{pmatrix} \tag{1.18}$$

$$\underline{y}'_{ik} = \frac{1}{r_{ik} + j(x_{ik} + x_{TCSC})} \tag{1.19}$$

Where: x_{TCSC} is the reactance of TCSC. x_{ik} is the reactance of line between buses i and k before adding the TCSC. x'_{ik} is the reactance of line between buses i and k after adding the TCSC.

1.5 Conclusion

Reactive power compensation is very important to be tackled , it is a factor that limitates the power transited in the transmission lines. Equipment based on power electronics, including their appropriate controls, offer effective solutions to this problem.

FACT systems have the ability to improve transient stability by using an appropriate command. They can also control the transmittable power of the line using three methods: serie compensation, shunt compensation and hybrid compensation.

In this chapter, reactive energy compensation technologies in power grid has been presented as well as FACT systems. The two FACT devices (SVC and TCSC) that will be used in this project have been modeled and detailed

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Chapter 2

Comprehensive Review of ORPD: Objectives, Constraints, and Metaheuristic Optimization Strategies

Abstract:

The motto of studying the optimal reactive power dispatch (ORPD) is the streamline of the management of additional reactive power sources that should be installed in the network. This chapter will firstly provide a comprehensive review of several possible objective functions used to solve the ORPD. The objective functions may be considered for a security aspect which can be implemented as a minimization of real power loss, minimization of voltage deviation and maximization of voltage stability index. On the other hand, it can be taken into account as a cost functions, which are generally implemented as VAR or/and fuel cost, or even a combination of different objectives as a multi-objective model. Secondly, a review of different constraints in ORPD is detailed in this part, where equality and inequality constraints as well as penalty constraints considerations handled by different research studies are reported. Thirdly, a comprehensive review on application of meta-heuristic optimization algorithms for the solution of ORPD problem is provided, taking into account the objective functions and different constraint models. The literature review is based on papers published in several journals. The meta-heuristic optimization-based models were categorized into four main categories: evolution-based, swarm-based, physics-based, and human behavior-based methods. For each category, the most popular optimization techniques are discussed. Finally, it was found that advanced meta-heuristic methods as well as combinational hybrid methods are most suitable and successful to solve ORPD problems.

2.1. Introduction

The optimal reactive power dispatch (OPRD) is a sub-problem of the optimal power flow (OFP) that seeks to properly manage the reactive power resources of the system. The control variables of the OPRD include transformer taps, target voltages in the generation bus and reactive power compensators. The OPRD is a complex mixed integer non-linear programming problem that combines continuous variables such as generator voltage profile, and discrete variables such as tap position transformers and reactive power compensators [1]. Because of this, most of the techniques used to address this problem are based on metaheuristics. Due to the complicated objective functions, constraints, and solution algorithms, ORPD is identified as one of the most challenging problems in power systems. After a detailed study of the large amount of previous works, we believe that an informative and succinct literature review in ORPD should summarize the objective function models, the constraint models, and the mathematical algorithms. These three components are briefly discussed next.

The objective of the ORPD is generally to minimize active power losses and improve the voltage profile [2]. However, some authors include as objective function an additional improvement of voltage stability [3]. Other possible objective functions may be cost-based, which means to minimize the possible cost related with ORPD such as variable and fixed Var installation cost, real power loss cost, and fuel cost. It is also reasonable to use a multi-objective model as the goal of the ORPD formulation.

The constraints in ORPD are more complicated than the objective functions. Conventional constraints may include the normal state (base case) power-flow limits and the contingency state power flow limits. However, more recent works proposed to include the voltage stability limits, under both normal state and contingency state. Additionally, main considerations of equality and inequality constraints handled by different research studies are reported in this chapter.

Traditionally, mathematical modeling based classical methods are not so successful in solving ORPD problems. That is why in this study, authors gave attention only to advanced metaheuristic optimization methods. They are becoming more and more popular in engineering applications because of its simple concepts, ease of implementation and avoid local optimum. It does not require gradient information, and it can be used to solve wide range of problems on different disciplines. They can be grouped in four main categories (see **Fig.2.1**): evolution-based swarm-based, physics-based, and human behavior-based methods.

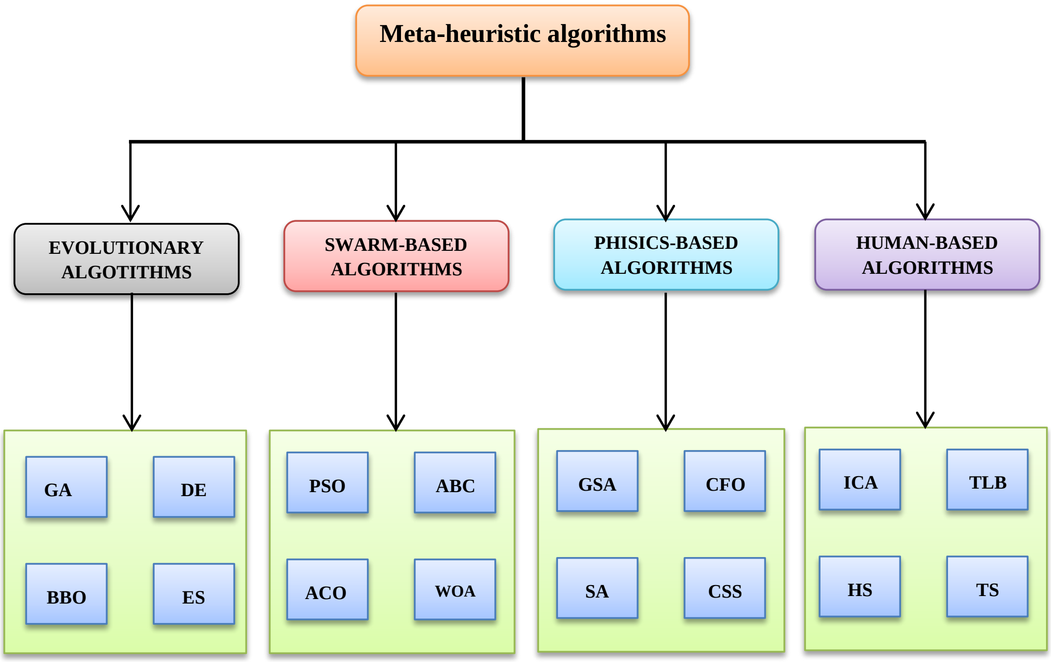

Fig.2.1. *Classification of meta-heuristic algorithms*

In the last decade, ORPD has been approached through different metaheuristics, such as: genetic algorithms (GA), differential evolution (DE), optimization by mean variance mapping (MVMO), evolutionary programming (EP), particle swarm optimization (PSO), Gravitational Search Algorithm (GSA), Charged System Search (CSS), Seeker Optimization Algorithm (SOA) , Exchange Market Algorithm (EMA).etc. In [4] authors presented the non-linear, non-convex and multimodal nature of ORPD. The aforementioned techniques have been shown to be effective in finding high-quality solutions to this problem. In particular, for the OPRD problem, the solution through particle swarm optimization and differential evolution has received great attention from researchers due to its ease of implementation and effectiveness [5]. Despite being effective in solving complex problems, metaheuristic techniques do not guarantee obtaining a global optimum. By solving complex multimodal problems, these methods can eventually be trapped in local optima. In addition, their speed of convergence depends on the appropriate adjustment of the parameters associated with each metaheuristic [6].

This chapter presents a bibliographic review of the different methods applied to the OPRD solution. The review was carried out starting from 2007, consulting publications of journals of the IEEE and Science Direct databases. The remainder of this chapter is organized as follows: **Section 2** provides the possible objectives in the ORPD literature. **Section 3** presents the different constraint models. A comprehensive review on employment of heuristic and metaheuristic optimization methods for optimal reactive power dispatch are presented in **Section 4**. Some comparative studies among methodologies to solve the ORPD are given in **Section 5**. Finally, the conclusion of this chapter is provided in **Section 6**.

2.2. Objective function models on ORPD

The ORPD can be solved as a single as well as a multi objective optimization problem. It can be formulated as follows:

$$\text{Minimize / Maximize } F(\mathrm{x}, \mathrm{u}) \quad \textbf{(2.1)}$$

$$\text{Subject to: } \begin{cases} h(x,u) = 0 \\ g(x,u) \leq 0 \end{cases} \quad \textbf{(2.2)}$$

Where $F(\mathrm{x},\mathrm{u})$is the objective function, $h\,(\mathrm{x},\mathrm{u})$is the set of equality constraints, and $\mathrm{g}\,(\mathrm{x},\mathrm{u})$is the set of inequality constraints.

The most recurrent objective functions in OPRD studies consist of the minimization of active power losses. In addition to that, it is also common to find as an objective function the minimization of the voltage deviation as well as improvement of the voltage stability index. However, some researchers also consider other objective functions such as the minimization of the investment cost of shunt compensation devices and the minimization of the fuel cost. The detailed discussions are presented as follows:

2.2.1. Minimize Real power loss

The basis of formulating ORPD problem is the minimization of real power loss, it can be expressed as indicated in [7].

$$F^{Ploss} = \min(\sum_{\substack{i=1 \\ j=1}}^{N} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j \cos\theta_{ij})) \quad \textbf{(2.3)}$$

Where $P_{loss}$is the total active loss of the system; g_{ij} is the conductance of the branch connected between the $i^{th}$and the j^{th} bus; θ_{ij} is the angle of admittance of the transmission line connected between the i^{th}th and j^{th}bus; N is the number of branches of the system, V_i,V_j are the voltage of i^{th} and j^{th} buses respectively.

2.2.2. Minimize load voltage deviation TVD

Another significant goal of reactive power optimization is to improve the voltage deviation TVD, which aim to sustain a proper voltage level at load buses. This objective function is usually defined as the sum of the deviations of the corresponding rated values at load buses. The general formulation of TVD minimization objective functions may be expressed as in **(2.4)**, **(2.5)**, **(2.6)**, and **(2.7)**.

$$F_1^{TVD} = min\left(\sum_{i=1}^{N_L} |V_{Li} - V_{Li}^{sp}|\right) \quad \textbf{(2.4)}$$

$$F_2^{TVD} = min\left(\sum_{i=1}^{N_L} \frac{|V_{Li} - V_{Li}^{sp}|}{N_L}\right) \quad \textbf{(2.5)}$$

$$F_3^{TVD} = min\left(\sum_{i=1}^{N_L} (V_{Li} - V_{Li}^{sp})^2\right) \quad \textbf{(2.6)}$$

$$F_4^{TVD} = min\left(\sum_{i=1}^{N_L} \frac{|V_{Li}^{sp} - V_{Li}|}{V_{L_i}^{max} - V_{L_i}^{min}}\right) \quad \textbf{(2.7)}$$

F_1^{TVD}, F_2^{TVD}, F_3^{TVD}, F_4^{TVD},are similar expressions that measure the voltage deviation, with respect to a certain value. In this case V_{Li} represents the voltage on thei^{th} load bus; $V_{Li}^{sp}$is the desired voltage magnitude at the i^{th}load bus (usually 1.0 pu), $N_L$is the total number of load buses, finally $V_{Li}^{min}$and V_{Li}^{max}represent the lower and upper limits of the voltage magnitude of the i^{th}, respectively.

2.2.3. Maximize voltage stability index

Some authors also include as an objective function the improvement of a voltage stability index. In [8] the voltage stability index expressed in **(2.8)**, **(2.9)**, and **(2.10)** is proposed.

$$F_1^{Lmax} = min\ L_{max} = \min\ [\max L_k],\ \ k \in \mathrm{N_L} \quad \textbf{(2.8)}$$

$$L_k = \left|1 - \sum_{i=1}^{N_G} F_{ji} \frac{V_i}{V_j}\right|^{[\{\theta_{ij}+(\delta_i-\delta_j)\}} \quad \textbf{(2.9)}$$

$$F_{ji} = -[Y_{ij}]^{-1}[Y_{ij}] \quad \textbf{(2.10)}$$

Where L_k is the voltage stability index (L-index) of buses; F_{ji} is the value of the element $ij^{th}$of the sub matrix obtained by the partial inversion of Y_{bus}; Y_{ij} is the admittance matrix of the j^{th}bus; Y_{ji} is the mutual admittance between the i^{th} and j^{th} buses; θ_{ij} is the phase angle of the term F_{ij}; δ_i, δ_j are the phase angle of the voltage at the i^{th} and j^{th} buses respectively; N_G is the number of generation buses.

Another index of stress stability monitoring commonly found in the literature [9] is given by **(2.11).**

$$F_2^{Lmax} = max\ (VMS) = max(min|eig(J)|) \quad \textbf{(2.11)}$$

Where J is the Jacobian matrix of the power flow; eig (J) are all eigen values of the Jacobian matrix; min | eig (J) | is the minimum of the eigenvalues of the Jacobian matrix and max (min | eig (J) |) indicates the maximization of the minimum eigenvalue in the Jacobian matrix.

Some authors like in reference [10] introduced voltage stability index as shown in **(2.12)**, **(2.13)** and **(2.14)**.

$$F_1^{Lmax} = \max L_k \qquad k \in N_L \tag{2.12}$$

$$L_k = \left|1 - \frac{V_{0k}}{V_{Li}}\right| \tag{2.13}$$

$$V_{0k} = \sum_{i=1}^{N_G} H_{2ki} V_{Li} \tag{2.14}$$

Where H_2 the generated sub matrix of the partial inversion of the matrixY_{bus}.

2.2.4. Minimizing VAR cost

The costs of the reactive power source can be divided into two parts: fixed installation cost, and operating costs. The fixed cost mainly consists of the sum of capital and installation cost of the devices. The operating or variable costs are consisting of heating losses cost and maintenance costs etc. However, the operating costs may differ from year to year. A better formulation of the VAR cost can be expressed with the formant given in (**2.15)**. This function is considered as a linear function and the more realistic model of VAR cost [11-13].

$$F^{VARcost} = \min\ (\mathrm{C_0} + \mathrm{C_1}.\mathrm{Q_c}) \tag{2.15}$$

Where $\mathrm{C_0}$ is the lifetime fixed cost prorated per hour ($/hour), $\mathrm{C_1}$ is the variable cost ($/hour) $\mathrm{Q_c}$ is the operational cost of compensation device.

2.2.5. Minimization of Fuel cost

Another significant goal of reactive power optimization is Fuel cost minimization. This objective function is usually well-defined as the sum of the individual polynomial cost function of real power injections for each generator. It can be presented as indicated in [14].

$$F^{fuelcost} = \min \sum_{i=1}^{N_g} \left(a_i + b_i P_{gi} + c_i P_{gi}^2\right) \tag{2.16}$$

Where $P_{gi}$is the active power generation at unit i, $a_i, b_i, and c_i$are the cost coefficients of the i^{th}generator, $N_g$is the number of thermal units

2.2.6. Multi-objective function

Several single objective functions have been detailed above. However, the aim objective of ORPD is to provide the system with efficient VAR compensation to allow the system to be operated under a correct balance between security and economic concerns. In recent years, the ORPD problem has been formulated as multi-objective optimization problem. Several methods have been presented to handle the multi-objective formulation of the ORPD problem. The common multi-objective approaches for ORPD are:

- ***The mathematical sum approach***

Multi-objective ORPD problem has been solved using the mathematical sum approach as an adaptive function **[15-20].** This model is very simple; it doesn't prefer any objective over the others.

- ***The weighted sum approach***

Multi-objective ORPD problem has been treated also using weighted objective functions **[21-25].** Weighted sum of different objectives can be added to the objective function terms as indicated in **(2.17).**

$$F= W_1 f_1 + W_2 f_2 + W_3 f_3 \quad \textbf{(2.17)}$$

For the weight factors used in this objective function, the following condition must be met:

$$W_1 + W_2 + W_3 = 1 \quad \textbf{(2.18)}$$

Where: W_1 ,W_2, and W_3 are the penalty coefficients associated with the several objective functions. Another way to represent the adaptive function of the ORPD is to use the inverse of the sum of the objective functions with the restrictions penalties as indicated in (2.19).

Table 2.1 *Classification of objective function models applied to ORPD.*

Objective functions	Reference papers
F^{Ploss}	[7], [21], [28], [37], [44], [46], [53], [55], [56], [62], [67], [68], [70], [71], [74], [75], [80], [83], [91], [97], [104]
F^{TVD}	[66]
$F^{L\,max}$	[8], [47]
$F^{VAR\ cost}$	[32]
F^{Ploss} & F^{TVD}	[10], [31], [42], [49], [52], [61], [63], [77], [78], [84], [103], [109]
F^{Ploss} &$F^{VARcost}$	[12], [13], [16], [18], [19], [20], [24]
F^{Ploss} &F^{TVD} &F^{Lmax}	[3], [9], [22], [45], [50], [60], [86], [87], [88], [94], [102], [107]
F^{Ploss} &F^{TVD} &$F^{VARcost}$	[23]
F^{Ploss} &F^{TVD} &F^{Lmax} &$F^{VARcost}$	[11]

Note that in this case the optimization process would be maximization.

$$\mathrm{F} = \frac{1}{W_1 f_1 + W_2 f_2 + W_3 f_3} \tag{2.19}$$

Table 2.1 presents some papers that utilized the objective functions described above. It is evident that the objective function implemented with the most recurrence is the minimization of active power losses.

2.3. Constraint models for ORPD

ORPD is usually recognized as an optimization problem in power systems, well-known as optimal power flow (OPF). For each bus there are six variables: active power generated(P_{gi}), reactive power generated(Q_{gi}), active power of load bus (P_{di}), reactive power of load bus(Q_{di}), bus voltage magnitude(V_i) and bus voltage angle(θ_i). Depending of the nature of bus, four of the six variables are known at each bus; however, the other two are unknown and should be calculated by using a suitable mathematical algorithm, then, a feasible solution can be obtained [26].

ORPD is formulated as a general constrained optimization problem, mathematically represented by **(2.2).** They may be classified as a group of equality constrains such as a power balance of load flow, as well as inequality constraints such as the physical limits of the system of control variables 'U' or the physical limits of the system dependent variables 'X'. ORPD is detailed mathematically as follow:

2.3.1 Equality Constraints

Active and reactive power balance for each bus is given by **(2.20)** and **(2.21)** respectively:

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{2.20}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{2.21}$$

2.3.2 Inequality Constraints

- ***Independent variables***

The independent inequality constraints are represented as follow [27]:

$$P_{slack\ bus}^{min} < P_{slack\ bus} < P_{slack\ bus}^{max} \tag{2.22}$$

$$P_{gi}^{min} < P_{gi} < P_{gi}^{max} \qquad i \in N_g \tag{2.23}$$

$$V_{gi}^{min} < V_{gi} < V_{gi}^{max} \qquad i \in N_g \tag{2.24}$$

$$T_k^{min} < T_k < T_k^{max} \qquad k \in N_T \tag{2.25}$$

$$Q_{Ci}^{min} < Q_{Ci} < Q_{Ci}^{max} \qquad i \in N_C \tag{2.26}$$

Where V_g,V_L are generation and load bus voltage respectively; $P_{gslack\ bus}$is real generation of slack generator; p_{gi}, Q_{gi} represent active and reactive power of i^{th} generator; p_{di}, Q_{di} represent active and reactive power of i^{th} load bus; G_{ij}, B_{ij} , $\theta_{ij}$are conductance, susceptance and Phase difference of voltages between $i^{th}$and j^{th} bus; T_k is the tap-setting of transformer of branch k

- ***Dependent variables (state variable limits)***

The limits of magnitude of voltage, reactive power delivered by the generators and chargeability of the transmission lines are given by the restrictions in **(2.27)**, **(2.28)** and **(2.29)**, respectively **[27].**

$$Q_{gi}^{min} < Q_{gi} < Q_{gi}^{max} \qquad i \in N_g \qquad (2.27)$$

$$V_{Li}^{min} < V_{Li} < V_{Li}^{max} \qquad i \in N_L \qquad (2.28)$$

$$S_{Li} < S_{Li}^{max} \qquad i \in N_L \qquad (2.29)$$

S_L is apparent power flow through L^{ith} transmission line; N is the buses' number ; N_G is the generators' number; N_T is the tap regulating transformers' number; N_{TL} is the transmission lines' number; N_C is the shunt VAR compensators' number; N_{PQ} is the number of PQ buses; r_{gi} is the penalty factor related to generators; $r_{Qi}$is the penalty factor related to generators reactive, ; r_{si} is the penalty factor related to power transmission line.

The dependent variables constraints are included into the objective function as a penalty terms **[28, 29].** The penalty function terms would be zero, if all the control variables are not exceeded the limits. Otherwise, the terms would be considered into the objective function. It can be written as follows:

$$F = P_{loss} + \sum_i^N r_{gi}(V_i - V_i^{lim})^2 \sum_i^N r_{Qi}(Q_i - Q_i^{lim})^2 \sum_i^N r_{si}(S_i - S_i^{lim})^2 \qquad (2.30)$$

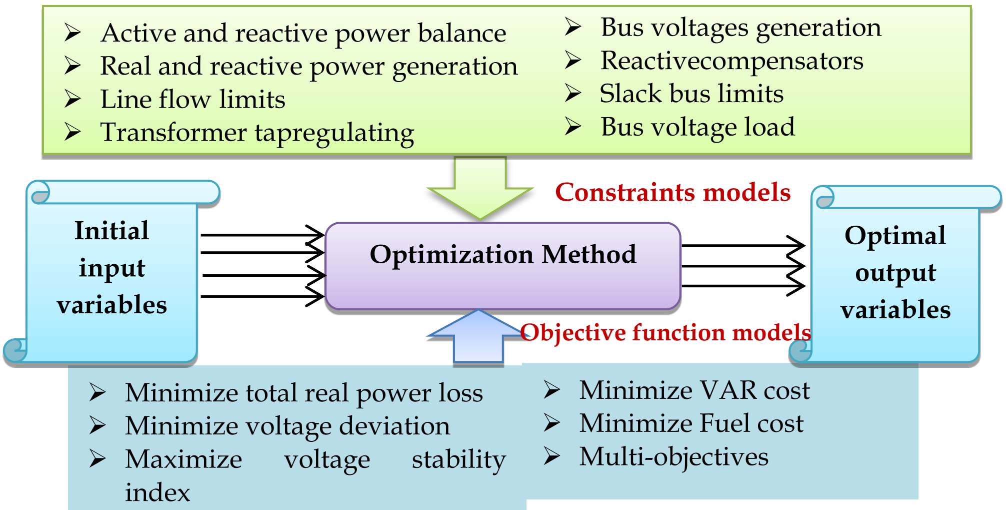

Fig.2.2 .*Elements of a general mathematical optimization model related to ORPD*

Fig.2.2 summarizes the above discussed elements forming a general mathematical optimization model. It describes all possible models of constraints and objective functions related to the ORPD.

