MULTI-OBJECTIVE OPTIMAL POWER FLOW

IN DEREGULATED ENVIRONMENT

BY

FOUAD RASHED FOUAD ZARO

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This thesis, is written by **FOUAD RASHED FOUAD ZARO,** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.**

Thesis Committee:

Prof. MOHAMMED ABIDO (Chairman)

Prof. IBRAHIM EL-AMIN (Member)

M. M. Mansour

Prof. MOHAMMED MANSOUR (Member)

Dr. SAMIR ABDUL-JAUWAD
(Department Chairman)

Dr. SALAM ZUMMO
(Dean of Graduate Studies)

Date: 1/2/10

بسـم الله الرحمـــن الرحـيم

{ قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ }

Dedicated
To

My Beloved Parents…

My Wife…

My Children…

My Holy Homeland Palestine…

FOUAD

ACKNOWLEDGMENT

In the name of Allah, the most gracious, the most merciful all praise is to Almighty Allah for having guided me all over my life. Acknowledgement is due to King Fahd University of Petroleum and Minerals for the great support to this work. My deep appreciation is reserved for thesis advisor ***Prof. Mohammed Abido*** for his guidance, valuable time and attention he devoted throughout the course of this work. My numerous intrusions into his office were always met with a considerate response and care. Thanks are also due to my thesis committee members ***Prof. Ibrahim El-Amin*** and ***Prof. Mohammed Mansour*** for their interest, attention and suggestions. I wish also to thank all other parties who has contributed to support me in this work, namely department chairman ***Dr. Samir Abdul-Jauwad*** and dean of graduate studies ***Dr. Salam Zummo*** and other faculty members for their support. My great appreciations are also due to all members of my family and to friends who give me the self-confidence to face the challenge.

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THESIS ABSTRACT

Name: Fouad Rashed Zaro.
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For decades, researchers have developed various models and algorithms to look for the optimal power flow (OPF) in different applications. Still research is ongoing to find OPF problems for the present day power system challenges such as a liberalized market or a deregulated power system. Traditional OPF provided a tool to achieve such task and has initially dealt with fuel cost only. Later, other objectives were incorporated into the OPF in the form of single objective. Recently, with the progress in evolutionary optimization techniques, it is possible to deal with multi-objective optimization problems.

This thesis presents a true multi-objective formulation of the OPF problem taking into consideration different operational constraints in order to ensure proper system operation. A multi-objective particle swarm optimization (MOPSO) has been proposed, developed and successfully implemented to solve the multi-objective OPF. The objective functions are to minimize fuel cost, wheeling cost and congestion management using TCSC device. A clustering algorithm is applied to manage the size of the Pareto set. Also, an algorithm based on fuzzy set theory is used to extract the best compromise solution. Two case studies have been used to test the proposed approach. The first case is IEEE 30-bus test system and the second case is 87-bus practical system. The results are compared with the available literature, it show the effectiveness of the proposed approach in solving true multi-objective OPF and also finding well distrusted Pareto solutions.

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ملخص الرسالة

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طور الباحثون نماذج وخوارزميات مختلفة لإيجاد التدفق الأمثل للطاقة الكهربائية في تطبيقات مختلفة, ومازال البحث مستمر لإيجاد حلول مناسبة للتحديات المعاصرة الناتجة عن خصخصة القطاع الكهربائي وإعادة هيكلته. خوارزمية التدفق الأمثل للطاقة التقليدية كانت تتعامل فقط مع تقليل تكاليف تشغيل محطات توليد الطاقة الكهربائية, لاحقاً عدة أهداف دمجت معاً لتشكيل هدف واحد, مؤخراً مع تطور التقنيات والخوارزميات أصبح بالإمكان التعامل مع أكثر من هدف في وقت واحد.

هذه الدراسة تمثل دراسة حقيقية لتدفق الطاقة الكهربائية الأمثل متعدد الأهداف, وتم استخدام طريقة (MOPSO) التي تعتمد على أحدث الطرق الرياضية الحديثة في مجال تحقيق الأمثلية. وهناك ثلاثة أهداف تم دراستها وهي تقليل تكاليف تشغيل محطات توليد الطاقة, وتقليل تكاليف استخدام نظام نقل الطاقة, وحل مشكلة فوق الحمل للخطوط أو الحد منها. وتم تطبيق خوارزمية لتحديد عدد الحلول المثالية المقدمة لمشغلي نظام الطاقة, وأيضاً تم استخدام خوارزمية تستند على نظرية مجموعة فازي لإيجاد الحل الوسطي الأمثل. الطريقة المقترحة طبقت على نظام اختبار قياسي IEEE 30-bus وعلى نظام حقيقي 87-bus , والنتائج أوضحت مدى فاعلية الطريقة المقترحة بعد أن تم مقارنتها مع نتائج الأبحاث السابقة المتوفرة .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران – المملكة العربية السعودية

يناير 2010م

NOMENCLATURE

B	Total line charging in p.u.
EA	Evolutionary Algorithm
FACTS	Flexible Alternating Current Transmission System
L	Line
MO	Multi Objective
MO-OPF	Multi-Objective Optimal Power Flow
MOP	Multi-objective Optimization Problem
MOPSO	Multi-Objective Particle Swarm Optimization
NO	Number of objective functions
OPF	Optimal Power Flow
P_G	Machine MW Output
P_L	Load MW
PSO	Particle Swarm Optimization
pu	Per Unit
Q_G	Machine Mvar Output
Q_L	Load Mvar
Q_{margin}	Reactive Power Reserve Margin
Q_c	Shunt Mvar
R	Resistance in p.u.
SCS	Single Contingency Severity
SI	Severity Index
SO	Single Objective
SOPSO	Single Objective Particle Swarm Optimization
T	Transformer Tap Changer Position
TCSC	Thyristor Controlled Series Capacitor
V	Bus Voltage
X	Reactance in p.u.

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

For decades researchers have developed various models and algorithms to look for the Optimal Power Flow (OPF) in different applications. Still research is ongoing to find OPF problems for the present day power system challenges such as a liberalized market. Traditionally, classical mathematical optimization methods have been used to effectively solve conventional OPF problems. Due to emergence of a deregulated electricity market and consideration of dynamic system properties, however, the traditional concepts and practices of power systems are overruled by an economic market management. So the requirements for OPF have become more complex than it was [1].

In the early stages, fuel cost optimization described as the economical dispatch was a very basic objective. Later, the load flow problem was combined with the

economical dispatch problem as an optimization problem. This has formulated the OPF which provided a tool to manipulate the system variables to reduce the fuel cost while meeting certain conditions and constraints to ensure proper system operation. At later stages, the application of OPF has gone far beyond the economical dispatch problem, depending on the selection of the objective function [2-4].

One of the most challenging problems in the operation of restructured power systems is congestion management. Congestion exists in both new and traditional systems. In a competitive power market, the system is said to be congested when the producers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond one or more transfer limits [5].

Congestion implies that some inexpensive generation may be unusable due to its location, making it necessary to utilize more expensive units at different locations. Congestion could be due to various reasons such as transmission line outages, generator outages, changes in energy demand and uncoordinated transactions [5].

Flexible Alternating Current Transmission System (FACTS) devices are based on controlling the firing angles of semiconductor power devices. They have applications in improvement of voltage and transfer capability and may also contribute to stability. They also provide a mean to control the flow of power,

which may enhance the operation of power systems. OPF is very helpful in setting these devices to achieve best control and best results. FACTS devices such as Thyristor Controlled Series Capacitor (TCSC) by controlling the power flows in the network can help to reduce the flows in heavily loaded lines [6].

Power transfer allocation is one of the major issues in deregulated power industry. There are many allocation methods for payment of electricity transmission systems: postage-stamp rate method, contract path method, MW-mile method, unused transmission capacity method, MVA-mile method, counter-flow method, distribution factors method (Rudnick distribution factor method), AC power flow methods, tracing methods are the Bialek's tracing (Node) method, the Kirschen's proportionality method and graph method [7].

Initially, the OPF was in the form of a single objective optimization problem. Solution methodologies were and still an open area for research. The reason for this is that practical power systems are non-linear with large dimension and possibly several conflicting objectives. For this, the use of traditional optimization techniques in solving the OPF required lot of simplifications, assumptions and manipulations. This was not only a difficult task but may also affect the solution.

To overcome the difficulties in traditional techniques, recently developed evolutionary optimization techniques have been proposed to solve the OPF with

promising success [8]. Moreover, with the recent developments in optimization techniques, it is possible to deal with multi-objective optimization problems which allow for expressing the trade-off between conflicting objectives. Researches in OPF have benefited from these achievements in the optimization field to formulate a true multi-objective OPF [9, 10].

1.2 THESIS MOTIVATION AND OBJECTIVES

Recent studies on OPF adopt a multi-objective formulation. The challenges in this field fall in the formulation of OPF, consideration of different objective functions and application of new optimization techniques. In some previous studies in this field, OPF with several objectives were combined in one objective function. Recent studies in this field seek to formulate a true multi-objective OPF. On the other hand, optimization techniques based on evolutionary algorithms are also progressing and new techniques are being proposed for solving multi-objective optimization techniques. These techniques are initially proposed to solve single objective optimization problem, and new researches proposed extension of such techniques to solve multi-objective cases. Most recently, true multi-objective optimization problem is also addressed under these subjects.

The objective of this thesis work is to formulate and solve OPF problem which takes into consideration congestion management and wheeling cost, to present a

new single-objective and multi-objective optimization models for solving the OPF using PSO. The particular objectives in this study are:

1. To formulate and solve the single-objective OPF using particle swarm optimization.
2. To formulate and solve a true multi-objective OPF using PSO where several objective functions can be optimized, subjected to a set of operational constraints.
3. To develop an approach for solving congestion management problem using thyristor controlled series capacitors (TCSC) device.
4. To develop an approach for wheeling cost by tracing active and reactive power flow.
5. To provide the power system operator with a candidate sets that represent optimal solutions and proposing the best compromise one.
6. To implement the proposed approach to different standard test systems as well as areal system to demonstrate its effectiveness.
7. To compare the performance of the proposed approach with the previously applied techniques.

1.3 THESIS APPROACH AND METHODOLOGY

This work can be divided into the following stages:

1. A comprehensive literature survey was carried out on the history of OPF, Congestion management using TCSC device, Tracing active and reactive power flow methods and Wheeling Cost. This survey has provided a general background on these topics formulation, past/current developments and solutions methodologies.

2. In line with the presented work in the literature, a true multi-objective optimal power flow is developed with selected objectives and constraints.

3. The outcomes of literature survey on the single and multi-objectives evolutionary algorithms are further reviewed considering simplicity, popularity and previous conclusions and studies. Then, Particle Swarm optimization technique is selected and proposed to solve the formulated single and multi-objective optimal power flow problem.

4. To simulate the proposed OPF formulation utilizing a PSO based multi-objective approach, a source code in MATLAB is developed. The source code includes subroutines to perform: normal load flow, OPF, determine location and parameters for TCSC device to treat congestion lines and to determine wheeling cost by tracing power flow.

5. The problem is simulated and tested on different standard systems of different dimensions. The results are compared with the available literature to verify and compare the performance of the proposed approach, with the previously applied techniques.

1.4 THESIS CONTRIBUTIONS

The contributions of this work to the field of Optimal Power Flow in deregulated environment can be considered in different aspects, such as:

- This work presents a true multi-objective formulation for the Optimal Power Flow, which is gaining more interest due to current needs in the field of power systems.
- This study presents an approach for solving the formulated multi-objective OPF. This approach is based on the concept of PSO which is reported to be easy and efficient. The approach is implemented for single and multi-objective OPF.
- This study presents an approach for solving congestion management problem using TCSC device by determines location and parameters.
- Also this study presents an approach for wheeling cost by tracing active and reactive power in electrical systems.
- The proposed problem formulation and proposed approach was tested on different systems.

1.5 STRUCTURE OF THE WORK

The remaining chapters in this thesis are organized as follow: Chapter 2 contains comprehensive literature survey about OPF, congestion management and wheeling cost and tracing methods. Chapter 3 addresses the problem congestion management and wheeling cost. Chapter 4 presents problem formulation for true multi-objective OPF and several objective functions to be considered in this study. Chapter 5 presents multi-objective problem optimization using PSO. Chapter 6 presents the simulation results for single objective optimization model with discussions. Chapter 7 presents the simulation results for the multi-objective optimization model. Chapter 8 presents the conclusions and recommendations for the future researches.

CHAPTER TWO

LITERATURE REVIEW

This chapter presents a comprehensive literature review of optimal power flow, congestion management using TCSC device and wheeling cost.

2.1 OPTIMAL POWER FLOW

2.1.1 Overview

The objective of an Optimal Power Flow (OPF) algorithm is to find a steady state operation point which minimizes generation cost, losses etc. or maximizes social welfare, loadability etc. while maintaining an acceptable system performance in terms of limits on generators' power, line flow limits, output of various compensating devices etc.

For decades researchers have developed various models and algorithms to look for the OPF in different applications. Still research is ongoing to find OPF problems for the present day power system challenges such as a liberalized market or a large penetration of renewable energy source. Traditionally, classical mathematical optimization methods have been used to effectively solve conventional OPF problems. Due to emergence of a deregulated electricity market and consideration of dynamic system properties, traditional concepts and practices of power systems are overruled by an economic market management. So the requirements for OPF have become more complex than it was. The OPF problem has been one of the most widely studied subjects in the power system community since Carpentier first published the concept in 1962[1].

OPF algorithms are among the tools present in many Energy Management Systems (EMSs) and their usefulness is increasingly being recognized by power utilities due to increased presence of independent power producers combined with deregulation of the power industry. The traditional OPF had no such rich techno- economic meaning as the new form OPF explicitly has. Research result of OPF in deregulated electricity market context can be extended into many research areas: locational real-time pricing, network congestion management, available transfer capability estimation, electricity transmission fee computation, etc [11].

The applications of OPF in electrical power systems can be summarized as follow [1]:

Application Field	Objective Functions of OPF Model
• Real-time electricity price computing.	• Max. social welfare.
• Network congestion management.	• Min. congestion management.
• Electricity transmission fee allocation.	• Min. generation cost/ max custom benefits.
• Available transmission capability computing.	• Max. total transmission capability.

2.1.2 Optimal Power Flow Methods

Traditionally, classical optimization methods were used to effectively solve OPF. But more recently due to incorporation of FACTS devices and deregulation of a power sector, the traditional concepts and practices of power systems are superimposed by an economic market management. So OPF have become complex. The most common optimization methods for OPF: Linear Programming method, Newton-Raphson method, Quadratic Programming method, Nonlinear Programming method, Interior Point method and Artificial Intelligence (AI) methods. AI methods include Artificial Neural Network, Fuzzy Logic Method, Genetic Algorithm Method, Evolutionary Programming, Ant Colony Optimization and Particle Swarm Optimization [12-41].

2.2 CONGESTION MANAGEMENT

2.2.1 Overview

One of the most challenging problems in the operation of restructured power systems is congestion management. Congestion exists in both new and traditional systems. In a competitive power market, the system is said to be congested when the producers and consumers of electric energy desire to produce and consume amounts that would cause the transmission system to operate at or beyond one or more transfer limits [42-47].

Congestion implies that some inexpensive generation may be unusable due to its location, making it necessary to utilize more expensive units at different locations. Congestion could be due to various reasons such as transmission line outages, generator outages, changes in energy demand and uncoordinated transactions [48-53].

In a liberalized electricity market, the transmission system operator (TSO) plays a crucial role in power system operation. Among many other tasks, TSO detects congestion situations and allocates the payments of electricity transmission. A software tool for congestion management and transmission price determination in electricity market is presented [54]. The congestion problems are solved

obtaining the feasible solution that minimizes the changes in the initial dispatch. Transmission prices are evaluated considering the existing system costs, the losses costs, the initial congestion costs and the operational costs.

A new approach to transmission congestion cost calculation has been introduced is an effort to rationalize and systemize the procedures for calculation of transmission congestion cost, based on security constrained optimal power flow [55]. It can be noted that, congestion has great impact on total generation cost.

Power system congestion is a major problem that system operators would face in the post-deregulated era. Therefore, investigation of techniques for congestion-freewheeling of power is of paramount interest [56]. The proposed technique has two contributions firstly a technique for optimum selection of participating generators has been introduced using generator sensitivities to the power flow on congested lines. Secondly an algorithm based on particle swarm optimization which minimizes the deviations of rescheduled values of generator power outputs from scheduled levels is introduced.

The approach that was discussed in [57] presents a novel approach to solve an OPF problem with embedded security constraints through the use of particle swarm optimizer algorithm with reconstruction operators, the major aim is to minimize the total operating cost, taking into account both operating security

constraints, and system capacity requirements. The cost operation includes: generation costs, transmission costs and consumer benefits.

2.2.2 Congestion Management using TCSC Device

FACTS devices are based on controlling the firing angles of semiconductor power devices. They have applications in improvement of voltage and transfer capability and may also contribute to the stability. They also provide a mean to control the flow of power, which may enhance the operation of power systems. OPF is very helpful in setting these devices to achieve best control and best results.

Congestion management is an important issue in deregulated power systems. FACTS devices such as TCSC by controlling the power flows in the network can help to reduce the flows in heavily loaded lines. Because of the considerable costs of FACTS devices, it is important to obtain optimal location for placement of these devices. In [6], two sensitivity-based methods have been developed for determining the optimal location of TCSC in an electricity market based on real power performance index and reduction of total system VAR power losses. The effect of TCSC on line outage in order to relieve congestion has also been studied. It can be observed from the results of line outage that the congestion is relieved by setting the installed TCSC.

In [58] a Cluster based congestion management in deregulated electricity market has been presented is concerned with the Real and Reactive power rescheduling problem in a deregulated market environment. The aim of the proposed work is to minimize deviations from transaction schedules and hence the congestion cost. The TCSC maximizes the power transfer capability between a specific power seller and a power buyer in a network. The TCSC is installed in the most congested lines and its effective has been analyzed. The method is formulated as a stochastic optimization problem and is solved by Particle Swarm Optimization.

2.3 WHEELING COST

2.3.1 General Wheeling Cost Methods

Power transfer allocation is one of the major issues in deregulated power industry. There are many allocation methods for payment of electricity transmission systems; postage-stamp rate method, contract path method, MW-mile method, unused transmission capacity method, MVA-mile method, counter-flow method, distribution factors method (Rudnick distribution factor method), AC power flow methods, tracing methods are the Bialek's tracing (Node) method, the Kirschen's proportionality method and graph method [7].

A hybrid power transfer allocation approach for deregulated power systems method has been introduced in [59]. It is based on combining the existing power flow tracing methods namely the commons, graph and node that determines the power share from generators to line flows and loads. The main advantages of the developed approach lie on its ability to calculate the allocation factors fairly and its applicability to almost any system. It also minimizes the computational burdens by clustering the system into small groups.

2.3.2 Major Wheeling Cost Methods

There are three major known methods for wheeling cost estimating. These are Bialek's tracing method, the Kirschen's proportionality method and Rudnick distribution factor method [7, 60-61].

a. **Rudnick distribution factor method (Distribution Factors Method):**

Distribution factors are calculated based on linear load flows [7]. In general, generation distribution factors have been used mainly in security and contingency analyses. They have been used to approximately determine the impact of generation and load on transmission flows. In recent years, these factors are suggested as a mechanism to allocate transmission payments in restructured power systems, as these factors can efficiently evaluate transmission usage. To recover the total fixed transmission costs, distribution factors can be used to allocate transmission payments to different users. By

using these factors, allocation can be attributed to transaction-related net power injections, to generators, or to loads. The distribution factors are given as follows:-

i. **Generation Shift Distribution Factors (GSDFs or A factors)**:

GSDFs or A factors provide line flow changes due to a change in generation. These factors can be used in determining maximum transaction flows for bounded generation and load injections. The A factor measures the incremental use of transmission network by generators and loads (consumers). Also GSDFs are dependent on the selection of reference (marginal) bus and independent of operational conditions of the system.

ii. **Generalized Generation Distribution Factors (GGDFs or D factors):**

They determine the impact of each generator on active power flows; thus they can be negative as well. Since GGDFs are based on the dc model, they can only be used for active power flows. GGDFs measure the total use (not incremental) of transmission network facilities produced by generator injections. GGDFs depend on line parameters, system conditions, and not on the choice of reference bus.

iii. **Generalized Load Distribution Factors (GLDFs or C factors):**

These are very similar to GGDFs. GLDFs determine the contribution of each load to line flows. GLDFs also allocate charges of the sub-transmission network to loads within a distribution company service area. GGDFs are also based on dc power flows. The C factors (GLDFs) measure the total use of transmission

network facilities by loads in which loads are seen as negative injections. As in the case of GGDFs, GLDFs depend on line parameters, system conditions, and not on the reference bus location.

b. The Bialek tracing (Node) method:

In Bialek's tracing method, it is assumed that nodal inflows are shared proportionally among nodal outflows [7, 60]. This method uses a topological approach to determine the contribution of individual generators or loads to every line flow based on the calculation of topological distribution factors. This method can deal with both dc power flow and ac power flows; that is, it can be used to find contributions of both active and reactive power flows. Bialek's tracing method considers:

1) Two flows in each line, one entering the line and the other exiting the line (to consider losses in line).
2) Generation and load at each bus.

The main principle used to trace the power flow will be that of proportional sharing.

c. The Kirschen proportionality (Commons) method:

Kirschen's tracing method is based on a set of definitions for domains, commons, and links [7, 60]. A domain is a set of buses that obtain power from a particular generator. A common is a set of contiguous buses supplied by the same set of generators. Links are branches that interconnect commons. Based on these

definitions, the state of system (an acyclic state graph) is represented by a directed graph that consists of commons and links, with directed flows between commons and the corresponding data for generations/loads in commons and flows on links.

The method uses a recursive procedure for calculating the contributions of generators (or loads) to commons, links, and loads (or generators), and line flows within each common. For a given common, the method assumes that the proportion of inflow traced to a particular generator is equal to the proportion of outflow traced to the same generator. As in Bialek's tracing method, Kirschen's tracing method can determine contributions from individual generators to line flows, and determine contributions of individual loads to line flows.

