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INTELLIGENT DISTRIBUTION VOLTAGE CONTROL WITH DISTRIBUTED GENERATION

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ABSTRACT

In this thesis, three methods for the optimal participation of the reactive power of distributed generations (DGs) in unbalanced distributed network have been proposed, developed, and tested. These new methods were developed with the objectives of maintain voltage within permissible limits and reduce losses.

The first method proposes an optimal participation of reactive power of all devices available in the network. The propose approach is validated by comparing the results with other methods reported in the literature. The proposed method was implemented using Simulink of Matlab and OpenDSS. Optimization techniques and the presentation of results are from Matlab. The co-simulation of Electric Power Research Institute's (EPRI) OpenDSS program solves a three-phase optimal power flow problem in the unbalanced IEEE 13 and 34-node test feeders. The results from this work showed a better loss reduction compared to the Coordinated Voltage Control (CVC) method.

The second method aims to minimize the voltage variation on the pilot bus on distribution network using DGs. It uses Pareto and Fuzzy-PID logic to reduce the voltage variation. Results indicate that the proposed method reduces the voltage variation more than the other methods. Simulink of Matlab and OpenDSS is used in the development of the proposed approach. The performance of the method is evaluated on IEEE 13-node test feeder with one and three DGs. Variables and unbalanced loads are used, based on real consumption data, over a time window of 48 hours.

The third method aims to minimize the reactive losses using DGs on distribution networks. This method analyzes the problem using the IEEE 13-node test feeder with three different loads and the IEEE 123-node test feeder with four DGs. The DGs can be fixed or variables. Results indicate that integration of DGs to optimize the reactive power of the network helps to maintain the voltage within the allowed limits and to reduce the reactive power losses.

The thesis is presented in the form of the three articles. The first article is published in the journal Electrical Power and Energy System, the second is published in the international journal Energies and the third was submitted to the journal Electrical Power and Energy System. Two other articles have been published in conferences with reviewing committee. This work is based on six chapters, which are detailed in the various sections of the thesis.

Keywords: Distribution network; coordinated voltage control; distributed generation; multi-objective optimization.

CONTRÔLE DE TENSION INTELLIGENT DES RÉSEAUX DE DISTRIBUTION AVEC GÉNÉRATION DISTRIBUÉE

Jose CASTRO MENDIETA

RÉSUMÉ

Dans cette thèse, trois méthodes pour la participation optimale de la puissance réactive de la génération distribuée (DG) des réseaux de distribution déséquilibrés ont été proposées, développées et testées. Ces nouvelles méthodes ont été développées avec les objectifs de maintenir la tension dans les limites admissibles et de réduire les pertes.

La première méthode propose une participation optimale de la puissance réactive de tous les dispositifs disponibles sur le réseau. La méthode proposée est validée en comparant les résultats obtenus avec d'autres méthodes décrites dans la littérature. Les méthodes ont été simulées dans Simulink de Matlab et OpenDSS. Les techniques d'optimisation et la présentation des résultats sont faites dans Matlab. Le logiciel développé par Electric Power Research Institute’s (EPRI) résout le problème d'écoulement de puissance triphasé déséquilibré dans les réseaux tests utilisés, IEEE 13 et 34 barres. Les résultats de cette étude montrent une meilleure réduction des pertes en comparaison avec la méthode de contrôle coordonnée de tension (CVC).

La deuxième méthode minimise la variation de tension dans la barre pilote sur le réseau de distribution en utilisant la génération distribuée (DG). Cette méthode utilise la technique de Pareto et la logique floue (Fuzzy-PID) pour réduire la variation de tension. Les résultats indiquent que la méthode proposée permet de réduire la variation de la tension plus que les autres méthodes. Simulink de Matlab et OpenDSS sont utilisées dans le développement de la méthode proposée. La performance de cette méthode est évaluée sur le réseau IEEE 13 barres avec une et trois DGs. Des charges variables et déséquilibrée sont utilisées en se basant, sur la consommation réelle d’une période de 48 heures.

La troisième méthode minimise les pertes de puissance réactive en utilisant les DGs dans les réseaux de distribution. Cette méthode analyse le problème en utilisant le réseau IEEE 13 barres avec trois différentes charges variables et le réseau IEEE 123 barres avec quatre DGs. Les DGs peuvent être fixes ou variables. Les résultats indiquent que l'intégration des DGs optimise la puissance réactive du réseau et aide à maintenir la tension dans les limites permises et de réduire les pertes de puissance réactive.

La thèse est présentée sous la forme de trois articles. Le premier article est publié dans la revue Electrical Power and Energy System, le second est publié dans International Journal Energies et le troisième a été soumis à la revue Electrical Power and Energy System. Deux autres articles ont été publiés dans des conférences avec comité de lecture.

Mots clés : Réseau de distribution; contrôle de la tension coordonnée; génération distribuée; optimisation multi-objectifs.

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LIST OF ABREVIATIONS

DG	Distributed generation
OLTC	On-load tap changer
CVC	Coordinated voltage control
MO	Multi-objective
SO	Single-objective
PVC	Primary voltage control
AVR	Automatic voltage regulators
SVC	Secondary voltage control
TVC	Tertiary voltage control
ΔV	Voltage regulation
OCVC	Optimal coordinated voltage control
IEEE	Institute of electrical and electronics engineers
PID	Proportional integral derivative
GA	Genetic algorithm
DM	Decision maker
CVCPF	Coordinated voltage control using Pareto and Fuzzy logic
SISO	Single-input and single-output
PF	Power factor
VPF	Variable power factor

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

$C_{i,k}$	Sensitivity matrix coefficient
f_j	Objective *j* of the MO function
G	Generator
P_{DG}	Active power of DG (kW)
P_L	Reactive power load (kW)
PF	Power factor
Q_{DG}	Reactive power of DG (kVAR)
q^{ref}	Reactive power constraint
Q_i	Reactive power generation (kVAR)
Q_l	Reactive power load (kVAR)
Q_{loss}	Reactive power loss (kVAR)
R_L	Line resistance
V_i	Voltage at bus *i*
V_{pref}	Reference voltage of pilot bus
$V_{pOptimo}$	Optimal voltage of pilot bus
κ	Regulator gain
X_L	Line reactance

Greek letters

λ	Weighting factor
w_i	Output membership
μ_i	Value of the output member

θ	angle

Symbols

W	Active power (W)
Q	Reactive power (VAR)
V	Voltage (p.u)
t	Time (s)

Measurement units

W	watt
kW	kilowatt
VAR	volt-ampere reactive
kVAR	kilo volt-ampere reactive
t	seconds/hours

Index

abs	Absolute value
sign	Sign
max	Maximum
min	Minimum

INTRODUCTION

Background

The electric power industry is continually growing due to increased demand. Previously, most power systems were operated with large centers of generation and transmission systems of energy. In these power systems, the voltage is stepped up to high voltage (HV) levels to be transmitted over long distances.

Many countries are building their economies based on renewable energy. Power Research Institute (EPRI) estimates that DG will be about 25% of the new generation by 2020. National Gas Foundation shows that this estimate could be even higher, account for nearly 30% (Duong et al., 2010) (Ahmidi et al., 2012).

Technological development, evolving energy policies, constraints on the construction, increasing demand on highly reliable electricity supply, the changes in power market, regulatory mandates and reduction of the usage of fossil fuel resources are influencing in the use of small-scale generation, and many of them will be directly connected to the distribution network, which is commonly called Distributed Generation (DG) (Ochoa et al., 2010; Zidan et El-Saadany, 2012). DG can come from renewable (solar photovoltaic, wind power, biomass, small geothermal plants, etc.) or non-renewable (internal combustion engines, combustion turbines and full cells) energy resources (Gao et al., 2014). As these DGs become increasingly integrated with the grid, they will impact the distribution network operation and control (Gong et al., 2016). Many studies have been performed to determine the optimal size and location of the DGs (Rios et Rubio, 2007; Sedighi et al., 2010; Shaaban et al., 2013). Therefore the impact of the DG in distribution networks must be studied (Kaabi et al., 2014).