2.4. Metaheuristic algorithms employed for ORPD problem

In the preceding two sections, the objective functions and the constraints models are discussed and detailed as the optimization formulation of the ORPD. Due to the nature of the ORPD problem (nonlinear and non-convex) most of the techniques applied to solve that problem are based on metaheuristic optimization. This section will discuss a literature review of the different metaheuristic approaches applied to the ORPD in the last few years based on papers that are published in IEEE-explore and Science-Direct. Metaheuristic methods are considered as a search techniques based on an intelligent procedure that may provide a sufficiently good solution to an optimization problem. This optimization process is not carried out with a rigorous mathematical process. In relation to the intelligent search procedure of the optimum, different principles or mechanisms have been proposed. The following is a classification of different metaheuristic used for the ORPD solution (**Fig. 2.1**)

2.4.1. Evolutionary-Based Algorithms

The term Evolutionary Algorithms (EA) is used to describe systems for solving optimization or search problems based on the concepts of biological evolution. It is a subset of evolutionary computation which uses an iterative process based on the development and growth of a population. This population is selected in a guided random search where the individuals are mixed and competed with each other such that the fittest prevail throughout the process allow reaching a desired objective. The paradigm of evolutionary computing techniques refers to the Darwinian principles in 1950s. Many evolutionary algorithms have been applied to solve the OPRD problem; the most used are cited in the following:

2.4.1.1. Genetic algorithms (GA)

Genetic algorithm (GA) one of the most used optimization algorithms, has been developed by John Holland in 1970 **[30].** It is an adaptive search procedures based on the principles derived from the concept of genetics. The Proper representation or coding of individuals from the population is a key aspect to the success of this type of methodology. Each individual represents a candidate a solution of the problem addressed. In the process of solution, the characteristics of the individuals are selected and transmitted to the new generations. GA requires three basic operators which are named according to the corresponding biological mechanisms: selection, crossover, and mutation.

A multi-objective optimization method based on genetic algorithm is proposed in [31] for solving non-convex ORPD problem taking into account the equality and inequality constrains. It is applied to optimize three objective functions such as loss and/or invest cost minimization. An improved genetic algorithm based on fuzzy membership function. Fuzzy approach is proposed in [32] for the optimal setting of power system variables considering two types of FACTS devices in order to solve a multi-objective ORPD. In [33] the solution of ORPD problem is provided by using hybrid genetic algorithm (GA) and nonlinear interior point method (IPM), the authors have decomposed the problem into two sub-problems, where GA is used to solve the discrete optimization with the continuous variables, and IPM solves the continuous optimization with the discrete variables, so the optimal solution can be achieved by solving the two sub-problems alternately. Other authors have implemented similar GA in solving ORPD such as in [34-39].

2.4.1.2. *Differential evolution (DE)*

Differential evolution DE was designed for continuous and unconstrained optimization problems. Its current extensions can handle mixed-variable problems and handle non-linear constraints. Currently, a large number of industrial and scientific applications rely on differential evolution. This technique was initially proposed by Storn and Price in 1997 [40]. The DE is an evolutionary model that emphasizes mutation. The solutions in the search space are represented by vectors (individuals) of real values and the generation of new individuals is carried out through differential mutation and crossing operators.

DE method is introduced in [41] for solving the non-convex ORPD. The authors found that DE requires relatively large populations to avoid premature convergence. A similar algorithm is utilized in [42, 43] for obtaining minimum power loss as well as improving the voltage deviation, also, it has been applied for large scale Algerian power system and it gives a considerable solution. In [44], the authors implemented multi-objective differential evolution (MO-DE) to solve multi-objective optimal reactive power dispatch (M-ORPD) problem by minimizing active power transmission loss and voltage deviation and maximizing voltage stability. Hybrid algorithm DE-EP is proposed in [45] to reduce the relatively large population size that increase the computational time. In addition, other modified DE for ORPD was reported in [46-50].

2.4.1.3. *Biogeography Based Optimization (BBO)*

Biogeography based Optimization (BBO) was introduced by Don Simon in 2008 **[51].** As many evolutionary algorithms, BBO is formed by a natural process, specifically, it surveyed by environmental geography, which examines the distribution of Biogeography species through time and space. BBO concept is mainly based on Migration and Mutation. BBO is an evolutionary algorithm (EA) that optimizes a function by randomly and iteratively improving candidate solutions according to method rules, and to the quality or performance measurement data.

In **[52]** Biogeography Based Optimization (BBO) technique is introduced to solve multi-constrained optimal reactive power dispatch (ORPD) problem in power system. ORPD considered as a multi-objective nonlinear optimization problem that minimizes the real power and bus voltage deviation. A similar optimization method is implemented in **[53]** for solving the ORPD in which both equality and inequality constraints are taken into account.

2.4.2. *Swarm Intelligence Algorithms*

Swarm intelligence (SI) refers to complex systems of multiple agents or populations, which contain numerous individuals, exhibiting intelligent behavior through cooperation and competition between them. The most representative SI algorithms are cited bellow.

2.4.2.1. *Particle swarm optimization (PSO)*

Particle swarm optimization PSO was originally designed and introduced by Eberhart and Kennedy **[54].** The PSO is a population algorithm based on the social behaviors of bird flocking. In the beginning, this algorithm had the intention of graphically simulating the dynamics of a herd of birds. Each individual within the swarm is represented by a vector in a space of multidimensional search. This vector is associated with a velocity vector that determines the next movement of the particle. The position and speed of each particle is updated based on its best position and the best overall position recorded by the swarm. It has been shown that this model can handle difficult optimization problems efficiently. The PSO was originally developed for real value spaces. However, many problems are defined in discrete value spaces with finite variables domain.

PSO has been introduced in **[55]** to solve the ORPD. To avoid premature convergence, authors proposed a particle swarm optimization with adaptively acceleration coefficients PSO-TVAC during iterations. In **[56]** Hybrid PSO-MVO is applied to solve multi-objective ORPD. The authors considered PSO for the exploitation phase and MVO for the exploration phase in uncertain environment, also, the Position and Speed of particle is modernized according to location of universes in each iteration. PSO-MVO method showed fast convergence rate due to use of roulette wheel selection method. A novel Fuzzy Adaptive Heterogeneous Comprehensive-Learning Particle Swarm Optimization (FAHCLPSO) algorithm is proposed in **[57].** In this reference a Fuzzy Logic (FL) method based on Fuzzy Inference System (FIS) is proposed to support and increase the search ability of the novel algorithm with enhancing exploration and exploitation processes to solve the ORPD problem. More applications of the PSO for the ORPD can be found in **[58, 59].** In addition, hybrid PSO algorithms or variants in operators have been proposed as indicated in **[60-64].**

2.4.2.2. Ant colony optimization (ACO)

Ant colony optimization ACO is a recent metaheuristic approach proposed by Dorigo et al in **[65].** The source of inspiration for the ACO is the tracking behavior of ants, which use a trail of pheromones as a way of communication. In analogy to the biological example, ACO is based on the indirect communication of the simple agents of the colony, which are guided by pheromone paths. The pheromone paths in ACO serve as distributed numerical information on which the agents rely to build probabilistic solutions to solve the problem. During the execution of the algorithm, individuals adapt reflecting their search experience and the collaboration of other agents.

In **[66]** ACO algorithm has been applied to solve ORPD in order to improve the voltage stability considering fact devises. A similar optimization method in **[67]** has been applied for the same ORPD but the objective function considered here is to minimize the transmission power losses under control and dependent variable constraints. Hybrid DE-ACO is applied in **[68]** to solve a single objective ORPD. The authors proposed approach which combines variable scaling mutation and probabilistic state transition rule used in the ant system to improve the solution of ORPD problem.

2.4.2.3. Artificial bee colony (ABC)

Artificial bee colony ABC emulates the behavior of honey bees in how they distribute their work to optimize nectar collection. In the ABC algorithm, the position of the food sources determines the solution and the amount of nectar represents the aptitude or goodness of the solution. This method has three basic elements that interact the behavior of foraging; there are employed bees that communicate to the observing bees the information of the food sources that they are exploiting, the observing bees visit the most promising food sources. Once the food sources have been depleted (either by the employed bees or by observers) they are filled and replaced by new sources found by the scout bees **[69].**

In [70] ABC algorithm has been applied to solve ORPD in order to minimize active power loss in power systems considering equality and inequality constrains, in which a penalty constraint handling strategy is proposed. Hybrid DE-ABC is introduced in [71] to overcome DE drawbacks of necessitating a large population size and strengthen the global search ability In order to minimize the computational time of simulation of ORPD problem.

2.4.2.4. *Cuckoo search algorithm (CSA)*

The cuckoo search algorithm has been introduced in [72], CSA is one of the newest optimization algorithms with few controlling parameters and successfully used in solving several global optimization problems. CSA algorithm is based on the parasite behavior of the "cuckoo" bird when it comes depositing on its eggs in other bird's nests. In the CS, each possible solution of the problem is associated to the coordinates of a nest that is occupied. It is part of an initial set of nests in which the eggs have been deposited. The best eggs will go unnoticed and survive, but the worst eggs will have a chance to be discovered and not survive. These nests that have failed will be replaced by new nests through Lévy flights. These flights constitute in movement in the search space that imitate the behavior of some birds, travel distance in a straight line and then make a sudden turn of ninety degrees in another direction, this distance traveled or jumps of a random length are defined by a distribution called Lévy distribution [73]. In ORPD CSA has been proposed several times. In [74] Cuckoo Search Algorithm (CSA) was introduced to optimize the control variables of the objective function which is considered as a minimization of real power loss. The authors in [75] used a SMES system along with synchronous generators & shunt capacitors to solve optimal reactive power dispatch ORPD based on CSA technique.

2.4.2.5. *Gray wolf Optimizer (GWO)*

The Gray wolf Optimizer algorithm was proposed in 2014 [76]. GWO is one of the newest optimization algorithms, which mimics the leadership hierarchy and the gray wolf hunting mechanism in nature. Four types of gray wolves are used, such as: alpha, beta, delta and omega for the simulation of the leadership hierarchy. In addition, the three main steps of the hunt are implemented, which are search, rodeo and attack of the dams. Authors in [77] applied GWO to solve the ORPD based on minimization of real power loss and voltage deviation. In [78] modified Multi-objective Grey Wolf Optimizer has been proposed to solve the ORPD problem. 2-archive concept was implemented to the base algorithm. Objective functions are: active power loss minimization and voltage Deviation minimization TVD.

2.4.2.6. Whale optimization algorithm (WOA)

The whale optimization algorithm WOA was presented in 2016 by Mirjalili and Lewis in 2016 **[79]** WOA is one of the latest novel meta-heuristic optimization algorithms, it imitates the bubble nut hitting strategy of humpback whales. It has 2 main mechanisms, encircling pray mechanism and updating position mechanism. Authors in **[80]** proposed the WOA to solve a single objective ORPD. WOA was applied successfully for minimizing the real power loss. WOA proved its effectiveness in solving large scale optimization problems.

2.4.3. Algorithms Based on Physical Phenomena

These algorithms are inspired by physical laws (forces between electric charges, gravity, river systems, etc.) for its operation. Although, there are many methods of metaheuristic optimization that are based on physical phenomena **[81].** The most representative are cited bellow:

2.4.3.1. Simulated annealing(SA)

The Simulated annealing SA was proposed by Kirkpatric, Gelatt and Vecci in **[82].** SA is founded based on the emulation of the annealing of steel and ceramics. This technique involves heating and then slowly cooling the material to vary its physical properties. In **[83]** authors proposed a parametric variation based SA technique to select the optimal parameters for proper convergence of SA in order to get the best solution for ORPD. Minimum power loss is considered as an objective function. Hybrid TS-SA has been proposed in **[84]** to solve the optimal reactive power dispatch problem in order to minimize active power and voltage deviation, the authors considered two types of objective functions with and without penalty constraints.

2.4.3.2. Gravitational search Algorithm (GSA)

The Gravitational search Algorithm GSA was proposed in 2009 **[85].** GSA is based on the gravitational and movement law. In this algorithm each agent is considered as an object and its mass represents its adaptation function. At the end of this algorithm the position of the highest mass object represents the best solution.

In **[86]** a simple gravitational search is used to solve nonlinear, non-convex ORPD problem. The objective of ORPD is considered to minimize the real power losses, voltage profile improvement and voltage stability enhancement. Improved GSA called an opposition-based gravitational search algorithm OGSA has been proposed in **[87]** to solve ORPD problem considering different objective functions as given in reference **[86].** The authors implemented opposition-based in OGSA to give a chance of starting with a closer (fitter) solution. A novel opposition-based self-adaptive modified gravitational search algorithm (OSAM-GSA) is proposed in [88] to solve a multi-objective ORPD problem. The authors used this approach for generation jumping and avoiding local optima. This modification developed the search ability of OSAM-GSA.

2.4.3.3. Water Cycle Algorithm (WCA)

WCA is a recently proposed physics based metaheuristic optimization algorithm, proposed in 2012 [89], then improved in 2015 [90]. WCA is inspired by hydrological cycle in nature. It is based on the continuous movement of river's water toward the sea in the real world. In [91] the authors proposed and utilized a modified WCA to tackle optimal reactive power dispatch. Both active power loss and voltage deviation are considered as an objective functions. A modified movement strategy of WCA is utilized to enrich random activities and the exploration potentials.

2.4.4. Human behavior based algorithms

Algorithms based Human behaviors are characterized by being independent of the specific knowledge of the problem in the search for solutions. The most prominent algorithms of this type in ORPD applications include:

2.4.4.1. Harmony Search (HS)

The cultural algorithm was introduced by Robert G. Reynolds in 1994 [92]. It consists in the generation of a space of beliefs that is divided into different categories. Harmonic Search (HS) is founded based on imitation of a phenomenon inspired by the process of improvisation of the musicians proposed by Zong Woo Geem in 2001 [93]. In the HS, each musician (decision variable) plays (iteration) a note (value) to find the best harmony (global optimum). This is done by following an established set of rules. In these categories, the belief space is updated after each iteration to find the best individual (solution candidate) of the population. In [94] harmony search algorithm is implemented to solve ORPD problem, the proposed algorithm is used to find the optimal settings of control variables. The authors in this reference considered three objective functions. Two test systems are utilized to show the performance of the introduced HS algorithm.

2.4.4.2. Imperialist competitive algorithm (ICA)

Imperialist competition algorithm ICA was introduced by Atashpaz-Gargari and Lucas in 2007 [95].This type of algorithms is based on the geopolitical interactions of the countries (which represent the solution candidates). During the iterative process, revolutions and annexations are presented; in this way they go eliminating weaker empires, giving way to stronger empires (better solution candidates).

In **[96]** a new modified ICA method further improves the performance of ICA method by taking advantage of Gaussian Bare-bones was applied to tackle a multi-objective optimization problem for both OPF and ORPD. Authors in **[97]** proposed hybrid modified imperialist competitive algorithm and invasive weed optimization ((MICA-IWO) for handling the optimal reactive power dispatch ORPD problem. In order to avoid falling into the local optima. A new method based IWO method to improve local search near the global best. Other modification also has done for ICA in order to improve algorithm's rate of convergence for a better solution.

2.4.4.3. *Teaching Learning Based Optimization (TLBO)*

Teaching learning based Optimization TLBO was introduced first in **[98],** and then it was modified and enhanced for several times **[99-101].** TLBO simulates the teaching-learning phenomenon that occurs in a classroom. The algorithm simulates two fundamental modes of learning: (i) through the teacher (known as the teacher's stage) and (ii) interacting with other students (known as the student's phase). TLBO is an algorithm where a group of students are known as the population and the different subjects offered to the students are analogous to the design variables of the optimization problem. The best solution of the population is considered as the teacher. In **[102]** a developed teaching learning based optimization algorithm is proposed to solve multi-objective ORPD problem. Quasi-opposition based learning (QOBL) concept is treated in order to minimize the time computation of the original TLBO. Objective functions took into consideration are minimum power loss, minimum voltage deviation and improvement of voltage stability. Similar LTBO was applied to solve the ORPD problem in **[103]** LTBO was proposed to solve a multi-objective problem based on minimum power loss and cost operation. Authors in **[104]** implemented Gaussian bare-Bones technique to a modified version of TLBO algorithm for minimizing the real power loss in the power system. Hybrid MTLBO-DDE was introduced in **[105]** to solve the ORPD problem. The new hybrid algorithm has better performance in both factors of global and local search.

2.4.4.4. *Artificial immune Algorithm (AIA)*

The immune algorithms are adaptive systems, inspired by the theory of immunology, as well as functions, principles and models observed in the immune system.

The artificial immune algorithm AIA was proposed by Dasgupta in 1999 **[106].** AIA is based on the principle of clonal selection and is a population-based algorithm in which antigens (candidate solution) and antibodies (target) interact to find an optimal solution following some biological rules. AIA is inspired by the human immune system which is a highly evolved, parallelized and distributed adaptive system that exposes the following strengths: immunological recognition, reinforced learning, characteristic extraction, immunological memory, diversity and robustness. The artificial system Immune combines all these strengths and has been gaining special attention due to its adaptive capacity of learning and memory. The main search power in AIA is based on the mutation operator and therefore, is the efficiency factor of this technique. The algorithm of artificial immune recognition performs the identification of foreign bodies as molecules that are not native to the body to be eliminated. In **[107]** a multi-objective adaptive immune algorithm was implemented for the ORPD solution. Loss minimization and maximization of voltage stability index are considered as an objective function.

2.4.4.5. *Bacterial Foraging Optimization algorithm (BFO)*

BFA inspired by E. coli bacteria that are present in the intestines of humans **[108].** BFO is based on the fact that natural selection tends to eliminate animals with poor strategies in the search for food, and favors those who have the successful search strategies. After many generations, poor search strategies will be eliminated or improved. The bacterial food search algorithm (BFO) was implemented in **[109]** to solve the ORPD problem. Active Power Loss and Voltage Stability index are considered as objective function.

2.5. Comparative study

In the technical literature several comparisons between methods are reported to address the ORPD problem. **Table.2.2** presents papers that carried out such comparisons and detailed the objectives, constraints, and test systems used to solve the ORPD for several literature paper research.

Table.2.2 *Matrix of objectives, constraints and solution algorithms for ORPD*

Reference	Proposed Method	Objective functions	Penalty Functions considered	Comparison techniques	Test system
[3]	QOTLBO	F^{Ploss}, F^{TVD}, $F^{L\,max}$	No	AG, SPEA, ED	IEEE 30-bus, 118-bus
[7]	DMSDE	F^{Ploss}	Yes	PSO-w, DE, AGA, CGA, PSO-cf, CLPSO	IEEE 30-bus, 57-bus, 118-bus
[8]	GA	$F^{L\,max}$	No	/	IEEE 30-bus, 57-bus
[9]	MOAIA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	IGA	IEEE 30-bus
[10]	NSGA-II, MNSGA-II	F^{Ploss}, F^{TVD}	Yes	CMAES ,SQP,PSO	IEEE 30-bus, 118-bus
[11]	MNSGA-II	F^{Ploss}, F^{TVD}, $F^{L\,max}$, $F^{VAR\,cost}$	No	NSGA-II	IEEE 30-bus, 118-bus, 69-bus Indian test system
[12]	ABC	F^{Ploss}, $F^{VAR\,cost}$	Yes	/	
[13]	EP	F^{Ploss}, $F^{VAR\,cost}$	Yes	/	IEEE 30-bus
[16]	DE	F^{Ploss}, $F^{VAR\,cost}$	Yes	EP, RGA	IEEE 30-bus
[18][19]	DE	F^{Ploss}, $F^{VAR\,cost}$	Yes	/	IEEE 30-bus
[20]	EP	F^{Ploss}, $F^{VAR\,cost}$	Yes	/	IEEE 57-bus, 118-bus
[21]	PSO-GA	F^{Ploss}	No	PSO, GA	IEEE 68-bus
[22]	SOA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	PSO-w, DE, AGA, CGA, PSO-cf, L-DE	IEEE 57-bus, 118-bus
[23]	HSA	F^{Ploss}, F^{TVD}, $F^{VAR\,cost}$	Yes	/	IEEE 30-bus
[24]	GA	F^{Ploss}, $F^{VAR\,cost}$	No	/	IEEE 30-bus
[28]	MASRL	F^{Ploss}	Yes	DPSO, IP	IEEE 30-bus, 162-bus
[31]	MGA	F^{Ploss}, F^{TVD}	No	MGA, FSGA	IEEE 30-bus
[32]	GA-DE-LA	$F^{VAR\,cost}$	No	Fuzzy-GA, SDE, SPSO, SGA	IEEE 30-bus
[37]	GA	F^{Ploss}	No	/	IEEE 30-bus, 118-bus
[42]	DE	F^{Ploss}, F^{TVD}	No	SQP	IEEE 14 and IEEE RTS 24-bus
[44]	DE	F^{Ploss}	Yes	ABC, ABC-DE, PSO, DE, CSSP	IEEE 14-bus, 30-bus, Algerian 114-bus
[45]	MODE	F^{Ploss}, F^{TVD}, $F^{L\,max}$	No	SPEA2	IEEE 30-bus, 57-bus, 118-bus
[46]	MTLA-DDE	F^{Ploss}	Yes	TLA , DE, MTLA, DDE	IEEE 14-bus, 30-bus, 118-bus
[47]	EPSDE	$F^{L\,max}$	No	GA,TLBO, SaDE	IEEE 14-bus, 25-bus
[49]	DE	F^{Ploss}, F^{TVD}	No	SF–DE, SP–DE, EC–DE, SR–DE ECHT–DE	IEEE 30-bus, 57-bus, 118-bus
[50]	DE	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	/	IEEE 30-bus
[52]	BBO	F^{Ploss}, F^{TVD}	No	ECHT, GPAC, LPAC, CA, IP-OPF, PSO	IEEE 30-bus, 118-bus
[53]	BBO	F^{Ploss}	Yes	SOA , L-SaDE, SPSO-07, CLPSO, PSO-cf, PSO-w	IEEE 30-bus, 57-bus
[55]	PSO-TVAC	F^{Ploss}	Yes	ACOR, ABC, LCA, DE, MTLA, PSO	IEEE 14-bus, 118-bus
[56]	PSO-MVO	F^{Ploss}	Yes	PSO,MVO	IEEE 30-bus
[60]	FAPSO	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	PSO	IEEE 30-bus, 118-bus
[61]	MOCIPSO	F^{Ploss}, F^{TVD}	Yes	IPSO,PSO	IEEE 30-bus, 57-bus
[62]	CPSO	F^{Ploss}	Yes	PSO	25-bus Penghu, IEEE 118-bus
[63]	HMPSO	F^{Ploss}, F^{TVD}	Yes	PSO, ED ,SaDE, EPSDE	IEEE 30-bus, Indian 75-bus
[66]	ACO	F^{TVD}	No	LP	IEEE Indian 24-bus power system
[67]	ACO	F^{Ploss}	Yes	PL, GA, PSO	IEEE 14-bus, 30-bus
[68]	DE-ACO	F^{Ploss}	Yes	DE, EP, PSO	IEEE 30-bus
[70]	ABC	F^{Ploss}	No	QEA, PSO, DE, IPM	IEEE 30-bus
[71]	DE-ABC	F^{Ploss}	No	DE, ABC	IEEE 14-bus, 30-bus, 57-bus
[74]	CSA	F^{Ploss}	No	IPM, PSO, CLPSO, DE	IEEE 118-bus
[75]	CSA	F^{Ploss}	No	MFO, GWO, FA, FPA, GSA	IEEE 30-bus
[77]	GWO	F^{Ploss}, F^{TVD}	Yes	GSA, PSO, CLPSO, ABC	IEEE 30-bus, 118-bus
[78]	2ArchMGWO	F^{Ploss}, F^{TVD}	Yes	MRPBIL-DE, MPSO, MBPBIL DEMO, NPGA-II	IEEE 30-bus, 57-bus, 118-bus
[80]	WOA	F^{Ploss}	Yes	ABC, PSO, PSO-TVAC	IEEE 14-bus, 30-bus, Algerian 114-bus
[83]	SA	F^{Ploss}	No	L-SACP-DE, CGA, DE, SPSO-	IEEE 57-bus