CHAPTER THREE

CONGESTION MANAGEMENT

AND WHEELING COST

3.1 CONGESTION MANAGEMENT USING TCSC DEVICE.

3.1.1 Overview

The restructuring of the electric power industry has involved paradigm shifts in the real-time control activities of the power grids. Managing dispatch is one of the important control activities in a power system. OPF has perhaps been the most significant technique for obtaining minimum cost generation patterns in a power system with existing transmission and operational constraints. The role of an independent system operator (ISO) in a competitive market environment

would be to facilitate the complete dispatch of the power that gets contracted among the market players. With the trend of an increasing number of bilateral contracts being signed for electricity market trades, the possibility of insufficient resources leading to network congestion may be unavoidable [62].

In this scenario, congestion management becomes an important issue. Real-time transmission congestion can be defined as the operating condition in which there is not enough transmission capability to implement all the traded transactions simultaneously due to some unexpected contingencies. It may be alleviated by incorporating line capacity constraints in the dispatch and scheduling process. This may involve re-dispatch of generation or load curtailment. Other possible means for relieving congestion are operation of phase-shifters or FACTS devices [62].

The concept of FACTS was first proposed by Hingorani [63]. FACTS devices have the ability to allow power systems to operate in a more flexible, secure, economic, and sophisticated way. Generation patterns that lead to heavy line flows result in higher losses, and weakened security and stability. Such patterns are economically undesirable. Further, transmission constraints make certain combinations of generation and demand unviable due to the potential of outages. In such situations, FACTS devices may be used to improve system performance by controlling the power flows in the grid. Studies on FACTS so far have mainly focused on device developments and their impacts on the power

system aspects such as control, transient and small signal stability enhancement, and damping of oscillations [64-70].

FACTS devices becomes important in the context of power system restructuring since they can expand the usage potential of transmission systems by controlling power flows in the network. FACTS devices are operated in a manner so as to ensure that the contractual requirements are fulfilled as far as possible by minimizing line congestion [64]. In this Study, treating congestion management with the help of one main type of FACTS devices is considered, namely TCSC.

The TCSC device contributes variable impedance to the transmission lines. It can have various roles in the operation and control of power systems, such as scheduling power flow, decreasing unsymmetrical components, reducing net loss, providing voltage support, limiting short-circuit currents, mitigating sub-synchronous resonance, damping the power oscillation, and enhancing transient stability and Several TCSC devices have been installed and operated by some utilities [62-64]. Therefore, the TCSC is used in this study to demonstrate proposed controller for congestion management problem.

3.1.2 Static Modeling of TCSC

TCSC allows increasing of the overall utilization of an electrical power network by controlling the power flow. Thus it is possible to relieve network congestions

by increasing the Total Transfer Capacity (TTC) over a congested link. For the optimal power dispatch formulation using TCSC controller, only the static model of this controller has been considered here. It is assumed that the time constants in TCSC are very small and hence this approximation is justified.

3.1.3 Thyristor Controlled Series Capacitor.

Thyristor controlled series capacitor (TCSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. The TCSC can be considered as a controllable reactance in static modeling.

The scheme of a TCSC is given in Figure 3.1. A parameter to describe the TCSC main circuit is λ.

$$\lambda = \sqrt{\frac{X_C}{X_L}} \tag{3.1}$$

Where

$X_C = \frac{1}{\omega C}$ and $X_L = \omega L$, $\omega = 2\pi f$, f : $frequency\,(Hz)$

Reasonable values for λ fall in the range of 2 to 4.

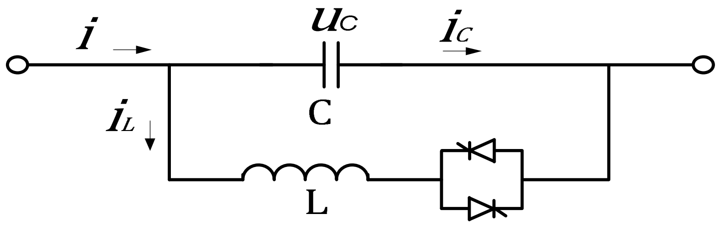


Figure 3.1: TCSC Model.

Figure 3.2 shows a model of a transmission line with a TCSC connected between buses *i* and *j*. The TCSC can be considered as a static reactance $-jX_{TCSC}$. This controllable reactance, X_{TCSC}, is directly used as the control variable to be implemented in the power flow equation. In this study, the working range of the TCSC is $\pm 0.5*X_{line}$.

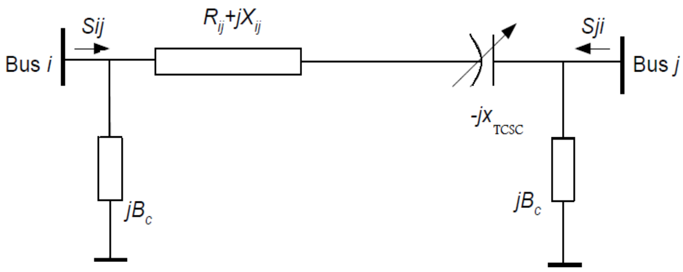


Figure 3.2: TCSC installed in a branch.

$$S_{ij}^{*} = P_{ij} - jQ_{ij} = V_i^{*} I_{ij} \tag{3.2}$$

$$= V_i^{*}[(V_i - V_j)Y_{ij} + V_i(jB_c)] \tag{3.3}$$

$$= V_i^{2}[(G_{ij} + j(B_{ij} + B_c)] - V_i^{*} V_j (G_{ij} + jB_{ij}) \tag{3.4}$$

Where

$$G_{ij} + jB_{ij} = 1 \big/ (R_L + jX_L - jX_{TCSC}) \tag{3.5}$$

Equating the real and imaginary parts of the above equations, the expressions for real and reactive power flows can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i\, V_j G_{ij} Cos(\delta_i - \delta_j) - V_i\, V_j B_{ij} Sin(\delta_i - \delta_j) \tag{3.6}$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_C) - V_i\, V_j G_{ij} Sin(\delta_i - \delta_j) + V_i\, V_j B_{ij} Cos(\delta_i - \delta_j) \tag{3.7}$$

Similarly, the real and reactive power flows from bus *j* to bus *i* can be expressed as

$$P_{ji} = V_j^2 G_{ij} - V_i\, V_j G_{ij} Cos(\delta_i - \delta_j) + V_i\, V_j B_{ij} Sin(\delta_i - \delta_j) \tag{3.8}$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_C) + V_i\, V_j G_{ij} Sin(\delta_i - \delta_j) + V_i\, V_j B_{ij} Cos(\delta_i - \delta_j) \tag{3.9}$$

The active and reactive power loss in the line can be calculated as

$$P_L = P_{ij} + P_{ji} \tag{3.10}$$

$$= V_i^2 G_{ij} + V_j^2 G_{ij} - 2V_i\, V_j G_{ij} Cos\ (\delta_i - \delta_j) \tag{3.11}$$

$$Q_L = Q_{ij} + Q_{ji} \tag{3.12}$$

$$= -V_i^2 (B_{ij} + B_C) - V_j^2 (B_{ij} + B_C) + 2V_i\, V_j B_{ij} Cos(\delta_i - \delta_j) \tag{3.13}$$

These equations are used to model the TCSC in the OPF formulations.

3.1.4 The Transmitted Active Power

The TCSC can be considered as a controllable reactance in series with the line reactance as shown in Figure 3.3. The transmitted active power is calculated from the general formula for transmitted active power on a line and is given as

$$P = \frac{U_1 U_2}{X + X_{TCSC}} Sin\,\delta \tag{3.14}$$

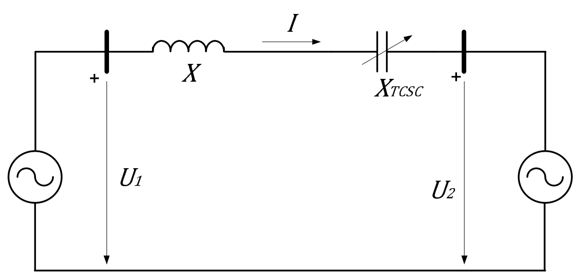


Figure 3.3: Two machine system with TCSC.

3.1.5 TCSC Device Location

The objectives for device placement may be one of the following:

1. Reduction in the real power loss of a particular line.
2. Reduction in the total system real power loss.
3. Reduction in the total system reactive power loss.
4. Maximum relief of congestion in the system.

For the first three objectives, methods based on the sensitivity approach may be used. If the objective of TCSC device placement is to provide maximum relief of congestion, the devices may be placed in the most congested lines or, alternatively, in locations determined by trial-and-error [71].

3.1.6 Single Contingency Sensitivity index

Single Contingency Sensitivity (SCS) index is adapted in this research to solve the optimal power flow with TCSC device and to eliminate line over loads in the system following single line outages. The SCS index used to rank the system branches according to their suitability for installing TCSCs.

Once the locations are determined, the problem of identifying the optimal TCSC parameters is formulated as an optimization problem and PSO based approach is applied to solve the OPF problem.

The severity of a contingency to line overload may be expressed in terms of the severity index (SI), which express the stress on the power system in the post contingency period

$$SI_j = \sum_{l=1}^{L_O} \left(\frac{S_l}{S_l^{\max}} \right)^2 \tag{3.15}$$

Where,

- S_l =MVA flow in line *l*.
- $S_l^{\max}$ = MVA rating of the line *l*.
- L_0 =set of overloaded lines.

To determine the best location of TCSC, a SCS index is calculated for all considered contingencies.

$$SCS_l = \sum_{j=1}^{n} SI_l \tag{3.16}$$

Where *n* is the number of allowed outage lines.

The SCS_l for branch *l* is defined as the sum of the sensitivities of branch *l* to all considered contingencies, where, SCS values are calculated for every branch using equation (3.15). Branches are then ranked by their corresponding SCS values. The branch with the largest SCS is considered as the best location for one TCSC. For a large scale power system, more than one TCSC may have to be installed in order to achieve the desired performance [72].

However, obvious budgetary constraints force the utilities to limit the number of TCSCs to be placed in a given system. Given such a limit on the total number of TCSCs to be installed in a power system, the locations of these TCSCs can be determined according to the ranking of branches and system topology. They will

be chosen starting from the top of this ranked list and proceeding downward with as many branches as the number of available TCSCs.

3.2 WHEELING COST

In this section, the Bialek's tracing method, the proportional sharing principle, upstream looking algorithm, downstream looking algorithm, and MVA-km wheeling cost method are discussed.

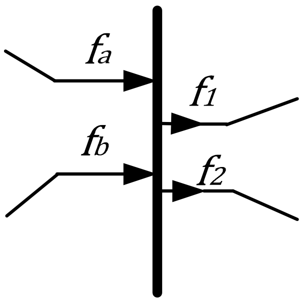
In Bialek's tracing method, it is assumed that nodal inflows are shared proportionally among nodal outflows. This method uses a topological approach to determine the contribution of individual generators or loads to every line flow based on the calculation of topological distribution factors. This method can deal with both dc power flow and ac power flows; that is, it can be used to find contributions of both active and reactive power flows. Bialek's tracing method considers:

- Two flows in each line, one entering the line and the other exiting the line (to consider losses in line).
- Generation and load at each bus.

Practically the only requirement for the input data is that Kirchhoffs Current Law must be satisfied for all the nodes in the network. In this respect the method

is equally applicable to real and reactive power flows and direct currents. Neglecting the Kirchhoff's Voltage Law does not introduce any further errors as the law has been already used to obtain the flows [73].

The main principle used to trace the power flow will be that of proportional sharing. Figure 3.4 shows four lines connected to a node. The outflows (f_1 and f_2) can be represented in terms of the inflows (f_a and f_b); in other words, we can determine how much of f_1 comes from f_a and how much of f_1 comes from f_b. The same applies to f_2.



$$f_1 = f_1 \frac{f_a}{f_a + f_b} + f_1 \frac{f_b}{f_a + f_b}$$

$$f_2 = f_2 \frac{f_a}{f_a + f_b} + f_2 \frac{f_b}{f_a + f_b}$$

Figure 3.4: Illustration of Proportional Sharing.

3.2.1 Tracing electricity using average line flows

Tracing electricity can be seen as a transportation problem of determining how the power injected by generators is distributed between the lines and loads of the network. The algorithm proposed in this study works only on lossless flows when the flows at the beginning and end of each line are the same.

The simplest way of obtaining lossless flows from the lossy ones is by assuming that a line flow is an average over the sending- and receiving-end flows and by adding half of the line loss to the power injections at each terminal node of the line [73].

3.2.2 Upstream looking algorithm

The algorithm for tracing the flow of electricity in this study is referred to as upstream looking as it looks at the flows inflowing to the network nodes. This technique develops a set of real power contribution factors and a set of reactive power contribution factors, which uses the results of AC power flow and the law of conservation of complex power. Using these contribution factors, the portion of generation of each generator in each transmission line and the portion of generation of each generator in the transmission losses can be calculated [73].

The upstream looking algorithm means to trace upstream to generators of source. It determines the gross power flow that shows how the power output from each of the generators would be distributed among the loads and lines. Under normal operation, all the power of generators is delivered to systems, but not from systems to generators.

The total flow P_i through node i (i.e. the sum of inflows or outflows) may be expressed, when looking at the inflows, as

$$p_{i} = \sum_{l \in \alpha_i^{(u)}} \left| P_{i-l} \right| + P_{Li} = \sum_{l \in \alpha_i^{(u)}} c_{li} P_l + P_{Li} \quad \text{for i= 1, 2, ..., n} \tag{3.17}$$

Where $\alpha_i^{(u)}$ is the set of nodes supplying directly node i (i.e. power must flow towards node i in the relevant lines), "P_{i-j}" is the line flow into node i in line j-i, and P_{Gi} is the generation at node i. As the losses have been eliminated,

$$\left| P_{j-i} \right| = \left| P_{i-j} \right| \tag{3.18}$$

The line flow $\left| P_{j-i} \right| = \left| P_{i-j} \right|$ can be related to the nodal flow at node j by substituting

$$\left| P_{i-j} \right| = c_{ji} P_j \tag{3.19}$$

Where $c_{ji} = \frac{\left| p_{j-i} \right|}{P_j}$ to give

$$P_i = \sum_{j \in \alpha_i^{(u)}} c_{ji} P_j + P_{Gi} \tag{3.20}$$

Which, on re-arrangement, becomes

$$P_i - \sum_{j \in \alpha_i^{(u)}} c_{ji} P_j = P_{Gi}$$

Or (3.21)

$$A_u P = P_G$$

Where A_u is the $(n \times n)$ upstream distribution matrix, P is the vector of nodal through flows and P_G is the vector of nodal generations. (i, j) element of A_u is equal to

$$[A_u]_{ij} = \begin{cases} 1 & for\ i = j \\ -c_{ji} = -\dfrac{\left|p_{j-i}\right|}{P_j} & for\ \ j \in \alpha_i^{(u)} \\ 0 & otherwise \end{cases} \tag{3.22}$$

Note that A_u is sparse and non symmetric. If A_u^{-1} exists

Then

$$P = A_u^{-1} P_G \tag{3.23}$$

And its i^{th} element is

$$P_i = \sum_{k=1}^{n} \left[A_u^{-1} \right]_{ik} P_{Gk} \qquad \text{for i = 1,2,..., n} \tag{3.24}$$

This equation shows that the contribution of the k^{th} system generator to i^{th} nodal power is equal to $\left[A_u^{-1} \right]_{ik} P_{Gk}$. Note that the same P_i is equal to the sum of the load demand, P_{Li} and outflows in lines leaving node i.

A line outflow in line (i-l) from node i can be therefore calculated, using the proportional sharing principle, as

$$\left|P_{i-l}\right| = \frac{\left|P_{i-l}\right|}{P_i} \sum_{k=1}^{n} \left[A_u^{-1}\right]_{ik} P_{Gk} \tag{3.25}$$

Similarly, the load demand P_{Li} can be calculated from *P,* as

$$p_{Li} = \frac{p_{Li}}{P_i} P_i = \frac{p_{Li}}{P_i} \sum_{k=1}^{n} \left[A_u^{-1}\right]_{ik} P_{Gk} \quad \text{for i = 1, 2, ..., n} \tag{3.26}$$

This equation shows that the contribution of the k^{th} generator to the i^{th} load demand is equal to $\frac{P_{Li}\, P_{Gk} \left[A_u^{-1}\right]_{ik}}{P_i}$ and can be used to trace where the power of a particular load comes from.

3.2.3 Downstream-looking algorithm

Now consider the dual, downstream-looking, problem when the nodal through-flow P_i is expressed as the sum of outflows [73]:

$$p_{i=} \sum_{l \in \alpha_i^{(d)}} \left|P_{i-l}\right| + P_{Li=} \sum_{l \in \alpha_i^{(d)}} c_{li} P_l + P_{Li} \quad \text{for i= 1, 2, ..., n} \tag{3.27}$$

Where $\alpha_i^{(d)}$ is, as before, the set of nodes supplied directly from node *i* and

$$c_{li} = \frac{\left|P_{i-l}\right|}{P_l}$$

This equation can be rewritten as

$$p_{i-}\sum_{l\in\alpha_i^{(d)}} c_{li}P_l = P_{Li}$$

$$A_d P = P_L \qquad (3.28)$$

Where A_d, is the *(n* x *n)* downstream distribution matrix and P_L is the vector of nodal demands. *(i, l)* element of A_d is equal to

$$\left[A_d\right]_{il} = \begin{cases} 1 & \text{for i = l} \\ -c_{li} = -\frac{\left|P_{i-l}\right|}{P_l} & \text{for } l \in \alpha_i^{(d)} \\ 0 & otherwise \end{cases} \qquad (3.29)$$

Note that A_d is also sparse and non symmetric. Adding A_u and A_d gives a symmetric matrix which has the same structure as the nodal admittance matrix. If A_d^{-1} exists then

$P = A_d^{-1}P_L$ and its i^{th} element is equal to

$$p_{i=}\sum_{k=1}^{n}\left[A_d^{-1}\right]_{ik} P_{Lk} \quad \text{i = 1, 2, ..., n} \qquad (3.30)$$

This equation shows how the nodal power P_i distributed between all the loads in the system. On the other hand, the same P_i is equal to the sum of the generation at node *i* and all the inflows in lines entering the node.

Hence the inflow to node *i* from line *i-j* can be calculated using the proportional sharing principle as

$$\left|P_{\text{i-j}}\right| = \frac{\left|P_{\text{i-j}}\right|}{P_i}P_i = \frac{\left|P_{\text{i-j}}\right|}{P_i}\sum_{k=1}^{n}\left[A_d^{-1}\right]_{ik} P_{Lk} \qquad (3.31)$$

The generation at a node is also an inflow and can be calculated using the proportional sharing principle as

$$P_{Gi} = \frac{P_{Gi}}{P_i} P_i = \frac{P_{Gi}}{P_i} \sum_{k=1}^{n} \left[A_d^{-1} \right]_{ik} P_{Lk} \quad \text{for i = 1, 2, ..., n} \tag{3.32}$$

This equation shows that the share of the output of the i^{th} generator used to supply the k^{th} load demand is equal to $\frac{P_{Gi} P_{Lk} \left[A_d^{-1} \right]_{ik}}{P_i}$ and can be used to trace where the power of a particular generator goes to.

3.2.4 MVA-km Method

Wheeling Cost of k^{th} Generator for Line i equals to [74]:

$$WheelingCost = l \left(\frac{Cent}{Hour.\ MVA.\ km} \right) S_{i,k}\ L_i \tag{3.33}$$

For a system with *nl branches* the total wheeling cost is computed as follows:

$$WheelingCost_{TOTAL} = \sum_{i=1}^{nl} l \left(\frac{Cent}{Hour.\ MVA.\ km} \right) S_i\ L_i \tag{3.34}$$

Where

- l : Weighting factor, in this study, $l=1$.
- $S_{i,k}$: Average MVA from generator k flows in branch *i.*
- S_i : Total Average MVA flows in branch *i.*
- L_i : Length of branch i (km).
- nl : Number of branches.

CHAPTER FOUR

PROBLEM FORMULATION

In this chapter, the problem will be formulated as a multi-objective optimal power flow problem (MO-OPF), with several constraints, control variables and selected objectives.

4.1 MULTI-OBJECTIVE OPTIMAL POWER FLOW

4.1.1 Overview

In a simple economic dispatch problem the aim is to find the MW output of all generating units which correspond to minimum possible fuel costs. The OPF not only seeks to find the optimal (minimum) fuel cost but also satisfies the power flow equations, load balance equation (equality constraints) and other equipment or operational controls such acceptable voltage range, equipment ratings (inequality constraints). Originally, OPF started in this form and later

other applications and requirements corresponding to other objectives were also considered in the problem, such as losses and stability [75].

4.1.2 Mathematical Formulation of the OPF

The general mathematical formulation of the multi-objective OPF can be written as shown below:

$$\min/\max\ F(x, u) = \left[f_1(x,u), f_2(x,u), \ldots, f_j(x,u), \ldots, f_n(x,u) \right] \tag{4.1}$$

Subject to: $$g(x,u) = 0 \tag{4.2}$$

$$h(x,u) \leq 0 \tag{4.3}$$

Where:

- n=1, 2,… number of objectives
- x: is a vector of dependent variables.
- u: is a vector of independent (control) variables.
- F: is a vector of objective functions.
- g(x,u): represents equality constraints.
- h(x,u): represents inequality constraints.

x includes:

- Real power P_{G1} generated at slack bus.
- Voltages at load buses V_L.
- Reactive power from generators Q_G.

- Power flow and loading on all branches; transmission lines and transformers S_l .

Hence, x can be expressed as

$$\mathbf{x}^T = [P_{G_1}, V_{L_1} \ldots V_{L_{NL}}, Q_{G_1} \ldots Q_{G_{NG}}, S_{l_1} \ldots S_{l_{nl}}] \tag{4.4}$$

Where N_L, N_G, and *nl* are number of load buses, number of generators, and number of transmission lines respectively.

u includes:

- Real power output P_G of all generator bus except at slack bus P_{G1}.
- Voltages at generator buses V_G.
- Reactive power from shunt elements Q_C.
- Transformer Taps T.