Problem Statement

Normally, voltage control devices in distribution networks are operated with the criterion that the voltage decreases along the feeder. The presence of the DGs makes this feature no longer valid and the DG has not been designed to control voltage (Song et al., 2013). These are some questions that may arise in distribution networks with the presence of DGs. Some impacts of the DGs in the network and several questions arise (Richardot et al., 2006) (Liu et al., 2016; Viawan et Karlsson, 2008):

- impact on protection: The change of power transits and short-circuit currents;
- impact on the voltage and the operation of on-load tap-changers (OLTC);
- impact on network stability and elimination of faults;
- How to include the DGs in the distribution network in order to ensure adequate voltage regulation?
- How to design a control algorithm to find a voltage and reactive power optimal using DGs?

Due to these impacts and questions, it is necessary to perform an adaptation of the system supervision and control of the network to improve the quality and reliability with the help of the DGs.

Authors in (Anwar et Pota, 2011; Kolenc et al., 2012; Ochoa et al., 2011; Ochoa et Harrison, 2011; Viawan et Karlsson, 2008) have demonstrated the reduction of power loss by optimally sizing and placing DGs in distribution networks. However, most of the studies have been performed on balanced distribution network.

Many researchers (Ahmidi et al., 2012; Barin et al., 2008; Calderaro et al., 2005; Duong et al., 2010; Gao et al., 2014; Maciel et Padilha-Feltrin, 2009; Masters, 2002) have studied the impact of DG in distribution networks, but there are no studies that calculate the reactive power values of DG in distribution networks with variable and unbalanced loads.

During the planning phase of DG integration in distribution networks, the goals that allow a reliable, secure and lower cost energy supply must be considered. To obtain this optimal situation, it is necessary to consider the creation of a model that includes the identified goals. These goals may include reduction in distribution loss, the reduction of the voltage variation and improvement in the reliability (Muttaqi et al., 2014; Tomoiaga et al., 2013).

Authors in (Kang et al., 2015; Richardot et al., 2006; Soroudi et al., 2011) use Coordinated Voltage Control (CVC) to analyze the impact of DG on distribution network. CVC needs the multi-objective (MO) function to minimize the voltage variation at the pilot bus located in the controlled area. Several methods have been proposed to solve the MO optimization voltage control problem (Griffin et al., 2000; Khalesi et Haghifam, 2009; Nara et al., 2001; Ngatchou et al., 2005).

This research provides the framework for planning and solves the problems of the DGs in distribution networks.

Research Objectives

The main contribution of this thesis is to propose new methods capable of coordinating optimally the reactive power of the different areas of the distribution network to maintain the voltage within the limits and reducing losses using DGs. In addition, these new techniques were conducted in distribution networks with unbalanced and variable loads.

The primary objective of this work is the optimal participation of reactive power of a DG at variable and unbalanced distribution network.

The optimal reactive power of a DG that would result in:

- minimum of the losses;
- improvement in feeder voltage profile;

- optimal injection of active and reactive power of a DG.

To accomplish the primary objective, the following secondary objectives are necessary:

1) investigate the impact of DG on losses and voltage profile;
2) improve and minimize the voltage variation in distribution network using DGs;
3) investigate the impact of variable and fixed DGs in distribution network.

Methodology

Objective 1 has been accomplished by developing a technique based on Pareto optimization to compute the different objectives of the MO function separately (Richardot et al., 2006). The proposed technique has been tested on the IEEE 13 and 34-node test feeders with unbalanced load and the results are compared using Coordinate Voltage Control (CVC) and OLTC method. Some disturbances are investigated and the results show the effectiveness of the proposed technique.

Objective 2 has been accomplished through the implementation of two techniques (Pareto optimization and Fuzzy-PID Logic) to find the optimal value of the reactive power of the DG that minimizes voltage variation on the buses. The first part uses Pareto optimization for solving the MO voltage control problem while the second part uses the reactive power of DG as a control variable to minimize the voltage variation. The effectiveness of the proposed technique is verified by testing on IEEE 13-node test feeder using variables and unbalanced loads. The results are compared using CVC and OLTC technique.

Objective 3 has been accomplished through the implementation of MO control problems with 2 objective functions. The first objective function represents the control of voltage deviation at the pilot buses and the second objective function is the management of the loss reduction. This new technique analyzes the problem from three perspectives: 1) the adoption of a fixed DG with variable power factor in real time and variable loads, 2) the implementation of a variable DG with variable power factor in real time and variable loads, and 3) analysis of losses and voltage using only OLTC (On-Load Tap Changer). The new technique is tested on the IEEE 13 and 123-node test feeders using variables and unbalanced loads. The results show that optimal integration of the DGs in distribution network helps to maintain stable voltage and to reduce the reactive power loss.

The programs used in Objectives 1, 2 and d 3 are: OpenDSS program to solve three phase power flow (Dugan et McDermott, 2011) and Matlab program is used for optimization.

This thesis includes six chapters. Chapters 3 through 5 are based on papers that have been written by the author and have been published or submitted for publication. Chapter 1 analyzes the DGs and their impact on voltage profile and distribution power losses in distribution network.

Chapter 2 discusses the techniques optimization techniques used in this thesis. The program OPenDSS used in this thesis is analyzed. In this chapter, we analyze its performance and demonstrate the advantages of the program with an example.

Chapter 3 presents the first paper: *"Optimal Voltage Control in Distribution Network in the presence of DGs"*. This paper published in the "International Journal of Electrical Power and Energy Systems" (Elsevier) describes the methodology to find the optimal value of the voltage at pilot bus with optimal participation of the reactive power of all devices available in the network. The integration of DGs is analyzed in two different distribution networks and some disturbances are analyzed. The proposed method is compared with the classical method of Coordinated Voltage Control and the typical method of OLTC for distribution network (Castro et al., 2016a).

Chapter 4 presents the second paper: *"Coordinated Voltage Control in Distribution Network with the presence of DGs and Variable Loads using Pareto and Fuzzy Logic"*. This paper was published in the International Journal Energies. This paper proposes a new approach for finding the optimal reactive power of the DG, which minimizes the voltage variation. This work is formulated using Pareto optimization and Fuzzy-PID logic. This paper is tested on the IEEE 13-node test feeder with one and three DGs (Castro et al., 2016b).

Chapter 5 presents the third paper: *"Power factor computation of distributed generation using multi-objective optimization"*. It is submitted to the International Journal of Electrical Power and Energy Systems. This paper demonstrates the benefits of the reactive power of the DGs. The problem is formulated as the minimization of the reactive power losses and the minimization of the voltage deviation at the pilot bus. Three case studies with different variables and unbalanced loads are presented in this chapter.

Chapter 6 is a summary and conclusions of the main results obtained in this thesis. Also, this chapter presents the recommendations a future research direction.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

The typical power system design is radial with large centers of generation and the consumers are usually located several hundred kilometers. However, this typical power system is slowly changing. The transmission and distribution network will be bolstered to transmit power generated from wind farm, geothermal and solar generations, etc. These are called distributed generators (DGs). DGs will increase substantially over the next few decades and their integration disturbs the radial nature of power flow through feeders.