				07	
[84]	HTSSA	F^{Ploss}, F^{TVD}	Yes /No	TS, SA	IEEE 30-bus
[86]	GSA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	BBO, DE, CLPSO,PSO, SARGA	IEEE 30-bus,57-bus,118-bus
[87]	OGSA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	GSA , NLP, CGA, AGA, PSO-w, PSO-cf, BBO, CLPSO, SPSO-07, L-DE, L-SACP-DE, L-SaDE, SOA	IEEE 30-bus,57-bus,118-bus
[88]	OSAMGSA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	EA, PSO, CA, GSA, EGA-DQLF PSO, FAPSO	IEEE 30-bus
[91]	WCA	F^{Ploss}	No	WCA, OGSA, GSA, CLPSO, PSO	IEEE 30-bus,57-bus,118-bus
[94]	HS	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	PSO,HAS, SARCGA, IPM, PSO, DE	IEEE 30-bus, 57-bus
[96]	GBICA	F^{Ploss}, F^{TVD}, $F^{fuel\ cost}$	No	JGGA, NSGA-II, OMOPSO, VEPSO, MOPSO-CD, iTDEA, NKEA, GDE3	IEEE 30-bus, 57-bus
[97]	MICA-IWO	F^{Ploss}	Yes	RGA, CMAES, MOPSO, NSGA-II, MNSGA-II, DE, PSO, ICA, IWO	IEEE 30-bus,57-bus,118-bus
[102]	QOTLBO	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	TLBO, PSO,FIPS, QEA, ACS, DE	IEEE 30-bus, 118-bus
[103]	TLBO	F^{Ploss}, F^{TVD}	Yes	BB-BC, HS, PSO, KH	IEEE 30-bus, 57-bus
[104]	GBTLBO	F^{Ploss}	Yes	BBPSO, BBDE	IEEE 14-bus, 30-bus
[107]	MOAIA	F^{Ploss}, F^{TVD}, $F^{L\,max}$	Yes	IGA	IEEE 30-bus
[109]	BFO	F^{Ploss}, F^{TVD}	Yes	/	39-bus New England power system

The fact that some authors compare their methods with several algorithms is highlighted. For example, in [67] comparison of swarm intelligence with a genetic algorithm is presented. In [44] Differential evolution (DE) with quadratic sequential programming (SQP) is compared and in [87] physical based algorithm GSA is compared with several algorithms based on swarm, evolutionary and human behavior.

Despite the multiple comparisons that have been reported between methodologies to address the ORPD, it is not possible to affirm that there is one superior to the others. This is because a particular characteristic of meta-heuristics is that their operators can be modified to improve their performance. In such a way that one can report the superiority of one method over another and later reverse this condition. For example, in [59] and [38] the superiority of evolutionary techniques against techniques based on swarm intelligence is shown; however, in [70] and [74] the opposite situation is shown.

2.6. Conclusion

This chapter presents the general background, objective functions, constraints, and algorithm techniques of Optimal Reactive Power Dispatch (ORPD). Several approaches of ORPD in the literature are summarized in **Table 2.2**. The mathematical formulation of the objective and aptitude functions commonly used in the ORPD was presented in **Table 2.1**, the proposed solution techniques were classified and some comparisons between methods were reported.

As a typical optimization problem, ORPD may be solved with several optimization methods. Traditionally, mathematical modeling based classical methods are not so effective in solving ORPD problems. In this chapter, authors have focused on advanced non-conventional methods. The most frequently used techniques to solve the ORPD are the Based-Swarm algorithms. This is can attribute to the fact that these techniques are those that enjoy greater disclosure among meta-heuristics techniques. On the other hand, a tendency was found in the last decade to approach the ORPD through swarm intelligence techniques and the application of less popular techniques in the field of power systems such as WOA, KH, EMA, GSA and TLBO. However, it was not possible to find conclusive evidence of the superiority of one technique (or family of methodologies) over another (or others) in particular, due to the stochastic nature of the metaheuristic optimization techniques.

Papers that compare metaheuristic techniques with classical mathematical optimization techniques for the ORPD solution show the superiority and advantages of applying the former. Although the use of metaheuristic techniques does not guarantee obtaining the optimal global solution, its main advantage lies in the versatility to handle multi-objective problems, restrictions and the fact of finding a set of high quality solutions.

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Chapter 3

Application Of Artificial Techniques to ORPD

Abstract:

In this chapter, problem formulation of ORPD problem is detailed, and several meta-heuristic techniques (PSO, PSO-TVAC, and WOA) have been applied to solve the ORPD problem. All of these methods have been examined and confirmed on the IEEE 14-bus and IEEE 30-bus test systems. Furthermore, a comparison study of the cited algorithms has been made to show their potential and prove their robustness and effectiveness in solving the ORPD problem.

3.1. Introduction

This chapter presents the application procedure of various metaheuristic techniques based on PSO, PSO-TVAC and WOA for solving optimal reactive power dispatch (ORPD) problem. Several main variables need to be controlled and set accordingly such as the voltage of generator buses, transformer tap setting, and shunt capacitors value. In recent developments on power system research, ORPD is gaining much more attention than before because that reactive power has an important effect on system security and operation. From there, proper distribution and management of reactive power are the major worry for utilities in our days.

In this chapter, we will apply all the metaheuristic techniques proposed to the problem of the optimal reactive power dispatch and of course demonstrate the efficiency of the application of all these techniques and the advantages they offer.

The core contribution of this chapter is that a novel approach based on the WOA technique is applied for ORPD in standard IEEE power systems (14 and 30 buses), in order to minimize the active power losses with satisfying the power system constraints. This chapter also compares the proposed approach with other optimization techniques, PSO and PSO-TVAC and others reported from the literature. Additionally, a statistical analysis has been taken serious to test whether significant differences exist between the several algorithms presented in this study. Finally, the simulation results of WOA show acceptable and remarkable results in solving this optimization problem.

3.2. ORPD Problem Formulation

3.2.1. Objective function

The formulation considered for solving ORPD problem in this chapter is, mainly, concerned with minimization of real power loss, it can be written as presented in section **2.2**

$$\text{Min } F(\mathrm{x}, \mathrm{u}) = P_{loss} = \sum_{k=1}^{N} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}) \quad \textbf{(3.1)}$$

Subject to:

$$\begin{cases} \mathrm{h}\ (\mathrm{x}, \mathrm{u}) = 0 \\ \mathrm{g}\ (\mathrm{x}, \mathrm{u}) \leq 0 \end{cases} \quad \textbf{(3.2)}$$

Where X is the set of control variables. It can be written by:

$$U^T = [V_{G1} \dots V_{GNG}, T_1 \dots T_{NT}, Q_{C1} \dots Q_{CNC}] \quad \textbf{(3.3)}$$

Where U is the set of dependent variables. It can be expressed as:

$$X^T = [V_{L1} \dots . V_{LNPQ}, S_{L1} \dots . S_{NTL}, Q_{G1} \dots . Q_{GNG}] \quad \textbf{(3.4)}$$

3.2.2. *Constraints*

The objective function is subjected to both inequality and equality constraints:

- ***Equality Constraints***

The equality constraint equations are giving the power balanced of load flow, cited as follows:

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N} V_j \,(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \quad \textbf{(3.5)}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N} V_j \,(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \quad \textbf{(3.6)}$$

- ***Inequality Constraints***

The inequality constraints considered in this part are mathematically expressed as follows:

- Generator constraints: Real and reactive power generation as well as generation bus voltages are bounded by their upper and lower limits, as follow:

$$\begin{aligned} V_{gi}^{min} < V_{gi} < V_{gi}^{max} \, \mathrm{i} \in \mathrm{N_g} \\ P_{gi}^{min} < P_{gi} < P_{gi}^{max} \, \mathrm{i} \in \mathrm{N_g} \\ Q_{gi}^{min} < Q_{gi} < Q_{gi}^{max} \, \mathrm{i} \in \mathrm{N_g} \end{aligned} \quad \textbf{(3.7)}$$

- Transformer tap regulating: is bounded by their lower and upper limits, as follows:

$$T_k^{min} < T_k < T_k^{max} \, \mathrm{k} \in \mathrm{N_T} \quad \textbf{(3.8)}$$

- Reactive compensators (Shunt VARs): are bounded by their limits as follows:

$$Q_{Ci}^{min} < Q_{Ci} < Q_{Ci}^{max} \, \mathrm{i} \in \mathrm{N_C} \quad \textbf{(3.9)}$$

The dependent variables constraints are included into the objective function as a penalty terms. Therefore, **(3.1)** is improved to **(3.10).**The penalty function terms would be zero, if all the control variables are not exceeded the limits. Otherwise, its terms would be considered into the objective function.

$$F = P_{loss} + \sum r_{gi}(V_i - V_i^{lim})^2 + \sum r_{Qi}(Q_i - Q_i^{lim})^2 \quad \textbf{(3.10)}$$

To make our research more reliable and efficient and to ensure the accurate results of total transmission loss, MATPOWER 4.1 toolbox [1] is introduced to calculate the power flow and to fulfill the equality constraints

3.3. Metaheuristics Techniques Applied To ORPD

3.3.1. Particle Swarm Optimization

In this section an efficient and particle swarm optimization (PSO) has been presented for solving the ORPD. The objective is to minimize the real power loss

A. Brief review of classic particle swarm optimization

Particle Swarm Optimization (PSO) was developed by J. Kennedy and R. Eberhart in 1995 **[2].** It's one of the population based stochastic search algorithms. In the PSO, population is consisted from candidate solutions which called particles. Particles are randomly initialized and moved around in the N–dimensional search space according to given measure of quality (fitness function). Every particle has a position $X_i = (x_i^1, x_i^2, ..., x_i^l)$ and a flight velocity $V_i = (v_i^1, v_i^2, ..., v_i^l)$. Indeed, each particle has its own best positions $P_{ibest} = (P_{ibest}^1, P_{ibest}^2, ..., P_{ibest}^l)$ and a global best position $G_{best} = (G_{best}^1, G_{best}^2, ..., G_{best}^l)$.

Each time step is characterized by the update of the velocity and the particle is moved to a new position which is the sum of the previous position and the new velocity:

$$X_r^{iter+1} = X_r^{iter} + c \times V_r^{iter+1} \qquad \textbf{(3.11)}$$

The update of the velocity from the previous velocity to the new velocity is obtained by:

$$V_r^{iter+1} = c \times w .V_r^{iter+1} + c_1.rand1.(P_{best}^{iter} - X_r^{iter}) + c_2.rand2.(G_{best}^{iter} - X_r^{iter}) \qquad \textbf{(3.12)}$$

Where, w is the inertia weight factor, c_1 et c_2 are cognitive and social component acceleration coefficients, *rand* is a uniform random value between $[0,1]$, X^{iter} and V^{iter} are respectively the position and the velocity of one particle i at iteration k, c is the constriction factor and can be calculated using **(3.13).**

$$C = \frac{2}{2 - \emptyset - \sqrt{\emptyset^2 - 4\emptyset}} \qquad \textbf{(3.13)}$$

Where: $\emptyset = c1 + c2$, w_{max}, w_{min} are the original value and the final value of inertia weight. $Iter_{max}$ and $Iter$ are the maximum iterative time and the current iterative time. The strategy oflinear descending inertia weight sets inertia weight using the following formula **[3].**

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \qquad \textbf{(3.14)}$$

The acceleration coefficients are considered as fixed values as fellow $C_1 = C_2 = 2.05$ **[4].**

The main optimization steps of the PSO based reactive power dispatch are illustrated on the flowchart **Fig.3.1.**

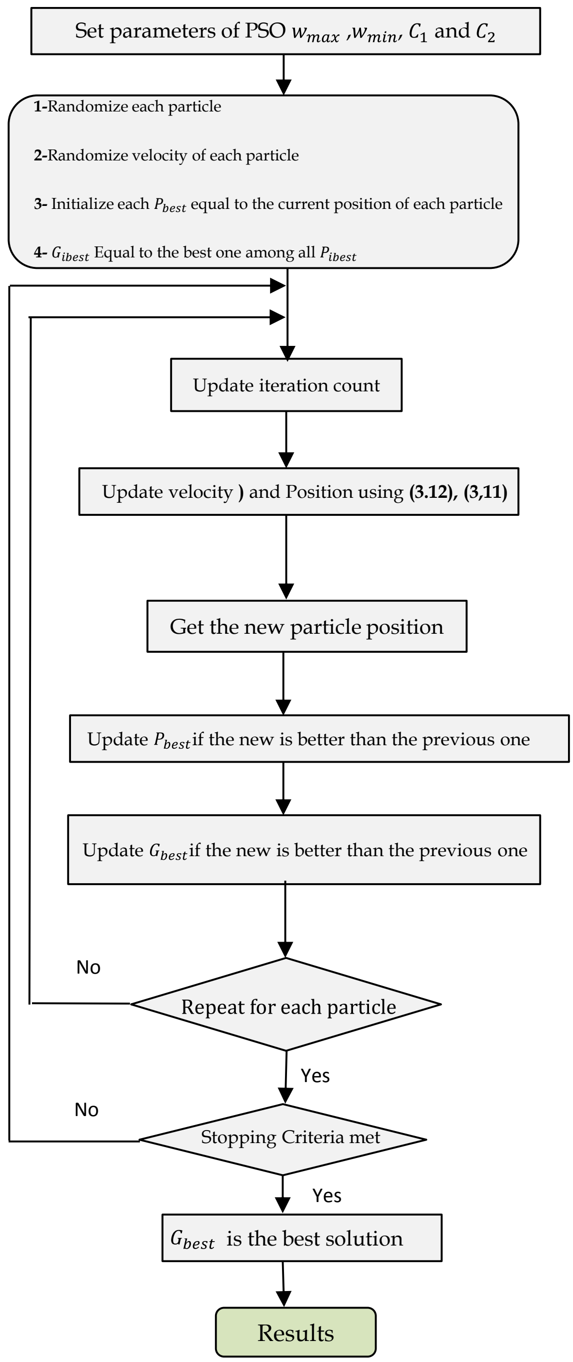

Fig 3.1. *Flow Chart of the PSO Based optimal Reactive Power Dispatch*

3.3.2. Particle Swarm Optimization With Time Varying Acceleration Coefficient

The convergence and solution quality of PSO is affected by selection of the acceleration coefficients. Relatively high value of the social component (C2) comparing with cognitive component (C1) leads particles to a local optimum prematurely and relatively high values of cognitive components results to wander the particles around the search space **[3,4].**The acceleration coefficients are fixed values in classic PSO. To improve the solution quality, these coefficients are updated in a way that the cognitive component is reduced and social component is increased as iteration proceeds. The acceleration coefficients are updated using the following equations:

$$C_1 = C_{1i} + \frac{c_{1f} - c_{1i}}{iter_{max}} \times iter \quad \textbf{(3.15)}$$

$$C_2 = C_{2i} + \frac{c_{2f} - c_{2i}}{iter_{max}} \times iter \quad \textbf{(3.16)}$$

Where: C_{1i},C_{1f}, C_{2i} and C_{2f} are initial and final values of cognitive and social acceleration factors respectively. Reference [2] reports 2.5 for each C_{1i} and C_{2f} and 0.5 for each C_{1f} and C_{2i} as the most effective values.

The main optimization steps of the PSO-TVAC based reactive power dispatch are as follows:

Step 1: *Initialization*:

Set the total iteration number, particle number, and initial velocity, randomly assigns the position of each particle in the design space. Then evaluate the fitness of each particle and save the global best known position, and the local best known position of each particle.

Step 2: *Update the positions and velocities*:

Updating the position and velocity of each particle by using formula **(3.11)**and formula **(3.12)**Then check whether the solution violates the limit or not. If the solution exceeds the limits, use **(3.10)** to penalize the violations.

Step 3: *Evaluate each particle:* Substitute the position of each particle into the objective function to calculate the evaluation value.

Step 4 *Update local best-known positions*: If the current fitness value is smaller than the historical best fitness value, update the local best-known position.

Step 5 *Update global best-known positions*.

Step 6 *Decide stopping criterion:*

Determine if the iteration has reached the maximum iteration number. If so, stop the optimization process and print the result, otherwise,$iter = iter + 1$, and go back to step 4.

The flow chart of the PSO based reactive power dispatch is illustrated in the **(Fig.3.2).**

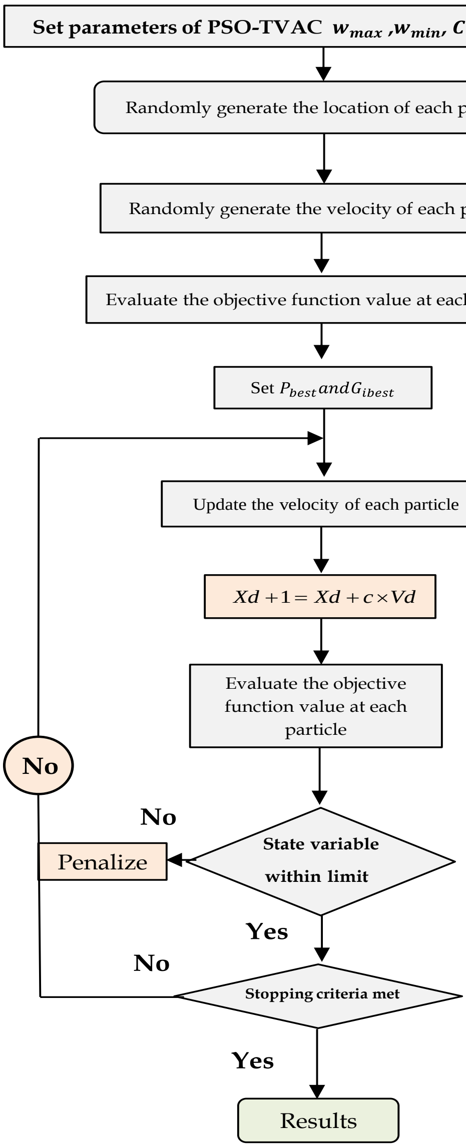

Fig.3.2 .*Flow Chart of the PSO-TVAC Based optimal Reactive Power Dispatch*

3.3.3. Whale Optimization Algorithm

3.3.3.1. *Brief review of Whale optimization Algorithm*

Whale Optimization Algorithm (WOA) is one of the latest novel nature-inspired meta-heuristic optimization algorithms. It has been introduced by Mirjalili and Lewis in 2016 [5] which is imitates the social behavior of humpback whales. Whales have many interesting points in their social behaviors'. They are considered to be the biggest mammals in the whole world, but the more impressive than the humpback whale size, is their intelligence and the sophisticated way on collective work. According to [6], only half whale's brain sleeps, because they must breathe on the surface of oceans, such as the humpback social structure of whales. Typically, whales live by itself or in small groups, in summer; they may stay together longer to feed cooperatively. Their favorite preys are krill and small fish herds. **Fig.3.3.** shows this mammal.

One of their most interesting behaviors is bubble-net feeding, a complex and coordinated tactic for catching many fish at once. The hunt begins as the whales dive beneath the school herring emitting high pitch calls. In a panic the fish flee to the surface, where the whales concentrate them by releasing columns of air bubbles along a circle or '9'-shaped path. The babbles act as a barrier where the fish will not swim through it, the whales coordinate their efforts so the bubbles around the herring, finally, the whale leader emits a sound that ques all the whales to ascend with mouths open [7].

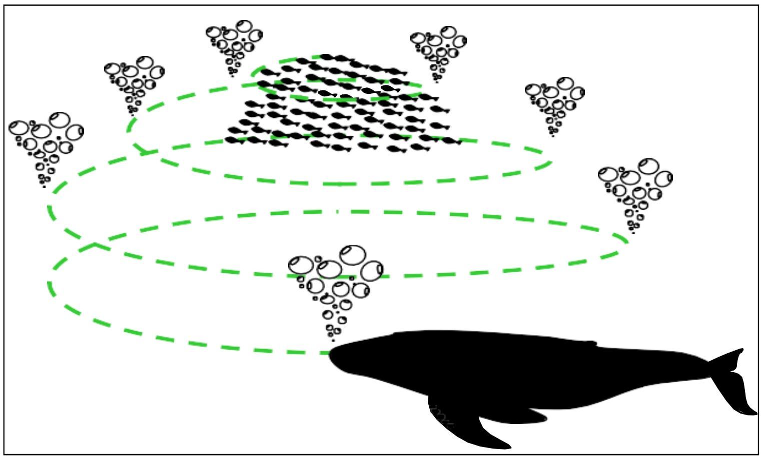

Fig.3.3. *Bubble-net hunting behavior of humpback whale*

The mathematic model for WOA is designated as follows:

A. **Shrinking Encircling Mechanism**

When the whales began hunting, they tend to encircle their prey (the currently best candidate solution is assumed as the target prey) then update their positions to the optimum solution. The following equations represent the encircling behavior [6]:

$$\vec{D} = \left| \vec{C}.\vec{X}^{*}(t) - \vec{X}(t) \right| \quad \textbf{(3.17)}$$

$$\vec{X}(t+1) = \vec{X}^{*}(t) - \vec{A}.\vec{D} \quad \textbf{(3.18)}$$

Where t specifies the current iteration; A and C are coefficient vectors; X* is the position vector of the best solution obtained; X is the position vector; | | is the absolute value; and (.) is an element-by-element multiplication.

It can be noted here that X* has to be updated in each trial run if there is a better solution. The vectors A and C are calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{3.19}$$

$$\vec{C} = 2\vec{r} \tag{3.20}$$

Where a is linearly decreased from 2 to 0 (in both exploration and exploitation phases) and r is a random vector limited into [0, 1].