Hence, u can be expressed as

$$\mathrm{u}^T = [V_{G_1} \ldots V_{G_{NG}}, P_{G_2} \ldots P_{G_{NG}}, T_1 \ldots T_{NT}, Q_{c1} \ldots Q_{c_{NC}}] \tag{4.5}$$

Where NT and NC are the number of the regulating transformers and shunt compensators respectively.

4.1.3 OPF Equality Constraints

The term g(x,u) represents equality constraints, which are basically the power

flow equations. A solution that is defined by *u* (control elements), is input to the load flow equations to obtain the corresponding *x* vector (dependent variables).

$$P_{G_i} - P_{D_i} - V_i \sum_{j=1}^{NB} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] = 0 \tag{4.6}$$

$$Q_{G_i} - Q_{D_i} - V_i \sum_{j=1}^{NB} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] = 0 \tag{4.7}$$

4.1.4 OPF Inequality Constraints

1. Generation constraints:

Generator voltages, real power outputs, and reactive power outputs are restricted by their lower and upper limits as follows:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}, \quad i = 1,\ldots, NG \tag{4.8}$$

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}, \quad i = 1,\ldots, NG \tag{4.9}$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}, \quad i = 1,\ldots, NG \tag{4.10}$$

2. Transformer constraints:

Transformer tap settings are bounded as follows:

$$T_i^{\min} \le T_i \le T_i^{\max}, \quad i = 1,\ldots, NT \tag{4.11}$$

3. Shunt VAR constraints:

Shunt VAR compensations are restricted by their limits as follows:

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max}, \;\; i = 1,\ldots, NC \qquad (4.12)$$

4. Security constraints:

These include the constraints of voltages at load buses and transmission line Loadings as follows:

$$V_{L_i}^{\min} \le V_{L_i} \le V_{L_i}^{\max}, \;\; i = 1,\ldots, NL \qquad (4.13)$$

$$S_{l_i} \le S_{l_i}^{\max}, \;\; i = 1,\ldots, nl \qquad (4.14)$$

4.1.5 Objective Functions for Optimal Power Flow

Different objectives can be considered in the formulation of multi-objective OPF. The purpose of the OPF study will determine which objectives to be considered. In this section, we present several objectives which will be used in this study.

1. Fuel Cost Minimization for Economic Dispatch

The traditional Economic Dispatch (ED) problem can be considered as a special case of the OPF, which aims to minimize the fuel cost. The generation fuel cost can be modeled as a quadratic function, where each machine is characterized by three parameters *a, b* and *c,* which are used to calculate the fuel cost associated with generator real MW output power. For a system with *n* units the total fuel cost is computed as follows:

$$Fuel\ Cost = \sum_{i=1}^{n} (a_i + b_i * P_i + c_i * P_i^2) \quad \$ / Hour \tag{4.15}$$

2. Wheeling cost minimization

As mentioned before in section (3.2.4), the total wheeling cost can be defined as the following:

$$WheelingCost_{TOTAL} = \sum_{i=1}^{nl} l \ \frac{Cent}{Hour.\ MVA.\ km} \ S_i \ L_i \quad \text{(Cent/Hour)} \tag{4.16}$$

It is aimed to minimize this objective.

3. Congestion management by minimize severity index

As mentioned before in section (3.1.6) the severity index can be defined as the following:

$$SI_j = \sum_{l=1}^{L_O} \left(\frac{S_l}{S_l^{\max}} \right)^2 \tag{4.17}$$

It is aimed to minimize this objective.

CHAPTER FIVE

THE PROPOSED APPROACH FOR MULTI-OBJECTIVE OPTIMAL POWER FLOW

5.1 MULTI-OBJECTIVE OPTIMIZATION: PRINCIPLE AND DEFINITIONS

In real world, optimization problems often involve a set of different objectives to be optimized simultaneously. These objectives could be conflicting and/or different types. These types of problems are known as "Multi-objective Optimization Problems (MOP)" (also called multi-criteria optimization, multi-performance or vector optimization).

Solving multi-objective optimization problems produces number of optimal solutions, generally known as set of Pareto Optimal Solutions. These solutions are optimal in the sense that no other solution is superior to them and none of them can be considered better than the others.

5.1.1 Multi-Objective Problem Formulation

A multi-objective optimization problem is defined by a function F(x) which maps a vector *x* (decision vector) to a vector of (NO) objective values, subjected to a set of equality and inequality constraints. The aim of such a problem is to find a set of decision vectors which would optimize (maximize or minimize) all objectives. In a mathematical formulation, this problem can be written as follows:

$$\min/\max\ F(x) = \left[f_1(x), f_2(x), \ldots, f_j(x), \ldots, f_n(x) \right] \quad (5.1)$$

Subject to: $$g(x) = 0 \quad (5.2)$$

$$h(x) \leq 0 \quad (5.3)$$

5.1.2 Pareto Front and Pareto Optimality

In single objective optimization problems, the optimization process ends up with one solution being the optimal solution. This is because the problem involves only one objective and there would be only one solution which achieves the best

maximum or minimum depending on the problem. However, in multi-objective optimization problem, due to presence of several objective functions to be optimized, it is very likely that an improvement in one objective might be on the expense of another function, and therefore, would have multiple solutions. These solutions cannot be said better than each other. In this case there is no best solution and it is left to decision maker to decide which solution to choose.

Selection between different solutions is not straight forward in multi-objective. The performance of each solution with respect to other solutions is measured by comparing the value of corresponding objective functions. If a solution X_1 achieves better results for all objectives with respect to another solution X_2, then we say that X_1 dominates X_2. The best solution is known as Pareto Optimal, and the collection of optimal solutions is known as (Optimal Pareto Set).

The following definitions explain the comparison between performances of two vectors in MOPs [9]:

(a) In a minimization problem, for two solutions X^1 and X^2, we say that X^1 dominates X^2 if:

1. $\forall i \in [1,2,\ldots,N_{obj}] : f_i(X^1) \leq f_i(X^2)$ (5.4)

2. $\exists\, i \in [1,2,\ldots,N_{obj}] : f_i(X^1) < f_i(X^2)$ (5.5)

In other words, X^1 dominates X^2 if the values of objective functions computed with X^1 are less than or equal to those calculated with X^2, and at least one value in X^1 is less than the corresponding value in X^2. However, if

all values for objective functions of X^1 are equal to those for X^2, or at least one value of X^1 is bigger, then, X^2 is not dominated by X^1. After comparing all solutions, all the non-dominated solutions are put together to form the Pareto-Optimal set.

(b) For a solution X^1, we say X^1 is Pareto Optimal if it is not dominated by any other solution in the search space. In other way, X^1 is Pareto Optimal if there are no other solutions which will improve some of the objective without simultaneously worsening any of the other objectives.

5.1.3 Fitness Assignment

The word "Fitness" is commonly used to describe performance of solutions. In single objective optimization problems, the objective value is used as a fitness function. However, in multi-objective optimization problem we have set of objectives which are normally conflicting. Therefore, different approaches were proposed to compute fitness and compare solutions. Reference [77 - 82] reviews different approaches for fitness evaluation: aggregation, Non-Pareto and Pareto optimum based approaches.

- **Aggregating Based Techniques:**

For numerical objective values with different scale, the simplest way to express

the fitness function would be to define a new augmented objective function comprising of the original objectives, as follows:

$$\min \sum_{i=1}^{\#objectives} w_i f_i(x) C_i \tag{5.6}$$

Where, C_i acts as scaling factors and w_i represents the importance of objective i. Although this could be computationally a simple approach, it requires understanding of the problem in order to set the weighting factors otherwise some of the objectives might dominate the others. Also, in order to obtain Pareto optimal solutions, several runs maybe need to be performed with different weighting factors. Reference [79] summarizes several aggregating approaches such as: weighted sum, goal programming and ε-constraints method.

- **Non-Pareto Based Approaches**

To avoid the difficulties in the aggregating approaches, alternative approaches based on special handling of the population and the objectives, were proposed in the literature. References [79-80] review several approaches and techniques which fall under this category. For example, Vector Evaluated Genetic Algorithm (VEGA) handles the objectives separately by assigning sub-population to each objective. In other approaches, such as the Lexicographic Ordering, the objectives are ranked in order of importance, and then, the optimal solution is obtained by optimizing the objectives one at a time starting from the most important one.

- **Pareto Based Approaches**

In the Pareto based approaches, the selection/reproduction is performed on the basis of dominance [83]. Different approaches were proposed to define the fitness of a particle, such as comparison of all objectives or ranking based on the number of dominated solutions [79]. With these approaches and the help of evolutionary optimization techniques, it is possible to find multiple solutions in a single run.

Different evolutionary algorithms are now available, such as Genetic Algorithm, Particle Swarm, Differential Evolution and Ant Colony optimization techniques. Initially, these methods were proposed to solve single objective optimization problems and now they are being extended to solve multi-objective optimization problems. In the following sections, the PSO presented in the previous chapter will be extended to solve MOP based on the concept of dominance.

5.2 PROPOSED MOPSO BASED APPROACH

True MOP using the concept of PSO is already reported in the literature [84-99]. In this work, a MOPSO approach is developed and applied to solve a true MO-OPF. The basic procedure for PSO has been described in [100-104], and will be extended in this chapter to solve MOPs. This section starts first by addressing three points related to the feasibility, size/clustering of Pareto set and the best

compromise solution. These terms are normally involved under the subject of multi-objective, and also will be used in this work.

5.2.1 Multi-Objective Particle Swarm Optimization

5.2.1.1 Basic Elements and Definitions

The basic elements of the proposed MOPSO technique are briefly stated and defined as follows [84-99]: -

- ✓ **Nondominated local set,** $S_j^*(t)$,:

It is a set that stores the nondominated solutions obtained by the j^{th} particle up to the current time. As the j^{th} particle moves through the search space, its new position is added to this set and the set is updated to keep only the nondominated solutions. An average linkage based hierarchical clustering algorithm is employed to reduce the nondominated local set size if it exceeds a certain prespecified value.

- ✓ **Nondominated global set,** $S^{**}(t)$,:

It is a set that stores the nondominated solutions obtained by all particles up to the current time. First, the union of all nondominated local sets is formed. Then, the nondominated solutions out of this union are members in the nondominated global set.

✓ **External set**:

It is an archive that stores a historical record of the nondominated solutions obtained along the search process. This set is updated continuously after each iteration by applying the dominance conditions to the union of this set and the nondominated global set. Then, the nondominated solutions of this union are members in the updated external set.

✓ **Local best,** $X_j *(t)$, and **Global best,** $X_j**(t)$,:

In order to guide the search towards the Pareto-optimal front, the global and local best individuals are selected as follows. The individual distances between members in nondominated local set of the j^{th} particle, $S_j*(t)$, and members in nondominated global set, $S**(t)$, are measured in the objective space. If $X_j*(t)$ and $X_j**(t)$ are the members of $S_j*(t)$ and $S**(t)$ respectively that give the minimum distance, they are selected as the local best and the global best of the j^{th} particle respectively.

5.2.1.2 Multi-Objective PSO Steps

The steps for MOPSO can be summarized as following [84-99]:-

Step 1: Initialization:

Set the time counter t=0 and generate randomly n particles, $\{X_j(0), j=1, \ldots, n\}$, where $X_j(0)=[x_{j,1}(0), \ldots, x_{j,m}(0)]$. $x_{j,k}(0)$ is generated by randomly selecting a value

with uniform probability over the k^{th} optimized parameter search space [x_k^{min} , x_k^{max}]. Similarly, generate randomly initial velocities of all particles, {$V_j(0)$, j=1, ..., n}, where $V_j(0)=[v_{j,1}(0), ..., v_{j,m}(0)]$. $v_{j,k}(0)$ is generated by randomly selecting a value with uniform probability over the k^{th} dimension [$-v_k^{max}$, v_k^{max}]. Each particle in the initial population is evaluated using the objective functions. For each particle, set $Sj^*(0)=\{Xj(0)\}$ and the local best $Xj^*(0)=Xj(0)$, j=1, ..., n. Search for the nondominated solutions and form the nondominated global set $S^{**}(0)$. The nearest member in $S^{**}(0)$ to $Xj^*(0)$ is selected as the global best $Xj^{**}(0)$ of the j^{th} particle. Set the external set equal to $S^{**}(0)$. Set the initial value of the inertia weight $w(0)$.

Step 2: Time updating:

Update the time counter $t = t+1$.

Step 3: Weight updating:

Update the inertia weight $w(t) = \alpha w(t-1)$.

Step 4: Velocity updating:

Using the global best and individual best of each particle, the j^{th} particle velocity in the k^{th} dimension is updated according to equation(5.2):

Step 5: Position updating:

Based on the updated velocities, each particle changes its position according to

equation (5.3). If a particle violates the its position limits in any dimension, set its position at the proper limit.

Step 6: Nondominated local set updating:

The updated position of the j^{th} particle is added to *Sj*(t).* The dominated solutions in *Sj*(t)* will be truncated and the set will be updated accordingly. If the size of *Sj*(t)* exceeds a prespecified value, the clustering algorithm will be invoked to reduce the size to its maximum limit.

Step 7: Nondominated global set updating:

The union of all nondominated local sets is formed and the nondominated solutions out of this union are extracted to be members in the nondominated global set *S**(t)*. The size of this set will be reduced by clustering algorithm if it exceeds a prespecified value.

Step 8: External set updating:

The external Pareto-optimal set is updated as follows.

Copy the members of *S**(t)* to the external Pareto set.

1. Search the external Pareto set for the nondominated individuals and remove all dominated solutions from the set.

2. If the number of the individuals externally stored in the Pareto set exceeds the maximum size, reduce the set by means of clustering.

Step 9: Local best and global best updating:

The individual distances between members in $S_j^*(t)$, and members in *S**(t),* are

measured in the objective space. If $X_j{*}(t)$ and $X_j{**}(t)$ are the members of $S_j{*}(t)$ and $S{**}(t)$ respectively that give the minimum distance, they are selected as the local best and the global best of the j^{th} particle respectively.

Step 10: Stopping criteria:

If the number of iterations exceeds its maximum preset limit then stop, else go to step 2.

The Figure 5.1 shows these ten steps.

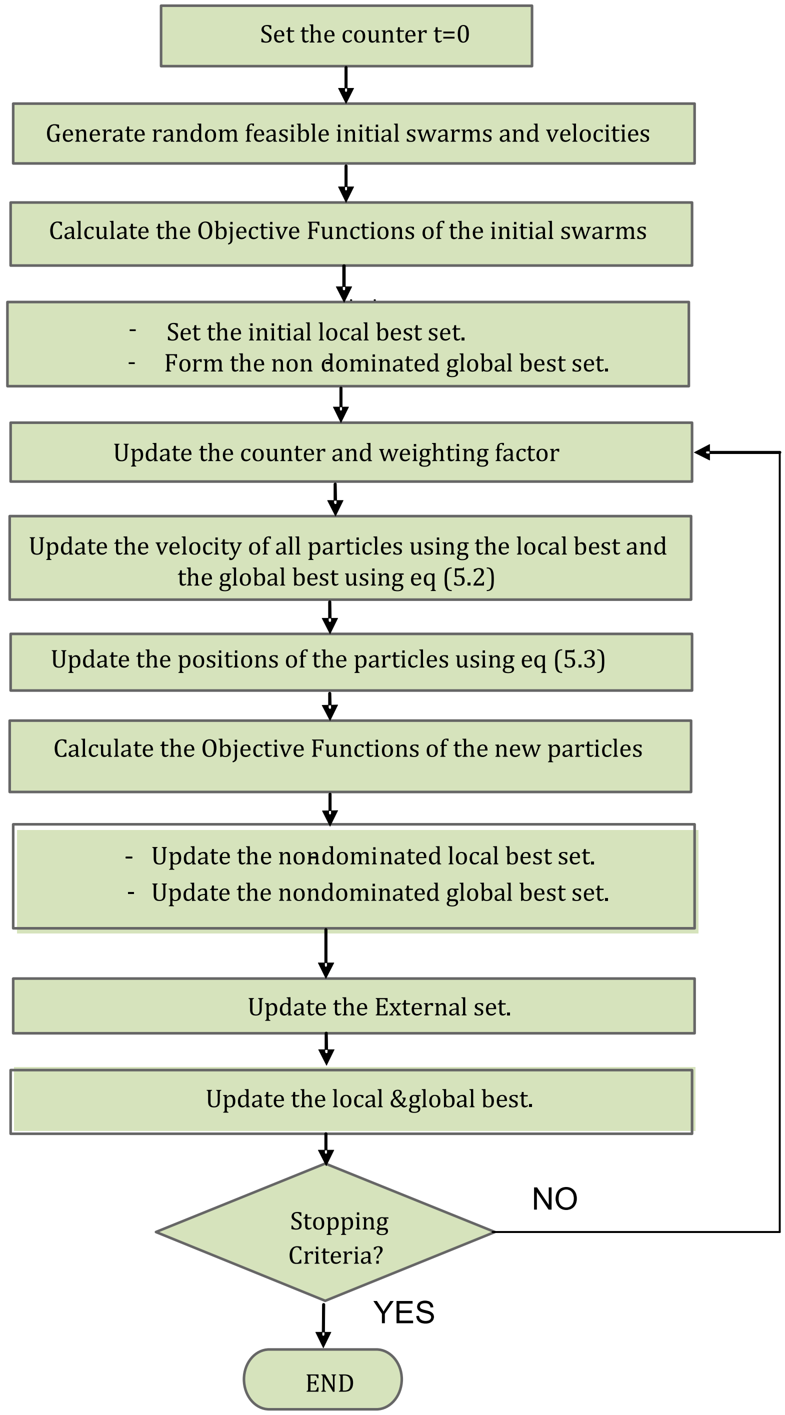


Figure 5.1: Flow Chart of MOPSO.

5.3 LIMITING THE SIZE OF PARETO SET BY CLUSTERING

In some problems, the Pareto optimal set can be extremely large. In this case, reducing the set of nondominated solutions without destroying the characteristics of the trade-off front is desirable from the decision maker's point of view. An average linkage based hierarchical clustering algorithm [105-107] is employed to reduce the Pareto set to manageable size. It works iteratively by joining the adjacent clusters until the required number of groups is obtained. It can be described as: given a set P which its size exceeds the maximum allowable size N, it is required to form a subset P^* with the size N. The algorithm is illustrated in the following steps.

Step 1: Initialize cluster set C; each individual $i \in P$ constitutes a distinct cluster.

Step 2: If number of clusters ≤ N, then go to Step 5, else go to Step 3.

Step 3: Calculate the distance of all possible pairs of clusters. The distance d_c of two clusters c_1 and $c_2 \in C$ is given as the average distance between pairs of individuals across the two clusters

$$d_c = \frac{1}{n_1 . n_2} \sum_{i_1 \in c_1, i_2 \in c_2} d(i_1, i_2) \tag{5.7}$$

Where n_1 and n_2 are the number of individuals in the clusters c_1 and c_2 respectively. The function d reflects the distance in the objective space between individuals i_1 and i_2.

Step 4: Determine two clusters with minimal distance d_c. Combine them into a larger one. Go to Step 2.

Step 5: Find the centroid of each cluster. Select the nearest individual in this cluster to the centroid as a representative individual and remove all other individuals from the cluster.

Step 6: Compute the reduced nondominated set P^* by uniting the representatives of the clusters.

5.4 BEST COMPROMISE SOLUTION

Although the multi-objective problem gives more than one solution, for the purpose of decision making and perhaps practical reasons, one is interested in only one solution (best compromise). In a minimization problem, this solution would be the one closer to the origin of the problem. One of the most widely used techniques in this regard is based on fuzzy set theory [108-109].

The procedure of this technique can be explained as follows:

- Search through all solutions to find F^{max} and F^{min} corresponding to each objective function. In a minimization problem F^{min} represents the best solution and F^{max} is the worst solution with respect to a certain objective function.

- Use the following linear membership function to calculate a membership function for each objective of all solutions.

$$u_i = \begin{cases} 1 & F_i = F_i^{\min} \\ \dfrac{F_i^{\max} - F_i}{F_i^{\max} - F_i^{\min}} & F_i^{\min} < F_i < F_i^{\max} \\ 0 & F_i = F_i^{\max} \end{cases} \tag{5.8}$$

From the above definition, $u_i = 1$ is completely satisfactorily, and $u_i = 0$ is not satisfactory. For a value in between, u_i will be between *1* and *0*. The above equation gives a measure of the degree of satisfaction for each objective function for a particular solution. It also scales the objective function into the range *1 ~ 0*, as shown in Figure 6.2.

- The corresponding membership function for a non-dominated solution *k*, is calculated as follows:

$$u^k = \frac{\sum_{i=1}^{NO} u_i^k}{\sum_{k=1}^{M} \sum_{i=1}^{NO} u_i^k} \tag{5.9}$$

Where,

M	Number of pareto solutions
NO	Number of objective functions

Finally, the solution that achieves the maximum membership function (u^k) represents the best compromise solution.

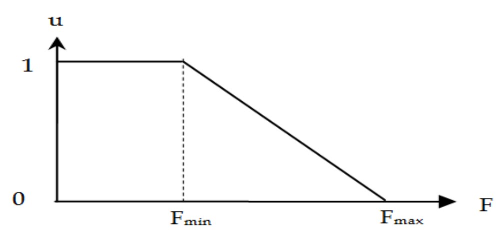


Figure 5.2: The Membership Function.

CHAPTER SIX

SIMULATION RESULTS FOR SINGLE OBJECTIVE OPTIMAL POWER FLOW

For the proposed PSO based approach, a source code was developed and implemented in MATLAB. The source code includes modules to perform the normal load flow, check feasibility, objectives calculations, and optimization. In this chapter, single objective OPF case studies will be simulated using the proposed approach considering the following objectives:

1. Fuel cost.
2. Wheeling cost.
3. Congestion management using TCSC (severity index).

In this study, two systems will be used to test the proposed approach IEEE 30-bus test system, and 87-bus real system. This chapter starts by brief descriptions of these systems

6.1 TEST SYSTEMS DATA

6.1.1 The IEEE-30 Bus Test System

This system is commonly used in various studies for different researches including OPF. This system includes 6 generators, 4 transformers, 41 branches, and 9 shunt elements. The total generation capacity is 600 MVA, the total load is 283.4 MW and 126.2 MVAR.