1.2 Impacts of Distributed Generators

Traditionally, the distribution networks were designed for a unidirectional power in which the primary substation was the only source of power. Then, voltage decreases towards the end of the radial feeder, and the load provokes a voltage drop. The integration of the DGs into the distribution network creates a reverse power flow which can degrade the protection system and cause problems with the voltage drop specifically on a network equipment used to control voltage (Dahal et Salehfar, 2013; Ren et al., 2010). Thus, despite the fact that the DGs were not intended for inclusion, the distribution network can still handle some amount of DGs as long as the appropriate protection functions are used. Some researchers (Castro et al., 2016a; Duong et al., 2010; Esmaili, 2013; Ochoa et Harrison, 2011) have shown that when DGs are added in appropriate quantities and operated at the right time and locations, they can actually improve the performance of the distribution network. Authors in (Song et al., 2013) proposed that the penetration level of DGs for a particular voltage level should be limited to maintain admissible power quality and reliability. The following sections examine the significant impacts of the DGs on the distribution network.

1.2.1 Voltage Stability

The voltage stability at the buses of the network is heavily dependent on the stability of the power system in the distribution network. The connection of DG can cause significant voltage rise in the network unless it absorbs reactive power. The change of reactive power may cause problems in voltage profile of the network requiring a review of voltage control. According to American national standard institute (ANSI) standard C84.1, the range of acceptable customer service voltage at distribution network is ± 5% of the nominal level. Moreover, if the capacity of the DGs is small compared to the total system capacity, the voltage at the connection point will change and will not affect the frequency (Dahal et Salehfar, 2013).

Many studies have been performed to better understand the impact of the DGs on voltage variation. Authors in (Barin et al., 2008; Dahal et Salehfar, 2013) have investigated the impact of the location and size of DGs on the voltage profile of a distribution network. Effects of the DGs on distribution losses and voltage variation have been presented in (Anwar et Pota, 2011; Ochoa et Harrison, 2011; Poornazaryan et al., 2016).

(Gao et Redfern, 2011; Gao et al., 2014) have proposed a method to control and improve the voltage profile by integrating DGs and daily load sequences into the distribution network. In (Hong et al., 2015) proposed the investment cost (installation, unit and maintenance cost) of the DG to improve the voltage profile. Three alternative analytical expressions to determine the best location and adequate power factor of the DG units whose active and reactive power were constrained by the voltage profile and reduced losses is present in (Hung. et al., 2013). The authors of (Babu et al., 2015; Kolenc et al., 2012) proposed the development of the control strategy to minimize the distribution line losses with respect to the voltage profile. A coordinated voltage control (CVC) scheme using fuzzy logic based power factor controller with multiple DGs for the voltage regulation of the distribution network is presented in (Gaonkar et Pillai, 2010).

Table 1.1 Summary of the reviewed studies on the impact on voltage stability

Reference	Objective
(Barin et al., 2008)	Develop a MO problem with a Bellman-Zadeh algorithm and fuzzy logic to identify the optimal site of a DG to minimize voltage variation.
(Dahal et Salehfar, 2013)	Combination of the particle swarm optimization technique and the Newton-Raphson load flow method is used to determine the optimal size of DGs to reduce the active power losses and minimize voltage variation.
(Anwar et Pota, 2011)	Optimum location and size of DG to decrease total system power loss and minimize voltage variation using repeated load flow.
(Ochoa et Harrison, 2011)	Optimal power flow is used to determine the optimal DG for reduce energy losses and voltage variation.
(Gao et Redfern, 2011)	New voltage control strategy that maximizes the power output of DG.
(Gao et al., 2014)	An adaptive Genetic algorithm is proposed to obtain the optimal DG.
(Hong et al., 2015)	Genetic algorithm was used to determine the optimal size of DG.
(Hung. et al., 2013)	The optimal sizes of DG considering the optimal power factor of DG for minimize losses and voltage variation.
(Kolenc et al., 2012)	The load-flow algorithm for minimize the voltage drop.
(Gaonkar et Pillai, 2010)	CVC using fuzzy logic based power factor controller.

1.2.2 Reactive Power

The main objective in the proposed methods is to coordinate the reactive power of the DG at the network. So, voltage and reactive power implies a proper coordination between the available voltage and reactive power control equipment. Traditionally, distribution network operators operate such equipment locally to maintain voltage within permissible limits and minimize reactive power losses (Ahmidi et al., 2012). In the operation stage, the distribution network operators have different methods to coordinate the voltage and reactive power control. Properly location and sizing shunt capacitors will decrease losses; the capacitor is based on the load size (Vu et al., 1996). Voltage and reactive power control has been used to evaluate the impact of DG inclusion in a distribution network (Duong et al., 2010; Ochoa et Harrison, 2011). These indices play a critical role on renewable energy, power quality, system stability and security. Authors in (Zhang. et al., 2015) have investigated the problem of voltage and reactive power control as the economics operations, the roles of DGs in the future retail electricity market.

To achieve a better voltage-VAr in distribution network an uncoordinated and coordinated voltage control have been presented in (Viawan et Karlsson, 2008). The voltage and reactive power control are operating locally in uncoordinated voltage control. The coordinated voltage control (CVC) means that the voltage and reactive power control equipment will be adjusted remotely and locally, based on wide area coordination, in order to obtain an optimum voltage profile and reactive power with the presence of DGs. Similarly, (Richardot et al., 2006) have demonstrated that DGs reduce the losses, the number of OLTC operations and the voltage fluctuation in distribution network. The contribution of DGs as ancillary services is significant with local control variable such as voltage regulation or power reduction is presented in (Thong et al., 2007). In system contingencies (Chi et al., 2014; Kojovic, 2002; Sheng et al., 2009a), the CVC in distribution network with DGs is presented for enhancing the ability of fast and coordinated voltage and reactive power control.

Numerous studies use different objectives functions and operating constraints in voltage and reactive power control. Authors in (Dehghani-Arani et Maddahi, 2013; Gao et al., 2014) still consider losses minimization and keeping the voltages within permissible limits as the main objectives and constraints in the voltage and reactive power control. Another objective is the flattering the voltage on the pilot bus (Richardot et al., 2006). Other references, such as (Anwar et Pota, 2011) consider the minimization of the reactive power losses as the main objective.

Table 1.2 Summary of the reviewed studies on the impact on Reactive Power

Reference	Method Used	DGs
(Ahmidi et al., 2012)	Probabilistic method	Multiple
(Duong et al., 2010)	Improving the analytical (IA)	Four types
(Ochoa et Harrison, 2011)	Optimal power flow	Multiple
(Zhang. et al., 2015)	Game theoretic	Multiple
(Viawan et Karlsson, 2008)	Coordinated voltage control	Single
(Richardot et al., 2006)	Genetic algorithm	Multiple
(Kojovic, 2002)	Alternative Transient Program	Single
(Chi et al., 2014)	Control strategy in DIgSILENT	Single
(Dehghani-Arani et Maddahi, 2013)	Pareto optimization	Single
(Gao et al., 2014)	Genetic algorithm	Multi-type
(Anwar et Pota, 2011)	Repeated load flow	Single

1.2.3 Distribution Losses

The transmission and distribution networks have an estimated 8-10 percent total loss and almost 70% of these losses occur in distribution network (Federico, Gonzalez et Lyra, 2005). The optimal location and size of DGs can significantly reduce the losses in distribution network. The DGs must be located at correct points on the network operated at the optimal output real and reactive power levels (Abu-Mouti et El-Hawary, 2011). Authors in (Anwar et Pota, 2011; Dahal et Salehfar, 2013; Hung et Mithulananthan, 2014; Sattarpour et al., 2015) have demonstrated the reduction in power losses by optimally sizing and placing DGs in distribution networks. A multi-objective function that includes minimizing the number of DGs and power losses as well as maximizing voltage stability is presented in (Esmaili, 2013). (Fu et al., 2015), the optimal allocation is formulated as a multi-objective function with support vector machines to find the Pareto front consisting of a set of possible solutions for loss reductions.