B. Spiral Updating Position

Mathematical spiral equation for position update between humpback whale and prey designed as follows:

$$\overrightarrow{D^{/}} = \left|\overrightarrow{X^{*}}(t) - \overrightarrow{X(t)}\right| \tag{3.21}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{D^{/}}.e^{bl}.(\cos 2\pi l) + \overrightarrow{X^{*}}(t) \tag{3.22}$$

Where: b is a constant for defining the shape of the logarithmic spiral, and l is a random number uniformly distributed in the range of [-1, 1].

The probability for each encircling way is assumed 50% for each one; either follows the shrinking encircling or logarithmic path during optimization. Mathematically it's modeled as follows:

$$\begin{aligned} \overrightarrow{X}(t+1) &= \overrightarrow{X^{*}}(t) - \vec{A}.\vec{D} \text{ if } p < 0.5 \quad \text{(a)} \\ \overrightarrow{X}(t+1) &= \overrightarrow{D^{/}}.e^{bl}.(\cos 2\pi l) + \overrightarrow{X^{*}}(t) \text{ if } p \geq 0.5 \quad \text{(b)} \end{aligned} \tag{3.23}$$

Where: p is a probability for each encircling way.

To perform a global search, we update the position of a search agent by a randomly chosen search agent instead of relying on the best search agent found so far, This technique is employed when the random values of A is greater than 1. The mathematical model is as follows:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_{rand}} - \overrightarrow{X(t)}\right| \tag{3.24}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A}.\vec{D} \tag{3.25}$$

Where: X_{rand} is chosen randomly from whales in the current trial run.

3.3.3.2. Computational Procedure of Whale optimization Algorithm

The computational procedure of WOA is illustrated in the following Algorithm [5]:

Start

Initialize the whales population Xi (i = 1, 2… n)

Calculate the fitness of each whale agent

X* is the best whale agent

While (t<maximum number of simulation run)

For each whale agent

Update a, A, C, l, and p (while t < maximum number of iterations)

If 1 (p<0.5)

If 2 |A|< 1

Update the position of the current whale agent by the Eq. (3.23.a)

Elseif 2 |A|≥ 1

Select a random whale agent (X rand)

Update the position of the current whale agent by the Eq. (3.25)

End if 2

elseif1 (p≥ 0.5)

Check if any search agent goes beyond the search space and amend it

Calculate the fitness of each search update

Update X* if there is a better solution

t=t+1

End while

Return X*

Update the position of the current search by the Eq. (3.23.b)

End if1

3.3.3.3. Implementation of WOA for ORPD Problem

WOA based approach is used for solving the ORPD problem, which aims to find the near global optimum values of control variables in order to minimize the active power loss while satisfying all the constraints said previously. The steps considered in optimizing the functions correlated to ORPD problem are enumerated in **Fig.3.4.**

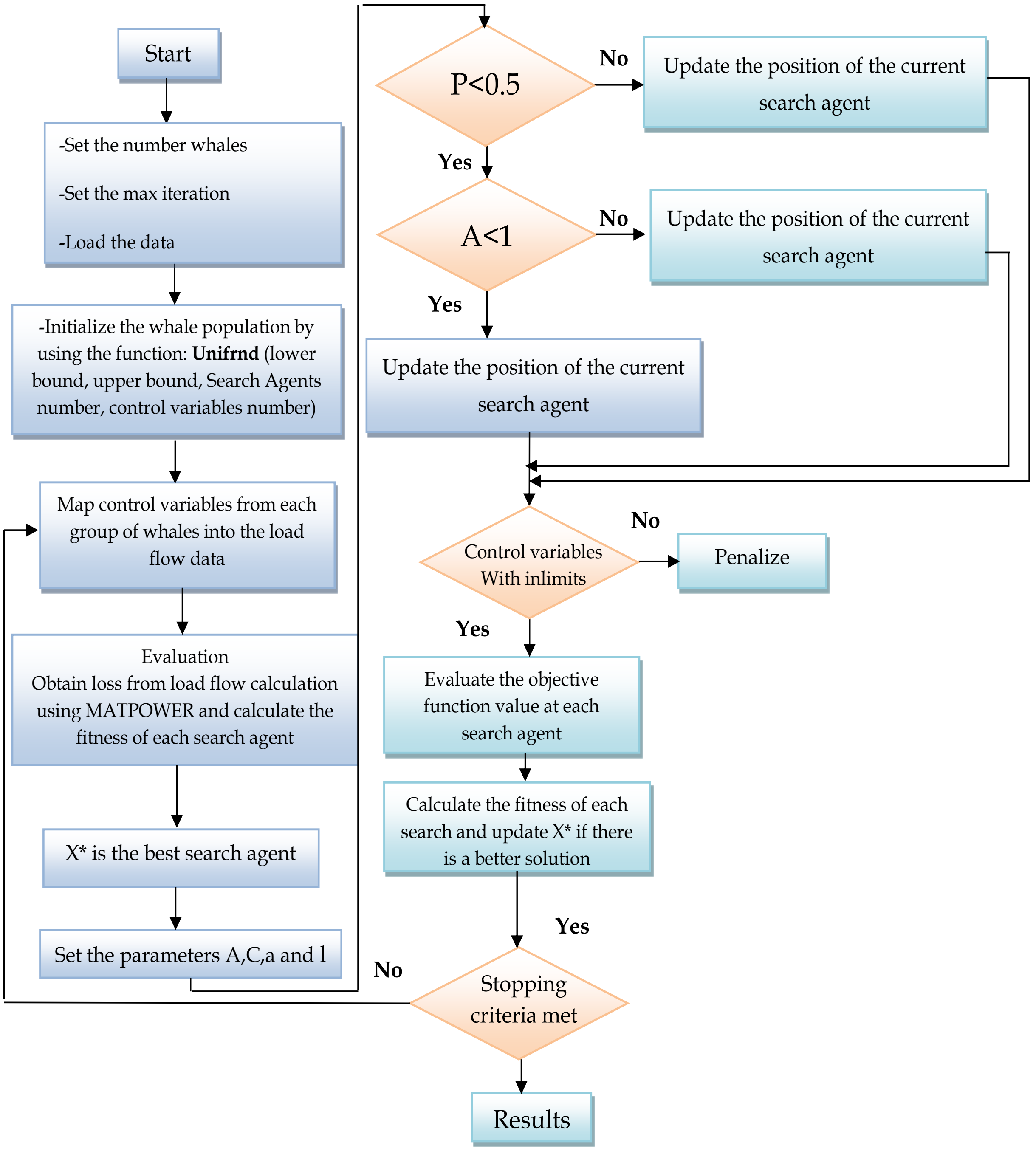

Fig. 3.4. *Flow chart of proposed WOA for solving ORPD*

3.4. Simulation Results and Discussion

For the purpose of verifying the performance and efficiency of the proposed WOA algorithm, tests are carried out on IEEE 14 bus and IEEE 30 bus. The description of these networks can be found in **Table.3.1**.All the simulations are carried out by using MATLAB 2008b, and computed on core (Tm) i7-3520M CPU a 2.90 GHz with 8 Go RAM.

For establishing the robustness of the proposed WOA, 30 independent test trial runs are performed for all the test cases with a comparative study reported in the following section.

To recognize the effect of population size (number of whales) on the performance of proposed WOA, 30 trial runs have been executed for several population sizes (20, 30, 40 and 60) for all case studies. The results of different population size for each case study (IEEE 14 bus, IEEE 30 bus) are presented respectively in **Fig.3.5, Fig.3.6** From **Fig.3.5,** it can be seen that 30 search agents is good enough to get the near global optimum value of real power loss and a higher consistency of the algorithm. From **Fig3.6,** it is observed that the best result is obtained for 40 search agents, which is adequate to get the best combination of control variables of ORPD. However, the consistency is fewer than obtained in 60 search agent.

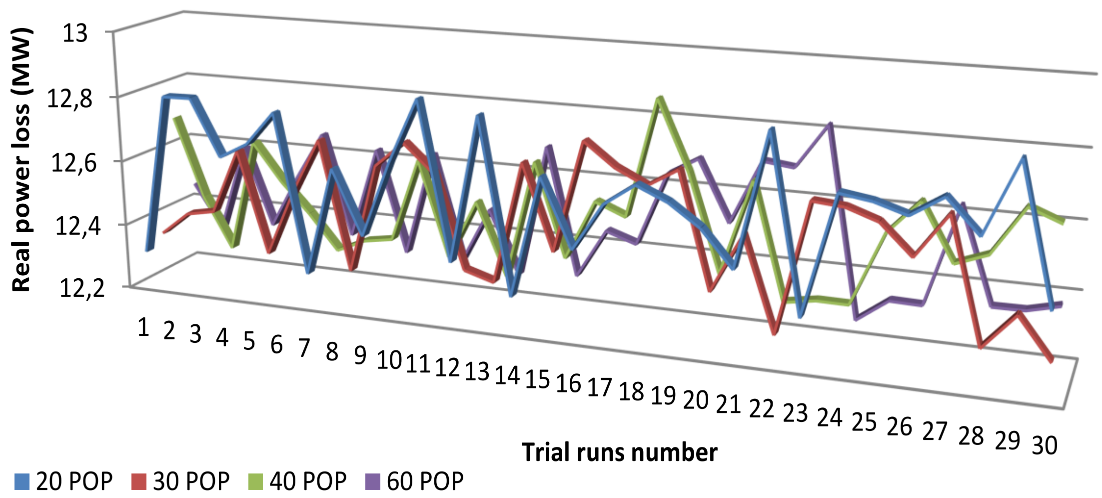

Fig.3.5. *Results of real power loss for different population size of whales, IEEE 14-bus.*

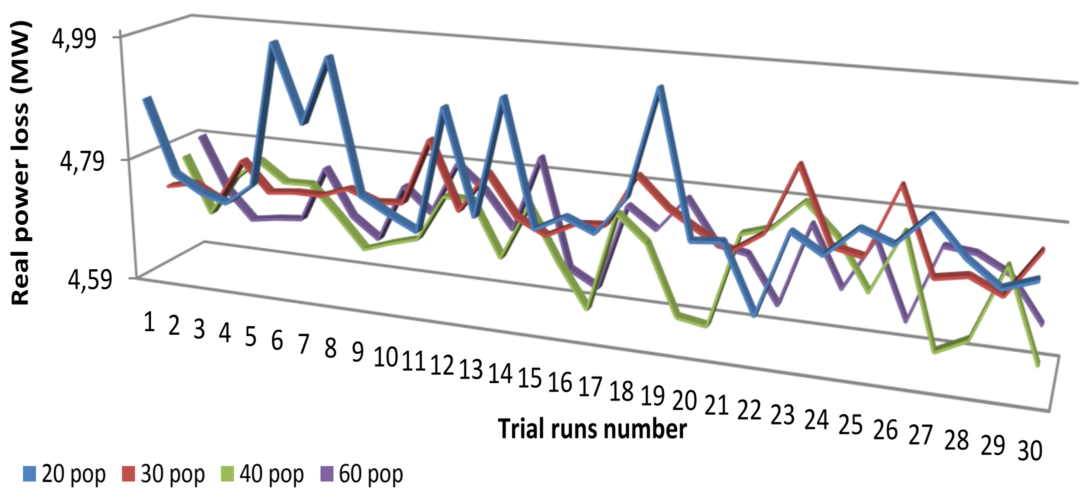

Fig.3.6. *Results of real power loss for different population size of whales, IEEE 30-bus*

3.4.1. Case study for IEEE 14 bus

The IEEE 14-bus test system includes five generators at the buses 1, 2, 3, 6 and 8, it consists also 20 transmission lines and 3 branches under load tap setting transformer branches [8].

Table.3.1. *Description of test systems*

Description	IEEE 14-bus	IEEE 30-bus
Buses	14	30
Lines	20	41
Generators	5	6
Tap transformers	3	4
Shunt capacitors	2	9
Load buses	9	24
Pload (MW)	259.00	283.40
Q load (Mvar)	73.50	126.20
P gen (MW)	272.39	289.211
Q gen (Mvar)	82.44	108.922
Initial P loss(MW)	13.393	5.811
Initial Q loss (Mvar)	54.54	32.417

The shunt reactive power sources are considered at buses 9 and 14. The load demand is 259.00 MW and 73.5 MVar on 100 MVA base. The variable limits are cited in **Table 3.2.**The upper and lower limits, as well as the near global optimum value of active and reactive power generations are shown in **Table 3.3.**

Table.3.2. *The limits of the control variables for IEEE 14-bus test system*

Variables limits	Lower limit (pu)	Upper limit (pu)
Voltages for generator bus	0.9	1.1
Voltages for load bus	0.9	1.1
Tap setting	0.9	1.1
shunt compensators Q_{C9} (MW)	0	18
shunt compensators Q_{C14} (MVar)	0	18

The shunt reactive power sources are considered at buses 9 and 14. The load demand is 259.00 MW and 73.5 MVar on 100 MVA base. The variable limits are cited in **Table 3.2.**The upper and lower limits, as well as the near global optimum value of active and reactive power generations are shown in **Table 3.3.**

In case of ORPD problems, the reactive power generation has to be considered rather than active power generation. Furthermore, it is necessary to declare the active and reactive generation outputs.

Table 3.3 shows the values of active and reactive power generation before and after optimization. It can be observed from this table that the active and reactive power generations are within their acceptable limits.

Table.3.3. *Range, initial and obtained setting of generator active and reactive power output*

Buses	1	2	3	6	8
P_{min}(MW)	332.4	100	100	100	100
P_{max}(MW)	0	0	0	0	0
Initial value (MW)	232.4	40	0	0	0
Optimal value (MW)	**231.39**	**40**	**0**	**0**	**0**
Q_{min}(MVar)	0	-40	0	-6	-6
Q_{max}(MVar)	10	50	40	24	24
Initial value (MVar)	-16.9	42.4	23.4	12.2	17.4
Optimal value (MVar)	**-5.49**	**29.26**	**20.79**	**7.24**	**21.98**

Table 3.4 summarizes the results of the optimal settings obtained by WOA and shows the best results of ORPD obtained by several algorithms. From this table, the results indicate that applying WOA leads to **12.255 Mw** active power loss, which is less compared to the developed algorithms PSO and PSO-TVAC (12.381 Mw and 12.279 Mw respectively) and the other one from the literature (12.3105 Mw) [9]. Furthermore, the percentage reductions are shown in this table. It can be seen that the proposed WOA gives 8.497% of loss reduction.

Table.3.4. *Comparison of results for IEEE 14-bus system*

Variables	Base case	MGBTLBO [27]	PSO	PSO-TVAC	WOA
V_1	1.06	1.1	1.1008	1.1013	1.1
V_2	1.045	1.0791	1.0804	1.0882	1.0859
V_3	1.01	1.0484	1.044	1.0585	1.0566
V_6	1.07	1.0553	1.0253	1.0418	1.0858
V_8	1.09	1.0326	1.077	1.044	1.1
T_{4-7}	0.9467	1.01	1.0357	1.042	0.95853
T_{4-9}	0.9524	1.01	1.0191	1.0176	1.0453
T_{5-6}	0.9091	1.03	1.0172	1.0747	1.0163
Q_{C9} (MVar)	18	3	8.6926	17.100	12.497
Q_{C14} (MVar)	18	7	7.0349	8.2049	8.0161
P_{loss} (MW)	13.393	12.3105	12.381	12.279	**12.255**
% Reduction	-	**8.082**	**7.556**	**8.311**	**8.497**

Fig.3.7. shows the loss reduction process for WOA, PSO, and PSO-TVAC simultaneously. From this figure, it can be observed that satisfying results can be achieved after about conducting 48 iterations, which reflects the excellent searching ability of WOA algorithm against the two other techniques for solving in general nonlinear problems (ORPD in our case of study).

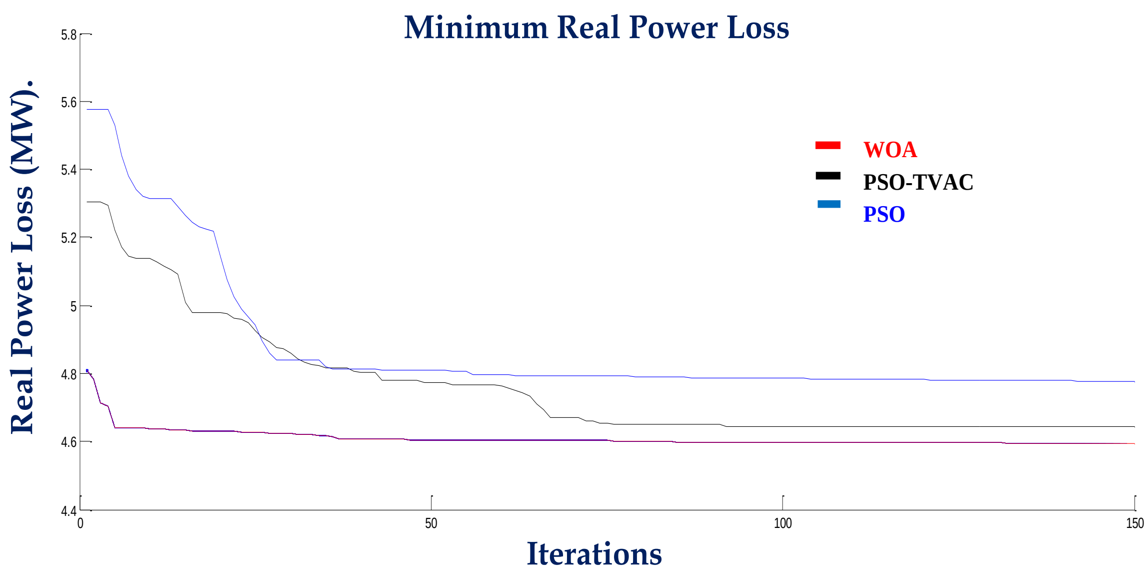

Fig.3.7. *Performance characteristics of algorithms for IEEE 14-bustestsystem*

3.4.2. Case study for IEEE 30 bus

The IEEE 30-bus system involves 6 generators, 41 lines, 4 transformers that are located at lines 6–9, 4–12, 9–12 and 27–28 **[10].** About this case study, 9 reactive compensators are installed at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29. Minimum and maximum limit settings for tap setting transformers, reactive compensators and generators voltages are tabulated in **Table.3.5.**

Table.3.5. *Limits of various variables for IEEE 30-bus test system*

Variables limits	Lower limit (pu)	Upper limit (pu)
Voltages for generator busV_g	0.9	1.1
Voltages for load busV_L	0.9	1.1
Tap setting T	0.9	1.1
shunt compensators Q_C (MVar)	0	5

Upper and lower limits, as well as the optimal value obtained of active and reactive power generations are cited in **Table.3.6**. From this table, it can be mentioned that the optimal values of active and reactive power generation are restricted by their upper and lower limits cited previously.

Table.3.6 *Range, initial and optimal setting of generator active and reactive power output*

Buses	1	2	5	8	11	13
P_{min}(MW)	20	20	15	10	10	12
P_{max}(MW)	200	80	50	35	30	40
Initial value (MW)	92.211	80	50	20	20	20
Optimal value (MW)	**98**	**80**	**50**	**20**	**20**	**20**
Q_{min}(MVar)	-20	-20	-15	-15	-10	-15
Q_{max}(MVar)	200	100	80	60	50	60
Initial value (MVar)	0	0	0	0	0	0
Optimal value (MVar)	**-14.12**	**21.58**	**28.33**	**35.45**	**7.32**	**12.82**

The performance characteristics of WOA and other two techniques are shown in **Fig.3.8.** It can be seen that the convergence of WOA algorithm has been obtained before 40th iteration, in comparison to the 60th and the 80th iteration attained by PSO and PSO-TVAC, respectively.

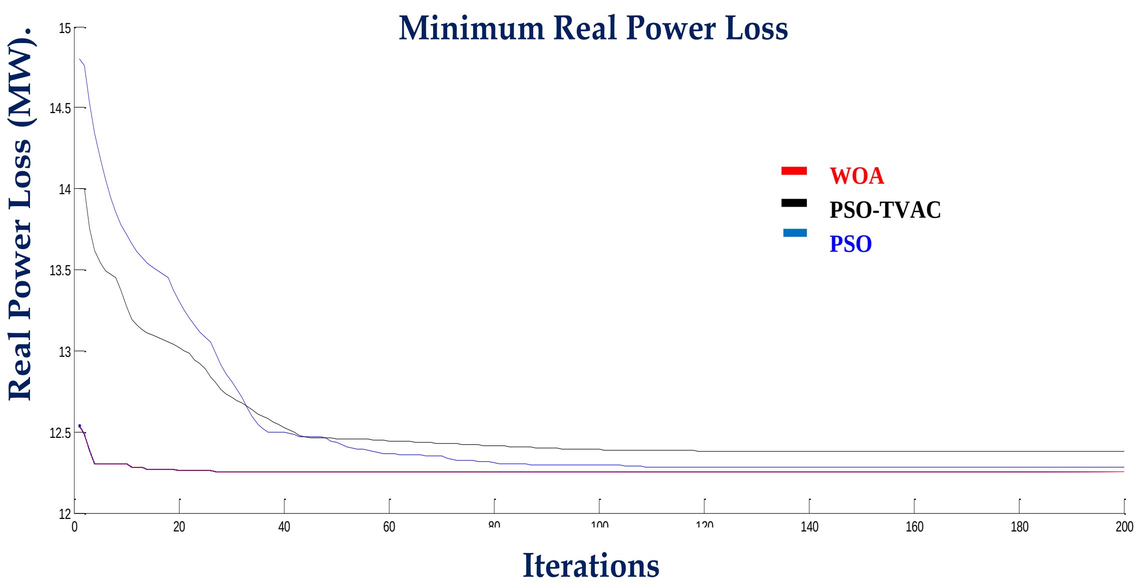

Fig.3.8. *Performance characteristics of algorithms for IEEE 30-bus test system*

From **Table.3.7,** it can be seen that the near global optimum result of active power loss obtained by WOA is **4.5943**MW, gives a remarkable value of power loss among all techniques examined and taken from the literature **[10,11].** The comparison with PSO and PSO-TVAC give respectively about 17.79% and 20.04% reduction of total power loss. Same thing for IEEE 30 bus, it is imperative to display the generators power output settings.