The data for this system is given in appendix-I that summarizes the data for buses, generators, transmission lines, transformers, loads, shunt elements, and cost coefficients. Figure 6.1 shows the single line diagram of the system.

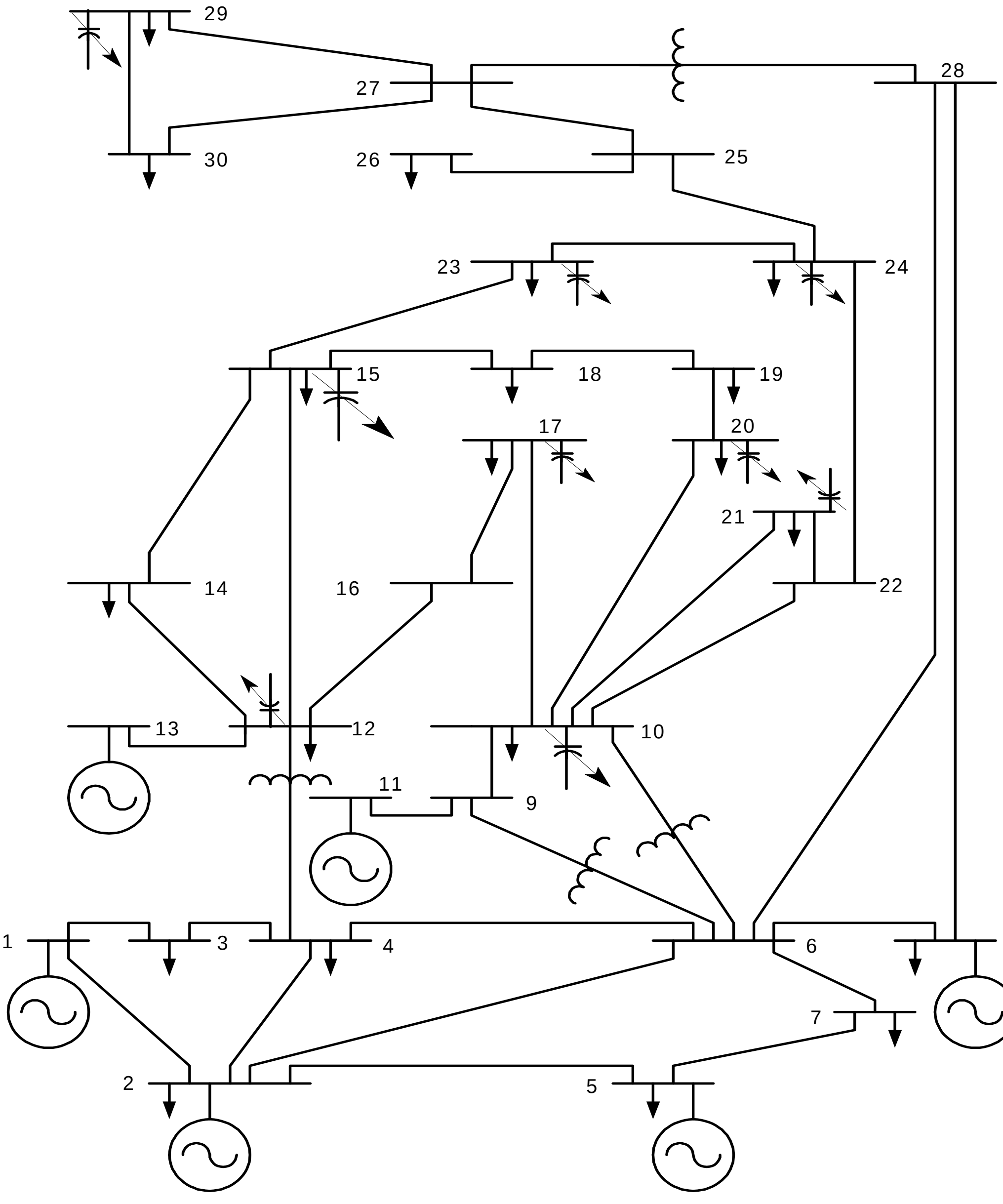


Figure 6.1: Single line diagram of IEEE 30-bus test system.

6.1.2 Data for Real System

The 87-bus real system includes 17 generators, 33 transformers, 167 transmission lines. The total generation and load of the system can be summarized as the following:

The total real power generation is	13009.82 MW
The total reactive power generation is	4595 MVAR
The total real power load is	12843.42 MW
The total reactive power load is	5504.42 MVAR

Assumptions due to lack of information:

1. The real power generation limits.
2. The reactive power generation limits.
3. The transmission lines capacity.
4. The transmission lines length.

The first three assumptions have been determined due to load flow results for base case, while the fourth one has been determined by using resistance value. The complete data of the system is given in appendix II.

6.2 SINGLE OBJECTIVE OPF WITH IEEE-30 BUS TEST SYSTEM

The following sub-sections present the results for the single objective OPF case studies performed on IEEE_30-bus test system using the proposed approach. Three cases are performed for the individual objective functions: fuel cost, wheeling cost and congestion management. In all of the single objective cases, the following parameters of the PSO were used: Population = 50, Iteration = 500, number of intervals = 10, inertia weight= 0.98, and velocity constants c_1=c_2=2.

6.2.1 Case-SO1: Fuel Cost Optimization

Using the quadratic generator cost model presented in equation (4.15) a single objective OPF using PSO was simulated with all parameters as mentioned before. Table 6.1 shows the optimized fuel cost for IEEE_30-bus test system and the corresponding settings for the control variables. The results show that the fuel cost reduced by 11.4%, and it can be seen that the relation between the fuel cost and other objectives is contradictory in nature. Figure 6.2 shows the fuel cost optimization of the system. The result mentioned above was compared to those in literature as shown in Table 6.2. Comparison shows that the proposed approach has produced better result.

TABLE 6.1: IEEE-30-bus test system, objective values and settings of control variables at optimal fuel cost (Case-SO1).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Generators Output (MW)	P_1	50	200	99.23	177.24
	P_2	20	80	80.00	48.77
	P_5	15	50	50.00	21.33
	P_8	10	35	20.00	21.19
	P_{11}	10	30	20.00	11.55
	P_{13}	12	40	20.00	12.00
Generators Voltage (p.u.)	V_1	0.95	1.10	1.05	1.10
	V_2	0.95	1.10	1.04	1.04
	V_5	0.95	1.10	1.01	1.06
	V_8	0.95	1.10	1.01	1.10
	V_{11}	0.95	1.10	1.05	1.10
	V_{13}	0.95	1.10	1.05	1.10
Transformer Taps Position	T_{6-9}	0.90	1.10	1.08	0.94
	T_{6-10}	0.90	1.10	1.07	1.10
	T_{4-12}	0.90	1.10	1.03	1.03
	T_{28-27}	0.90	1.10	1.07	0.98
Shunt Elements (MVAR)	Qc_{10}	0.00	5.00	0.00	5.00
	Qc_{12}	0.00	5.00	0.00	4.96
	Qc_{15}	0.00	5.00	0.00	5.00
	Qc_{17}	0.00	5.00	0.00	3.49
	Qc_{20}	0.00	5.00	0.00	3.24
	Qc_{21}	0.00	5.00	0.00	5.00
	Qc_{23}	0.00	5.00	0.00	0.52
	Qc_{24}	0.00	5.00	0.00	5.00
	Qc_{29}	0.00	5.00	0.00	2.51
OBJECTIVE VALUES					
Fuel Cost ($/Hour)				**901.84**	**799.21**
Wheeling Cost ($/Hour)				1,796.81	1,835.04
Severity Index				4.31	4.65

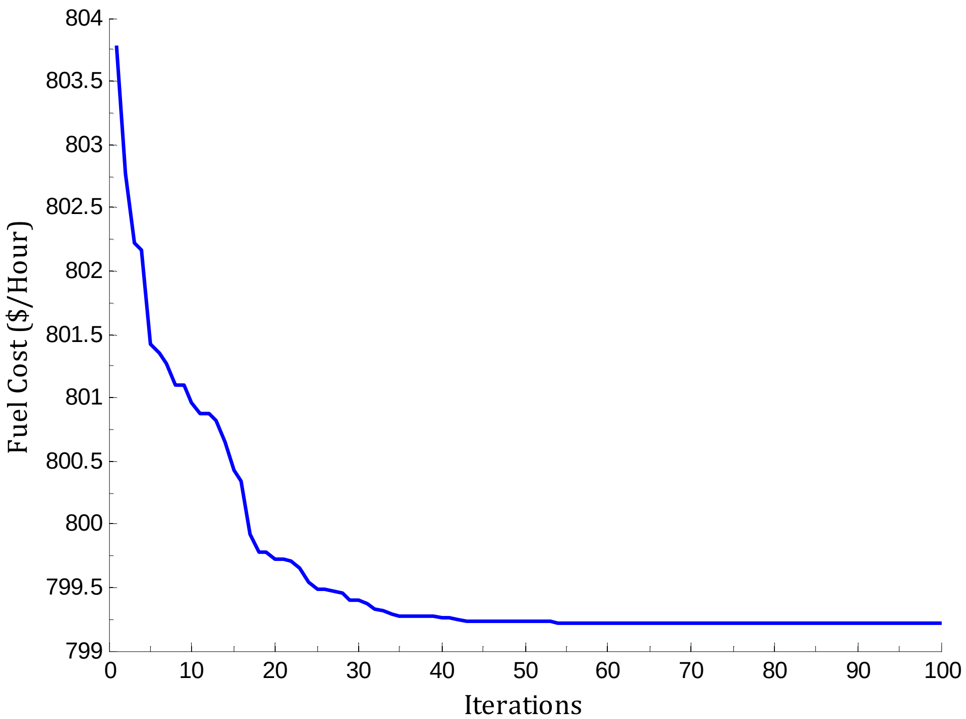


Figure 6.2: IEEE_30-bus test system, fuel cost optimization (Case-SO1).

TABLE 6.2: Comparison between fuel cost optimization result for IEEE 30-bus with literature results.

Reference#	Approach	Fuel Cost ($/Hour)
[110]	Gradient Projection Method	804.850
[112]	Tabu Search Algorithm	802.290
[111]	Genetic Algorithm	802.060
[113]	Binary Particle Swarm Optimization	801.560
[8]	Differential Evolution	800.560
----	**The Proposed Approach (PSO)**	**799.210**

6.2.2 Case-SO2: Wheeling Cost Optimization.

Using upstream and downstream looking algorithm and MAV-km method the wheeling cost of the whole system can be determined as presented in section 3.2.

- **<u>Tracing real power flow</u>**

Using the equation (3.26) can be determined the amount of real power supplied by a particular generator to a particular load and how the demand in each of the loads can be calculated as the sum of contributions from individual generators as shown in the Table 6.3.

- **<u>Tracing reactive power flows:</u>**

As the only requirement for the proposed method is that Kirchhoff's current law must be obeyed, the method is equally well applicable to trace reactive power flows. The main problem with reactive flows, however, is that the reactive power loss of a line may be quite considerable when compared with the flow itself.

To deal with this problem additional, fictitious, nodes need to be added in the middle of each line which will act as reactive power sources or sinks responsible for line generation/consumption. The nodes numbered from 31 to 71 are the fictitious line nodes in order with the lines in Table I.2. Nodes 31, 32, 33, 34, 35,

36, 37, 39, 40, 41, 44 and 45 act as the reactive power sources while nodes 38, 42, 43, and nodes 46 to 71 act as the reactive power sinks.

The Table 6.4 allows one to trace how reactive power flows all over the network. The Tables 6.5 and 6.6 show real and reactive power contribution of the generators in each line respectively.

TABLE 6.3: IEEE_30-bus test system, distribution of real power using upstream looking algorithm.

Load (MW)	Generation (MW)						
	G_1	G_2	G_5	G_8	G_{11}	G_{13}	Total
L_2	9.22	12.48	-	-	-	-	21.70
L_3	2.84	-	-	-	-	-	2.84
L_4	5.92	2.10	-	-	-	-	8.02
L_5	18.99	25.72	49.5	-	-	-	94.20
L_7	13.02	9.81	0.05	-	-	-	22.87
L_8	6.34	4.77	-	18.89	-	-	30.00
L_{10}	1.81	1.36	-	-	2.77	-	5.94
L_{12}	4.92	1.74	-	-	-	4.84	11.51
L_{14}	2.68	0.95	-	-	-	2.64	6.27
L_{15}	3.63	1.28	-	-	-	3.57	8.48
L_{16}	1.54	0.55	-	-	-	1.52	3.60
L_{17}	3.32	1.71	-	-	2.06	1.94	9.03
L_{18}	1.39	0.49	-	-	-	1.37	3.25
L_{19}	3.32	1.92	-	-	2.84	1.44	9.52
L_{20}	0.68	0.51	-	-	1.05	-	2.24
L_{21}	5.35	4.03	-	-	8.19	-	17.57
L_{23}	1.40	0.50	-	-	-	1.38	3.28
L_{24}	3.02	1.79	-	-	2.76	1.19	8.77
L_{26}	1.70	1.23	-	0.18	0.29	0.13	3.53
L_{29}	1.32	0.99	-	0.17	-	-	2.47
L_{30}	5.70	4.29	-	0.73	-	-	10.72
Total	98.58	78.57	49.54	19.98	20.00	20.00	286.67

TABLE 6.4: IEEE_30-bus test system, distribution of reactive power using downstream looking algorithm.

Load (MVAR)	Generation (MVAR)														
	G_2	G_{11}	G_{13}	G_{31}	G_{32}	G_{33}	G_{34}	G_{35}	G_{36}	G_{37}	G_{39}	G_{40}	G_{41}	G_{44}	G_{45}	Total
L_1	-	-	-	1.54	-	-	-	-	-	-	-	-	-	-	-	1.54
L_3	-	-	-	0.62	0.58	-	-	-	-	-	-	-	-	-	-	1.20
L_4	-	-	0.51	0.30	0.28	0.40			0.11	-	-	-	-	-	-	1.60
L_5	1.45	-	-	0.39		0.46	0.29	-	-	-	-	-	-	-	-	2.58
L_7	1.40	3.60	0.31	0.55	0.17	0.68	0.27	0.35	0.06	0.12	2.06	1.30	-	-	-	10.88
L_8	0.05	8.60	0.74	0.45	0.41	0.58	-	0.84	0.15	0.28	-	-	0.80	-	3.56	16.46
L_{10}	-	1.89	0.11	-	-	-	-	-	-	-	-	-	-	-	-	2.00
L_{12}	-	-	7.49	-	-	-	-	-	-	-	-	-	-	-	-	7.49
L_{14}	-	-	1.60	-	-	-	-	-	-	-	-	-	-	-	-	1.6
L_{15}	-	-	2.50	-	-	-	-	-	-	-	-	-	-	-	-	2.50
L_{16}	-	-	1.80	-	-	-	-	-	-	-	-	-	-	-	-	1.80
L_{17}	-	-	5.80	-	-	-	-	-	-	-	-	-	-	-	-	5.80
L_{18}	-	-	0.90	-	-	-	-	-	-	-	-	-	-	-	-	0.90
L_{19}	-	-	3.40	-	-	-	-	-	-	-	-	-	-	-	-	3.40
L_{20}	-	0.53	0.16	-	-	-	-	-	-	-	-	-	-	-	-	0.70
L_{21}	-	10.59	0.61	-	-	-	-	-	-	-	-	-	-	-	-	11.19
L_{23}	-	-	1.60	-	-	-	-	-	-	-	-	-	-	-	-	1.60
L_{24}	-	2.35	4.34	-	-	-	-	-	-	-	-	-	-	-	-	6.69
L_{26}	0.01	0.91	0.92	0.02	0.02	0.03	-	0.04	0.01	-	-	-	-	0.20	0.13	2.30
L_{29}	0.01	0.41	0.04	0.02	0.02	0.03	-	0.04	0.01	0.01	-	-	-	0.19	0.13	0.90
L_{30}	0.01	0.88	0.08	0.05	0.04	0.06	-	0.09	0.02	0.03	-	-	-	0.40	0.27	1.90
L_{38}	-	-	1.99	-	-	-	-	-	-	-	-	-	-	-	-	1.99
L_{42}	-	0.84		-	-	-	-	-	-	-	-	-	-	-	-	0.84
L_{43}	-	0.67	0.04	-	-	-	-	-	-	-	-	-	-	-	-	0.70
L_{46}	-	3.48		-	-	-	-	-	-	-	-	-	-	-	-	3.48
L_{47}	-	1.62		-	-	-	-	-	-	-	-	-	-	-	-	1.62
L_{48}	-	0.15	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.16
L_{49}	-	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	0.02
L_{50}	-	0.29	0.02	-	-	-	-	-	-	-	-	-	-	-	-	0.31
L_{51}	-	0.13	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.14
L_{52}	-	-	2.49	-	-	-	-	-	-	-	-	-	-	-	-	2.49
L_{53}	-	-	0.23	-	-	-	-	-	-	-	-	-	-	-	-	0.23
L_{54}	-	-	0.71	-	-	-	-	-	-	-	-	-	-	-	-	0.71
L_{55}	-	-	0.30	-	-	-	-	-	-	-	-	-	-	-	-	0.30
L_{56}	-	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	0.02
L_{57}	-	-	0.16	-	-	-	-	-	-	-	-	-	-	-	-	0.16
L_{58}	-	-	0.20	-	-	-	-	-	-	-	-	-	-	-	-	0.20
L_{59}	-	-	0.14	-	-	-	-	-	-	-	-	-	-	-	-	0.14
L_{60}	-	-	0.04	-	-	-	-	-	-	-	-	-	-	-	-	0.04
L_{61}	-	-	0.03	-	-	-	-	-	-	-	-	-	-	-	-	0.03
L_{62}	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
L_{63}	-	0.10	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.11
L_{64}	-	-	0.11	-	-	-	-	-	-	-	-	-	-	-	-	0.11
L_{65}	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
L_{66}	0.01	0.03	0.03	-	-	-	-	-	-	-	-	-	-	-	-	0.08
L_{67}	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02
L_{68}	-	0.59	0.05	0.03	0.03	0.04	-	0.06	0.01	0.02	-	-	-	0.27	0.18	1.27
L_{69}	-	0.09	0.01			0.01	-	0.01	0.01	-	-	-	-	0.04	0.03	0.20
L_{70}	-	0.17	0.02	0.01	0.01	0.01	-	0.02	-	0.01	-	-	-	0.08	0.05	0.38
L_{71}	-	0.04	-	-	-	-	-	-	-	0.01	-	-	-	0.02	0.01	0.08
Total	2.91	37.97	39.52	3.99	1.57	2.30	0.56	1.45	0.37	0.48	2.06	1.3	0.8	1.21	4.36	100.9

TABLE 6.5: IEEE_30-bus test system, real power contribution of generators to lines.

Line Bus - Bus	Generation (MW)						Total
	G_1	G_2	G_5	G_8	G_{11}	G_{13}	
1-2	58	-	-	-	-	-	58
1-3	40.58	-	-	-	-	-	40.58
2-4	13.34	18.07	-	-	-	-	31.41
3-4	37.74	-	-	-	-	-	37.74
2-5	19	25.74	-	-	-	-	44.74
2-6	16.44	22.27	-	-	-	-	38.72
4-6	24.81	8.78	-	-	-	-	33.58
5-7	0.02	0.02	0.05	-	-	-	0.09
6-7	13	9.79	-	-	-	-	22.79
6-8	6.71	5.05	-	-	-	-	11.75
6-9	6.96	5.24	-	-	-	-	12.2
6-10	6.11	4.6	-	-	-	-	10.71
9-11	-	-	-	-	20	-	20
9-10	6.96	5.24	-	-	20	-	32.2
4-12	20.35	7.2	-	-	-	-	27.55
12-13	-	-	-	-	-	20	20
12-14	3.64	1.29	-	-	-	3.58	8.5
12-15	8.27	2.93	-	-	-	8.13	19.33
12-16	3.51	1.24	-	-	-	3.45	8.21
14-15	0.96	0.34	-	-	-	0.95	2.24
16-17	1.97	0.70	-	-	-	1.94	4.60
15-18	2.85	1.01	-	-	-	2.81	6.67
18-19	1.47	0.52	-	-	-	1.44	3.42
19-20	1.86	1.40	-	-	2.84	-	6.09
10-20	2.54	1.91	-	-	3.89	-	8.34
10-17	1.35	1.02	-	-	2.06	-	4.43
10-21	4.95	3.73	-	-	7.58	-	16.26
10-22	2.42	1.82	-	-	3.70	-	7.94
21-22	0.4	0.30	-	-	0.61	-	1.31
15-23	2.75	0.97	-	-	-	2.70	6.42
22-24	2	1.50	-	-	3.06	-	6.56
23-24	1.35	0.48	-	-	-	1.32	3.14
24-25	0.32	0.19	-	-	0.29	0.13	0.93
25-26	1.7	1.23	-	0.18	0.29	0.13	3.53
25-27	1.4	1.05	-	0.18	-	-	2.63
28-27	8.5	6.40	-	1.09	-	-	15.98
27-29	3.28	2.47	-	0.42	-	-	6.17
27-30	3.74	2.81	-	0.48	-	-	7.03
29-30	1.96	1.48	-	0.25	-	-	3.69
8-28	0.37	0.28	-	1.09	-	-	1.73
6-28	8.14	6.13	-	-	-	-	14.27

TABLE 6.6: IEEE_30-bus test system, reactive power contribution of generators to lines.