Introducing multi-objective function for minimizing voltage unbalanced factor and real power loss, improving of voltage profile and increasing of economical profit is presented in (Dehghani-Arani et Maddahi, 2013). (Hung et Mithulananthan, 2014) presents a new multi-objective index to determine the optimal size and power factor of DG for reducing power losses and enhancing loadability. The influence of DG on distribution line losses with respect to voltage profile is presented in (Kolenc et al., 2012). The proposed model by (Li et al., 2013) integrates costs, losses, and voltage index to achieve optimal size and site of DG in distribution networks.

The problem of minimizing losses in distribution networks using fixed and variable DGs, and the trade-off between energy losses and more generation is presented in (Ochoa et Harrison, 2011). (Young-Jin et al., 2013) proposes a method to decrease the number of switching devices operations, as well as to reduce the power losses in distribution networks, while maintaining the grid voltage within the allowed ranges.

Table 1.3 Summary of the reviewed studies on the impact on losses

Reference	Method Used	DGs
(Abu-Mouti et El-Hawary, 2011)	Artificial bee colony	Single
(Dahal et Salehfar, 2013)	Particle Swarm Optimization and Newton-Raphson	Single
(Hung et Mithulananthan, 2014)	Exhaustive load flow	Multiple
(Esmaili, 2013)	Fuzzy logic	Different type
(Fu et al., 2015)	Adaptive reactive control	Photovoltaic
(Dehghani-Arani et Maddahi, 2013)	Pareto optimization	Single
(Kolenc et al., 2012)	Load flow algorithm	Multiple
(Li et al., 2013)	Game theory	Single
(Ochoa et Harrison, 2011)	Optimal power flow	Multiple
(Young-Jin et al., 2013)	Dynamic programming algorithm	Single

1.3 Optimization techniques

Several optimization techniques are used by researchers for an optimal integration of DGs in distribution network. (Abu-Mouti et El-Hawary, 2011) presents an optimization approach that employs an artificial bee colony algorithm to determine the optimal DG size, power factor and location in order to minimize the real power loss. The appropriate selection and the optimal DG location are determined using the fuzzy logic and the Bellman-Zadeh algorithm in (Barin et al., 2008). (Ahmidi et al., 2012) use a multilevel control system, and a probabilistic method is used to predict the available reactive power reserve. A repeated load flow is used to find an appropriate size and location of DG to reduce significantly the total power loss in distribution network (Anwar et Pota, 2011). A novel algorithm combining the MO particle swarm optimization (MOPSO) with support vector machine is proposed to find the optimal allocation of DG in distribution network (Fu et al., 2015). (Kiprakis et Wallace, 2004) analyze the implications of the DGs in distribution networks, they use a deterministic system and fuzzy logic to adjust the power factor in response to the terminal voltage. (Li et al., 2013; Zhang. et al., 2015) work with Game Theory and MO optimization problems that allow minimizing total system power losses and maximizing voltage improvement. DGs can reduce distribution losses if they are placed appropriately in distribution network with the implementation method of tabu search as demonstrated in (Nara et al., 2001). In (Ochoa et Harrison, 2011) a multi-period AC optimal power flow (OPF) is used to determine the optimal accommodation of DGs in a way that minimizes the system energy losses.

All of the reviewed works have shown that with proper allocation of DGs, the reliability of distribution system can be enhanced significantly while reducing the distribution network losses and maintains voltage within permissible limits.

CHAPTER 2

BACKGROUND CONCEPTS

2.1 Introduction

This chapter presents the basic theoretical concepts used in this thesis. First, we present the optimization techniques. Then, a brief description of Pareto and fuzzy logic is given. Secondly, the OpenDSS program is analyzed. At this point, we explained how a distribution network can be included in OpenDSS. Finally, we show how Simulink of Matlab and OpenDSS work together.

2.2 Optimization Techniques

Optimization techniques play an important role in the success of DG integration activities. Multi-Objective problems on distribution networks are usually handled in two ways. A simple method is to convert the MO problem into a Single-objective (SO) problem by constraint, weighting, or membership (Li et Qiu, 2015; Moradi et al., 2014). Although this method has proven its effectiveness, it is difficult to describe or obtain precisely the weights of different objectives. Another disadvantage is that the calculation procedure has to be restarted when the weights are changed (Wu et al., 2011). Pareto optimization uses the concept of non-dominated solutions. MO problem can be optimized simultaneously and a set of optimum solutions is obtained using a decision maker. The MO problem can be formulated as a non-linear model (Kumar, Samantaray et Kamwa, 2015). In this thesis, we use Pareto optimization to resolve the MO problem.

2.2.1 Pareto Optimization

MO problem is different than single-objective (SO) problem as there is a vector of objective functions (two or more), which must be optimized simultaneously and subject to a set of equality and inequality constraints. To compare candidate solutions to the Multi-Objective (MO) problem, the concepts of Pareto front and Pareto solutions are commonly used and can be viewed as a simple baseline technique for MO optimization (Gatter et al., 2016). This allows us to calculate a set of optimal solutions from the Pareto frontier. Thus, the set of optimal solutions constitute an interesting trade-off (Ke-yan et al., 2015; Muller-Hannemann et al., 2001).

2.2.1.1 Pareto Frontier

A multi-objective (MO) problem involves multiple objective functions. In mathematical terms, a MO problem can be formulated as:

$$\min(F_1(x), F_2(x), \dots, F_k(x)) \quad (2.1)$$

where k ≥ 2 is the number of objectives and x is the feasible set of decision vectors with some constraint functions.

Figure 2.1 illustrates a simple case of minimizing two objectives simultaneously (F_1, F_2), with the solid line indicating the Pareto frontier. Each point of the frontier represents a unique model parameterization, so Pareto identifies multiple Pareto optimal solutions and all solutions in a Pareto set are equally optimal. Point C is not on the Pareto Frontier because it is dominated by both point A and point B. So, point C is a Dominated solution and the point A and point B are Non-dominated solutions.

In this thesis, Matlab function (gamultiobj) finds the Pareto frontier of the objectives defined subject to the linear inequalities constraints using genetic algorithm (MathWorks, 2014). Genetic Algorithm is an evolutionary computing that emulates the biological process. A population of individuals representing different solutions is evolving to find the optimal solutions. The fittest individuals are chosen, mutation and crossover operations applied, thus yielding a new generation (Ngatchou et al., 2005).

The gamultiobj uses a controller elitist genetic algorithm (NSGA-II) for favors individuals with better fitness values (rank). A controlled elitist (GA) also favors individual that can help increase the diversity of the population. We use the default values for the Genetic algorithm. Table 2.1 shows the defaults values for Genetic Algorithm's parameters.