Table.3.7. *Comparison of results for IEEE 30-bus system*

Variables	initial	ABC [28]	GSA [30]	PSO	PSO-TVAC	WOA
V_1	1.05	1.1	1.0716	1.1	1.0971	1.1
V_2	1.04	1.0615	1.0221	1.093	1.0876	1.0963
V_5	1.01	1.0711	1.0400	1.0731	1.0658	1.0789
V_8	1.01	1.0849	1.0507	1.0743	1.07	1.0774
V_{11}	1.05	1.1	0.9771	1.0275	1.0669	1.0955
Q_{C13}	1.05	1.0665	0.9676	1.0335	1.0995	1.0929
T_{6-9}	1.078	0.97	1.0984	1.0161	0.97571	0.9936
T_{6-10}	1.069	1.05	0.9824	1.0008	0.92692	0.9867
T_{4-12}	1.032	0.99	1.0959	1.0089	0.99968	1.0214
T_{28-27}	1.068	0.99	1.0585	1.0245	0.96481	0.9867
Q_{C10}	0	5	1.6537	3.6433	1.0303	3.1695
Q_{C12}	0	5	4.3722	3.5418	3.2628	2.0477
Q_{C15}	0	5	0.1199	1.6649	4.4982	4.2956
Q_{C17}	0	5	2.0876	4.0095	4.6258	2.6782
Q_{C20}	0	4.1	0.3577	4.0649	1.4852	4.8116
Q_{C21}	0	3.3	0.2602	4.0831	4.548	4.8163
Q_{C23}	0	0.9	0.0000	4.1428	3.5751	3.5739
Q_{C24}	0	5	1.3839	3.9482	4.6527	4.1953
Q_{C29}	0	2.4	0.0003	2.2461	3.2407	2.0009
P_{loss} **(MW)**	5.812	4.6022	4.5143	4.7779	4.6469	**4.5943**
% Reduction	-	**20.81**	**22.32**	**17.79**	**20.04**	**20.95**

3.5. Statistical study

Due to the stochastic nature of the studied algorithms, it is imperative to run the algorithms several times on the same problem instance in order to get the result values, which could vary at every execution. Instead of relying on the statistics of the collected results (best, medium, worst and standard deviation), it is essential to perform an analysis of variance (One-way ANOVA) **[12],** to give a certain level of confidence to our study and evaluate which algorithms are most suitable in solving the ORPD problem.

The one-way ANOVA test compares the means between the results obtained by our proposed algorithm WOA and other own developed PSO and PSO-TVAC. It is aimed to define whether data from the three algorithms have a common mean and find out whether the algorithms are actually different in the measured characteristic. In this study, a significance level of 1% is considered, i.e., if the P-value is less than 0.01, it means that there is statistical significant difference between the performance of WOA method and other own developed methods.

Table 3.8 and **Table 3.9** represent respectively the one-way ANOVA results obtained from the experimented algorithms in three cases (IEEE 14 bus, IEEE 30 bus). **Table 3.10** summarizes the F-ratio and the P-value of the ANOVA results obtained. As it shown in this table, it can be observed that p-value is extremely less than 0.01 for all cases, which means WOA is statistically different from the PSO and PSO-TVAC.

Table 3.8 *Analysis of variance for the results case IEEE 14-bus*

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.152196376	2	0.076098	6.768	0.00185	4.8577
Within Groups	0.97819039	87	0.011244			
Total	1.130386766	89				

Table 3.9 *Analysis of variance for the results case IEEE 30-bus*

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.410599756	2	1.2053	28.958	0.000000000229	4.8577
Within Groups	3.6210838	87	0.041622			
Total	6.031683556	89				

Table.3.10. *One-way ANOVA test for the results obtained by PSO, PSO-TVAC and the proposed WOA method.*

Case study	P-value	F-ratio
IEEE 14-BUS	0.000000000229	28.978
IEEE 30-BUS	0.00185	6.768

3.6. Conclusions

In this chapter, a different meta-heuristic algorithms PSO, PSO-TVAC and recent meta-heuristic technique namely whale optimization algorithm (WOA) was successfully applied to solve the optimal reactive power dispatch (ORPD) problem. The proposed WOA method has been examined and tested on the IEEE 14-bus system, IEEE 30-bus. To validate the effectiveness of the proposed algorithm, the obtained results were compared with those obtained from two methods developed by us (PSO and PSO-TVAC) and others reported from the literature.

Considering the cases and comparative studies presented in this chapter, WOA algorithm appears to be very effective in particular for its fast convergence to the global optimum as well as its significant active loss reduction. Based on one way ANOVA statistical test, the significance of its results against other methods (PSO and PSO-TVAC), has been confirmed and gives more confidence to our study.

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Chapter 4

ORPD Under Various Contingency Conditions

Abstract:

Most of researchers solved and analyzed the ORPD problem in the normal conditions. However, network collapses appear in contingency conditions. In this chapter, ORPD under several contingencies is presented using the proposed WOA technique. To ensure viability of the power system in contingency conditions, several critical cases are simulated in order to prevent and prepare the power system to face such situations. The results obtained are carried out using IEEE 30 bus test system.

4.1. Introduction

The present day power systems are forced to be operated much closer to stability limits due to the increased demand for electric power than ever before. In such a stressed condition, the system may enter into network collapse problems that were responsible for many system block outs in many countries across the world [1]. In the past many wide spread blackouts have occurred in interconnected power systems. Therefore it is necessary to insure that power system should be operated most economically such that power is delivered reliably. Contingency analysis is a well-known function in modern Energy Management Systems (EMS). The goal of this power system analysis function is to give information to the operator about the static security state of power system.

In the modern days, the power system is becoming wide and complex. Contingency Analysis of a power system is a major task in power system planning and operation. In general, line outage, transformer outage and generator outage are most common type of outages; they may lead to over loads in other branches and/or sudden system voltage rise or drop.

In this chapter several outages will be studied and discussed (line outage, and transformer outage) in order to guarantee the following conditions:

- Getting the minimum power loss as much as it's possible
- Getting the power system stability after the increase of the power system load (voltage level, active and reactive power and load tap changer value are in the secure range)

For this reason, we propose an approach which is based on FACT devices as a corrective action scheme in order to withstand the violations caused by the different outages.

4.2. Contingency Analysis in Power System

One of the essential goals of reactive energy planning is to ensure the viability and continuity of operation of the electrical energy system in many different states. Authors in [2] introduced the concept of the preventive (normal), emergency, and restorative operating states and their associated controls, which mean that power system, may be identified to be operating in a number of states. The three states are defined as follows [3]:

4.2.1. Preventive state

The preventive state is actually the normal state. The term preventive was used to stress the security aspect of the normal operation. Normal operating condition usually means that all the apparatus are running within their prescribed limits, and all the system variables are within acceptable ranges. The system should also continue to operate normally even in the case of credible contingencies. The operator should predict such contingencies and take preventive control actions (as economically as possible) such that the system integrity and quality of power supply is maintained.

4.2.2. Emergency state

The power system enters an emergency state when some of the components operating limits are violated; some of the states wander outside the acceptable ranges, or when the system frequency starts to decrease. The control objective in the emergency state is to relieve system stress by appropriate actions.

4.2.3. Restorative state

Restorative state is the condition when some parts (or whole) of the system has lost power. The control objective in this state is to steer the system to a normal state again by taking appropriate actions.

An important part of security study therefore, moves around the power system's ability to withstand the effects of contingencies. A particular system state is said to be secure only with reference to one or more specific contingency cases and a given set of quantities monitored for violation. Most power systems are operate in such a way that any single contingency will not leave other components heavily overloaded. So that cascading failure are avoided. Contingency analysis is the study of the outage of elements such as transmission lines, transformers and generators, and investigation of the resulting effects on line power flows and bus voltages of the remaining system. Contingencies referring to disturbances such as transmission element outages or generator outages may cause sudden and large changes in both configuration and state of the system. Contingencies may result in severe violations of the operating constraints. Consequently, planning for contingencies forms an important aspect of secure operation.

System security can be said to comprise of three major functions that are carried out in energy control center:

System monitoring: System monitoring supplies the power system operations or dispatches with pertinent up-to-date information on the conditions of the power system on real time basis as load and generation change. Telemetry systems measure, monitor and transit the data, voltages, currents, current flows and the status of circuit breakers and switches in every substation in a transmission network.

***Contingency analysis*:** Modern operation computers have contingency analysis programs stored in them. These foresee possible system troubles (outages) before they occur. They study outage events and alert the operators to any potential overloads or serious voltage violations

Corrective action analysis: The third major security function, corrective action analysis, permits the operators to change the operation of the power system if a contingency analysis program predicts a serious problem in the event of the occurrence of a certain outage. Thus this provides preventive and post-contingency control .A simple example of corrective action is the shifting of generation from one station to another. This may result in change in power flows and causing a change in loading on overloaded lines.

4.3. Violations caused by a contingency

Line outage and generator outage are generally most common type of contingencies. These contingencies mainly cause two types of violations **[4]**:

4.3.1. Low Voltage Violations

This type of violation occurs at the buses. This suggests that the voltage at the bus is less than the specified value. The operating range of voltage at any bus is generally 0.95-1.05 p.u. Thus if the voltage falls below 0.95 p.u then the bus is said to have low voltage. If the voltage rises above the 1.05 p.u then the bus is said to have a high voltage problem. It is known that in the power system network generally reactive power is the reason for the voltage problems. Hence in the case of low voltage problems reactive power is supplied to the bus to increase voltage profile. In the case of high voltage reactive power is absorbed at the buses to maintain the system normal voltage

4.3.2. Line MVA Limits Violations

This type of contingency occurs in the system when the MVA rating of the line exceeds given rating. This is mainly due to the increase in the amplitude of the current flowing in that line. The lines are designed in such a way that they should be able to withstand 125% of their MVA limit. Based on utility practices, if the current crosses the 80-90 % of the limit, it is declared as an alarm situation. Different types of corrective actions to solve this problem are explained later in the next parts.

4.4. Corrective action scheme

Corrective Action Scheme (CAS) is the key components for any power system utility planning. These are the steps which the utilities need to take in order to get the system back to its normal operation. Corrective Action Scheme as the name suggests are the necessary actions which need to be taken to solve the violations caused by a contingency. Corrective Action Schemes are also defined as Special Protection Schemes or System Integration Schemes. The CAS is designed to mitigate specific critical contingencies that initiate the actual system problems. There may be a single critical outage or there may be several critical single contingency outages for which correction action is needed. There may also be credible double or other multiple contingencies for which remedial action is needed. Each critical contingency may require a separate arming level and different corrective actions [5].

4.5. Proposed approach

In the preventive mode, we want the system to remain reliable for the current nominal operating point, even after very severe incidents; there is no readjustment of reactive energy immediately after the appearance of the default. On the other hand, for the corrective mode, the reactive energy is readjusted to try to return the system to a normal operating state after an outage. The goal of the planner is to plan and install reactive energy compensation resources at the best locations so that necessary and sufficient corrective adjustments are triggered at the right time for a set of incidents.

It should be noted that the preventive mode is more conservative than the corrective mode; also, the solution in preventive mode needs more sources of reactive energy than that of the corrective mode. For this reason, in the proposed approach, we adopted the corrective mode as a contingency condition.

In this chapter, we are concerned with the optimal reactive power dispatch problem under contingency conditions in corrective mode. We will first increase the load to a certain level, then two main outages will be applied which leads the power system to be violated. After that, a corrective action scheme based on FACT devises will be proposed to see whether the solution proposed is able to mitigate contingencies conditions or not.

The following load levels are defined as follow:

- Level 1: current nominal load level (normal operating mode).
- Level 2: The nominal load level is estimated at 150% of the load current rating for IEEE 30 bus test system.

Before proceeding with the algorithmic analysis of the chosen corrective mode, it is necessary to define the type of outages. In fact, the number of outages can be very large and it would become too complex and complicated to take them all into consideration. In practice, only a few major outages are considered, including two main ones presented in this study:

a) Loss of line **b)** Loss of a transformer

In contingency conditions, the objective function to be minimized always represents the active losses penalized by a penalty function added to the initial objective function as cited in (**3.10**).

4.6. Application of ORPD under contingency conditions

In order to verify the effectiveness of the proposed approach and validate the obtained results, IEEE 30 bus test system is considered using WOA algorithm. For comparison purpose, another algorithm is also implemented for solving the ORPD problem under contingency conditions, namely, Particle Swarm Optimization with time varying acceleration coefficient (PSO-TVAC). In this section, the limits of the control variables considered are similar to that is presented in chapter 3, **Table.3.5.**

4.6.1. Contingencies and violations

In this section, several scenarios have been tested to provoke several violations on the reactive power flow. The uniform load variation estimated at 150% from the base case. The outages are the loss of line 2-5, and the loss of transformer 28-27. In **Table.4.1** Four different

Table.4.1 *Different case Studies*

CASES:	IEEE 30 BUSES
CASE 1	Base case (normal condition)
CASE 2	Uniform load variation of 50% from base case
CASE 3	Uniform load variation of 50% from base case & loss of line 2-5
CASE 4	Uniform load variation of 50% from base case & loss of transformer 28-27

study cases are considered to see the ability of the proposed approach to withstand the effects of contingencies proposed.

In this part, ORPD is run several times considering the generator bus voltages and transformer tap settings as control variables. **Table.4.2** presents the initial value of real power loss for every case study. For case 1 the power system operates in normal conditions without any violation as we demonstrated in chapter 03. For case 2, the operating condition of the system considered is 50% increase in total load. In case 03, line 5-2 has been eliminated, the power system operates under contingency condition with many violations. Another outage has been applied in case 04, transformer 28-27 was eliminated and provokes a several violations in the parameter of the network.

Table.4.2. *Initial value of real power loss for every case study*

Cases	Case 1	Case 2	Case 3	Case 4
Initial P_{loss} (MW)	**5.518**	**22.31**	**39.937**	**21.826**

Table 4.3 present the results obtained by running the ORPD for different case studies using WOA and PSO-TVAC methods respectively. In comparing the results, we can notice that the minimum active power losses in all cases obtained by the proposed method are considerably reduced compared the initial power loss values presented in **Table 4.2**. For example, for Case 1, the proposed method WOA allows to reduce the active power losses from **5.812 MW** to **4.7970 MW**. Also, for cases 2 to 4 we get further reduction of active power losses when using the WOA method. From these results we can see that the minimum found by the proposed method is better than the PSO-TVAC method. This comparison proves the superiority of the proposed method.

Table.4.3. *Comparison of results for IEEE 30-bus system*

Algorithms	PSO-TVAC				WOA			
Variables	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
V_1	1.1004	1.1018	1.1027	1.1018	1.1000	1.1000	1.1000	1.1000
V_2	1.0949	1.0901	1.1009	1.0913	1.0943	1.1000	1.1000	1.1000
V_5	1.0756	1.0568	1.0271	1.0592	1.0757	1.1000	1.0265	1.0791
V_8	1.0776	1.0624	1.0878	1.0660	1.0762	1.1000	1.0871	1.0769
V_{11}	1.1001	1.1001	1.1000	1.1001	1.1000	1.1000	1.1000	1.0790
V_{13}	1.1001	1.1002	1.1001	1.1001	1.1000	1.1000	1.0263	1.0772
T_{6-9}	1.0803	1.0766	1.0066	1.0952	1.0360	1.1000	1.1000	1.1000
T_{6-10}	0.8755	0.8755	1.3495	0.8920	0.9090	0.9482	1.1000	1.1000
T_{4-12}	1.0374	1.0872	1.0707	1.1199	1.0243	1.1000	1.1000	1.1000
T_{28-27}	0.9789	0.9609	0.9885	/	0.9779	1.1000	0.9939	/
P_{loss} (MW)	**4.8020**	**20.127**	**33.7547**	**19.834**	**4.7970**	**19.9978**	**33.7138**	**19.6762**

It can be seen also from this table, that after increasing of total load from case 2 to 4 and the outages of line 2-5 and the transformer 28-27, the real power loss has been augmented, as well as the voltage profile of load buses has been deregulated, for instance, for cases from 2 to 4, the load buses 29 and 30 have exceeded the allowable limits for the best operation of the power system as shown **fig.4.1.**

Upper and lower limits, as well as the optimal value obtained of active and reactive power generations for all cases are cited in **Table.4.4.** From this table, it can be mentioned that the optimal values of active and reactive power generation are not restricted by their upper and lower limits cited previously for the cases 2, 3 and 4, and that in caused by the increase of the load power and the outages proposed. For instance, in case 3 where the load demand increased to 150% from the base case and line 2-5 has been eliminated. The optimal reactive power generation value of $\boldsymbol{Q_{G8}}$ and $\boldsymbol{Q_{G11}}$ give the values **101.51** and **80.19 Mvar**, which are exceeded their upper and lower limits 60 and 50 Mvar, respectively. Same thing for case 4, several violations appeared after running the program.

Table.4.4. *Range, initial and optimal setting of generator active and reactive power output*

Buses		1	2	5	8	11	13
P_{min}(MW)		20	20	15	10	10	12
P_{max}(MW)		200	80	50	35	30	40
Initial value (MW)		92.211	80	50	20	20	20
Optimal value (MW)	**case 1**	98.2	80	50	20	20	20
	case 2	**215.10**	80	50	35	25	40
	case 3	**228.81**	80	50	30	30	40
	case 4	**254.78**	80	50	20	20	20
Q_{min}(MVar)		-20	-20	-15	-15	-10	-15
Q_{max}(MVar)		200	100	80	60	50	60
Initial value (MVar)		0	0	0	0	0	0
Optimal value (MVar)	**Case1**	-8.21	20.15	28.44	45.48	20.04	26.37
	Case2	-58.68	46.54	75.66	**98.48**	41.24	58.11
	Case3	-49.59	62.28	59.84	**101.51**	**80.19**	54.81
	Case4	-53.03	74.16	60.47	**75.40**	44.56	57.52

Note: *Values in **bold** indicate the effect of various outages in optimal values of active and reactive power generations.*

From the results obtained by WOA and those shown in **Fig.4.1** and **Fig.4.2**, the proposed method is robust in solving complex problems in normal and contingency conditions. Several violations can be observed in case 2, 3 and 4. In case 2 lines 1-2, 5-2 are exceeded the maximum limits. In case 3 line 2-5 was eliminated, so the lines 1-2 and 5-7 are overloaded. As well as the case 4. There were several violations caused by the outage of the transformer 28-27.

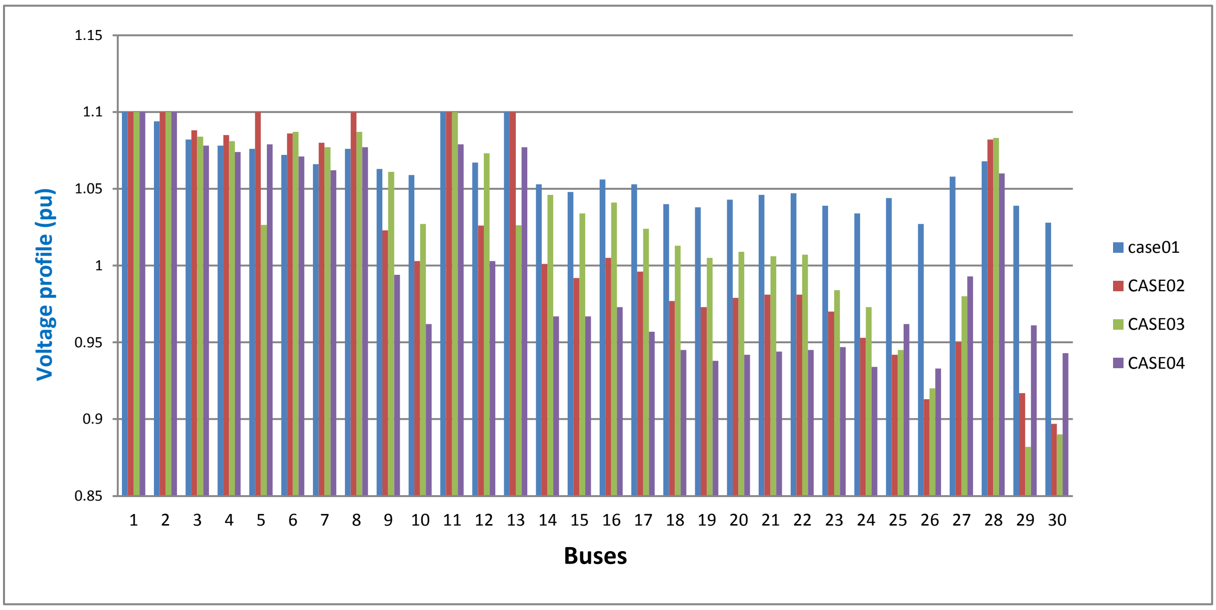

Fig.4.1. *voltage profile for all cases obtained by WOA*

Note: the discontinuity in the curve is due to the elimination of the line 2-5

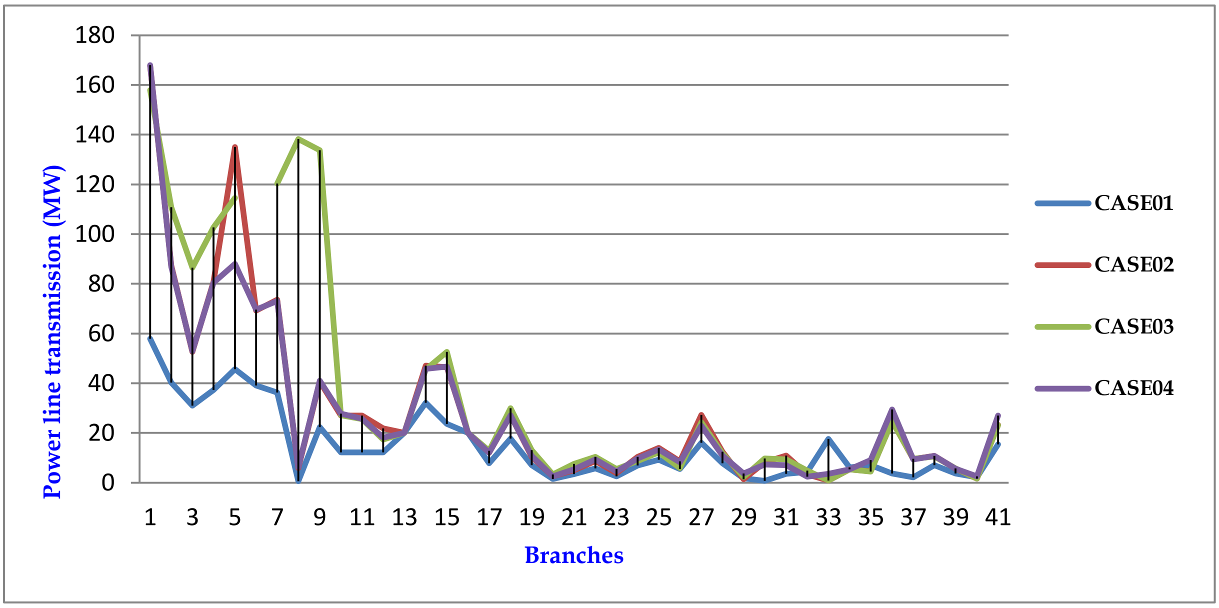

Fig.4.2. *Line transmission power for all cases*

As a summary, ORPD has been solved in contingency conditions using the WOA method. Several violations were appeared after running the algorithm for different case studies. So, In order to withstand the problem faced, corrective action scheme is proposed in the next section.