Line	Generation (MVAR)														
Bus - Bus	G_{2}	G_{11}	G_{13}	G_{31}	G_{32}	G_{33}	G_{34}	G_{35}	G_{36}	G_{37}	G_{39}	G_{40}	G_{41}	G_{44}	G_{45}	Total
31-1	-	-	-	3.22	-	-	-	-	-	-	-	-	-	-	-	3.22
31-2	-	-	-	0.77	-	-	-	-	-	-	-	-	-	-	-	0.77
1-32	-	-	-	1.67	-	-	-	-	-	-	-	-	-	-	-	1.68
32-3	-	-	-	1.67	1.57	-	-	-	-	-	-	-	-	-	-	3.24
33-2	-	-	-	-	-	0.92	-	-	-	-	-	-	-	-	-	0.92
33-4	-	-	-	-	-	1.37	-	-	-	-	-	-	-	-	-	1.37
2-34	2.83	-	-	0.75	-	0.9	-	-	-	-	-	-	-	-	-	4.51
34-5	2.83	-	-	0.75	-	0.9	0.56	-	-	-	-	-	-	-	-	5.07
2-35	0.08	-	-	0.02	-	0.03	-	-	-	-	-	-	-	-	-	0.13
35-6	0.08	-	-	0.02	-	0.03	-	1.45	-	-	-	-	-	-	-	1.58
3-36	-	-	-	1.05	0.99	-	-	-	-	-	-	-	-	-	-	2.04
36-4	-	-	-	1.05	0.99	-	-	-	0.37	-	-	-	-	-	-	2.41
4-37	-	-	1.26	0.75	0.7	0.98	-	-	0.26	-	-	-	-	-	-	3.95
37-6	-	-	1.26	0.75	0.7	0.98	-	-	0.26	0.48	-	-	-	-	-	4.43
38-4	-	-	1.77	-	-	-	-	-	-	-	-	-	-	-	-	1.77
12-38	-	-	3.76	-	-	-	-	-	-	-	-	-	-	-	-	3.76
5-39	1.38	-	-	0.37	-	0.44	0.27	-	-	-	-	-	-	-	-	2.48
39-7	1.38	-	-	0.37	-	0.44	0.27	-	-	-	2.06	-	-	-	-	4.54
6-40	0.02	3.6	0.31	0.19	0.17	0.24	-	0.35	0.06	0.12	-		-	-	-	5.07
40-7	0.02	3.6	0.31	0.19	0.17	0.24	-	0.35	0.06	0.12	-	1.3	-	-	-	6.36
6-41	0.05	8.6	0.74	0.45	0.41	0.58	-	0.84	0.15	0.28	-	-	-	-	-	12.1
41-8	0.05	8.6	0.74	0.45	0.41	0.58	-	0.84	0.15	0.28	-		0.8	-	-	12.9
42-6	-	14.56	-	-	-	-	-	-	-	-	-	-	-	-	-	14.56
9-42	-	15.4	-	-	-	-	-	-	-	-	-	-	-	-	-	15.42
43-6	-	0.27	0.02	-	-	-	-	-	-	-	-	-	-	-	-	0.29
10-43	-	0.94	0.05	-	-	-	-	-	-	-	-	-	-	-	-	0.99
6-44	0.01	2.64	0.23	0.14	0.12	0.18	-	0.26	0.05	0.09	-	-	-	-	-	3.71
44-28	0.01	2.64	0.23	0.14	0.12	0.18	-	0.26	0.05	0.09	-	-	-	1.21	-	4.92
45-8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.56	3.56
45-28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.8	0.8
46-9	-	34.5	-	-	-	-	-	-	-	-	-	-	-	-	-	34.5
11-46	-	37.97	-	-	-	-	-	-	-	-	-	-	-	-	-	37.97
9-47	-	19.09	-	-	-	-	-	-	-	-	-	-	-	-	-	19.09
47-10	-	17.47	-	-	-	-	-	-	-	-	-	-	-	-	-	17.47
10-48	-	0.69	0.04	-	-	-	-	-	-	-	-	-	-	-	-	0.73
48-20	-	0.53	0.03	-	-	-	-	-	-	-	-	-	-	-	-	0.56
49-10	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	1
17-49	-	-	1.02	-	-	-	-	-	-	-	-	-	-	-	-	1.02
10-50	-	9.56	0.55	-	-	-	-	-	-	-	-	-	-	-	-	9.11
50-21	-	9.27	0.53	-	-	-	-	-	-	-	-	-	-	-	-	9.8
10-51	-	4.4	0.25	-	-	-	-	-	-	-	-	-	-	-	-	4.65
51-22	-	4.27	0.24	-	-	-	-	-	-	-	-	-	-	-	-	4.51
52-12	-	-	37.03	-	-	-	-	-	-	-	-	-	-	-	-	37.03
13-52	-	-	39.52	-	-	-	-	-	-	-	-	-	-	-	-	39.52
12-53	-	-	3.87	-	-	-	-	-	-	-	-	-	-	-	-	3.87
53-14	-	-	3.64	-	-	-	-	-	-	-	-	-	-	-	-	3.64
12-54	-	-	12.85	-	-	-	-	-	-	-	-	-	-	-	-	12.85
54-15	-	-	12.14	-	-	-	-	-	-	-	-	-	-	-	-	12.14
12-55	-	-	9.05	-	-	-	-	-	-	-	-	-	-	-	-	9.05
55-16	-	-	8.75	-	-	-	-	-	-	-	-	-	-	-	-	8.75
14-56	-	-	2.05	-	-	-	-	-	-	-	-	-	-	-	-	2.05
56-15	-	-	2.03	-	-	-	-	-	-	-	-	-	-	-	-	2.03
15-57	-	-	4.65	-	-	-	-	-	-	-	-	-	-	-	-	4.65

TABLE 6.6: IEEE_30-bus test system, reactive power contribution of generators to lines (Contd).

Line	Generation (MVAR)														
Bus - Bus	G_2	G_{11}	G_{13}	G_{31}	G_{32}	G_{33}	G_{34}	G_{35}	G_{36}	G_{37}	G_{39}	G_{40}	G_{41}	G_{44}	G_{45}	Total
57-18	-	-	4.49	-	-	-	-	-	-	-	-	-	-	-	-	4.49
15-58	-	-	7.01	-	-	-	-	-	-	-	-	-	-	-	-	7.01
58-23	-	-	6.82	-	-	-	-	-	-	-	-	-	-	-	-	6.82
16-59	-	-	6.96	-	-	-	-	-	-	-	-	-	-	-	-	6.96
59-17	-	-	6.81	-	-	-	-	-	-	-	-	-	-	-	-	6.81
18-60	-	-	3.59	-	-	-	-	-	-	-	-	-	-	-	-	3.59
60-19	-	-	3.56	-	-	-	-	-	-	-	-	-	-	-	-	3.56
22-24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19-61	-	-	0.16	-	-	-	-	-	-	-	-	-	-	-	-	0.16
61-20	-	-	0.13	-	-	-	-	-	-	-	-	-	-	-	-	0.13
62-21	-	1.31	0.08	-	-	-	-	-	-	-	-	-	-	-	-	1.39
22-62	-	1.31	0.08	-	-	-	-	-	-	-	-	-	-	-	-	1.39
22-63	-	2.95	0.17	-	-	-	-	-	-	-	-	-	-	-	-	3.12
63-24	-	2.85	0.16	-	-	-	-	-	-	-	-	-	-	-	-	3.02
23-64	-	-	5.22	-	-	-	-	-	-	-	-	-	-	-	-	5.22
64-24	-	-	5.11	-	-	-	-	-	-	-	-	-	-	-	-	5.11
24-65	-	0.5	0.92	-	-	-	-	-	-	-	-	-	-	-	-	1.43
65-25	-	0.5	0.92	-	-	-	-	-	-	-	-	-	-	-	-	1.43
25-66	-	0.94	0.96	0.02	0.02	0.03	-	0.04	0.01	0.01	-	-	-	0.2	0.14	2.38
66-26	-	0.91	0.92	0.02	0.02	0.03	-	0.04	0.01	0.01	-	-	-	0.2	0.13	2.3
67-25	-	0.45	0.04	0.02	0.02	0.03	-	0.04	0.01	0.01	-	-	-	0.2	0.14	0.97
27-67	-	0.45	0.04	0.02	0.02	0.03	-	0.04	0.01	0.01	-	-	-	0.21	0.14	0.99
68-27	-	2.05	0.18	0.11	0.1	0.14	-	0.2	0.04	0.07	-	-	-	0.94	0.62	4.45
28-68	-	2.64	0.28	0.14	0.12	0.18	-	0.26	0.05	0.09	-	-	-	1.21	0.8	5.72
27-69	-	0.8	0.07	0.04	0.04	0.05	-	0.08	0.01	0.03	-	-	-	0.36	0.24	1.73
69-29	-	0.7	0.06	0.04	0.03	0.05	-	0.07	0.01	0.02	-	-	-	0.32	0.21	1.52
27-70	-	0.8	0.07	0.04	0.04	0.05	-	0.08	0.01	0.03	-	-	-	0.37	0.24	1.73
70-30	-	0.62	0.05	0.03	0.03	0.04	-	0.06	0.01	0.02	-	-	-	0.29	0.19	1.35
29-71	-	0.29	0.02	0.01	0.01	0.02	-	0.03	0.01	0.01	-	-	-	0.13	0.09	0.62
71-30	-	0.25	0.02	0.01	0.01	0.02	-	0.02	-	0.01	-	-	-	0.12	0.08	0.54

Having contribution of generators to lines and loads, now wheeling cost can be calculated by using equation (3.34). The optimal settings for control variables as shown in Table 6.7 have been determined using PSO.

The results show that the wheeling cost was reduced by nearly 25.8%, and the wheeling cost and the fuel cost have contradictory relation. Figure 6.3 shows the wheeling cost optimization of the system.

TABLE 6.7: IEEE-30 Bus Test System, Objective Values and Settings of Control Variables at Optimal Wheeling Cost (Case-SO2).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Generators Output (MW)	P_1	50.00	200.00	99.23	74.25
	P_2	20.00	80.00	80.00	80.00
	P_5	15.00	50.00	50.00	50.00
	P_8	10.00	35.00	20.00	35.00
	P_{11}	10.00	30.00	20.00	30.00
	P_{13}	12.00	40.00	20.00	18.07
Generators Voltage (p.u.)	V_1	0.95	1.10	1.05	1.05
	V_2	0.95	1.10	1.04	1.00
	V_5	0.95	1.10	1.01	1.04
	V_8	0.95	1.10	1.01	1.09
	V_{11}	0.95	1.10	1.05	1.00
	V_{13}	0.95	1.10	1.05	1.03
Transformer Taps Position	T_{6-9}	0.90	1.10	1.08	0.98
	T_{6-10}	0.90	1.10	1.07	0.91
	T_{4-12}	0.90	1.10	1.03	1.01
	T_{28-27}	0.90	1.10	1.07	1.00
Shunt Elements (MVAR)	Qc_{10}	0.00	5.00	0.00	3.19
	Qc_{12}	0.00	5.00	0.00	5.00
	Qc_{15}	0.00	5.00	0.00	5.00
	Qc_{17}	0.00	5.00	0.00	3.96
	Qc_{20}	0.00	5.00	0.00	2.26
	Qc_{21}	0.00	5.00	0.00	5.00
	Qc_{23}	0.00	5.00	0.00	5.00
	Qc_{24}	0.00	5.00	0.00	5.00
	Qc_{29}	0.00	5.00	0.00	4.62
OBJECTIVE VALUES					
Fuel Cost ($/Hour)				901.84	926.24
Wheeling Cost ($/Hour)				**1,796.81**	**1,333.21**
Severity Index				4.31	2.87

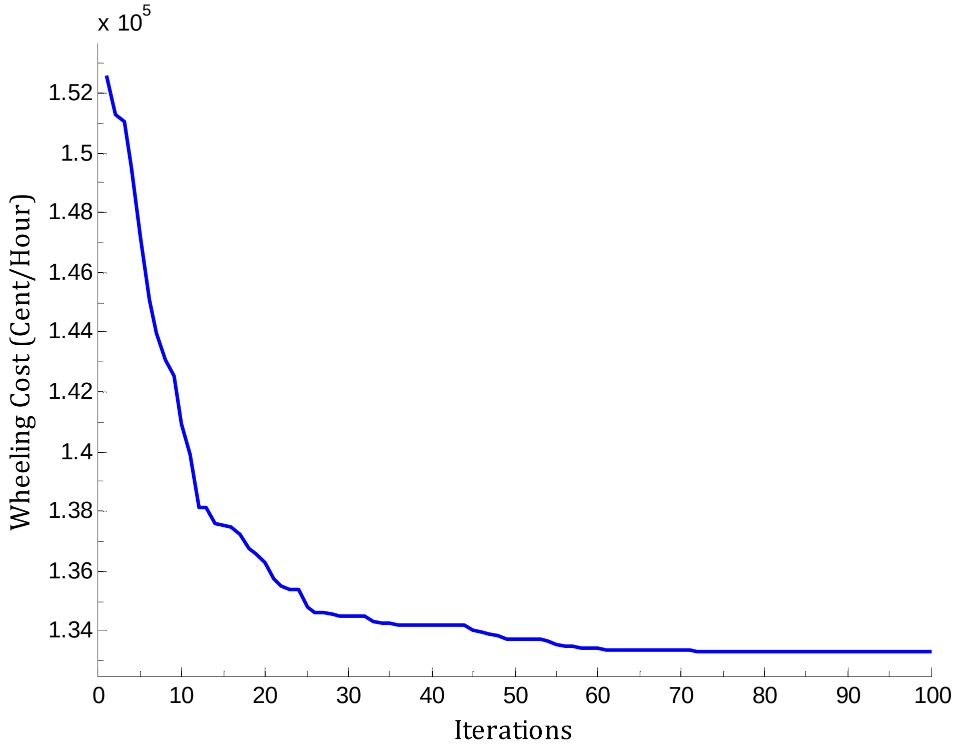


Figure 6.3: IEEE_30-bus test system, wheeling cost optimization (Case-SO2).

6.2.3 Case-SO3: Congestion Management Optimization.

The TCSC can be considered as a static reactance $-jX_{TCSC}$. This controllable reactance, X_{TCSC}, is directly used as the control variable to be implemented in the power flow equation as mentioned before in section 3.1. In this study, the working range of the TCSC is ±0. 5*X_{line}.

The best location for installing TCSC device in the system is the line (22-24) that has been determined using equation (3.16). The best parameter of TCSC is 0.48*X_{22-24} that has been determined using PSO.

Table 6.8 shows the optimized severity index for IEEE_30-bus test system and the severity index was reduced nearly by 71.7%, and the severity index and the fuel cost have contradictory relation. Figure 6.4 shows the severity index optimization of the system.

Table 6.9 shows the optimized severity index for IEEE_30-bus test system under stress factor equals to 1.35, without TCSC and with TCSC.

TABLE 6.8: IEEE_30-bus test system, objective values and settings of control variables at optimal congestion management (Case-SO3).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Generators Output (MW)	P_1	50.00	200.00	99.23	75.39
	P_2	20.00	80.00	80.00	80.00
	P_5	15.00	50.00	50.00	38.35
	P_8	10.00	35.00	20.00	24.54
	P_{11}	10.00	30.00	20.00	30.00
	P_{13}	12.00	40.00	20.00	40.00
Generators Voltage (p.u.)	V_1	0.95	1.10	1.05	1.10
	V_2	0.95	1.10	1.04	1.08
	V_5	0.95	1.10	1.01	1.09
	V_8	0.95	1.10	1.01	1.04
	V_{11}	0.95	1.10	1.05	1.10
	V_{13}	0.95	1.10	1.05	1.08
Transformer Taps Position	T_{6-9}	0.90	1.10	1.08	0.99
	T_{6-10}	0.90	1.10	1.07	0.90
	T_{4-12}	0.90	1.10	1.03	0.90
	T_{28-27}	0.90	1.10	1.07	0.95
Shunt Elements (MVAR)	Qc_{10}	0.00	5.00	0.00	1.34
	Qc_{12}	0.00	5.00	0.00	0.00
	Qc_{15}	0.00	5.00	0.00	2.93
	Qc_{17}	0.00	5.00	0.00	0.91
	Qc_{20}	0.00	5.00	0.00	5.00
	Qc_{21}	0.00	5.00	0.00	0.00
	Qc_{23}	0.00	5.00	0.00	4.98
	Qc_{24}	0.00	5.00	0.00	5.00
	Qc_{29}	0.00	5.00	0.00	5.00
jX_{TCSC} (p.u.)	L_{22-24}	-0.09	0.09	0.00	0.086
OBJECTIVE VALUES					
Fuel Cost ($/Hour)				901.84	911.64
Wheeling Cost ($/Hour)				1,796.81	1,621.18
Severity Index				**4.31**	**1.22**

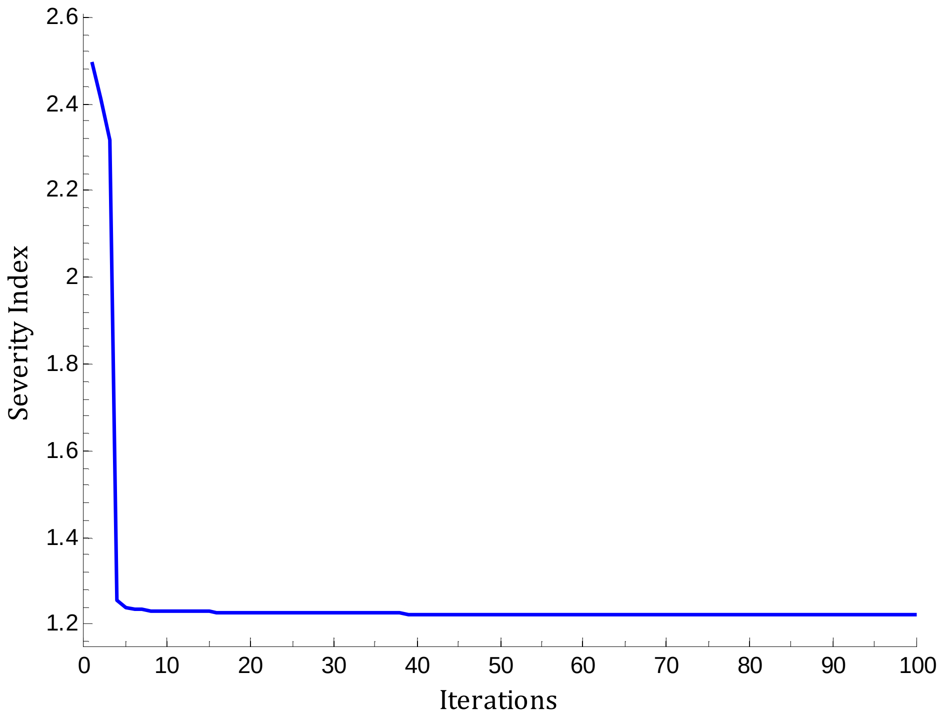


Figure 6.4: IEEE_30-bus test system, severity index optimization (Case-SO3).

TABLE 6.9: IEEE_30-bus test system under stress factor, objective values and settings of control variables at optimal congestion management without TCSC and with TCSC.

Variables		**Stress Factor = 1.35**		
		Base Case	**Optimal value without TCSC**	**Optimal value with TCSC**
Generators Output (MW)	P_1	185.08	151.28	148.77
	P_2	80.00	80.00	80.00
	P_5	50.00	50.00	50.00
	P_8	27.00	35.00	35.00
	P_{11}	27.00	30.00	30.00
	P_{13}	27.00	40.00	40.00
Generators Voltage (p.u.)	V_1	1.05	1.10	1.10
	V_2	1.04	1.02	1.01
	V_5	1.01	1.10	1.01
	V_8	1.01	1.04	1.06
	V_{11}	1.05	1.00	1.10
	V_{13}	1.05	1.10	1.07
Transformer Taps Position	$T_{6\text{-}9}$	1.08	0.96	1.05
	$T_{6\text{-}10}$	1.07	1.09	0.90
	$T_{4\text{-}12}$	1.03	1.02	0.95
	$T_{28\text{-}27}$	1.07	1.00	0.95
Shunt Elements (MVAR)	Qc_{10}	0.00	2.41	2.77
	Qc_{12}	0.00	5.00	4.37
	Qc_{15}	0.00	5.00	3.43
	Qc_{17}	0.00	3.28	4.02
	Qc_{20}	0.00	4.25	4.41
	Qc_{21}	0.00	4.73	3.39
	Qc_{23}	0.00	5.00	3.52
	Qc_{24}	0.00	4.33	5.00
	Qc_{29}	0.00	1.16	3.00
jX_{TCSC} (p.u.)	$L_{1\text{-}3}$	0.00	0.00	-0.0226
	$L_{3\text{-}4}$	0.00	0.00	0.0066
	$L_{4\text{-}6}$	0.00	0.00	0.0060
	$L_{12\text{-}15}$	0.00	0.00	-0.0040
OBJECTIVE VALUES				
Severity Index		**21.32**	**10.76**	**5.20**

6.3 SINGLE OBJECTIVE OPF WITH 87-BUS REAL SYSTEM

The following sub-sections present the results for the single objective OPF case studies performed on 87-bus real system using the proposed approach. Two cases are performed for the individual objective functions: fuel cost, and wheeling cost. In all of the single objective cases, the following parameters of the PSO were used: Population = 50, Iteration = 100, number of intervals = 10, inertia weight= 0.98 and velocity constants c_1=c_2=2.

6.3.1 Case-SO4: Fuel Cost Optimization.

Using the quadratic generator cost model presented in equation (4.15) a single objective OPF using PSO was simulated with all parameters as mentioned before.

The Table 6.10 shows the optimized fuel cost for 87-bus real system and the corresponding settings for the control variables. The results show that the fuel cost reduced by 32%, and it can be seen that the relation between the fuel cost and wheeling cost is contradictory in nature. Figure 6.5 shows the fuel cost optimization of the system.