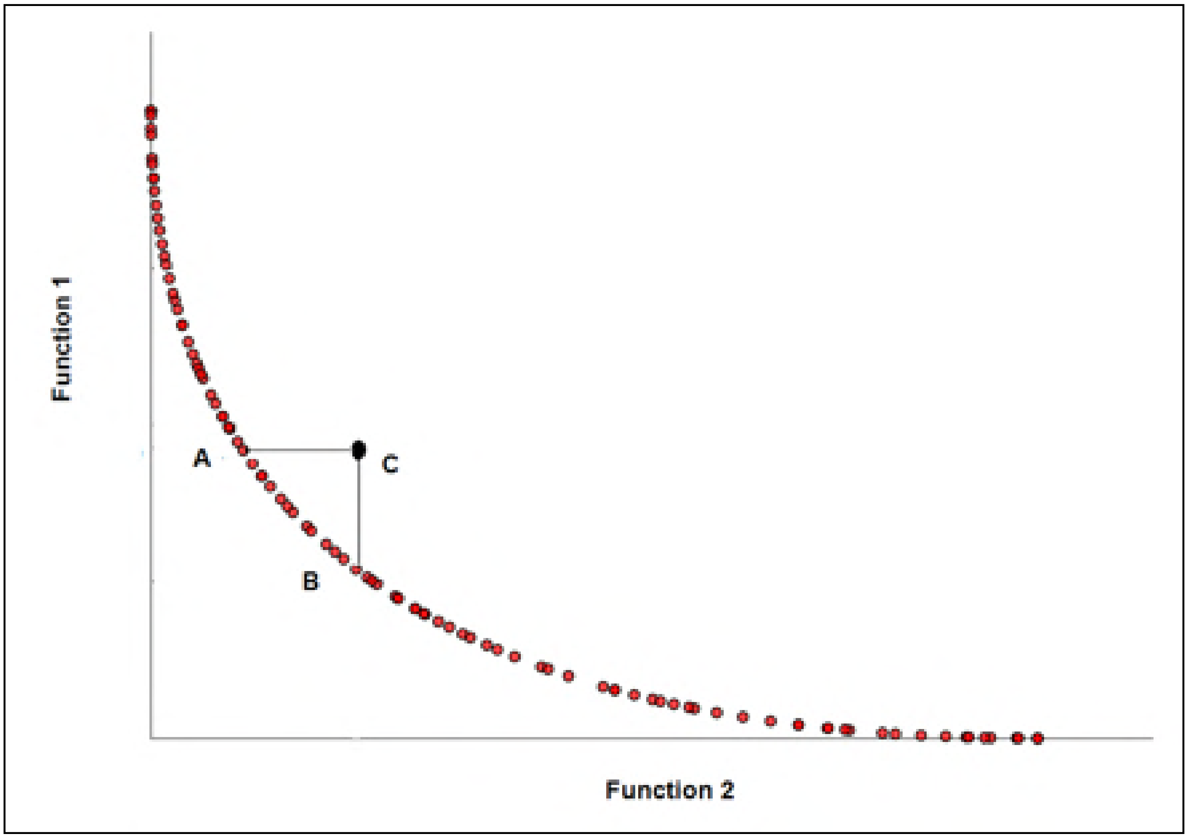

Figure 2.1 Illustration of Pareto frontier for two objectives

Table 2.1 Genetic Algorithm (Default values)

PopulationType: 'doubleVector'
PopInitRange: [-10, 10]
PopulationSize: '50'
EliteCount: '0.05*PopulationSize'
CrossoverFraction: 0.8000
ParetoFraction: [0.35]

MigrationDirection: 'forward'

MigrationInterval: 20

MigrationFraction: 0.2000

Generations: '100*numberOfVariables'

TimeLimit: Inf

FitnessLimit: -Inf

StallGenLimit: 50

StallTest: 'averageChange'

StallTimeLimit: Inf

TolFun: 1.0000e-06

TolCon: 1.0000e-06

InitialPopulation: [default]

InitialScores: [defaul]

NonlinConAlgorithm: 'auglag'

InitialPenalty: 10

PenaltyFactor: 100

PlotInterval: 1

CreationFcn: gacreationdependent

FitnessScalingFcn: fitscalingrank

SelectionFcn: selectionstochunif

CrossoverFcn: crossoverscattered

MutationFcn: [mutationconstraintdependent] [1] [1]

DistanceMeasureFcn: [default]

HybridFcn: [default]

Display: 'final'

PlotFcns: [1]

OutputFcns: [default]

Vectorized: 'off'

UseParallel: 0

In terms of speed, Pareto seems to perform consistently well, despite being essentially a simple algorithm. The primary reason for this is its ability to find multiple Pareto-optimal solutions in one single simulation run (Knowles et Corne, 1999). Some researchers (Habibi et al., 2013; Maciel et Padilha-Feltrin, 2009; Richardot et al., 2006; Soroudi et al., 2011) use Pareto to minimize the MO problem and determine the optimal DGs size and location minimizing the power losses. Many researchers use Pareto distribution networks to solve optimization problems.

2.2.1.2 Decision Maker (DM)

The set of non-dominated solutions representing the Pareto frontier are optimal solutions. DM finds the only optimal solution to this optimization problem. Hence, some additional constraints are required to single out a solution. In this thesis, the objective is to minimize losses and to maintain voltage within permissible limits. So, mathematically it can be formulated as:

$$DM = Min \sum_{j=1}^{N} \lambda_j F_j \tag{2.2}$$

$$DM = Min \sum_{i \in DG} \lambda_i^q \left(\frac{Ql_{i1} - Ql_{i2}}{a(P_{DGi1} - P_{DGi2})} \right) \tag{2.3}$$

Equations (2.2 and 2.3) represent the DM used in the thesis. The set of solutions that minimizes losses is chosen using Equation (2.2). Equation (2.3) chooses the set of optimal solutions that minimizes a single objective of MO problem. In addition, the set of solutions may be chosen developing equations to new DMs by applying different settings at the decision stage, according to specific circumstances.

2.2.2 Fuzzy Logic

In recent years, the number and variety of applications of fuzzy logic have increased significantly. Fuzzy logic is not a control strategy in itself, this is a method of combining several control rules which may have conflicting objectives and arriving at a decision. Fuzzy logic may be viewed as a methodology for computing with words rather than numbers. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solutions (MathWorks, 2014). Fuzzy logic is a generalization in which the true values of variables may be any real number between 0 and 1. Fuzzy logic is useful for dealing with vagueness and ambiguity; this is based on the fuzzy sets theory, where uncertainties are handled in a direct way without many realizations (Ni et al., 2016). In distribution networks problems, the membership grades of fuzzy logic sets are uncertain (Figueroa-Garcia et al., 2012). Advantages of the fuzzy logic are:

1. Rules can be described in natural language and easily translated into fuzzy logic
2. Many rules can be combined to produce complex behaviour.

In fuzzy logic, the calculus of fuzzy rules provides this mechanism. The inputs and outputs parameters of the system are “somehow” related (Loetamonphong et al., 2002; Takagi et Sugeno, 1985). The authors (Esmaili, 2013; Gaonkar et Pillai, 2010; Ghatee et Hashemi, 2009) propose Fuzzy logic for optimal placement and sizing of DGs.

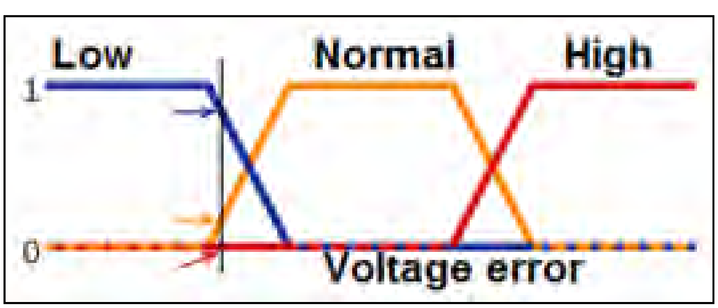

Figure 2.2 Input fuzzy membership functions

Figure 2.2 shows the expressions Low, Normal and High that represent the values on the scale of voltage error. A point on that scale has three values. The vertical line represents a particular value of Voltage error that the three arrows measure. This measure could be interpreted as “not High”, may describe it as “slightly Normal” and “fairly Low”.

Fuzzy operators for the voltage error (ΔV) that uses a control Power Factor might look like this:

$$IF\ (\Delta V = Low)\ THEN\ u_1 = PF_{min}$$
$$IF\ (\Delta V = Normal)\ THEN\ u_2 = PF_{nom}$$
$$IF\ (\Delta V = High)\ THEN\ \ u_3 = PF_{max} \tag{2.4}$$

Using these fuzzy operators (equation 2.4) and Figure (2.2), the output will be a combination of PF_{min} and PF_{nom}. The determinism is very important to use in control and decision systems using fuzzy logic.