4.6.2. Corrective action scheme to mitigate problems caused by contingency

As mentioned previously, one of the essential goals of reactive energy planning is to ensure the viability and continuity of operation of the power system in safe conditions. ORPD under contingency conditions has provoked several violations as we noticed in the previous section which put the power system in instability situation. For that, corrective action scheme (CAS) is needed in order to get the system back to its normal operation.

As we have seen in the previous section, real power loss has been increased as well as the voltage profile and the reactive power supply have been exceeded le limits allowable because of an overload and the two outages applied. In this case, several violations appeared which caused an instable reactive power dispatch through the lines. For this reason, we propose an approach that is aim to mitigate the violations caused by the outages applied which leads to a contingency condition in power system operation. Initially, the solution used is to change the grid topology by the construction of new power lines, but this is often difficult for economic and political reasons, Therefore, we propose the use of FACTS devices to remedy the different problems previously encountered.

Application of FACTS devices is a very effective solution to minimize real power loss and voltage collapse due to their fast and very flexible control. Nevertheless, the damping effect of FACTS devices is known to be strongly influenced by their location **[6].** In order to highlight the influence of two types FACTS (SVC, TCSC) on the power that can be transmitted, the improvement of voltage profile, and the reduction of the active losses, simulations are carried out in two cases:

- SVC and TCSC devices are taken separately
- SVC and TCSC placed simultaneously in the selected buses

4.6.2.1. ORPD under contingency conditions considering SVC

To test the influence of the SVC in mitigating the problems caused by outages, the static compensator is modeled as a variable source of the reactive power. The choice of the optimal location of the SVC is based on the determination of the lowest voltage load buses in the power system by running the power flow. After getting the results, the load buses 26 and 30 respectively are selected as locations of the SVCs.

ORPD is run several times considering the generator bus voltages, transformer tap settings and SVC devises as control variables based on WOA method. To demonstrate the effectiveness of the proposed approach, tow SVC were installed on load buses 26 and 30. The two SVCs located at bus numbers 26 and 30 are fixed at 25 MVAR for each one. The objective is to minimize the real power loss, and the mitigate the problems caused by outages such as improving the voltage profile and gets back the line power transmission in its allowable limits.

The simulation results obtained by the WOA method in the presence of SVC are presented in **Table.4.5**. It can be noted that the SVCs connected to the load buses 26 and 30 injects the needed quantity of reactive power to buses 26 and 30 for every case studies, moreover, active power loss has been reduced compared to the previous section (without SVC)

Table.4.5 *Comparison of results for IEEE 30-bus system considering SVC.*

Algorithms	WOA			
Variables	Case 1	Case 2	Case 3	Case 4
V_1	1.1000	1.1000	1.1000	1.1000
V_2	1.1000	1.0908	1.1000	1.0920
V_5	1.0779	1.0618	1.0334	1.0549
V_8	1.0857	1.0686	1.1000	1.0705
V_{11}	1.0821	1.1000	1.1000	1.0928
V_{13}	1.0845	1.0613	1.1000	1.1000
T_{6-9}	1.0163	1.0115	1.0102	1.0400
T_{6-10}	1.0451	1.0202	1.1000	1.0542
T_{4-12}	1.0483	1.0159	1.1000	1.0437
T_{28-27}	1.0585	1.0231	0.9857	/
Q_{SVC26}	23.6280	22.3349	20.7662	17.7788
Q_{SVC30}	13.3419	10.6052	25.0000	16.1261
P_{loss} (MW)	4.5908	19.1596	27.2033	15.0272

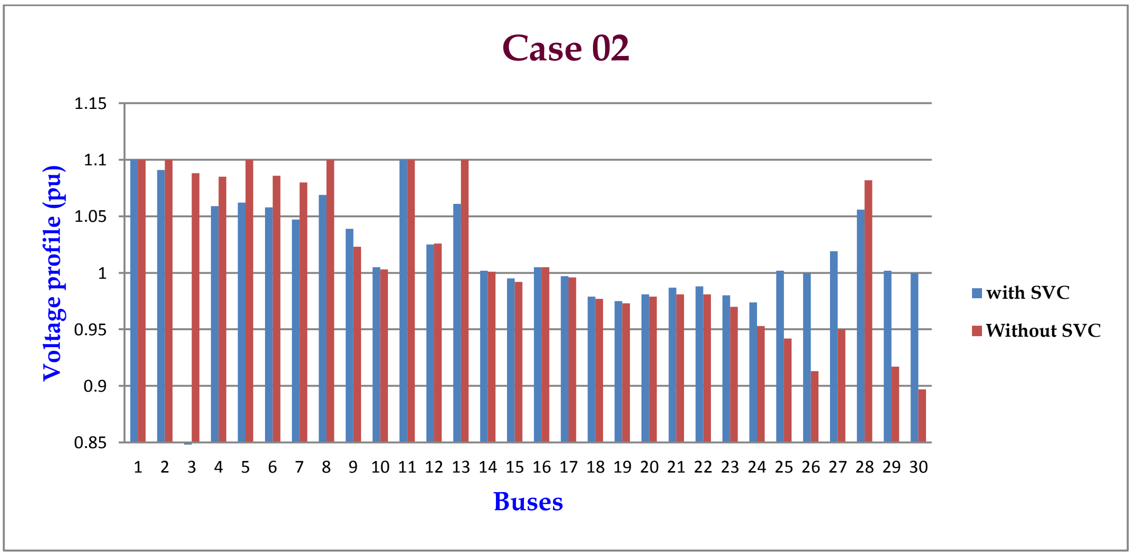

Fig.4.3. *voltage profile for case 02 with and without SVC*

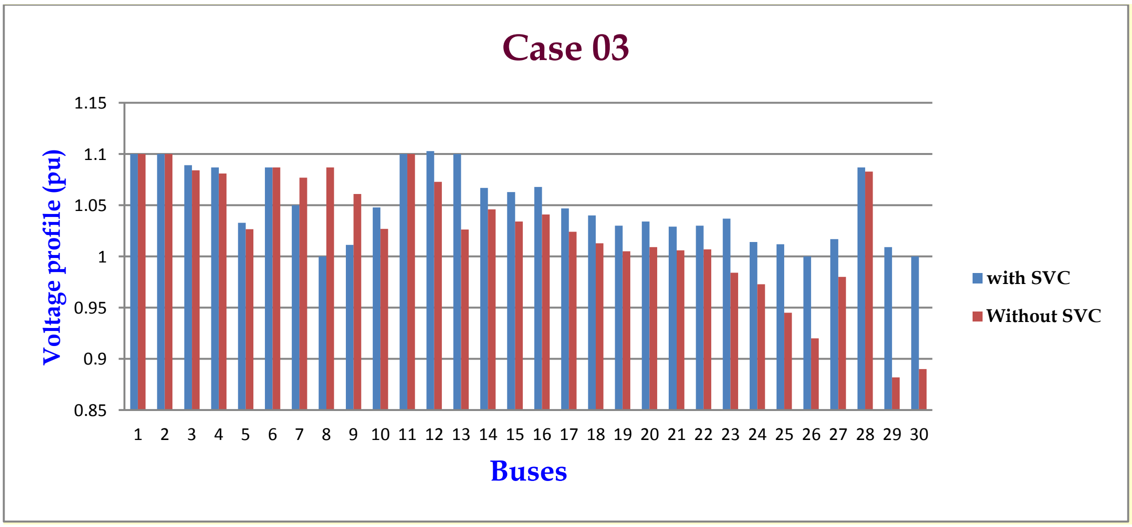

Fig.4.4. *voltage profile for case 03 with and without SVC*

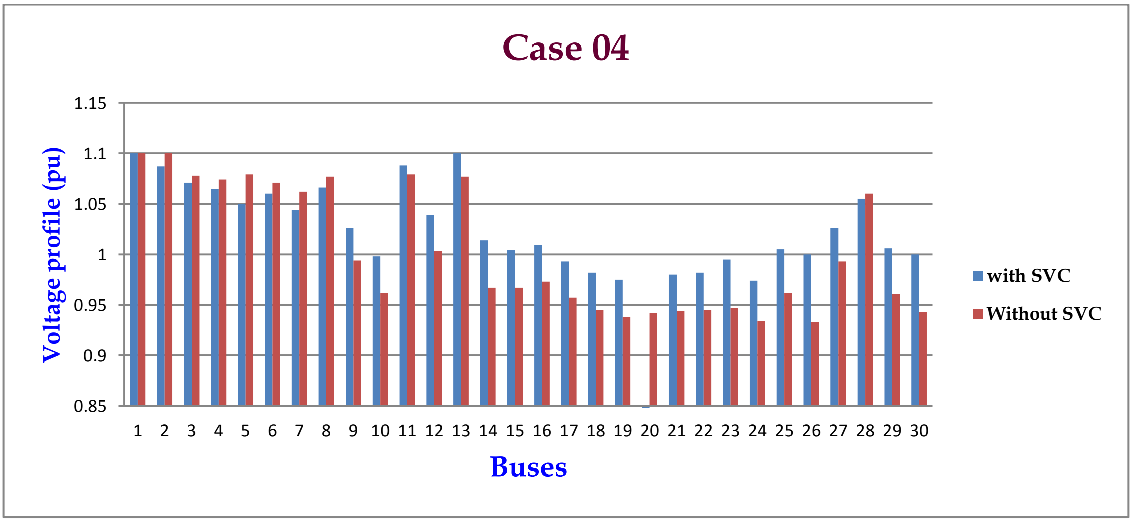

Fig.4.5. *Voltage profile for case 04 with and without SVC*

4.6.2.2. *ORPD under contingency conditions considering TCSC*

Deregulated power systems suffer from congestion management problems. They also cannot fully utilize transmission lines due to the excessive power loss that it could cause. Such FACTS devices as Thyristor-controlled series compensators (TCSCs), by controlling the power flow in the network, it can help reducing the power flow in heavily loaded lines. They can also minimize the power loss of the systems.

Different methods are used for the optimal location of TCSC, such as the loss sensitivity index and the overload index of a transmission line in an electrical network [7]. In this part, We will based on the second location method, so according to the previous case studies, the TCSC devise will be installed in line 2-6 because it's the heavily loaded line in the grid after line 2-5 that is assumed eliminated in our case study.

After the optimal selection of the TCSC location, its size must be optimized, which ensures control of the transported power and reduction of transport losses, This study is carried out for a range of TCSCs from 20% to 80% of the line reactance.

The simulation results obtained by the WOA method in the presence of TCSC are presented in **Table.4.6**.

Table.4.6 *Comparison of results for IEEE 30-bus system considering TCSC.*

Algorithms	WOA			
Variables	Case 1	Case 2	Case 3	Case 4
V_1	1.1000	1.1000	1.1000	1.1000
V_2	1.0939	1.0830	1.1000	1.1000
V_5	1.0805	1.0480	1.0240	1.1000
V_8	1.0737	1.0593	1.0900	1.1000
V_{11}	1.0912	1.1000	1.1000	1.1000
V_{13}	1.1000	1.1000	1.1000	1.1000
T_{6-9}	0.9754	1.0055	1.0560	1.1000
T_{6-10}	1.0741	1.0829	1.1000	0.9282
T_{4-12}	1.1000	1.0783	0.9747	1.1000
T_{28-27}	1.0592	0.9669	1.1000	/
$X_{TCSC\ 2-6}$	0.0460	0.0460	0.0460	0.0460
P_{loss} (MW)	**4.596**	**19.168**	**27.239**	**15.330**

It was found that TCSC reactance responds according to the requirement, moreover, active power loss has been reduced compared to the previous section (without FACTs). The line power transmission, with and without TCSC for case 2 is presented in **Fig.4.6**. It can be noticed that, although small improvement in system performance after TCSC insertion has been obtained.

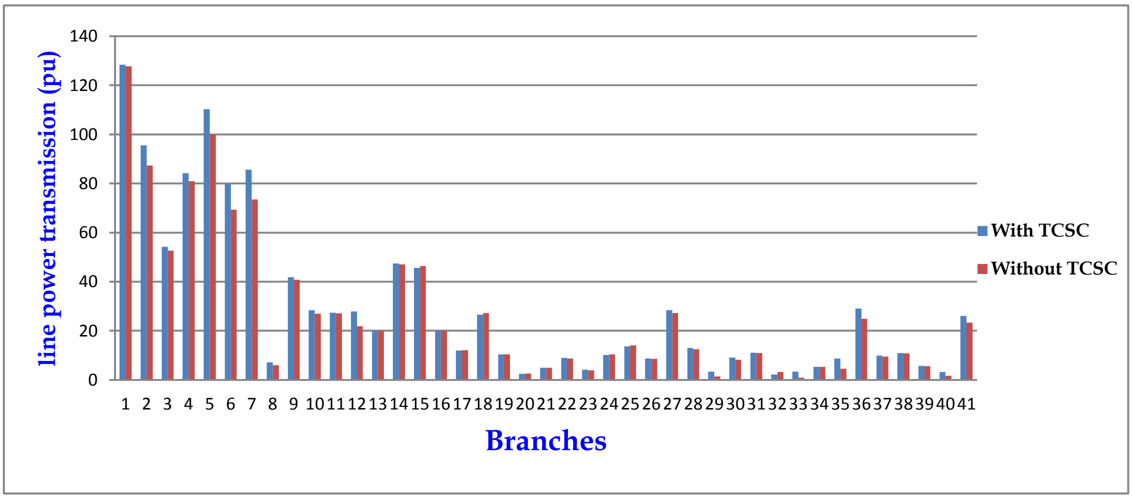

Fig.4.6. *Line power transmission for case 02 with and without TCSC*

4.6.2.3. ORPD under contingency conditions considering SVC & TCSC

In this part, the tow devises are considered in order to mitigate the violations caused by the outages. The approach proposed in as follow:

- TCSC installed in the branch 2-6
- SVC Placed at load buses 26 and 30

The simulation results founded by the WOA method in the presence of SVC and TCSC simultaneously are presented in **Table.4.8**. From this table, it can be noted that the values of the voltage generation, tap settings and Fact devises are within their respective limits. Real power loss has been reduced and gives the best values in all cases compare to previous sections where the FACT devises were considered separated.

Figures 4.7, 4.8 and 4.9 show the voltage profile for all the cases. From this figures, we note that the combination of two FACTS (SVC and TCSC) provides a better voltage profile compared to the case of SVC alone.

Comparing the combination SVC-TCSC and SVC, SVC improves the voltage profile in the areas near their locations, where SVC-TCSC combination improves the voltage profile in all load buses. The line power transmission, with SVC, TCSC and both SVC-TCSC for all cases is presented in **Figures 4.10, 4.11 and 4.12**. It can be observed the enhancement obtained by implementing both SVC-TCSC compare to the cases where the facts implemented separately.

Table.4.7 *Comparison of results for IEEE 30-bus system considering SVC & TCSC.*

Algorithms	WOA			
Variables	**Case 1**	**Case 2**	**Case 3**	**Case 4**
V_1	1.1000	1.1000	1.1000	1.1000
V_2	1.0952	1.0939	1.1000	1.0901
V_5	1.0737	1.0614	1.0330	1.0665
V_8	1.0793	1.0715	1.1000	1.0615
V_{11}	1.1000	1.0933	1.1000	1.1000
V_{13}	1.0755	1.0682	1.1000	1.1000
T_{6-9}	1.0340	1.0451	0.9196	1.0572
T_{6-10}	1.0362	0.9847	1.1000	1.0577
T_{4-12}	1.1000	1.1000	1.1000	1.0577
T_{28-27}	1.0367	1.0013	0.9961	/
Q_{SVC26}	20.3434	18.6930	1.2385	23.8102
Q_{SVC30}	22.4290	19.4344	1.5018	0.5273
$X_{TCSC\ 2-6}$	0.1393	0.1411	0.0401	0.1355
P_{loss} (MW)	4.5857	18.6410	26.3683	14.7260