TABLE 6.10: The 87-Bus Real System, Objective Values and Settings of Control Variables at Optimal Fuel Cost (SO4).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Generators Output (MW)	P_1	500.00	3000.00	2,445.60	2,112.89
	P_2	200.00	2000.00	1,560.00	464.57
	P_3	500.00	3000.00	2,480.00	1,956.89
	P_4	50.00	1000.00	98.00	493.93
	P_5	20.00	1000.00	49.00	270.38
	P_6	50.00	1000.00	342.40	367.99
	P_7	50.00	1000.00	336.80	1,000.00
	P_8	50.00	1000.00	241.50	417.92
	P_9	200.00	1000.00	1,000.00	462.38
	P_{10}	50.00	1000.00	400.00	1,000.00
	P_{11}	100.00	1000.00	600.00	350.19
	P_{12}	50.00	1000.00	197.00	380.11
	P_{13}	50.00	1000.00	336.00	1,000.00
	P_{14}	100.00	1000.00	615.00	402.45
	P_{15}	100.00	1000.00	590.00	417.51
	P_{16}	100.00	1000.00	615.00	527.90
	P_{17}	100.00	1000.00	392.00	314.21
Generators Voltage (p.u.)	V_1	0.95	1.10	1.00	1.02
	V_2	0.95	1.10	0.99	0.99
	V_3	0.95	1.10	1.00	1.03
	V_4	0.95	1.10	1.00	1.10
	V_5	0.95	1.10	1.00	0.99
	V_6	0.95	1.10	1.00	1.06
	V_7	0.95	1.10	1.00	0.99
	V_8	0.95	1.10	1.00	1.02
	V_9	0.95	1.10	1.00	1.04
	V_{10}	0.95	1.10	1.00	0.98
	V_{11}	0.95	1.10	1.00	1.00
	V_{12}	0.95	1.10	1.00	1.05
	V_{13}	0.95	1.10	0.99	1.07
	V_{14}	0.95	1.10	1.02	1.06
	V_{15}	0.95	1.10	1.02	1.07
	V_{16}	0.95	1.10	1.00	0.99
	V_{17}	0.95	1.10	1.00	1.00

TABLE 6.10: The 87-Bus Real System, Objective Values and Settings of Control Variables at Optimal Fuel Cost (Case-SO4) (Contd).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Transformer Tap	$T_{34\text{-}13}$	0.90	1.10	1.02	1.10
	$T_{35\text{-}14}$	0.90	1.10	1.03	1.10
	$T_{36\text{-}15}$	0.90	1.10	1.017	0.92
	$T_{38\text{-}2}$	0.90	1.10	1.05	0.92
	$T_{40\text{-}76}$	0.90	1.10	1.05	1.04
	$T_{72\text{-}3}$	0.90	1.10	1.05	1.03
	$T_{52\text{-}4}$	0.90	1.10	1.03	0.93
	$T_{53\text{-}5}$	0.90	1.10	1.03	1.04
	$T_{53\text{-}42}$	0.90	1.10	1.03	0.95
	$T_{52\text{-}6}$	0.90	1.10	1.03	1.01
	$T_{46\text{-}7}$	0.90	1.10	1.03	0.96
	$T_{46\text{-}8}$	0.90	1.10	1.03	1.05
	$T_{46\text{-}68}$	0.90	1.10	1.03	1.00
	$T_{46\text{-}68}$	0.90	1.10	1.03	0.90
	$T_{48\text{-}69}$	0.90	1.10	1.00	0.90
	$T_{48\text{-}69}$	0.90	1.10	1.00	0.93
	$T_{53\text{-}67}$	0.90	1.10	1.00	0.99
	$T_{53\text{-}67}$	0.90	1.10	1.00	1.03
	$T_{53\text{-}52}$	0.90	1.10	0.97	0.97
	$T_{53\text{-}52}$	0.90	1.10	0.97	0.95
	$T_{57\text{-}1}$	0.90	1.10	1.05	1.06
	$T_{61\text{-}16}$	0.90	1.10	1.01	1.07
	$T_{61\text{-}17}$	0.90	1.10	1.01	1.06
	$T_{71\text{-}73}$	0.90	1.10	0.98	1.05
	$T_{71\text{-}73}$	0.90	1.10	0.98	1.09
	$T_{71\text{-}73}$	0.90	1.10	0.98	1.02
	$T_{71\text{-}73}$	0.90	1.10	0.98	0.98
	$T_{74\text{-}70}$	0.90	1.10	1.00	0.98
	$T_{74\text{-}70}$	0.90	1.10	1.00	1.10
	$T_{83\text{-}9}$	0.90	1.10	1.02	0.96
	$T_{83\text{-}10}$	0.90	1.10	1.02	0.98
	$T_{78\text{-}11}$	0.90	1.10	1.03	0.95
	$T_{78\text{-}11}$	0.90	1.10	1.03	1.04
OBJECTIVE VALUES					
Fuel Cost ($/Hour)				**162,644.6**	**110,194.64**
Wheeling Cost ($/Hour)				26,030.53	31,715.71

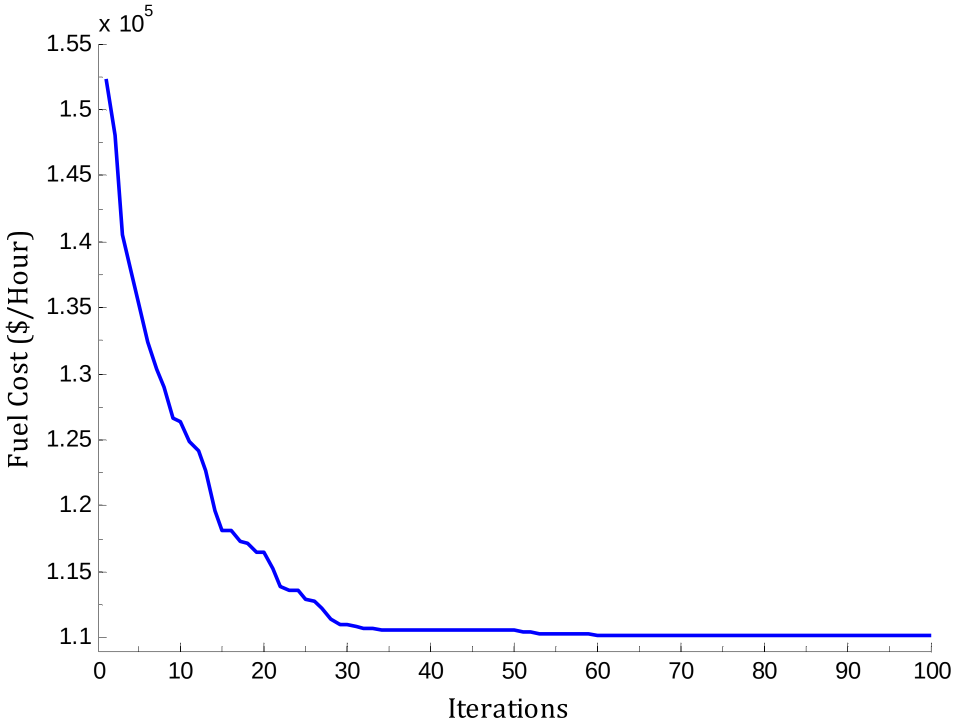


Figure 6.5: The 87-bus real system, fuel cost optimization (Case-SO4).

6.3.2 Case-SO5: Wheeling Cost Optimization.

Using upstream and downstream looking algorithm and MAV-km method the wheeling cost of the whole system can be determined as presented in section 3.2.

The result of this case shows a reduction in wheeling cost by 20%, and the relation between the fuel cost and wheeling cost is contradictory relation in nature as shown in Table 6.11. Figure 6.6 shows the wheeling cost of the system.

TABLE 6.11: The 87 bus real system, objective values and settings of control variables at optimal wheeling cost (Case-SO5).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Generators Output (MW)	P_1	0.00	5000	2445.60	1636.90
	P_2	0.00	2000	1560.00	1901.08
	P_3	0.00	3000	2480.00	3000.00
	P_4	0.00	1000	98.00	50.00
	P_5	0.00	1000	49.00	20.00
	P_6	0.00	2000	342.40	463.10
	P_7	0.00	2000	336.80	58.54
	P_8	0.00	2000	241.50	209.71
	P_9	0.00	2000	1000.00	671.18
	P_{10}	0.00	1000	400.00	1000.00
	P_{11}	0.00	2000	600.00	1000.00
	P_{12}	0.00	1000	197.00	734.74
	P_{13}	0.00	1000	336.00	57.73
	P_{14}	0.00	2000	615.00	271.88
	P_{15}	0.00	2000	590.00	166.89
	P_{16}	0.00	2000	615.00	379.34
	P_{17}	0.00	1000	392.00	290.12
Generators Voltage (p.u.)	V_1	0.95	1.10	1.00	1.03
	V_2	0.95	1.10	0.99	1.05
	V_3	0.95	1.10	1.00	1.03
	V_4	0.95	1.10	1.00	1.06
	V_5	0.95	1.10	1.00	1.02
	V_6	0.95	1.10	1.00	1.05
	V_7	0.95	1.10	1.00	0.97
	V_8	0.95	1.10	1.00	1.08
	V_9	0.95	1.10	1.00	0.98
	V_{10}	0.95	1.10	1.00	1.01
	V_{11}	0.95	1.10	1.00	1.08
	V_{12}	0.95	1.10	1.00	1.01
	V_{13}	0.95	1.10	0.99	1.00
	V_{14}	0.95	1.10	1.02	1.05
	V_{15}	0.95	1.10	1.02	1.05
	V_{16}	0.95	1.10	1.00	1.03
	V_{17}	0.95	1.10	1.00	0.99

TABLE 6.11: The 87 bus real system, objective values and settings of control variables at optimal wheeling cost (Case-SO5) (Contd).

Variables		Limits		Base Case	Optimal Value
		Lower	Upper		
Transformer Tap	T_{34-13}	0.90	1.10	1.02	1.03
	T_{35-14}	0.90	1.10	1.03	0.99
	T_{36-15}	0.90	1.10	1.017	0.99
	T_{38-2}	0.90	1.10	1.05	1.06
	T_{40-76}	0.90	1.10	1.05	1.10
	T_{72-3}	0.90	1.10	1.05	1.03
	T_{52-4}	0.90	1.10	1.03	1.08
	T_{53-5}	0.90	1.10	1.03	0.99
	T_{53-42}	0.90	1.10	1.03	1.07
	T_{52-6}	0.90	1.10	1.03	1.00
	T_{46-7}	0.90	1.10	1.03	1.06
	T_{46-8}	0.90	1.10	1.03	1.00
	T_{46-68}	0.90	1.10	1.03	1.05
	T_{46-68}	0.90	1.10	1.03	1.03
	T_{48-69}	0.90	1.10	1.00	1.04
	T_{48-69}	0.90	1.10	1.00	1.03
	T_{53-67}	0.90	1.10	1.00	1.08
	T_{53-67}	0.90	1.10	1.00	0.96
	T_{53-52}	0.90	1.10	0.97	1.05
	T_{53-52}	0.90	1.10	0.97	0.96
	T_{57-1}	0.90	1.10	1.05	1.01
	T_{61-16}	0.90	1.10	1.01	0.96
	T_{61-17}	0.90	1.10	1.01	1.02
	T_{71-73}	0.90	1.10	0.98	1.02
	T_{71-73}	0.90	1.10	0.98	1.02
	T_{71-73}	0.90	1.10	0.98	1.02
	T_{71-73}	0.90	1.10	0.98	0.95
	T_{74-70}	0.90	1.10	1.00	1.03
	T_{74-70}	0.90	1.10	1.00	1.01
	T_{83-9}	0.90	1.10	1.02	1.02
	T_{83-10}	0.90	1.10	1.02	0.99
	T_{78-11}	0.90	1.10	1.03	0.95
	T_{78-11}	0.90	1.10	1.03	0.92
OBJECTIVE VALUES					
Fuel Cost ($/Hour)				162,644.61	200,582.18
Wheeling Cost ($/Hour)				**26,030.53**	**20,911.60**

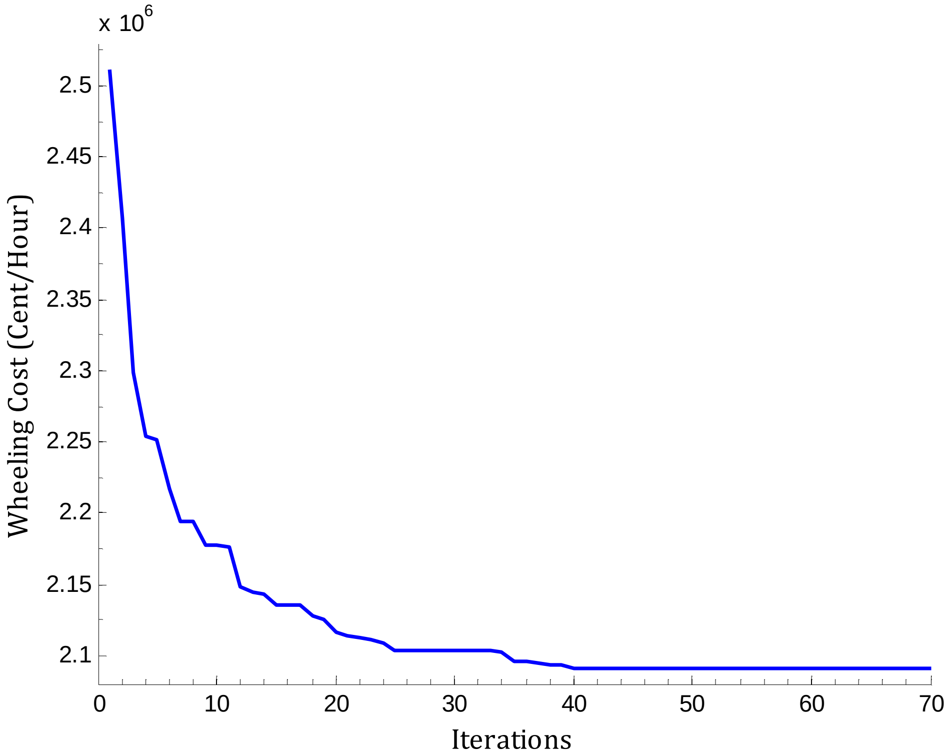


Figure 6.6: The 87-bus real system, wheeling cost optimization (Case-SO5).

CHAPTER SEVEN

SIMULATION RESULTS FOR MULTI-OBJECTIVE OPTIMAL POWER FLOW

7.1 MULTI-OBJECTIVE OPF CASE STUDIES.

In this section, a true MO-OPF considering two objectives at a time will be performed using the IEEE_30-bus test system and 87-bus real system to check performance and the effectiveness of the proposed approach.

7.1.1 Case-MO1: Optimization of Fuel & Wheeling Costs for IEEE_30-Bus Test System.

From the results in sections 6.2.1and 6.2.2, it is noticed that the wheeling cost

and fuel cost have conflicting relation. In this section, a case of multi-objective minimization considering fuel cost and wheeling cost is simulated using the proposed approach with Population=50, Iteration=1000 and size of the Pareto optimal set was limited to 20 solutions.

The Figure 7.1 shows a plot describing the trade-off relation between fuel cost and wheeling cost for the approximated Pareto optimal set which are well distributed over the objectives ranges. The best compromise solution as well as the two solutions corresponding to best individuals; i.e best fuel cost and best wheeling cost are provided in Table 7.1.

TABLE 7.1: IEEE_30-bus test system, objective values and settings of control variables of the best individual/compromise solutions at optimized fuel cost and wheeling cost (Case-MO1).

Variables		Limits		MO-OPF		
		Lower	Upper	Best Fuel Cost	Best Wheeling Cost	Best Compromise
Generators Output (MW)	P_1	50.00	200.00	169.27	78.72	135.08
	P_2	20.00	80.00	49.05	77.25	45.83
	P_5	15.00	50.00	21.73	47.23	35.99
	P_8	10.00	35.00	24.89	35.00	33.59
	P_{11}	10.00	30.00	14.79	30.00	27.01
	P_{13}	12.00	40.00	12.00	19.09	12.00
Generators Voltage (p.u.)	V_1	0.95	1.10	1.10	1.10	1.07
	V_2	0.95	1.10	1.04	1.06	1.03
	V_5	0.95	1.10	1.05	1.07	1.02
	V_8	0.95	1.10	1.05	1.07	1.07
	V_{11}	0.95	1.10	1.04	1.04	1.03
	V_{13}	0.95	1.10	1.04	1.05	1.03
Transformer Taps Position	T_{6-9}	0.90	1.10	1.01	1.01	1.00
	T_{6-10}	0.90	1.10	0.95	0.90	0.91
	T_{4-12}	0.90	1.10	1.03	1.02	1.01
	T_{28-27}	0.90	1.10	1.00	1.01	1.01
Shunt Elements (MVAR)	Qc_{10}	0.00	5.00	4.39	3.04	3.26
	Qc_{12}	0.00	5.00	3.39	3.82	3.21
	Qc_{15}	0.00	5.00	2.35	4.66	4.10
	Qc_{17}	0.00	5.00	3.92	3.19	4.67
	Qc_{20}	0.00	5.00	2.87	1.43	1.89
	Qc_{21}	0.00	5.00	3.09	5.00	3.63
	Qc_{23}	0.00	5.00	2.13	2.25	3.07
	Qc_{24}	0.00	5.00	4.14	2.05	3.02
	Qc_{29}	0.00	5.00	4.52	3.48	2.66
OBJECTIVE VALUES						
Fuel Cost ($/Hour)				**800.65**	909.73	829.97
Wheeling Cost ($/Hour)				1,707.65	**1,411.15**	1,506.58
Severity Index				5.07	4.11	3.12

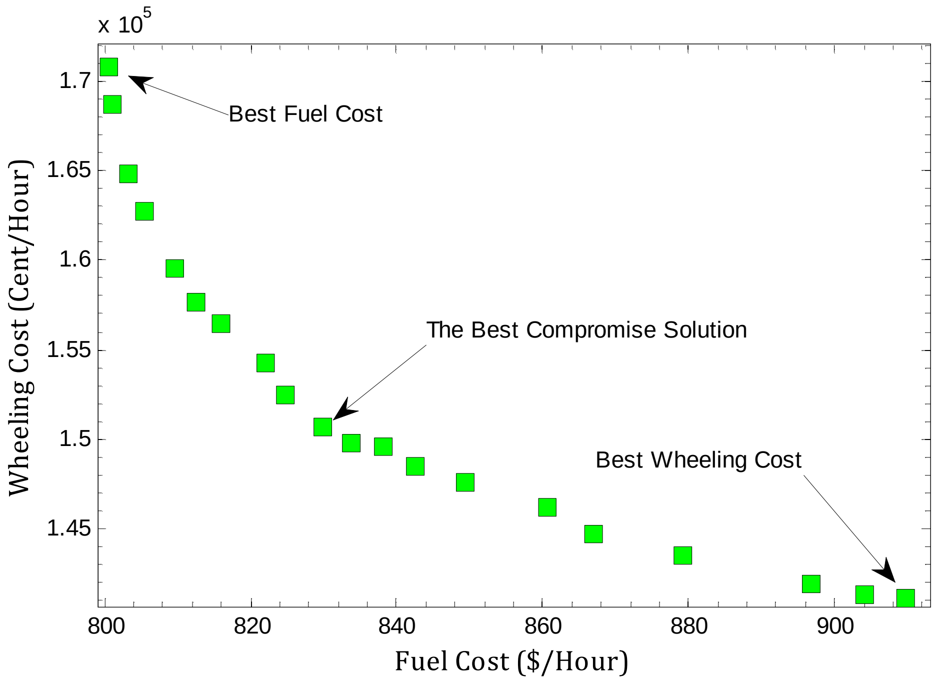


Figure 7.1: IEEE_30-bus test system MO optimization of fuel and wheeling costs (Case-MO1).

7.1.2 Case-MO2: Optimization of Fuel Cost and Severity Index for IEEE_30-Bus Test System.

From the results in sections 6.2.1and 6.2.3, it is noticed that the severity index and fuel cost have contradictory relation. In this section, a case of multi-objective minimization considering fuel cost and severity index is simulated using the proposed approach with Population=50, Iteration=2000 and size of the Pareto optimal set was limited to 20 solutions.

The Figure 7.2 shows a plot describing the trade-off relation between fuel cost and severity index for the approximated Pareto optimal set which are well distributed over the objectives ranges. The best compromise solution as well as the two solutions corresponding to best individuals; i.e best fuel cost and best severity index are provided in Table 7.2.

TABLE 7.2: IEEE_30-bus test system, objective values and settings of control variables of the best individual/compromise solutions at optimized fuel cost and severity index (Case-MO2).

Variables		Limits		MO-OPF		
		Lower	Upper	Best Fuel Cost	Severity Index	Best Compromise
Generators Output (MW)	P_1	50.00	200.00	174.55	116.71	144.41
	P_2	20.00	80.00	45.23	67.21	56.47
	P_5	15.00	50.00	19.32	27.70	23.56
	P_8	10.00	35.00	27.32	32.72	33.66
	P_{11}	10.00	30.00	13.57	12.00	16.17
	P_{13}	12.00	40.00	12.00	33.50	16.12
Generators Voltage (p.u.)	V_1	0.95	1.10	1.10	1.10	1.1
	V_2	0.95	1.10	1.06	1.10	1.06
	V_5	0.95	1.10	1.06	1.10	1.06
	V_8	0.95	1.10	1.07	1.10	1.07
	V_{11}	0.95	1.10	1.08	1.10	1.07
	V_{13}	0.95	1.10	1.10	1.10	1.09
Transformer Taps Position	T_{6-9}	0.90	1.10	0.98	1.00	0.99
	T_{6-10}	0.90	1.10	1.03	1.10	1.04
	T_{4-12}	0.90	1.10	1.04	0.90	1.01
	T_{28-27}	0.90	1.10	1.00	1.00	1.01
Shunt Elements (Mvar)	Qc_{10}	0.00	5.00	2.41	2.50	1.99
	Qc_{12}	0.00	5.00	2.15	4.22	2.52
	Qc_{15}	0.00	5.00	2.96	3.63	2.38
	Qc_{17}	0.00	5.00	3.79	1.51	2.87
	Qc_{20}	0.00	5.00	2.93	4.81	3.21
	Qc_{21}	0.00	5.00	2.19	2.52	2.64
	Qc_{23}	0.00	5.00	2.61	3.62	2.86
	Qc_{24}	0.00	5.00	3.37	5.00	3.77
	Qc_{29}	0.00	5.00	3.41	5.00	4.12
jX_{TCSC} (p.u.)	L_{22-24}	-0.09	0.09	-0.061	0.018	-0.027
OBJECTIVE VALUES						
Fuel Cost ($/Hour)				**800.37**	839.46	808.14
Wheeling Cost ($/Hour)				1,822.27	1,760.07	1,701.36
Severity Index				5.38	**1.23**	2.64

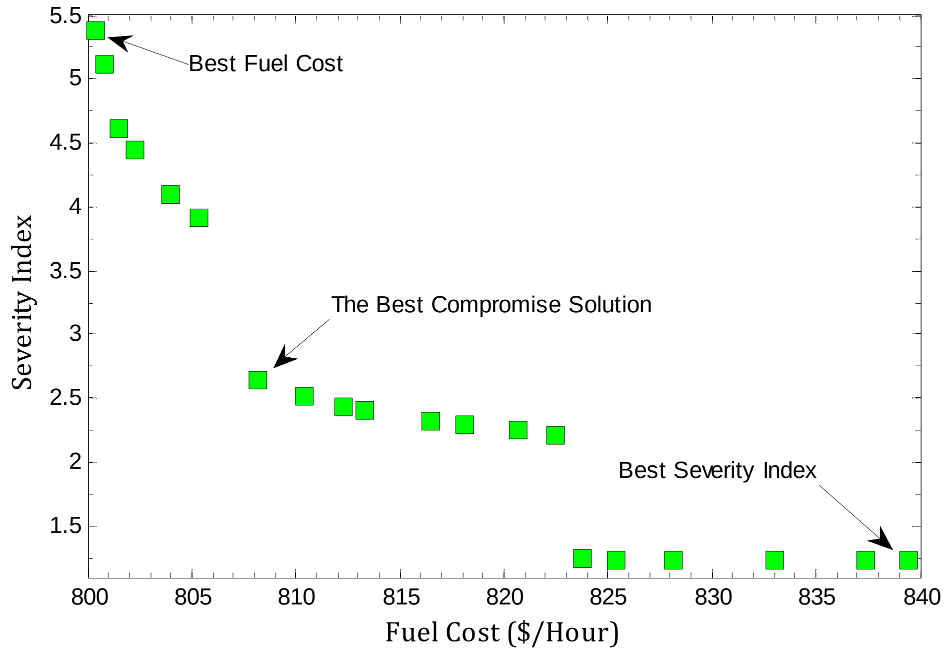


Figure 7.2: IEEE_30-bus test system MO optimization of fuel cost and severity index (Case-MO2).