Two of the most important types of Fuzzy Inference System (FIS) are: Mamdani and Sugeno models. In this thesis, we use the Sugeno model. This model simplifies the calculations of the output and can be either linear or constant. The final output is a weighted average of each rule’s output (Bijwe et Raju, 2006).

2.2.3 Fuzzy-PI Controller

A proportional integral derivate controller (PID controller) continuously calculates an error value as the difference between a measured process and a desired set point. Some researchers (Dutta et al., 2014; Loetamonphong et al., 2002) present PID and Fuzzy logic working together. Fuzzy logic can help to compensate for the lack of information, adding the experience from personnel related to the process using IF-THEN rules.

A proportional integral (PI) is a special case of the classical PID controller. A PI controller is a controller that produces proportional plus integral control action. A fuzzy-PI controller is a generalization of the conventional PI controller that uses an error signal and its derivative as input signals. So, Fuzzy-PI controllers have two inputs and one output. Figure 2.3 shows the error voltage (ΔV) and its derivative as inputs (National Instruments, 2006) (Instruments, 2012).

The benefit of the fuzzy-PI controller is that does not have a special operating point. Also, fuzzy-PI controller can implement nonlinear control strategies and this one uses linguistic rules (National Instruments, 2006).

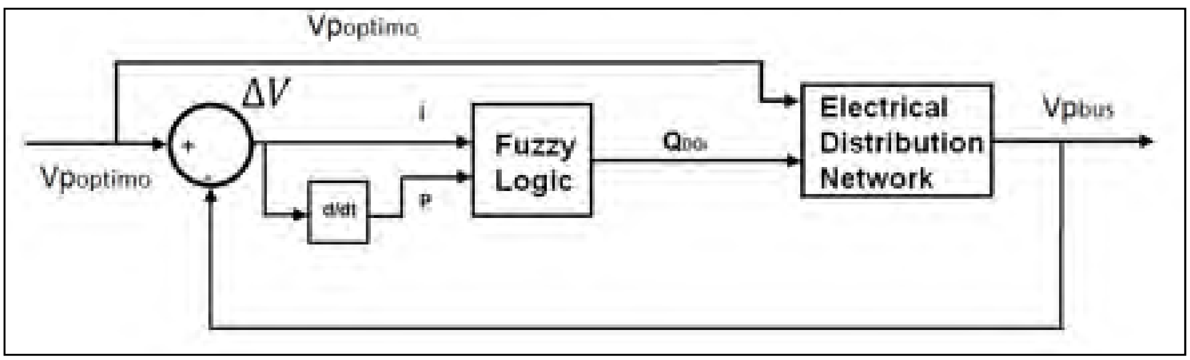

Figure 2.3 Fuzzy-PI controller

(DeJesus et al., 2006) use Pareto and Fuzzy logic for an optimal participation of reactive power of all devices available in the network. A set of solutions is obtained from Pareto, which optimizes the maximum possible number of solutions and fuzzy logic determines the optimal power injections of DGs.

2.3 OpenDSS program

OpenDss is a simulation software for distribution networks. It is developed by EPRI (Electric Power Research Institute) since more than 12 years (Dugan et McDermott, 2011). The program was originally supposed as a tool for the analysis of the interconnections of distributed generation, but its continued evolution has led to the development of the other features as the studies of efficiency in the provision of energy and harmonic studies.

2.3.1 OPenDSS structure

OpenDSS software has been used to:

- planning and analysis of distribution networks;
- poly-phase AC circuit analysis;
- analysis of interconnection of distributed generation;
- simulations windmills plant;
- improving distribution network efficiency;
- studies of harmonics and inter harmonics.

The program includes several modes of solutions, such as:

- power flow (snapshot mode, time mode);
- harmonic Analysis;
- dynamic Analysis;
- calculation shorted.

OpenDss is designed to receive instructions in text form allowing greater flexibility for users. Figure 2.4 (Dugan et McDermott, 2011) shows how the various modules interact within OpenDSS structure.

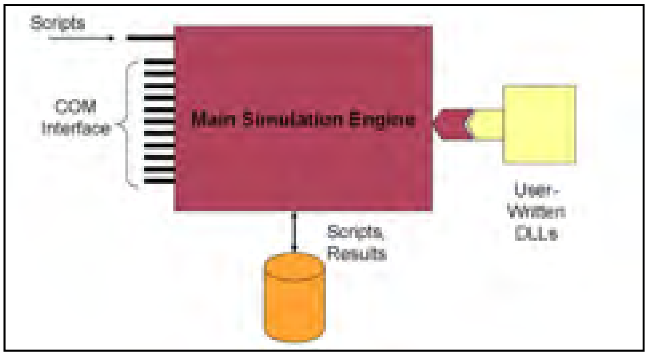

Figure 2.4 OpenDSS structure

OpenDSS represents distribution circuit through nodal admittance equations. Each system's element is represented by a primitive nodal admittance matrix. Each primitive matrix is attached to the admittance matrix of the system, so the system of equations representing the electric network is solved with the assistance of sparse matrices algorithms.

2.3.2 Modeling in OpenDSS on distribution networks

Many researchers have worked on distribution networks using OpenDSS program (Martinez et Guerra, 2014; Nagarajan et Ayyanar, 2015; Song et al., 2012; Venkatesan, Solanki et Solanki, 2012). OpenDSS represents the distribution network with a great accuracy; that is, the system is three-phase and run under unbalanced conditions and the load is voltage-dependent (Martinez-Velasco et Guerra, 2014). OpenDSS can include generation and new loads perform calculations over variable time step size.

In this thesis, the program is driven from Matlab (Figure 2.4), which is used to calculate the input data and the control of the procedure. The distribution network IEEE 13-node test feeder is used. The values used in this calculation are in Appendix I.

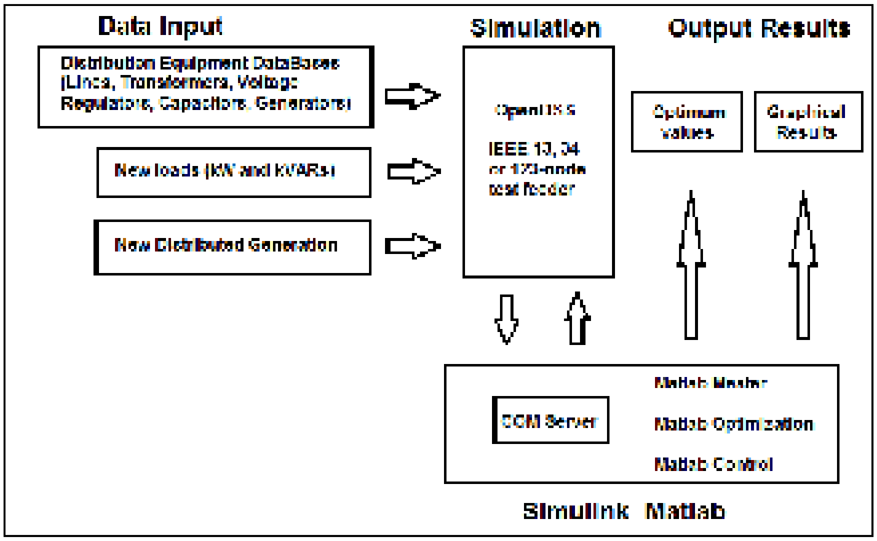

Figure 2.5 Block diagram of the implemented procedure

IEEE 13-node test feeder is relatively small. Appendix II shows the code of OpenDSS for this network.