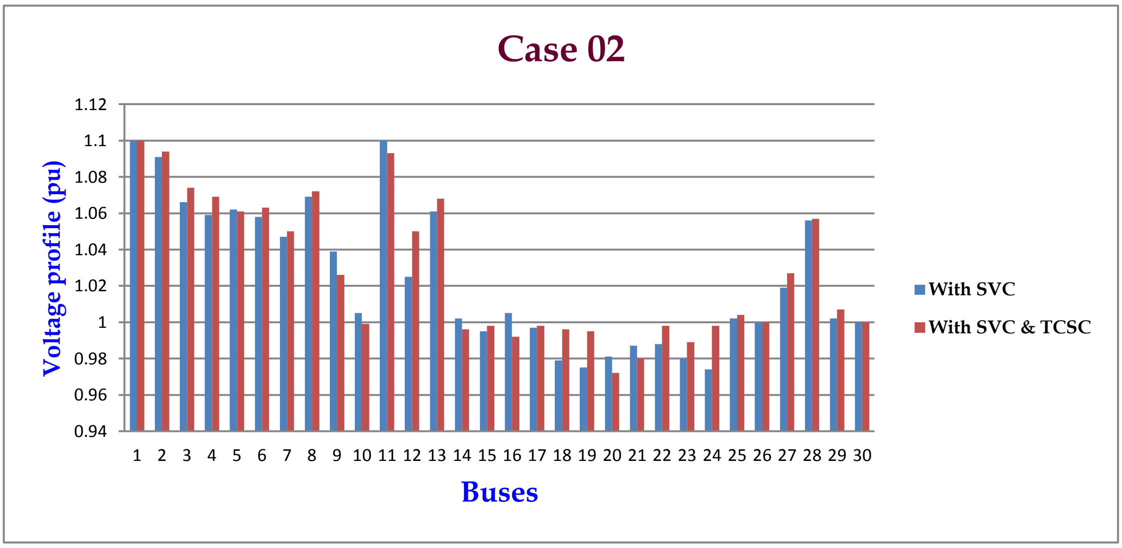

Fig.4.7. *Voltage profile for case 02 with SVC and Both SVC-TCSC*

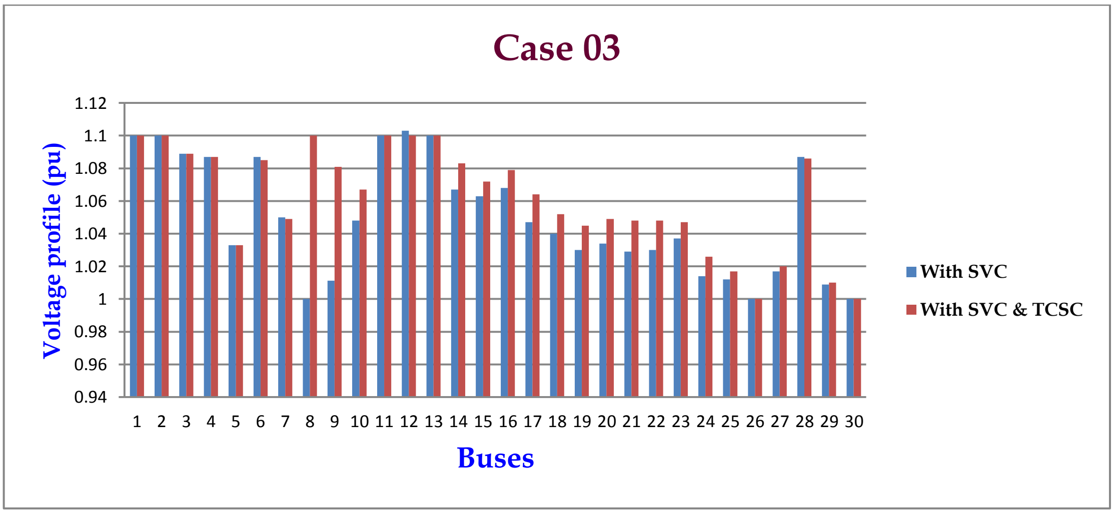

Fig.4.8. *Voltage profile for case 03 with SVC and Both SVC-TCSC*

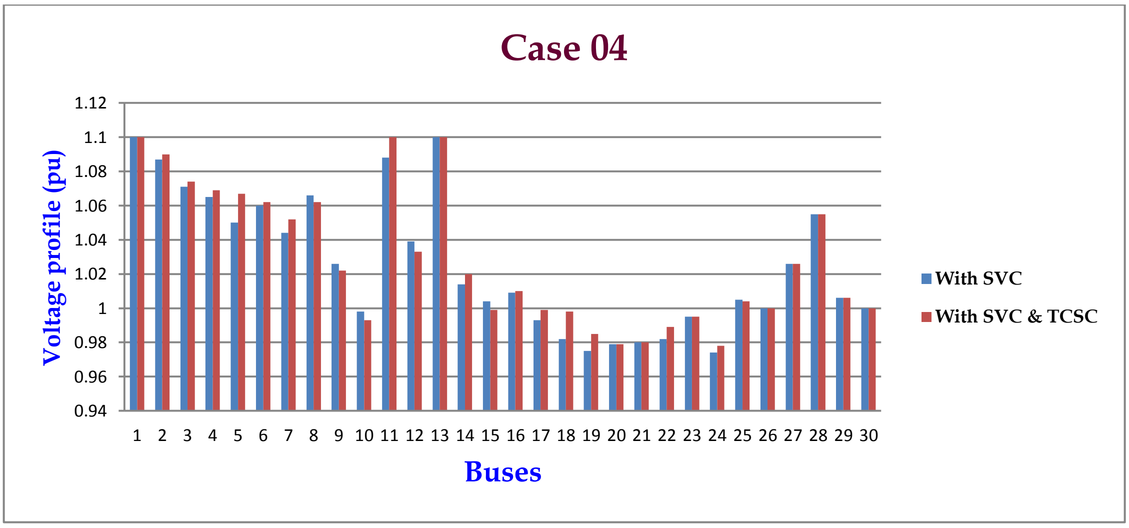

Fig.4.9. *Voltage profile for case 04 with SVC and Both SVC-TCSC*

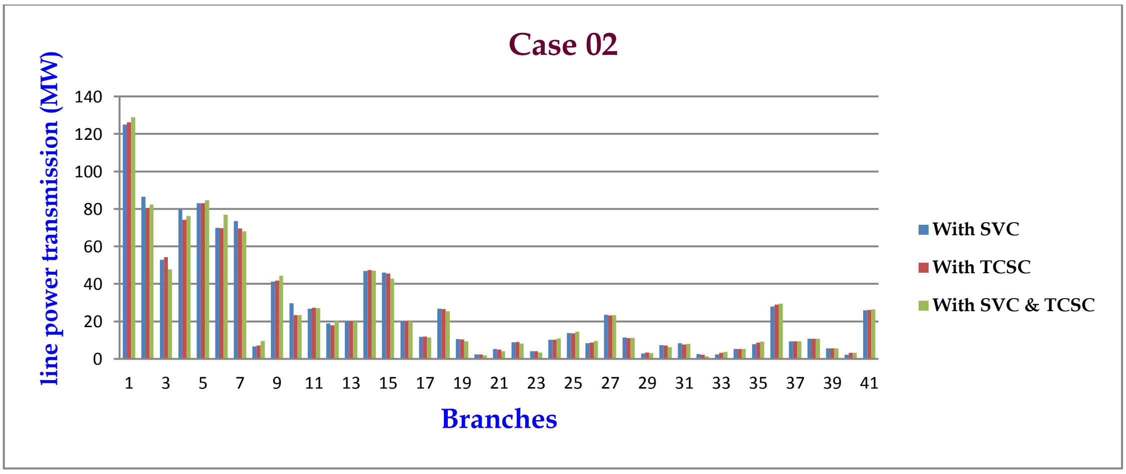

Fig.4.10. *Line power transmission for case 02 with SVC, TCSC and* both SVC-TCSC

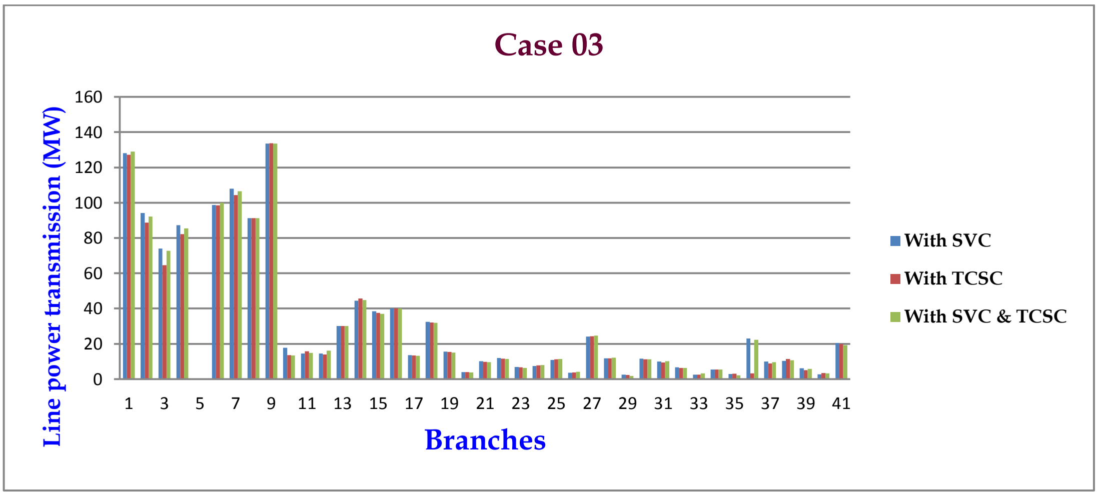

Fig.4.11. *Line power transmission for case 03 with SVC, TCSC and* both SVC-TCSC

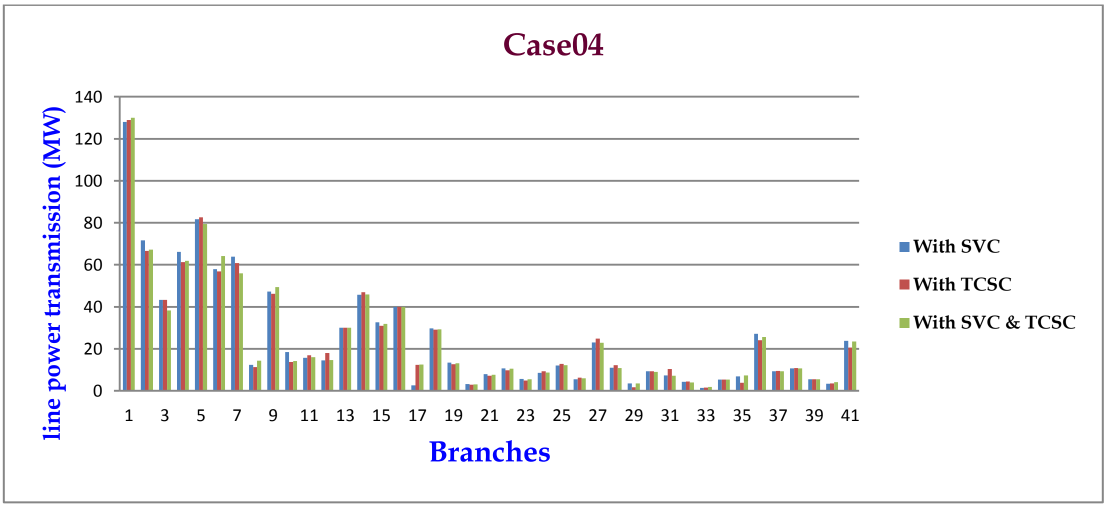

Fig.4.12. *Line power transmission for case 04 with SVC, TCSC and* both SVC-TCSC

4.7. Conclusion

In this chapter, we presented the problem of optimal reactive power dispatch ORPD when the system is under contingency conditions. The types of outages studied as well as the algorithmic analysis of readjustment of the FACT devises to mitigate the violation caused by outages were presented in detail.

Application of FACTS devices has improved considerably the system stability and it's prove that the system is relieved from the stressed condition after getting several violations caused by the outages.

Until now, we have analyzed the problem of reactive energy planning in a normal and under contingency conditions. The details of the various applications carried out using IEEE

30 bus test system. The validation of the proposed approach in real and practical power system is the subject of the following chapter.

4.8 References

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Chapter 05

ORPD for Large Scale Power System in Normal Conditions and Under Contingency Conditions

Abstract:

In this chapter, problem formulation of ORPD has been examined and confirmed on the real and large scale 114 bus Algerian power system for normal and contingency conditions. Several meta-heuristic techniques (PSO, PSO-TVAC, and WOA) as we have used in previous chapters have been applied to solve the ORPD problem.

5.1. Introduction

The optimization methods developed have been validated in chapter 03 to solve the ORPD problem in normal conditions, as well as in chapter 04 under contingency conditions. In this chapter, to prove the effectiveness of WOA for solving similar problems in larger scale and real power systems, the ORPD is performed on practical and large-scale 114 bus Algerian power test system.

5.2. Practical Algerian electric power system

In order to verify the effectiveness of WOA in solving nonlinear and non-convex problems in larger dimensions, the ORPD is performed on practical and large-scale Algerian power test system with 114 bus. **Fig.5.1** shows the map of Algerian electric test system. This network contains 15 generators, 175 lines, 99 load-bus, and 16 tap changer transformers from line 160 to line 175 [1].

The total system real and reactive power demands in normal conditions are 3727 MW and 2070 MVar. The setting for minimum and maximum boundaries for generators voltages, transformers tap setting, and reactive compensation devices are cited in **Table 5.1.**

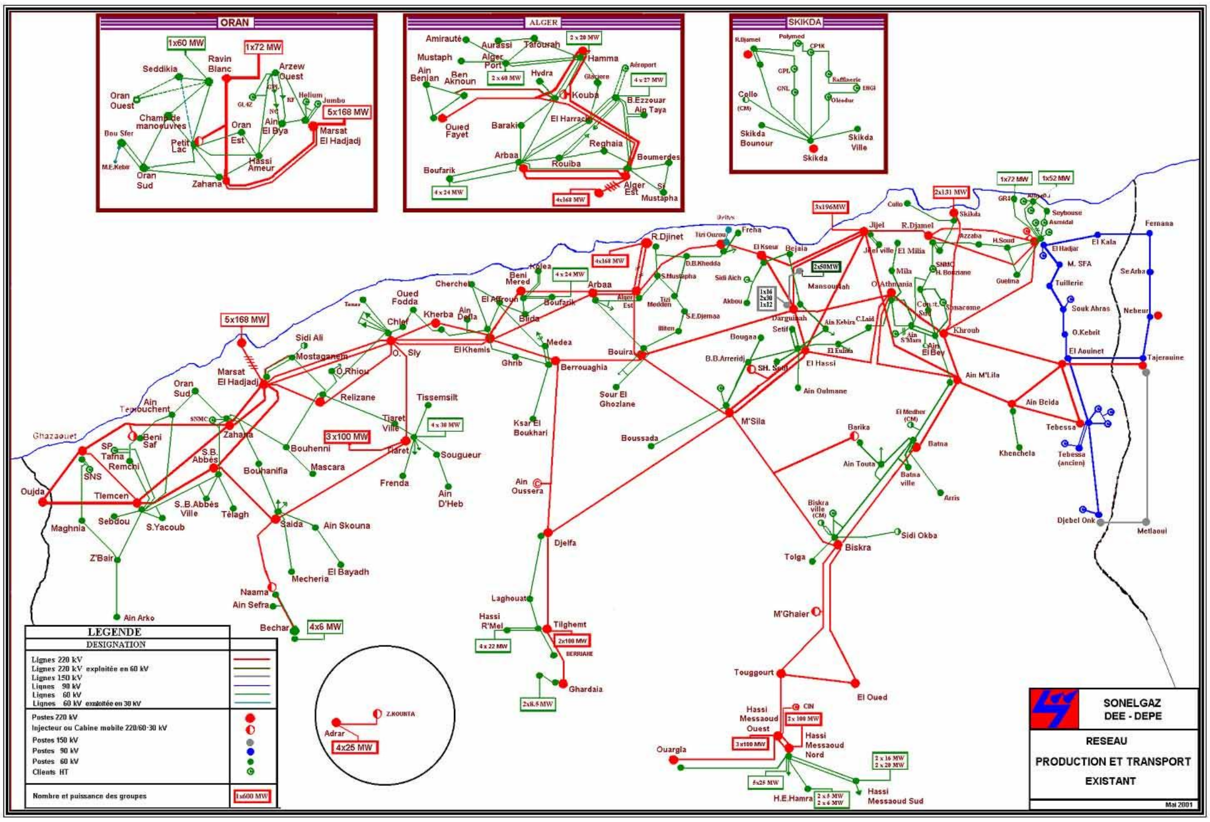

Fig.5.1. *Algerian electric power system map*

Table.5.1 *Limits of various variables for Algerian 114-bus test system.*

Variables limits	Lower limit (pu)	Upper limit (pu)
Voltages for generator bus	0.9	1.1
Voltages for load bus	0.9	1.1
Tap setting	0.9	1.1
Shunt compensators Q_C	0	0.25
$\boldsymbol{Q_{SVC}}$	0	0.25
$\boldsymbol{X_{TCSC}}$	0.2	0.8

In this chapter, ORPD has been performed for tow case studies:

5.3. ORPD in normal conditions

5.3.1. Simulation results

In this part (normal conditions), the control variable is defined in 38 dimensional space, contains 15 voltage generations, 16 tap changer transformers, and 07 reactive compensation devices are installed at buses 41, 50, 55, 66, 67, 77, and 93 [2].

30 trial runs have been executed for several population sizes (20, 30, 40 and 60) similar to the previous case studies (IEEE 14 bus and IEEE 30 bus) presented in chapter 03. The results of different population size are presented in **Fig5.2**, form this figure**,** it is observed that best results has been reached for 20 search agents, however the consistency took its better place when considering a 30 search agents number.

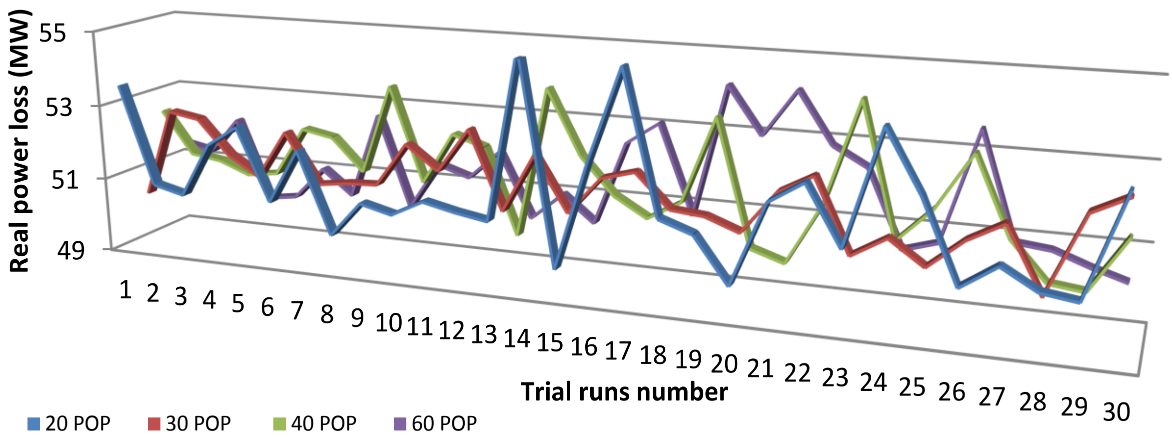

Fig. 5.2.*Results of real power loss for different population size of whales, Algerian 114-bus.*

The optimal settings of control variables and reduction values for active power loss over 30 independent runs are represented in **Table.5.2.** Even for a large test power system, the near global optimum power loss obtained by WOA took a value of **49.784**; these results show the superiority of the WOA technique over the other considered methods. The three proposed techniques WOA, PSO and PSO-TVAC obtains respectively, **26.19%, 24.17%, and 19.77%** of active power loss reduction.

Table.5.2.*Comparison of results for Algerian 114-bus system.*

Variables	Base Case	PSO	PSO-TVAC	WOA
V_4	1.07	1.0447	1.0351	1.0906
V_5	1,05	1.044	1.0363	1.0901
V_{11}	1,05	1.0454	1.0481	1.0906
V_{15}	1,04	1.0387	1.0198	1.091
V_{17}	1,08	1.0484	1.0437	1.0905
V_{19}	1,03	1.0182	1.0327	1.0892
V_{22}	1,04	1.0144	1.0311	1.09
V_{52}	1,05	1.0219	1.0364	1.0909
V_{80}	1,08	1.0514	1.0407	1.0824
V_{83}	1,05	1.0682	1.0552	1.0895
V_{98}	1,05	1.0577	1.0452	1.0895
V_{100}	1,08	1.0806	1.0719	1.0901
V_{101}	1,08	1.0646	1.0465	1.0908
V_{109}	1,05	1.0693	1.0643	1.0903
V_{111}	1,02	1.0573	1.0541	1.0903
T_{88-80}	1.03	1.0025	1.0021	1.0899
T_{90-81}	1.03	0.98926	0.99363	1.0061
T_{93-86}	1.03	0.98409	1.0004	1.0061
T_{41-42}	1.03	1.0035	1.0248	1.0661
T_{57-58}	1.03	0.9692	1.0176	1.0303
T_{43-44}	1.03	1.0035	0.9738	1.07
T_{59-60}	1.03	0.9979	1.0373	1.007
T_{63-64}	1.03	1.0331	1.0249	1.0303
T_{71-72}	1.03	1.0196	1.0059	1.0052
T_{18-17}	1.03	1.0259	1.0275	1.0053
T_{20-21}	1.03	0.97363	0.9804	0.97601
T_{26-27}	1.03	1.0217	0.98989	1.0067
T_{26-28}	1.03	0.9765	0.97195	1.0061
T_{30-31}	1.03	1.0494	0.98385	1.0049
T_{47-48}	1.03	0.96623	0.98857	1.0055
T_{76-74}	1.03	0.98411	1.0004	1.0777
Q_{C41}	0	10.469	23.703	10.488
Q_{C50}	0	15.697	19.369	24.876
Q_{C55}	0	23.66	13.59	22.935
Q_{C66}	0	22.568	16.317	24.876
Q_{C67}	0	19.672	20.867	24.876
Q_{C77}	0	19.308	10.484	24.876
Q_{C93}	0	18.24	16.915	13.949
P_{loss}(MW)	67.456	54.117	51.153	**49.784**
Reduction %	-	19.77	24.17	**26.19**

The convergence characteristics obtained by different methods are presented in **Fig.5.3**. It can be observed that the proposed WOA algorithm converges rapidly towards the near global optimum solution and gives better improvement of transmission loss compared to PSO and PSO-TVAC in solving the ORPD problem.

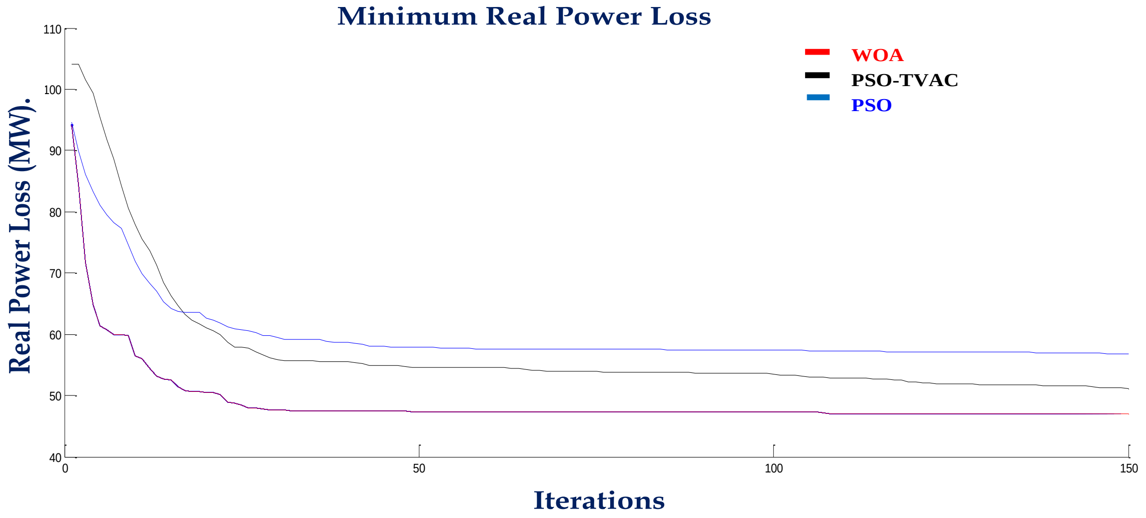

Fig.5.3.*Performance characteristics of WOA algorithm for equivalent Algerian test system*

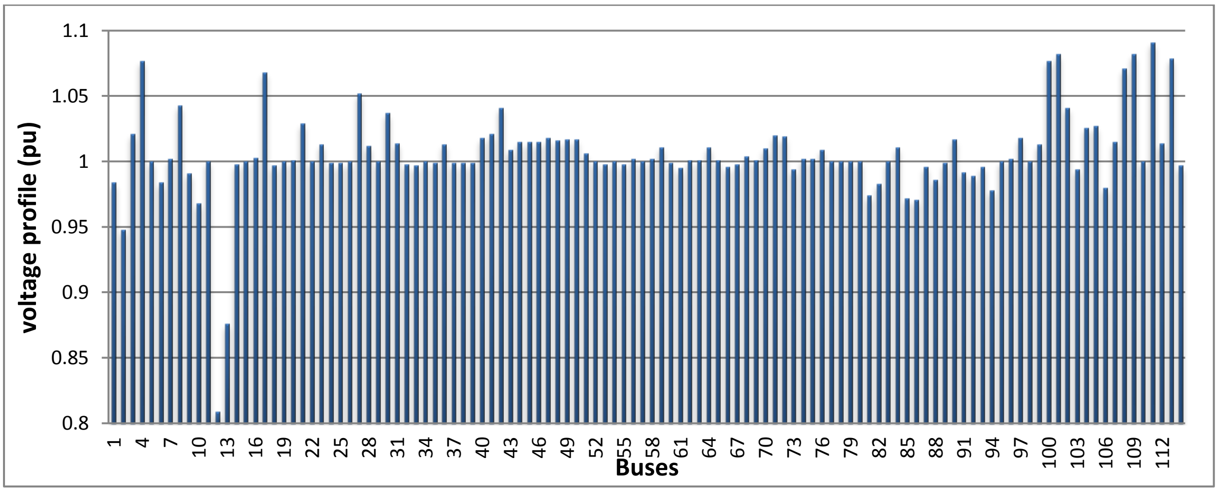

Fig.5.4.*Voltage profile after power flow*

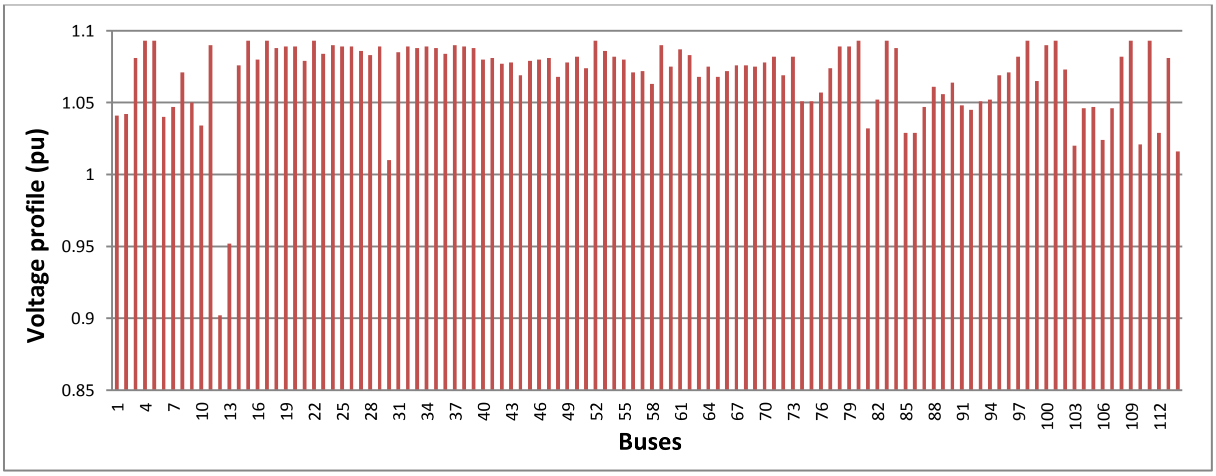

Fig.5.5.*Voltage profile after optimal reactive power flow*

ORPD in normal conditions has been solved successfully using WOA method; there were no remarkable violations that affect the power system operation. Next section will discuss the ORPD problem under contingency conditions to see whether this method is able to solve that king of problems or not.

5.4. ORPD under contingency conditions

In this part (contingency conditions), the control variables are defined similar to the previous section. In this section, several scenarios have been tested to solve the optimal reactive power dispatch problem. The uniform load variation estimated at 115% from the base case. The outages are the loss of line **17-27** and the loss of generator **11** [2]. In **Table.5.3,** three different study cases are considered to see how the proposed approach can withstand the effects of contingencies proposed.

Table.5.3.*Different case Studies*

CASES	IEEE 30 BUSES
CASE 1	Uniform load variation of 15% from base case
CASE 2	Uniform load variation of 15% from base case & loss of lines 17-27
CASE 3	Uniform load variation of 15% from base case & loss of generator 11

Table.5.4 presents the initial value of real power loss for every case study after a power flow.