7.1.3 Case-MO3: Optimization of Fuel Cost and Wheeling Cost for 87-Bus Real System.

From the results in sections 6.3.1 and 6.3.2, it is noticed that the wheeling cost and fuel cost have a contradictory relation. In this section, a case of multi-objective minimization considering fuel cost and wheeling cost is simulated using the proposed approach with Population=50, Iteration=500 and size of the Pareto optimal set was limited to 20 solutions.

The Figure 7.3 shows a plot describing the trade-off relation between fuel cost and wheeling cost for the approximated Pareto optimal set which are well distributed over the objectives ranges. The best compromise solution as well as the two solutions corresponding to best individuals; i.e best fuel cost and best wheeling cost are provided in Table 7.3.

TABLE 7.3: The 87-bus real system, objective values and settings of control variables of the best individual/compromise solutions at optimized fuel cost and wheeling cost (Case-MO3).

Variables		Limits		MO-OPF		
		Lower	Upper	Best Fuel Cost	Best Wheeling Cost	Compromise Solution
Generators Output (MW)	P_1	0.00	5000	2044.91	2178.24	1984.66
	P_2	0.00	2000	543.98	473.49	491.64
	P_3	0.00	3000	1984.72	2180.70	2188.22
	P_4	0.00	1000	292.85	50.00	211.03
	P_5	0.00	1000	177.83	20.00	142.52
	P_6	0.00	2000	331.59	463.95	301.96
	P_7	0.00	2000	941.11	962.03	997.61
	P_8	0.00	2000	421.55	141.97	417.44
	P_9	0.00	2000	1000.00	1000.00	1000.00
	P_{10}	0.00	1000	702.94	997.17	929.48
	P_{11}	0.00	2000	523.10	989.04	654.45
	P_{12}	0.00	1000	450.68	440.07	516.96
	P_{13}	0.00	1000	623.47	418.23	552.52
	P_{14}	0.00	2000	457.05	411.85	350.56
	P_{15}	0.00	2000	476.24	289.09	327.99
	P_{16}	0.00	2000	708.61	528.36	588.47
	P_{17}	0.00	1000	228.86	372.47	257.20
Generators Voltage (p.u.)	V_1	0.95	1.10	1.01	1.00	1.02
	V_2	0.95	1.10	1.05	1.03	1.04
	V_3	0.95	1.10	1.06	1.08	1.07
	V_4	0.95	1.10	0.99	1.01	1.02
	V_5	0.95	1.10	1.04	1.02	1.04
	V_6	0.95	1.10	1.04	1.01	1.03
	V_7	0.95	1.10	1.02	1.00	1.04
	V_8	0.95	1.10	1.02	0.99	1.03
	V_9	0.95	1.10	1.01	0.99	1.02
	V_{10}	0.95	1.10	1.05	1.07	1.05
	V_{11}	0.95	1.10	1.02	1.00	1.04
	V_{12}	0.95	1.10	1.03	1.05	1.03
	V_{13}	0.95	1.10	1.00	1.02	0.98
	V_{14}	0.95	1.10	1.03	1.00	1.01
	V_{15}	0.95	1.10	1.03	0.96	1.01
	V_{16}	0.95	1.10	1.01	1.01	1.02
	V_{17}	0.95	1.10	1.01	1.02	1.01

TABLE 7.3: The 87-bus real system, objective values and settings of control variables of the best individual/compromise solutions at optimized fuel cost and wheeling cost (Case-MO3) (Contd).

Variables		Limits		MO-OPF		
		Lower	Upper	Best Fuel Cost	Best Wheeling Cost	Compromise Solution
Transformer Tap	T_{34-13}	0.90	1.10	1.05	1.01	1.07
	T_{35-14}	0.90	1.10	1.02	1.05	1.03
	T_{36-15}	0.90	1.10	1.01	1.07	1.02
	T_{38-2}	0.90	1.10	1.03	1.06	1.02
	T_{40-76}	0.90	1.10	1.02	1.00	1.03
	T_{72-3}	0.90	1.10	1.00	1.00	0.99
	T_{52-4}	0.90	1.10	1.02	1.04	1.01
	T_{53-5}	0.90	1.10	0.99	1.02	0.99
	T_{53-42}	0.90	1.10	1.04	0.99	1.01
	T_{52-6}	0.90	1.10	0.96	0.99	0.94
	T_{46-7}	0.90	1.10	1.00	1.03	0.99
	T_{46-8}	0.90	1.10	1.01	1.07	1.01
	T_{46-68}	0.90	1.10	1.01	1.01	1.00
	T_{46-68}	0.90	1.10	1.01	1.00	1.01
	T_{48-69}	0.90	1.10	1.00	1.04	0.98
	T_{48-69}	0.90	1.10	1.01	1.00	0.99
	T_{53-67}	0.90	1.10	0.99	1.02	1.03
	T_{53-67}	0.90	1.10	0.97	0.95	0.99
	T_{53-52}	0.90	1.10	1.00	0.98	0.99
	T_{53-52}	0.90	1.10	1.02	1.00	1.04
	T_{57-1}	0.90	1.10	1.05	1.06	1.03
	T_{61-16}	0.90	1.10	0.95	0.99	0.96
	T_{61-17}	0.90	1.10	1.00	1.04	1.04
	T_{71-73}	0.90	1.10	0.96	1.06	1.00
	T_{71-73}	0.90	1.10	1.03	1.03	1.05
	T_{71-73}	0.90	1.10	1.03	0.97	1.00
	T_{71-73}	0.90	1.10	0.97	0.98	0.95
	T_{74-70}	0.90	1.10	0.96	0.90	0.93
	T_{74-70}	0.90	1.10	1.02	1.05	1.00
	T_{83-9}	0.90	1.10	1.01	1.01	1.00
	T_{83-10}	0.90	1.10	0.96	0.92	0.96
	T_{78-11}	0.90	1.10	0.97	0.98	0.98
	T_{78-11}	0.90	1.10	1.00	0.98	1.02
OBJECTIVE VALUES						
Fuel Cost ($/Hour)				**123,699.96**	143,253.17	127,132.47
Wheeling Cost ($/Hour)				23,860.31	**20,554.66**	22,130.72

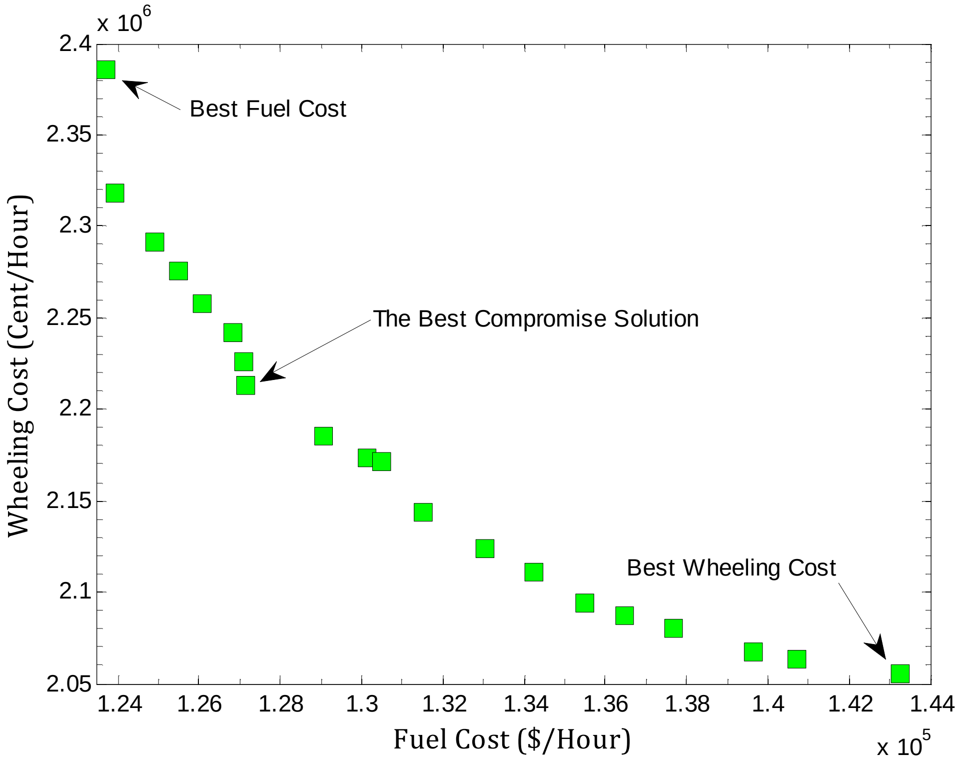


Figure 7.3: The 87-bus real system MO optimization of fuel and wheeling costs (Case-MO3).

7.2 RESULTS COMPARISON

In this thesis work, several single and multi-objective OPF were performed on the IEEE_30-bus test systems and 87-bus real system, using PSO. Three objectives were considered in this study: fuel cost, wheeling cost, congestion management (severity index). Single objective OPF was performed for each objective to determine the minimum limit for each objective and any contradictory relation between the objectives. Then, several MO-OPF cases were simulated. Algorithms were used to perform clustering and also determine the best compromise solution. Comparison between the results in single objective cases, best individual objectives and best compromise in MO-OPF for IEEE 30-bus test systems and the 87-bus real system are summarized in Tables 7.4 and 7.5. For the cases of MO-OPF, the results corresponding to the best individuals are close to their corresponding objectives in the case of single objective. This indicates the effectiveness of the proposed approach in finding the alternative solutions which optimize both objectives and express the trade-off between the two objectives over the range of limits of objectives.

TABLE 7.4: IEEE_30-bus test system, single and multiobjective optimization of OPF comparison.

	Fuel Cost ($/Hour)	Wheeling Cost ($/Hour)	Severity index
Base Case	901.84	1,796.81	4.31
Best of individual optimization	799.21	1,333.21	1.22
Multi-Objective optimization	800.37	1,411.15	1.23
Best compromise solution	808.14	1,506.58	2.64

TABLE 7.5: The 87-bus real system, single and multiobjective optimization of OPF comparison.

	Fuel Cost ($/Hour)	Wheeling Cost ($/Hour)
Base case	162,644.61	26,030.53
Best of individual optimization	110,194.64	20,911.60
Multi-Objective optimization	123,699.96	20,554.66
Best compromise solution	127,132.47	22,130.72

CHAPTER EIGHT

CONCLUSIONS AND FUTURE WORK

The conclusion and possible future work in view of this thesis results are presented below.

8.1 CONCLUSIONS AND FINDINGS

The traditional optimal power flow problem was discussed in this thesis. The problem was formulated as single and true multi-objective problem considering equality and inequality constraints such as machine limits, allowable voltage and loading constraints. Different objective functions such as fuel cost, wheeling cost, and congestion management have been considered. A proposed PSO was developed and applied to solve several case studies using IEEE-30 bus test system and 87-bus real system.

The conclusions and findings of this work can be summarized as follows:

- A true MO-OPF was formulated. Three objectives were considered in this study: 1) fuel cost, 2) wheeling cost, 3) severity index. The proposed formulation seeks to maintain the exact problem formulation, to address its nonlinearity and boundary constraints without any need for making further simplifications.
- This work proposed a MOPSO; changing conventional SOPSO to a MOPSO required redefinition of global and local best individuals since, in MOPSO, there is no absolute global best, but rather a set of nondominated solutions. In addition, there may be no single local best individual for each particle of the swarm.
- A clustering algorithm is applied to enable the decision maker to control the size of the approximated Pareto set.
- A technique based on fuzzy set theory is implemented to extract the best compromise solution to aid the decision making process.
- The proposed approach was developed using MATLAB program, and simulated using IEEE-30-bus test system and 87-bus real system. First, single objective OPF cases considering the three objectives mentioned earlier were performed to explore the optimal values of each objective and also gain an idea about any contradictory relation between the objectives. Then, MO-OPF cases were performed considering two objectives at a time.
- The results of the simulations were compared to the available results in the literature. The results have indicated the effectiveness of the proposed approach in optimization and finding well distributed Pareto solutions.

- Application of MO-OPF to a practical case has been carried out. This can help the electricity utilities and pool operators to optimize the systems for better utilization of resources and maintain the system security.

8.2 FUTURE WORK DIRECTIONS

Following are some extensions that may be taken into consideration in future:

- Other objectives may also be investigated in a multi-objective optimal power flow formulation such as maximizing the social welfare, maximizing the custom benefits and optimizing reactive power dispatch.
- Applying the method on practical large dimension systems, to show the practicality and capability of MOPSO in solving real practical problems.
- Different FACTS controllers like SSSC, STATCOM and SVC may also be implemented in a MO-OPF for treating congestion management problem using dynamic model for these controllers.

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APPENDICES

APPENDIX-I

DATA OF IEEE-30 BUS TEST SYSTEM

TABLE I-1: Bus Data for IEEE-30 Bus Test System

Bus #	Bus Voltage (p.u.)			P_g (MW)			Q_g (Mvar)		Loads (MW/Mvar)		Q_{shunt} (Mvar)			Fuel Cost Parameters		
	V^o	V^{min}	V^{max}	P^o	P^{min}	P^{max}	Q^{min}	Q^{max}	P_L	Q_L	Q_c^{fixed}	Q_c^{min}	Q_c^{max}	A	B	C
1	1.05	0.95	1.10	---	50	200	-20	200	---	--	---	--	---	0.0	200	37.5
2	1.04	0.95	1.10	80	20	80	-20	100	21.7	12.7	---	--	---	0.0	175	175
3	---	0.95	1.05	---	---	---	---	--	2.4	1.2	---	--	---	---	--	---
4	---	0.95	1.05	---	---	---	---	--	7.6	1.6	---	--	---	---	--	---
5	1.01	0.95	1.10	50	15	50	-15	80	94.2	19.0	---	--	---	0.0	100	625
6	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
7	---	0.95	1.05	---	---	---	---	--	22.8	10.9	---	--	---	---	--	---
8	1.01	0.95	1.10	20	10	35	-15	60	30.0	30.0	---	--	---	0.0	325	83.4
9	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
10	---	0.95	1.05	---	---	---	---	--	5.8	2.0	0.0	0.0	5.0	---	--	---
11	1.05	0.95	1.10	20	10	30	-10	50	---	--	---	--	---	0.0	300	250
12	---	0.95	1.05	---	---	---	---	--	11.2	7.5	0.0	0.0	5.0	---	--	---
13	1.05	0.95	1.10	20	12	40	-15	60	---	--	---	--	---	0.0	300	250
14	---	0.95	1.05	---	---	---	---	--	6.2	1.6	---	--	---	---	--	---
15	---	0.95	1.05	---	---	---	---	--	8.2	2.5	0.0	0.0	5.0	---	--	---
16	---	0.95	1.05	---	---	---	---	--	3.5	1.8	---	--	---	---	--	---
17	---	0.95	1.05	---	---	---	---	--	9.0	5.8	0.0	0.0	5.0	---	--	---
18	---	0.95	1.05	---	---	---	---	--	3.2	0.9	---	--	---	---	--	---
19	---	0.95	1.05	---	---	---	---	--	9.5	3.4	---	--	---	---	--	---
20	---	0.95	1.05	---	---	---	---	--	2.2	0.7	0.0	0.0	5.0	---	--	---
21	---	0.95	1.05	---	---	---	---	--	17.5	11.2	0.0	0.0	5.0	---	--	---
22	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
23	---	0.95	1.05	---	---	---	---	--	3.2	1.6	0.0	0.0	5.0	---	--	---
24	---	0.95	1.05	---	---	---	---	--	8.7	6.7	0.0	0.0	5.0	---	--	---
25	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
26	---	0.95	1.05	---	---	---	---	--	3.5	2.3	---	--	---	---	--	---
27	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
28	---	0.95	1.05	---	---	---	---	--	---	--	---	--	---	---	--	---
29	---	0.95	1.05	---	---	---	---	--	2.4	0.9	0.0	0.0	5.0	---	--	---
30	---	0.95	1.05	---	---	---	---	--	10.6	1.9	---	--	---	---	--	---

TABLE I-2: Branches Data for IEEE-30 Bus Test System

#	From Bus #	To Bus #	R (pu)	X (pu)	B (pu)	Rate (MVA)	Tapon	Tap	Tap^{min}	Tap^{max}
1	1	2	0.0192	0.0575	0.0528	130	---	---	---	---
2	1	3	0.0452	0.1852	0.0408	130	---	---	---	---
3	2	4	0.0570	0.1737	0.0368	65	---	---	---	---
4	3	4	0.0132	0.0379	0.0084	130	---	---	---	---
5	2	5	0.0472	0.1983	0.0418	130	---	---	---	---
6	2	6	0.0581	0.1763	0.0374	65	---	---	---	---
7	4	6	0.0119	0.0414	0.0090	90	---	---	---	---
8	5	7	0.0460	0.1160	0.0204	70	---	---	---	---
9	6	7	0.0267	0.0820	0.0170	130	---	---	---	---
10	6	8	0.0120	0.0420	0.0090	32	---	---	---	---
11	6	9	0.0000	0.2080	0.0000	65	6	1.078	0.90	1.10
12	6	10	0.0000	0.5560	0.0000	32	6	1.069	0.90	1.10
13	9	11	0.0000	0.2080	0.0000	65	---	---	---	---
14	9	10	0.0000	0.1100	0.0000	65	---	---	---	---
15	4	12	0.0000	0.2600	0.0000	65	4	1.032	0.90	1.10
16	12	13	0.0000	0.1400	0.0000	65	---	---	---	---
17	12	14	0.1231	0.2559	0.0000	32	---	---	---	---
18	12	15	0.0662	0.1304	0.0000	32	---	---	---	---
19	12	16	0.0945	0.1987	0.0000	32	---	---	---	---
20	14	15	0.2210	0.1997	0.0000	16	---	---	---	---
21	16	17	0.0824	0.1932	0.0000	16	---	---	---	---
22	15	18	0.1070	0.2185	0.0000	16	---	---	---	---
23	18	19	0.0639	0.1292	0.0000	16	---	---	---	---
24	19	20	0.0340	0.0680	0.0000	32	---	---	---	---
25	10	20	0.0936	0.2090	0.0000	32	---	---	---	---
26	10	17	0.0324	0.0845	0.0000	32	---	---	---	---
27	10	21	0.0348	0.0749	0.0000	32	---	---	---	---
28	10	22	0.0727	0.1499	0.0000	32	---	---	---	---
29	21	22	0.0116	0.0236	0.0000	32	---	---	---	---
30	15	23	0.1000	0.2020	0.0000	16	---	---	---	---
31	22	24	0.1150	0.1790	0.0000	16	---	---	---	---
32	23	24	0.1320	0.2700	0.0000	16	---	---	---	---
33	24	25	0.1885	0.3292	0.0000	16	---	---	---	---
34	25	26	0.2544	0.3800	0.0000	16	---	---	---	---
35	25	27	0.1093	0.2087	0.0000	16	---	---	---	---
36	28	27	0.0000	0.3960	0.0000	65	28	1.068	0.90	1.10
37	27	29	0.2198	0.4153	0.0000	16	---	---	---	---
38	27	30	0.3202	0.6027	0.0000	16	---	---	---	---
39	29	30	0.2399	0.4533	0.0000	16	---	---	---	---
40	8	28	0.0636	0.2000	0.0428	32	---	---	---	---
41	6	28	0.0169	0.0599	0.0130	32	---	---	---	---

APPENDIX-II

DATA OF 87-BUS REAL SYSTEM

TABLE II-1: Bus Data 87 Bus Real System.