2.3.3 OpenDSS access from Matlab

Matlab uses the built-in ActiveX server to communicate with the COM Server of the OpenDSS, so the server of the OpenDSS, will be the interface between the two programs (Figure 2.4).

In this thesis, Matlab is changing the loads and incorporating DGs. We attached some lines set of the interface between Matlab and OpenDSS most used in this dissertation (table 2.2).

(Dugan et McDermott, 2011) has other interfaces needed for different applications.

Table 2.2 Interface between Matlab and OpenDSS program

Interface	Comments
[DSSStartOK, DSSObj, DSSText] = DSSStartup	%OpenDSS run
DSSText.command='Compile (C:\Users\jrcastro\Dropbox\2015 UTPL\ETS\Trabajo2\Carga variable\IEEE13MasterT2.dss)'	% Runs the main file
DSSText.Command=['New Load.1 Bus1=634.1 Phases=1 Conn=Wye Model=1 kV=0.277 kW=' num2str(Wv(1)) ' kvar=' num2str(Vv(1))]	% Add a new load on the bus 634
DSSText.command = ['new generator.Gen1 Bus1= 675 phases=3 kV=4.16 kw=' num2str(MyDG) ' pf=' num2str(MyNextFP) ' enabled=true']	% Add a new generator on the bus 675
DSSText.Command = ['Transformer.Reg1.Taps=[1.0 ' num2str(MyNextTap)]	% Regulation of taps
DSSText.Command='New EnergyMeter.Main Line.650632 1'	% Add an Energy Meter object
DSSSolution.Solve	% Solves executes the solution
DSSText.Command='Buscoords IEEE13Node_BusXY.csv ! load in bus coordinates'	% The bus coordinates

CHAPTER 3

OPTIMAL VOLTAGE CONTROL IN DISTRIBUTION NETWORK IN THE PRESENCE OF DGs.

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Abstract

Nowadays, integration of new devices like Distributed Generation, small energy storage and smart meter, to distribution networks introduced new challenges that require more sophisticated control strategies. This paper proposes a new technique called Optimal Coordinated Voltage Control (OCVC) to solve a multi-objective optimization problem with the objective to minimize the voltage error at pilot buses, the reactive power deviation and the voltage error at the generators. OCVC uses Pareto optimization to find the optimal values of voltage of the generators and OLTC. It proposes an optimal participation of reactive power of all devices available in the network.

OCVC is compared with the classical method of Coordinated Voltage Control and is tested on the IEEE 13 and 34 Node test feeders with unbalanced load. Some disturbances are investigated and the results show the effectiveness of the proposed technique.

Keywords: distribution network; Coordinated Voltage Control (CVC); Distributed Generation (DG); Multi-Objective Optimization; Power Loss; On Load Tap Changer (OLTC).

3.1 Introduction

The climate changes and the new technologies have led to major changes in electricity generation and consumption patterns. The equipment connected to the distribution network is becoming more diversified including renewable energy that is known as Distributed Generation (DG), small energy storage, and smart meter. It consequently requires more advanced algorithms for voltage and VAR control.

The DGs may trigger variation of voltage and change the direction of power flow in the distribution network. The voltage rise depends on the amount of active and reactive power injected by the DGs. Some researches (Ahmidi et al., 2012; Anwar et Pota, 2011; Habibi et al., 2013) have studied the impact on the voltage, the reduction of losses, and the determination the optimum size and location of the DGs. Also, improper DG size and inappropriate location may cause high power loss and problems in the voltage profile (Anwar et Pota, 2011; Kiprakis et Wallace, 2004; Maciel et Padilha-Feltrin, 2009).

Other researches (Sheng et al., 2009a; Vu et al., 1996) represent the variation voltage in each control area by the variations at some selected buses called “pilot buses”. Then, the aim is to keep the voltages at pilot buses within a fixed range around set point values.

On the other hand, it is common to use the on-load tap-changer (OLTC) and switch shunt capacitors to control voltage in distributed network (Larsson et Karlsson, 2003). In some networks, these devices are operated locally without wide coordination with the others. In (Biserica et al., 2011; Richardot et al., 2006), the authors presents an approach using the DGs and OLTCs for voltage regulation and losses reduction.

Coordinated Voltage Control (CVC) in distribution network adjusts the voltage in pilot buses. CVC uses the multi-objective (MO) function to minimize the voltage variation at the pilot buses(Richardot et al., 2006). CVC in distribution networks adjusts the voltage on pilot buses located in the controlled area. To do so, it minimizes the MO optimization problem using a deterministic method. So, the problem to solve is to minimize the following objectives (Biserica et al., 2011; Richardot et al., 2006): Objective 1: voltage deviation at pilot buses; Objective 2: reactive power production ratio deviation; and Objective 3: generators voltage deviation (OLTC + DGs).

In (Viawan et Karlsson, 2008), the authors have made a comparison in distribution networks, between uncoordinated and coordinated voltage control, without and with DGs involved in the voltage control. The result indicates that using DG in the voltage control will reduce the losses, the number of OLTC operations and will decrease the voltage fluctuation in distribution network.

The authors in (Ngatchou et al., 2005; Richardot et al., 2006; Soroudi et al., 2011) solve the MO function converting the objectives into a single objective (SO) function; in this case, the objective is to find the solution that minimizes the single objective. The optimization solution results in a single value that represents a compromise among all the objectives.

Previous researches adequately solved the problem of MO function using DG in distribution network. There is no research that is able to adequately coordinate the different areas of the distribution network and focus on the benefits that a better use of reactive power of DG can provide to the distribution systems with unbalanced load.

To overcome the problem cited above, this paper proposes a new technique called optimal coordinated voltage control (OCVC). OCVC is capable of coordinating different areas of the distribution network including all sources of active and reactive power present in the distribution network. OCVC uses Pareto optimization to solve all the different objectives of the Multi-Objective function separately and finds the optimal values so that the network gets lower losses. OCVC will also have a good performance with various disturbances that occur in the distribution network.

The original contributions of this paper are described as follows:

a) disturbances in distribution network are investigated;
b) optimal participation of reactive power of a DG at unbalanced distribution network;
c) the minimization of the losses;
d) the objectives of the MO function are resolved separately.

This paper is organized as follows. Section 3.2 presents the coordinated voltage control in distribution network. The Pareto Multi-Objective optimization is explained in section 3.3. The proposed approach on optimal coordinated voltage control is explained in section 3.4. Section 3.5 presents a case study and some results using the proposed approach. Finally, a conclusion is given in section 3.6.

3.2 Coordinated Voltage Control in Distribution Network

Nowadays, a hierarchical voltage regulation strategy with three levels has been developed by some electric utilities to prevent voltage deterioration and to allow a better use of existing reactive power resources. Each level acts with a different time constant: Primary voltage control (PVC) is locally performed by automatic voltage regulators (AVR), secondary voltage control (SVC) makes reactive power production-consumption balance and tertiary voltage control (TVC) is based on optimization methods taking into account economical and technical aspects of power system operation (Richardot et al., 2006).

SVC is an important level for improving power-system voltage dynamic performance, where voltage deviation at pilot buses is minimized. This problem can be generalized to integrate voltage deviation at generators and reactive power generation. In this case, we talk about Coordinated Voltage Control (CVC) (Richardot et al., 2006).