Table.5.4. *Initial value of real power loss for every case study*

Cases	Case 1	Case 2	Case 3
Initial P_{loss}(MW)	112.475	114.782	136.447

Table.5.5 presents the results obtained by running the ORPD for different case studies using WOA method. In comparing the results, we can observe that the minimum active power losses in all cases obtained by the proposed method are considerably reduced compared to the initial power loss values presented in **Table 5.4**. For example, for Case 1, the proposed method WOA allows to reduce the active power losses from **112.475 MW** to **79.2602 MW.**

It can be seen also from this table that the real power loss has been increased, as well as the voltage profile of load buses has been deregulated, for instance, for all cases the load buses 12 and 13 have exceeded the allowable limits for the best operation of the power system as shown **fig.5.5**

Table.5.5. *optimal setting of control variables for all cases*

Variables	Case 01	Case 02	Case 03
V_4	1.1000	1.0959	1.1000
V_5	1.0928	1.0864	1.1000
V_{11}	1.1000	1.0957	1.1000
V_{15}	1.1000	1.0960	1.1000
V_{17}	1.0999	1.0910	1.1000
V_{19}	1.0923	1.0926	1.0911
V_{22}	1.0920	1.0920	1.1000
V_{52}	1.0951	1.0956	1.0868
V_{80}	1.0990	1.0737	1.0961
V_{83}	1.0969	1.0925	1.1000
V_{98}	1.0978	1.0890	1.1000
V_{100}	1.0992	1.0787	1.0974
V_{101}	1.0942	1.0846	1.1000
V_{109}	1.0931	1.0871	1.0829
V_{111}	1.1000	1.0926	1.0264
T_{88-80}	1.0948	1.0910	1.0858
T_{90-81}	1.0733	1.0814	1.0929
T_{93-86}	1.0106	1.0661	1.0907
T_{41-42}	1.0784	1.0939	1.1000
T_{57-58}	1.0212	1.0446	1.0070
T_{43-44}	1.0275	1.0939	1.1000
T_{59-60}	1.0130	1.0939	1.1000
T_{63-64}	1.0212	1.0446	1.0070
T_{71-72}	1.0720	1.0939	1.1000
T_{18-17}	1.0197	1.0347	1.1000
T_{20-21}	0.9889	0.9820	1.0201
T_{26-27}	1.0248	1.0939	1.1000
T_{26-28}	1.0243	1.0939	1.1000
T_{30-31}	1.0156	1.0938	1.1000
T_{47-48}	1.0271	1.0631	1.1000
T_{76-74}	1.0116	1.0350	1.1000
Q_{C41}	23.1546	23.9263	25.0000
Q_{C50}	23.1546	23.9263	25.0000
Q_{C55}	23.1546	23.9263	25.0000
Q_{C66}	23.1546	23.9263	25.0000
Q_{C67}	23.1546	23.9263	25.0000
Q_{C77}	23.1546	23.9263	25.0000
Q_{C93}	23.1546	23.9263	25.0000
P_{loss}(MW)	**79.260**	**85.514**	**98.634**

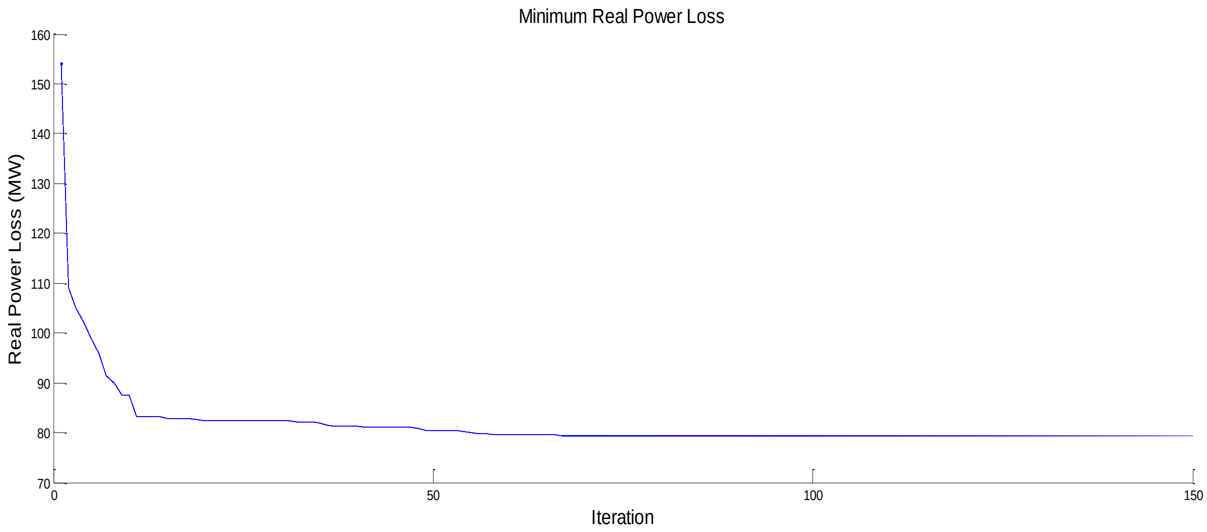

Fig.5.6.*Performance characteristics of WOA algorithm for Case 01*

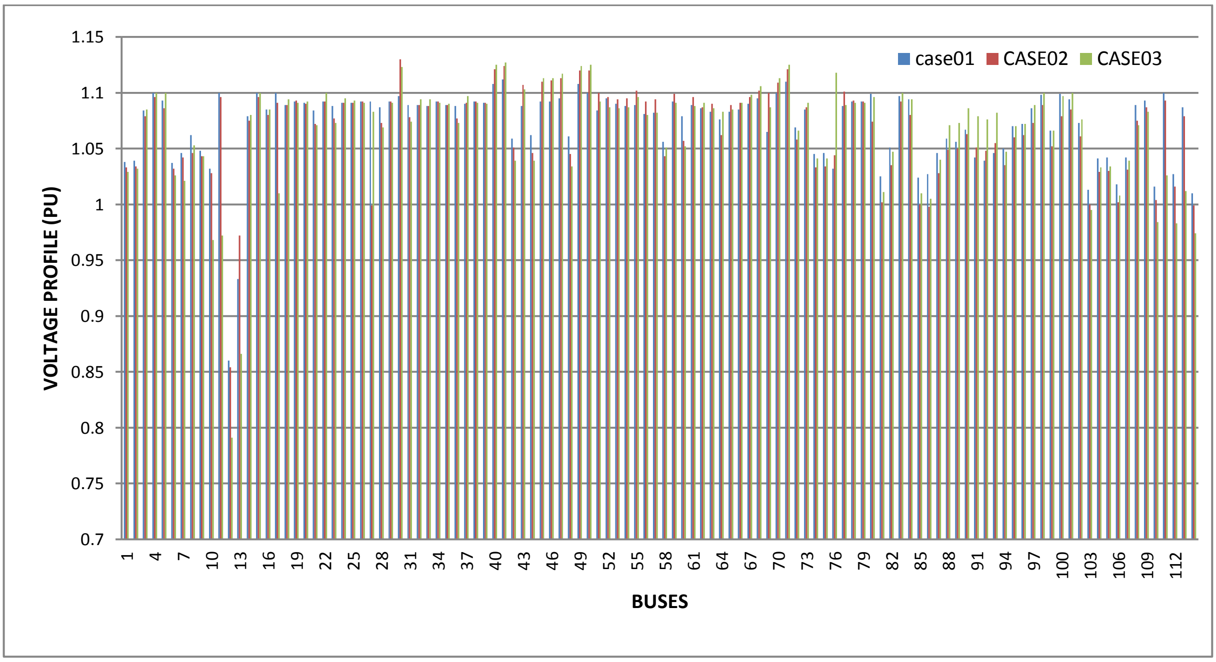

Fig.5.7. *Voltage profile for all cases obtained by WOA*

From the results obtained by WOA and those shown in **Fig.5.7**, the proposed method is robust in solving complex problems in normal and contingency conditions for large scale and equivalent real power system. Several violations can be observed in case 1, 2, and 3. It can be seen that the buses 12, 13, 30, 40, 41, 49, 50, 71 have exceeded the allowable limits for all cases.

As a summary, ORPD has been solved in contingency conditions using the WOA method. Several violations were appeared after running the algorithm for different case studies. So, In order to withstand the faced problems, corrective action scheme is proposed in the next section.

5.4.1. Corrective action scheme to mitigate problems caused by contingency

Similar to the case study IEEE 30 bus performed in chapter 04, outages applied for large scale power system has also provoked several violations. So, to get the system back to its normal operation, a corrective action scheme is essential. FACTS devices are proposed to mitigate the different problems previously encountered.

In this part, tow devises are considered in order to mitigate the violations caused by the outages. The approach proposed in as follow:

- TCSC installed in the branch 4-42
- SVC Placed at load buses 12

The choice of the optimal location of the SVC is based on the determination of the lowest voltage load buses in the power system by running the power flow. After getting the results, the load buses 12 is selected as location of the SVC fixed at 40 MVAR. The objective is to minimize the real power loss, and the mitigate the problems caused by outages such as improving the voltage profile and gets back the line power transmission in its allowable limits.

The TCSC devise will be installed in line 4-42 because it’s the heavily loaded line the grid.

After the optimal selection of the TCSC location, its size must be optimized, which ensures control of the transported power and reduction of transport losses, This study is carried out for a range of TCSCs from 20% to 80% of the line reactance.

The simulation results founded by the WOA method in the presence of SVC and TCSC simultaneously are presented in **Table.5.6**. From this table, it can be noted that the values of the control variables are in the allowable limits. Real power loss has been reduced and gives the best values in all cases compare to previous section (without FACT devises).

Table.5.6. *Comparison of results for IEEE 114-bus system considering SVC & TCSC.*

Variables	Case 01	Case 02	Case 03
V_4	1.0967	1.0616	1.0933
V_5	1.0854	1.0613	1.0933
V_{11}	1.0932	1.0622	1.0933
V_{15}	1.0879	1.0622	1.0932
V_{17}	1.0912	1.0626	1.0933
V_{19}	1.0931	1.0521	1.0931
V_{22}	1.0941	1.0581	1.0933
V_{52}	1.0878	1.0406	1.0933
V_{80}	1.0816	1.0626	1.0932
V_{83}	1.0849	1.0629	1.0933
V_{98}	1.0914	1.0440	1.0933
V_{100}	1.0890	1.0576	1.0933
V_{101}	1.0896	1.0610	1.0931
V_{109}	1.0927	1.0632	1.0930
V_{111}	1.0913	1.0225	1.0933
T_{88-80}	1.0850	1.0628	1.0931
T_{90-81}	1.0919	1.0634	1.0669
T_{93-86}	1.0967	1.0582	1.0643
T_{41-42}	1.0949	1.0638	1.066
T_{57-58}	1.0414	1.0172	1.0202
T_{43-44}	1.0884	1.0636	1.0673
T_{59-60}	1.0954	1.0542	1.0673
T_{63-64}	1.0414	1.0172	1.0202
T_{71-72}	1.0962	1.0610	1.0654
T_{18-17}	1.0894	1.0635	1.0621
T_{20-21}	0.9811	1.0064	1.0153
T_{26-27}	1.0839	1.0636	1.0628
T_{26-28}	1.0887	1.0553	1.0608
T_{30-31}	1.0869	1.0611	1.0652
T_{47-48}	1.0884	1.0293	1.0629
T_{76-74}	1.0951	1.0610	1.0673
Q_{C41}	23.7829	3.8529	24.8227
Q_{C50}	23.7829	3.8529	24.8227
Q_{C55}	23.7829	3.8529	24.8227
Q_{C66}	23.7829	3.8529	24.8227
Q_{C67}	23.7829	3.8529	24.8227
Q_{C77}	23.7829	3.8529	24.8227
Q_{C93}	23.7829	3.8529	24.8227
Q_{SVC30}	0.3267	9.5600	24.4211
$X_{TCSC\ 2-6}$	0.0100	0.0233	0.0081
P_{loss}(MW)	**76.8671**	**80.4585**	**82.752**

Fig.5.8, Fig.5.9 and Fig.5.10 show the voltage profile for all the cases. From this figures, we note that the proposed corrective action scheme based FACT devises improved considerably the system stability and minimized the real power loss in all cases as wel as the voltage profile.

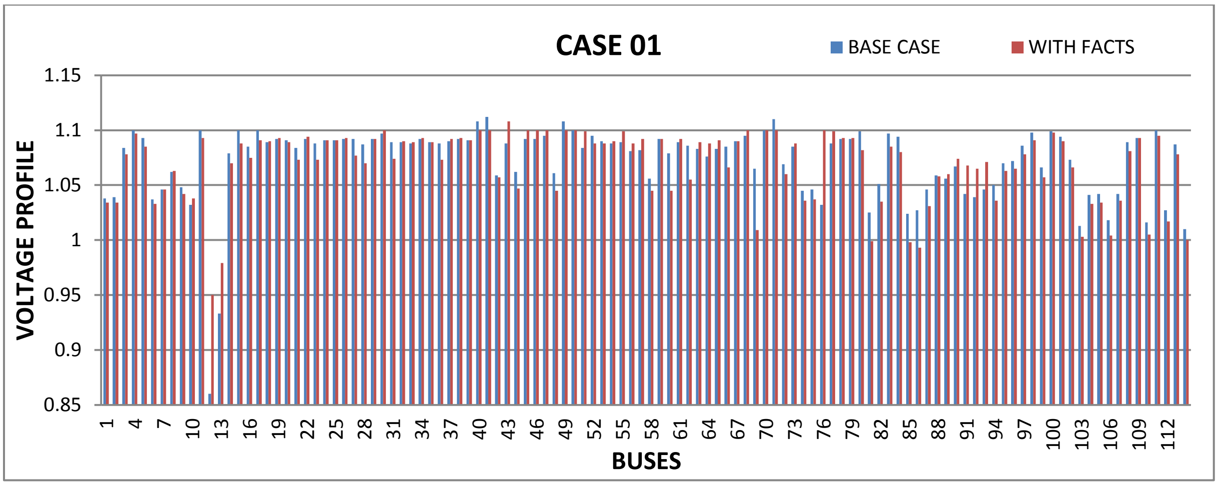

Fig.5.8. *Voltage profile for case 01 with and without SVC-TCSC*

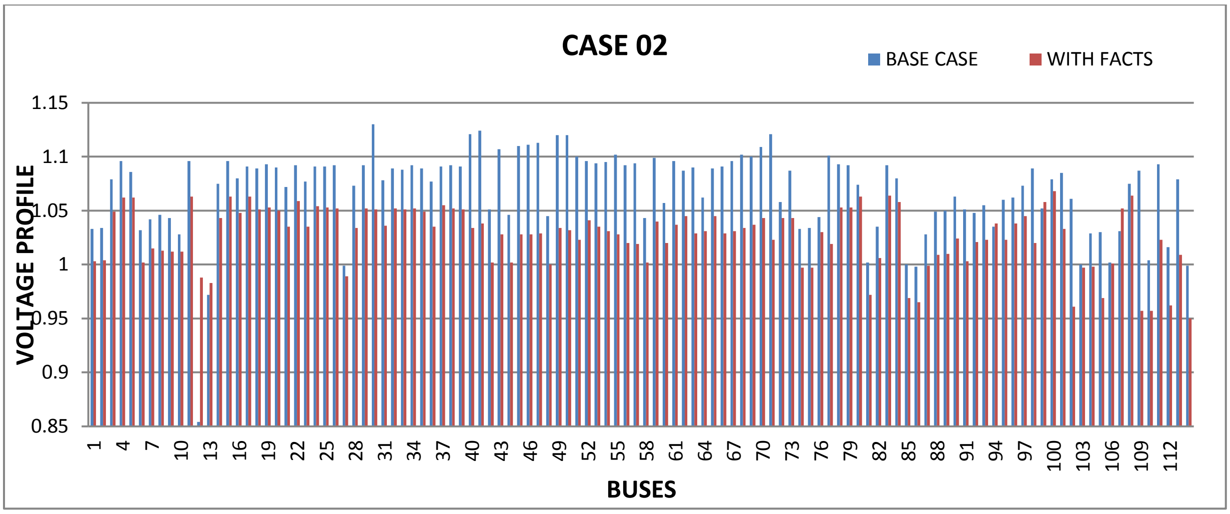

Fig.5.9. *Voltage profile for case 02 with and without SVC-TCSC*

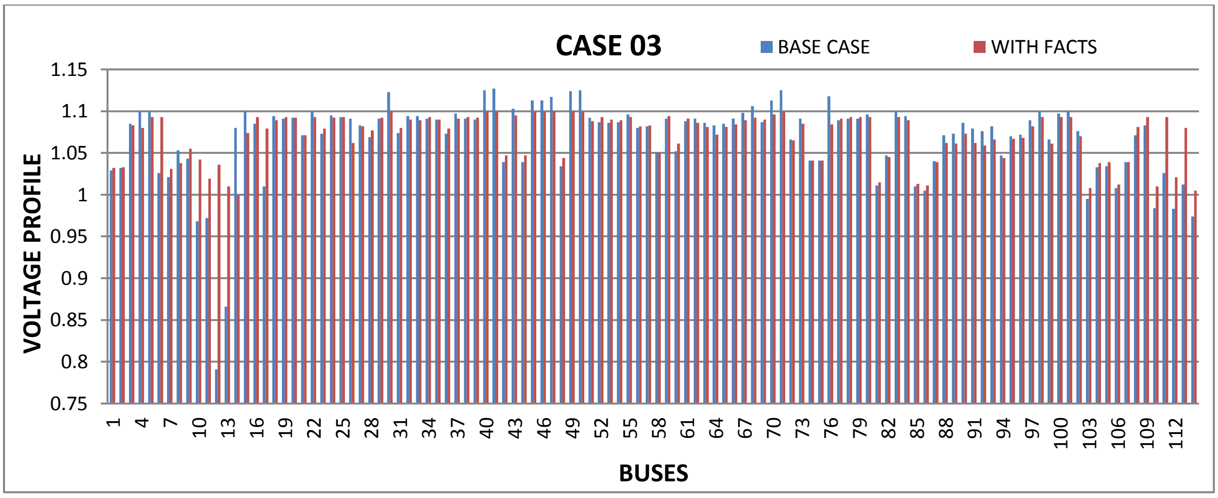

Fig.5.10. *Voltage profile for case 03 with and without SVC-TCSC*

5.4. Conclusion

In this chapter, we have validated the different algorithms used in this thesis for large scale 114 bus Algerian power system under normal and contingency conditions to solve the problem of optimal reactive power dispatch ORPD. The types of outages studied as well as the algorithmic analysis of readjustment of the FACT devises to mitigate the violation caused by outages were presented in detail.

Application of FACTS devices has improved considerably the system stability and minimized the real power loss in all cases. it's proved that the system is relieved from the stressed condition to the normal operation after getting several violations caused by the outages.

5.5. References

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Chapter 6

General Conclusion

Abstract:

In this chapter, a brief general conclusion which summarizes the work done in this thesis of the well-known optimal reactive power dispatch ORPD problem in normal and under contingency conditions is presented. Scope for future research takes a place at the end of this thesis, that shows the general possibilities which can be taken in consideration in the future

6.1. General Conclusion

One of the main objectives in controlling power systems is making the best allocation of reactive energy without violating any of the constraints existing in the power system. So, efficient distribution of reactive power is required to ensure the viability and continuity of the electrical energy system operation in the many different states.

In this thesis, optimal reactive power dispatch ORPD problem was applied and solved in normal and under contingencies for several critical case studies. PSO, PSO-TVAC and WOA algorithms and MATPOWER 4.1 toolbox are applied to reduce the real power loss in the power networks without exceeding the allowable limits of the constraints; also, an exterior penalty function method is also employed. The robustness and efficiency of the proposed new method is validated on nonlinear ORPD function using the IEEE 14-bus system, IEEE 30-bus system and the practical and large-scale equivalent Algerian electric 114-bus power system. Also, it was compared to recent methods addressing the same problem.

Among the conclusions drawn, we can say that:

Review of various existing methods for the ORPD problem in power system is carried out in chapter 2. We could say that all these methods are proved to be efficient in solving that kind of nonlinear and non-convex problems. However, the most frequently used techniques to solve the ORPD are the Based-Swarm algorithms. So, this is can attribute to the fact that these techniques are those that enjoy greater disclosure among meta-heuristics techniques.

It was not possible to find conclusive evidence of the superiority of one technique (or family of methodologies) over another (or others) in particular, due to the stochastic nature of the meta-heuristic optimization techniques.

In the normal conditions, our simulation results illustrate that the performance of the proposed algorithm appears to be very effective in particular for its fast convergence to the global optimum as well as its significant active loss reduction. In that mode we could note that:

- The proposed approach can significantly reduce the power loss in power systems, maintain the voltage within acceptable limits, and it can be easily employed in real life.

- Applying WOA algorithm to address the reactive power dispatch problems is feasible and can achieve considerable economic benefits.
- Based on one way ANOVA statistical test, the significance of its results against other methods (PSO and PSO-TVAC) has been confirmed which gives more confidence to our study.

Even for contingency conditions, our proposed algorithms prove their effectiveness in solving complex problems under several outages. We could constant that:

- After increasing the load to a certain level and applying several main outages , we could notice that the real power loss has been augmented compared to a normal condition mode, as well as the voltage profile of load buses has been deregulated.
- Real power loss has been reduced and gives the best values in all cases compare to previous sections where the FACT devises were considered separated.
- The combination of two FACTS (SVC and TCSC) provides a better voltage profile compared to the case of SVC alone.
- The corrective action scheme based on SVC improves the voltage profile in the areas near their locations. However, SVC-TCSC combination improves the voltage profile in all load buses.
- It can be observed the enhancement obtained by implementing both SVC-TCSC compare to the cases where the facts implemented separately.
- Application of FACTS devices as a corrective action scheme has improved considerably the system stability and it's prove that the system is relieved from the stressed condition after getting several violations caused by the outages.
- The proposed method is robust in solving complex problems for large scale power system (114 Algerian power test system) in normal and contingency conditions.
- The solution proposed was able to mitigate the violations caused by the outages applied in all case studies.

6.2. Scope for future research

The proposed WOA to solve the ORPD problem with bus voltage limits, limits on reactive power generation, and tap changing constraints for minimizing the real power loss could be extended to be applied for multi-objectives.

The ORPD problem can be solved using hybrid artificial intelligent techniques to improve the computational speed. Hence the present approach and the results presented in this work will encourage further research in this field.

The WOA algorithm developed in this thesis will be extremely useful for electric power utilities for enhancing the various types of economic dispatch problems and the unit commitment scheduling problem in an electric power system.