Bus #	Bus Voltage (p.u.)			P_g (MW)			Q_g (Mvar)		Loads (MW/Mvar)		Q_{shunt} (Mvar)			Fuel Cost Parameters		
	V^o	V^{min}	V^{max}	P^o	P^{min}	P^{max}	Q^{min}	Q^{max}	P_L	Q_L	Q_c^{fixed}	Q_c^{min}	Q_c^{max}	A	B	C
1	1	0.95	1.05	2445.6	500	3000	-500	2000	100	51.6	---	---	---	0	200	37.5
2	0.989	0.95	1.05	1560	200	2000	-500	1000	72	37.2	---	---	---	0	175	175
3	1	0.95	1.05	2480	500	3000	-500	2000	100	51.6	---	---	---	0	200	37.5
4	1	0.95	1.05	98	50	1000	-500	500	0	0	---	---	---	0	325	83.4
5	1	0.95	1.05	49	20	1000	-500	500	0	0	---	---	---	0	175	175
6	1	0.95	1.05	342.4	50	1000	-500	500	0	0	---	---	---	0	300	250
7	1	0.95	1.05	336.8	50	1000	-500	500	0	0	---	---	---	0	200	37.5
8	1	0.95	1.05	241.5	50	1000	-500	500	0	0	---	---	---	0	175	175
9	1	0.95	1.05	1000	200	1000	-500	500	0	0	---	---	---	0	100	175
10	1	0.95	1.10	400	50	1000	-500	500	0	0	---	---	---	0	325	83.4
11	1	0.95	1.05	600	100	1000	-500	500	0	0	---	---	---	0	300	250
12	1	0.95	1.10	197	50	1000	-500	500	0	0	---	---	---	0	300	250
13	0.9933	0.95	1.05	336	50	1000	-500	1000	40	20.8	---	---	---	0	200	37.5
14	1.0152	0.95	1.05	615	100	1000	-500	1000	150	76.5	---	---	---	0	175	175
15	1.0227	0.95	1.05	590	100	1000	-500	1000	136	70.5	---	---	---	0	175	175
16	1	0.95	1.05	615	100	1000	-500	1000	100	50	---	---	---	0	175	175
17	1	0.95	1.05	392	100	1000	-500	1000	0	0	---	---	---	0	300	250
18	1.0034	0.95	1.05	0	---	---	---	---	80.8	43.6	---	---	---	---	---	---
19	1.0007	0.95	1.05	0	---	---	---	---	176.8	0.4	---	---	---	---	---	---
20	0.9984	0.95	1.05	0	---	---	---	---	649.3	285.5	---	---	---	---	---	---
21	1.0034	0.95	1.05	0	---	---	---	---	1.442	68	---	---	---	---	---	---
22	1.002	0.95	1.05	0	---	---	---	---	396	0	---	---	---	---	---	---
23	1.002	0.95	1.05	0	---	---	---	---	118.4	61.3	---	---	---	---	---	---
24	1.0027	0.95	1.05	0	---	---	---	---	97.8	49.6	---	---	---	---	---	---
25	1	0.95	1.10	0	---	---	---	---	68.8	35.6	---	---	---	---	---	---
26	0.988	0.95	1.10	0	---	---	---	---	24.7	2.9	---	---	---	---	---	---
27	1.0142	0.95	1.05	0	---	---	---	---	39.4	20.4	---	---	---	---	---	---
28	1.0135	0.95	1.05	0	---	---	---	---	95.2	24.4	---	---	---	---	---	---
29	0.9986	0.95	1.05	0	---	---	---	---	59.5	30.8	---	---	---	---	---	---
30	1.0189	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
31	1.0188	0.95	1.05	0	---	---	---	---	93.9	0.7	---	---	---	---	---	---
32	1.0102	0.95	1.05	0	---	---	---	---	83.3	24.2	---	---	---	---	---	---
33	1.0044	0.95	1.05	0	---	---	---	---	191.5	102.8	---	---	---	---	---	---
34	1.02	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
35	1.02	0.95	1.05	0	---	---	---	---	100	51.8	---	---	---	---	---	---
36	1.02	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
37	1.0043	0.95	1.05	0	---	---	---	---	118.6	34.4	---	---	---	---	---	---
38	1	0.95	1.05	0	---	---	---	---	126.2	63	---	---	---	---	---	---
39	0.9668	0.95	1.05	0	---	---	---	---	313.9	178.9	---	---	---	---	---	---
40	1	0.95	1.05	0	---	---	---	---	203.4	122.2	---	---	---	---	---	---

TABLE II-1: Bus Data 87 Bus Real System (Contd)

Bus #	Bus Voltage (p.u.)			P_g (MW)			Q_g (Mvar)		Loads (MW/Mvar)		Q_{shunt} (Mvar)			Fuel Cost Parameters		
	V^o	V^{min}	V^{max}	P^o	P^{min}	P^{max}	Q^{min}	Q^{max}	P_L	Q_L	Q_c^{fixed}	Q_c^{min}	Q_c^{max}	A	B	C
41	0.979	0.95	1.05	0	---	---	---	---	137.8	75.4	---	---	---	---	---	---
42	0.9754	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
43	0.9962	0.95	1.05	0	---	---	---	---	32.6	4.4	---	---	---	---	---	---
44	0.9968	0.95	1.05	0	---	---	---	---	52.4	27.1	---	---	---	---	---	---
45	0.9892	0.95	1.05	0	---	---	---	---	152	33.8	---	---	---	---	---	---
46	1.0145	0.95	1.05	0	---	---	---	---	103.9	94.7	---	---	---	---	---	---
47	1.0138	0.95	1.05	0	---	---	---	---	179	33.1	---	---	---	---	---	---
48	1.0185	0.95	1.05	0	---	---	---	---	195.3	-8.9	---	---	---	---	---	---
49	1.0234	0.95	1.10	0	---	---	---	---	16	8.3	---	---	---	---	---	---
50	0.993	0.95	1.05	0	---	---	---	---	27.3	15.1	---	---	---	---	---	---
51	1.0146	0.95	1.05	0	---	---	---	---	86.7	44.9	---	---	---	---	---	---
52	1.0227	0.95	1.05	0	---	---	---	---	513.3	130	---	---	---	---	---	---
53	1.0047	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
54	0.9929	0.95	1.05	0	---	---	---	---	316.3	169.7	---	---	---	---	---	---
55	0.9737	0.95	1.05	0	---	---	---	---	349.2	215.9	---	---	---	---	---	---
56	0.9742	0.95	1.05	0	---	---	---	---	68.6	35.5	---	---	---	---	---	---
57	1.0326	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
58	1.0031	0.95	1.05	0	---	---	---	---	178.1	51.5	---	---	---	---	---	---
59	0.9663	0.95	1.10	0	---	---	---	---	296.6	149.4	---	---	---	---	---	---
60	0.9696	0.95	1.05	0	---	---	---	---	373.2	189.9	---	---	---	---	---	---
61	0.9772	0.95	1.10	0	---	---	---	---	0	0	---	---	---	---	---	---
62	0.9626	0.95	1.05	0	---	---	---	---	156.9	72.1	---	---	---	---	---	---
63	0.9479	0.95	1.05	0	---	---	---	---	415.5	184.2	---	---	---	---	---	---
64	0.9559	0.95	1.05	0	---	---	---	---	385.2	180.3	---	---	---	---	---	---
65	0.9516	0.95	1.10	0	---	---	---	---	390.9	256.4	---	---	---	---	---	---
66	0.9479	0.95	1.10	0	---	---	---	---	356.7	172.8	---	---	---	---	---	---
67	1.0195	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
68	1.0123	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
69	1.0183	0.95	1.10	0	---	---	---	---	0	0	---	---	---	---	---	---
70	1.0193	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
71	1.0098	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
72	1.0323	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
73	1.0216	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
74	1.0029	0.95	1.05	0	---	---	---	---	0	0	---	---	---	---	---	---
75	1.0189	0.95	1.05	0	---	---	---	---	88.1	21.4	---	---	---	---	---	---
76	1.03	0.95	1.05	0	---	---	---	---	0	-89.4	---	---	---	---	---	---
77	1.0115	0.95	1.05	0	---	---	---	---	230.5	158.6	---	---	---	---	---	---
78	1.0153	0.95	1.05	0	---	---	---	---	330.5	190.5	---	---	---	---	---	---
79	1.0098	0.95	1.05	0	---	---	---	---	450	269.4	---	---	---	---	---	---
80	1.0133	0.95	1.10	0	---	---	---	---	513.6	32.2	---	---	---	---	---	---
81	1.0109	0.95	1.05	0	---	---	---	---	194.4	74.4	---	---	---	---	---	---
82	1.0102	0.95	1.05	0	---	---	---	---	658.5	271.8	---	---	---	---	---	---
83	1.0177	0.95	1.05	0	---	---	---	---	56.8	36.4	---	---	---	---	---	---
84	1.0223	0.95	1.05	0	---	---	---	---	170.1	277.8	---	---	---	---	---	---
85	1.0198	0.95	1.05	0	---	---	---	---	151.2	115.7	---	---	---	---	---	---
86	1.0154	0.95	1.05	0	---	---	---	---	623.1	65.1	---	---	---	---	---	---
87	1.0241	0.95	1.05	0	---	---	---	---	31.4	73.2	---	---	---	---	---	---

TABLE II-2: Branches Data for 87 Bus Real System.

#	From Bus #	To Bus #	R (pu)	X (pu)	B (pu)	Tapon	Tap	Tap^{min}	Tap^{max}
1	18	19	0.0005	0.0051	0.0088	---	---	---	---
2	18	21	0.0005	0.0043	0.008	---	---	---	---
3	18	23	0.0004	0.0036	0.0273	---	---	---	---
4	18	24	0.0003	0.0024	0.0044	---	---	---	---
5	18	25	0.0004	0.0036	0.0068	---	---	---	---
6	18	28	0.0097	0.0839	0.1595	---	---	---	---
7	18	32	0.0033	0.0285	0.054	---	---	---	---
8	18	33	0.0015	0.0133	0.025	---	---	---	---
9	18	73	0.002	0.0175	0.0333	---	---	---	---
10	18	73	0.002	0.0175	0.0333	---	---	---	---
11	19	20	0.0007	0.0067	0.0118	---	---	---	---
12	20	25	0.0004	0.0031	0.0058	---	---	---	---
13	20	33	0.001	0.0092	0.0173	---	---	---	---
14	20	38	0.0041	0.0351	0.0667	---	---	---	---
15	20	73	0.0026	0.0222	0.0422	---	---	---	---
16	20	73	0.0028	0.0242	0.0461	---	---	---	---
17	21	22	0.0002	0.0015	0.0234	---	---	---	---
18	21	24	0.0002	0.0019	0.0036	---	---	---	---
19	21	33	0.0007	0.0063	0.0119	---	---	---	---
20	21	34	0.0022	0.0195	0.0365	---	---	---	---
21	21	73	0.0022	0.0187	0.0356	---	---	---	---
22	22	23	0	0.0001	0	---	---	---	---
23	26	38	0.0025	0.0218	0.0415	---	---	---	---
24	26	38	0.0025	0.0218	0.0415	---	---	---	---
25	26	64	0.0031	0.0295	0.056	---	---	---	---
26	27	31	0.0028	0.0247	0.0469	---	---	---	---
27	27	32	0.0074	0.0635	0.1211	---	---	---	---
28	28	32	0.0046	0.0585	0.1059	---	---	---	---
29	28	40	0.0228	0.2003	0.3525	---	---	---	---
30	28	40	0.0227	0.1992	0.3525	---	---	---	---
31	29	38	0.0009	0.0079	0.0149	---	---	---	---
32	29	38	0.0009	0.0079	0.0149	---	---	---	---
33	30	31	0.0001	0.001	0.0009	---	---	---	---
34	30	31	0.0001	0.001	0.0009	---	---	---	---
35	30	75	0	0.0001	0.2813	---	---	---	---
36	31	32	0.0082	0.0706	0.1344	---	---	---	---
37	32	33	0.0036	0.0311	0.0591	---	---	---	---
38	32	73	0.0041	0.0351	0.0668	---	---	---	---
39	33	35	0.0013	0.0123	0.084	---	---	---	---
40	33	36	0.0013	0.012	0.0437	---	---	---	---
41	33	37	0	0.0004	0.0007	---	---	---	---
42	33	37	0	0.0004	0.0007	---	---	---	---
43	33	38	0.003	0.0253	0.0481	---	---	---	---
44	33	38	0.003	0.0253	0.0481	---	---	---	---
45	34	35	0	0.0003	0.0349	---	---	---	---

TABLE II-2: Branches Data for 87 Bus Real System (Contd).

#	From Bus #	To Bus #	R (pu)	X (pu)	B (pu)	Tapon	Tap	Tap^{min}	Tap^{max}
46	34	38	0.0018	0.0157	0.0298	---	---	---	---
47	35	36	0	0.0003	0.0421	---	---	---	---
48	38	39	0.0055	0.0471	0.0903	---	---	---	---
49	38	39	0.0055	0.0471	0.0903	---	---	---	---
50	38	64	0.0025	0.0217	0.041	---	---	---	---
51	38	66	0.0039	0.0334	0.0643	---	---	---	---
52	39	41	0.0041	0.0364	0.0697	---	---	---	---
53	39	41	0.0041	0.0364	0.0697	---	---	---	---
54	39	61	0.0012	0.0102	0.2302	---	---	---	---
55	39	61	0.0012	0.0102	0.2302	---	---	---	---
56	39	65	0.0015	0.0125	0.0233	---	---	---	---
57	39	65	0.0015	0.0125	0.0233	---	---	---	---
58	41	50	0.002	0.0169	0.032	---	---	---	---
59	41	50	0.002	0.0169	0.032	---	---	---	---
60	41	56	0.0033	0.028	0.055	---	---	---	---
61	41	56	0.0033	0.028	0.055	---	---	---	---
62	43	44	0.0023	0.0201	0.0373	---	---	---	---
63	43	45	0.004	0.0342	0.0659	---	---	---	---
64	43	45	0.004	0.0342	0.0659	---	---	---	---
65	43	46	0.01	0.0859	0.1555	---	---	---	---
66	44	46	0.0077	0.0658	0.1182	---	---	---	---
67	46	47	0.0003	0.0026	0.005	---	---	---	---
68	46	47	0.0003	0.0026	0.005	---	---	---	---
69	46	48	0.0038	0.034	0.0647	---	---	---	---
70	46	48	0.0038	0.034	0.0647	---	---	---	---
71	46	50	0.0056	0.0478	0.0906	---	---	---	---
72	46	54	0.0025	0.0211	0.0402	---	---	---	---
73	46	54	0.0025	0.0211	0.0402	---	---	---	---
74	46	55	0.0025	0.0217	0.0411	---	---	---	---
75	48	49	0.0066	0.0641	0.1222	---	---	---	---
76	48	49	0.0066	0.0641	0.1222	---	---	---	---
77	48	51	0.0017	0.0163	0.0312	---	---	---	---
78	48	51	0.0017	0.0163	0.0312	---	---	---	---
79	50	53	0.0014	0.012	0.03	---	---	---	---
80	50	53	0.0014	0.012	0.03	---	---	---	---
81	50	55	0.0031	0.0264	0.051	---	---	---	---
82	53	58	0.0005	0.0046	0.0087	---	---	---	---
83	53	58	0.0005	0.0046	0.0087	---	---	---	---
84	57	67	0.001	0.0182	0.3147	---	---	---	---
85	57	67	0.001	0.0182	0.3147	---	---	---	---
86	57	68	0.0016	0.0323	0.4771	---	---	---	---
87	57	70	0.0005	0.0106	0.1572	---	---	---	---
88	59	60	0.0002	0.0022	0.678	---	---	---	---
89	59	62	0.0002	0.0024	0.3228	---	---	---	---
90	59	74	0.0045	0.0336	0.0657	---	---	---	---

TABLE II-2: Branches Data for 87 Bus Real System (Contd).

#	From Bus #	To Bus #	R (pu)	X (pu)	B (pu)	Tapon	Tap	Tap^{min}	Tap^{max}
91	60	61	0.0006	0.0053	0.2619	---	---	---	---
92	60	61	0.0006	0.0053	0.2619	---	---	---	---
93	62	65	0.0009	0.0088	0.3293	---	---	---	---
94	63	65	0.0005	0.0042	0.008	---	---	---	---
95	63	66	0.0002	0.0016	0.0031	---	---	---	---
96	63	66	0.0002	0.0016	0.0031	---	---	---	---
97	63	74	0.0038	0.0295	0.0597	---	---	---	---
98	64	66	0.0014	0.0117	0.0227	---	---	---	---
99	67	68	0.0006	0.0123	0.216	---	---	---	---
100	67	69	0.0012	0.024	0.4207	---	---	---	---
101	67	70	0.0009	0.0175	0.2589	---	---	---	---
102	67	77	0.0037	0.0678	1.1775	---	---	---	---
103	67	77	0.0037	0.0678	1.1775	---	---	---	---
104	68	69	0.0006	0.0117	0.2047	---	---	---	---
105	68	79	0.0032	0.0571	0.9937	---	---	---	---
106	68	79	0.0032	0.0571	0.9937	---	---	---	---
107	70	72	0.0015	0.0243	0.4216	---	---	---	---
108	70	72	0.0015	0.0243	0.4217	---	---	---	---
109	71	72	0.0012	0.0192	0.333	---	---	---	---
110	71	72	0.0012	0.0192	0.3331	---	---	---	---
111	71	72	0.0012	0.0192	0.3331	---	---	---	---
112	71	72	0.0012	0.0192	0.3329	---	---	---	---
113	77	82	0.0001	0.0013	0.0234	---	---	---	---
114	77	82	0.0001	0.0013	0.0234	---	---	---	---
115	77	83	0.0007	0.0095	0.1753	---	---	---	---
116	77	83	0.0007	0.0095	0.1753	---	---	---	---
117	78	79	0.001	0.0178	0.3272	---	---	---	---
118	78	80	0.0002	0.0029	0.0535	---	---	---	---
119	78	81	0.0026	0.0439	0.8062	---	---	---	---
120	78	81	0.0026	0.0439	0.8062	---	---	---	---
121	78	82	0.0005	0.0085	0.1566	---	---	---	---
122	78	86	0.001	0.0165	0.3038	---	---	---	---
123	79	86	0.0009	0.0157	0.2882	---	---	---	---
124	80	82	0.0006	0.0106	0.1947	---	---	---	---
125	81	84	0.0025	0.0424	0.779	---	---	---	---
126	81	84	0.0025	0.0424	0.779	---	---	---	---
127	83	85	0.0029	0.0418	0.7452	---	---	---	---
128	83	85	0.0029	0.0418	0.7452	---	---	---	---
129	83	86	0.0005	0.0078	0.1441	---	---	---	---
130	83	86	0.0005	0.0078	0.1441	---	---	---	---
131	84	85	0.0028	0.0405	0.7227	---	---	---	---
132	84	85	0.0028	0.0405	0.7227	---	---	---	---
133	84	87	0.0032	0.0541	0.99	---	---	---	---
134	84	87	0.0032	0.0541	0.99	---	---	---	---
135	34	13	0.0005	0.0244	0	34	1.0781	0.9	1.1

TABLE II-2: Branches Data for 87 Bus Real System (Contd).

#	From Bus #	To Bus #	R (pu)	X (pu)	B (pu)	Tapon	Tap	Tap^{min}	Tap^{max}
136	35	14	0.0003	0.0153	0	35	1.03	0.9	1.1
137	36	15	0.0003	0.017	0	36	1.0174	0.9	1.1
138	38	2	0.0001	0.0067	0	38	1.048	0.9	1.1
139	40	76	0.0019	0.0894	0	40	1.05	0.9	1.1
140	72	3	0.0001	0.0041	0	72	1.0526	0.9	1.1
141	52	4	0.001	0.0505	0	52	1.03	0.9	1.1
142	53	5	0.002	0.098	0	53	1.03	0.9	1.1
143	53	42	0.0003	0.0165	0	53	1.03	0.9	1.1
144	52	6	0.0001	0.0066	0	52	1.03	0.9	1.1
145	46	7	0.0003	0.0136	0	46	1.03	0.9	1.1
146	46	8	0.0004	0.0223	0	46	1.03	0.9	1.1
147	46	68	0.0002	0.0134	0	46	1.025	0.9	1.1
148	46	68	0.0002	0.0134	0	46	1.025	0.9	1.1
149	48	69	0.0002	0.0134	0	48	1	0.9	1.1
150	48	69	0.0002	0.0134	0	48	1	0.9	1.1
151	53	67	0.0002	0.0134	0	53	1	0.9	1.1
152	53	67	0.0002	0.0133	0	53	1	0.9	1.1
153	53	52	0.0022	0.1248	0	53	0.9668	0.9	1.1
154	53	52	0.0022	0.1248	0	53	0.9668	0.9	1.1
155	57	1	0.0001	0.0046	0	57	1.0526	0.9	1.1
156	61	16	0.0003	0.0159	0	61	1.0054	0.9	1.1
157	61	17	0.0004	0.0201	0	61	1.0125	0.9	1.1
158	71	73	0.0002	0.013	0	71	0.975	0.9	1.1
159	71	73	0.0002	0.013	0	71	0.975	0.9	1.1
160	71	73	0.0002	0.013	0	71	0.975	0.9	1.1
161	71	73	0.0002	0.013	0	71	0.975	0.9	1.1
162	74	70	0.0002	0.013	0	74	1	0.9	1.1
163	74	70	0.0002	0.013	0	74	1	0.9	1.1
164	83	9	0	0.0156	0	83	1.02	0.9	1.1
165	83	10	0	0.0261	0	83	1.02	0.9	1.1
166	78	11	0	0.0127	0	78	1.03	0.9	1.1
167	78	12	0	0.0578	0	78	1.03	0.9	1.1

PUBLICATIONS

1. "Multi-Objective Optimal Power Flow in Deregulated Environment", Submitted to the 1st students Conference 2010, Riyadh, Saudi Arabia.
2. "Multi-Objective Optimal Power Flow using Particle swarm optimization under Deregulated Environment of Power Systems", Submitted to WCCI, 2010, Barcelona, Spain.
3. "Tracing Power Flow and Wheeling Cost Considering Complex Power", under preparation to be submitted to IEEE transactions on power systems.
4. "Congestion management by determining Optimal Location and Parameters of TCSC in Deregulated Power Systems", under preparation to be submitted to IEEE transactions on power systems.

VITA

- Fouad Rashed Fouad Zaro.
- Palestinian nationality.
- Born in Hebron City of Palestine in 1981.
- Received Bachelor's degree in Science of Electrical Engineering from Palestine Polytechnic University, Hebron-Palestine in June 2004.
- Working as Research Assistant in Electrical Engineering Department of King Fahd University of Petroleum and Minerals, since August of 2007.
- I was lecturer in Palestine Polytechnic University from September of 2005 up to June of 2007.
- Present address: King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia 31261, P.O. box# 1209.
- Permanent address: Palestine Polytechnic University, Hebron, Palestine.
- Mobile #: +966 597 620 452
- E-mails: zarofuad@yahoo.com, zarofuad@hotmail.com, zaro@kfupm.edu.sa