3.2.1 Problem formulation

The voltage in a distribution network at some selected buses (pilot buses), the reactive power production and the generator's voltage deviation are tied together. Any increase or decrease in voltage at pilot buses will increase or decrease the reactive power production and generator voltage respectively. Therefore, this problem can be formulated as an optimization problem as explained below:

3.2.1.1 Voltage at pilot bus

CVC in distribution networks adjust the voltage at pilot buses. In a mathematical form, the problem can be written as follows:

$$F_1 = \sum_{i \in P} \lambda_i \left[\kappa \left(V_i^{ref} - V_i \right) - \sum_{k \in G} C_{i,k}^{V} \cdot \Delta V_k \right]^2 \qquad (3.1)$$

Where: P and G are the sets of pilot and generator buses indices; V_i^{ref}, V_i and ΔV_k are set-point voltage, actual voltage and voltage deviation at bus *i*, i.e. the difference of voltage values between two computing steps; $C_{i,k}^{V}$ is the sensitivity matrix coefficient linking the voltage variation at bus *i* and bus *k* respectively; λ_i and κ are weighting factor and regulator gain respectively.

3.2.1.2 Reactive power production

The second objective is the reactive power production ratio deviation. In OCVC, it represents the management of the reactive power of DG in the regulated area. This objective is modelled as follows:

$$F_2 = \sum_{i \in G} \lambda_i^q \left[\kappa \left(q^{ref} - \frac{Q_i}{Q_i^{MAX}} \right) - \sum_{k \in G} C_{i,k}^Q \cdot \Delta V_k \right]^2 \tag{3.2}$$

Where: is the set of generator buses indices; Q_i and Q_i^{MAX} are actual and maximum reactive power generations at bus *i*; $q^{ref} = \sum_{i \in G} Q_i / \sum_{i \in G} Q_i^{MAX}$ is the uniform set-point reactive power value within the regulated area; $C_{i,k}^Q$ is sensitivity matrix coefficients linking respectively voltage variation at bus *i* and bus *k*; λ_i^q and κ are weighting factor and regulator gain respectively.

3.2.1.3 Voltage at generators

CVC in distribution networks adjust the voltage at the generators. The mathematical model for the third objective is as follows:

$$F_3 = \sum_{i \in G} \lambda_i^v \left[\kappa \left(V_i^{ref} - V_i \right) - \Delta V_i \right]^2 \tag{3.3}$$

where: G is the set of generator buses indices; V_i^{ref}, V_i and ΔV_i are the set-point voltage, actual voltage and voltage deviation respectively at the bus *i*, i.e. the difference of voltage values between two computing steps; λ_i^v and κ are weighting factor and regulator gain respectively.

3.2.2 Optimization constraints

The constraints above considered the technical and economic issue of the distribution network. The voltage limits, voltage drop, reactive power and the weights are the main constraints (Martins et al., 2001; Richardot et al., 2006; Sheng et al., 2009b).

3.2.2.1 Voltage Constraints

The constraints of voltage on the pilot and generator buses are used to determine the safe operation values. In distribution networks an acceptable steady voltage range is considered within ± 5% of the operating voltage at DG (Masters, 2002).

$$V_i \in \left[V_i^{min}; V_i^{MAX}\right] \text{ for } i \in P \cup G \tag{3.4}$$
$$|\Delta V_i| \leq \Delta V_i^{MAX} \text{ for } i \in G$$

3.2.2.2 Reactive power constraint

In this work, the control and efficient management of the reactive power are the main objectives. Therefore, the control of the production of the reactive power of the DG is very important. In (Ahmidi et al., 2012) an acceptable power factor for the DG is of ± 0.91.

$$q^{ref} = \sum_{i \in G} Q_i / \sum_{i \in G} Q_i^{MAX} \tag{3.5}$$

Where: $|Q_i| \leq Q_i^{max}$

3.2.2.3 Weights constraints

The weights of the objectives are important because they give priority to an objective that depends on the conditions of operation. These weights are related as described in relation (3.6).

$$\lambda_i + \lambda_i^q + \lambda_i^v = 1 \tag{3.6}$$

Where: $\lambda_i, \lambda_i^q, \lambda_i^v$ are weighting factors for bus *i*.

The optimization problem (3.1) to (3.6) ensures an optimal voltage profile of the distribution network. The optimization solution results in a single value that reflects a compromise in all objectives (Abido, 2004).

The weighting factors are managed in real time using fixed values depending on the voltage value at the pilot bus. They coordinate the different areas of the distribution network to obtain the optimal values of the voltage and reactive power.

3.2.3 Pilot Bus

Monitoring and the control of the voltage level at the pilot bus allow the control of the voltage in that area. Then, the voltage at the pilot bus must reflect the voltage profile of the entire control area (Conejo et al., 1994; Erbasu et al., 2005).

A simple method called barycentre to find the pilot bus is illustrated below. This method requires the following three steps.

Step1: Compute $V_{bar} = \sum_{j=1}^{N} V_i$

Step2: Find $\Delta V_i = V_{bar} - V_i$

Step3: Choose the bus number with min $|\Delta V_i|$ as the pilot bus.

In this paper, this method is used. The networks (IEEE 13 and 34 Nodes) used in this work, have loads in some buses. If we put out sequentially these loads, we will produce N variations of the voltage at the buses. If we sum up these N variations of the voltage, we will get V_{bar}. The next step is to obtain ΔV_i. Finally, we choose the minimum value of the pilot bus has the corresponding index *i*. Table 3.1 shows the pilot bus selected.

Table 3.1 Pilot bus for IEEE 13 and IEEE 34 buses

	IEEE 13	IEEE 34
Pilot bus	Bus 671	Bus 888

3.2.4 The On-load taps Changer (OLTC)

OLTC are normally located in the transformer between transmission and distribution network and they are quite common to maintain the voltage in medium voltage network (Leisse et al., 2010). Normally, the highest voltage point of the network is the sending-end bus bar and the voltage is decreased along the feeder due to line impedance and loads. The typical mathematical model of the voltage drop is as follows (Gao et Redfern, 2011):

$$\Delta V = V_1 - V_2 \approx \frac{R_L\, P_L + X_L\, Q_L}{V_2} \tag{3.7}$$

Where P_L, Q_L are the active and reactive power of load; R_L, X_L are respectively the line resistance and reactance; V_1, V_2 are the sending-end voltage and load bus voltage respectively.

Due to the structure and properties of the distribution networks the most effective way of regulating the voltage is OLTC. The OLTC changes the voltage by alternating the turns ratio of the primary side and secondary transformers. When a DG is connected to the distribution network, the voltage drop is approximated as follows (Gao et Redfern, 2011):

$$\Delta V = V_1 - V_2 \approx \frac{R_L\,(P_L - P_{DG}) + X_L\,(Q_L - (\pm Q_{DG}))}{V_2} \tag{3.8}$$

Where P_{DG} and Q_{DG} are the active and reactive power of DG.

The extent of voltage regulation (ΔV) is limited by the number of positions and the step size between positions. In (Kersting, 2001) the characteristics of our OLTCs are displayed.

3.3 Pareto Optimization

Conversion of the multi-objective function into a single-objective function has several limitations (Abido, 2004; Ngatchou et al., 2005):

1) it takes a priori knowledge of the objectives;
2) single-objective function leads to only one solution;
3) trade-offs between objectives cannot be easily evaluated;
4) the solution may not be obtained unless the search space is convex.

Pareto optimization solves the problem of multi-objective functions separately. It aims to find and to compare the set of acceptable solutions and present them to the decision maker (DM) who will choose among them the final solution (Figure 3.1). Nowadays and due to the computational advances, it is possible to use techniques based on metaheuristic algorithms to determine the Pareto frontier by optimizing all the objectives separately(Smith, 2002). These methods include genetic algorithms (GA), evolutionary algorithms (EA) and evolutionary strategies (ES) which only differ in the way the fitness selection, mutation and crossover operations are performed.

In this work, we use Matlab (gamultiobj function) to find minimum of multiple functions using genetic algorithm and obtain the Pareto frontier. For each set of solutions, Decision Maker (DM) calculates the minimum of the sum of the three objectives (minimum of losses); the set of solutions that have the minimum is selected (Dehghani-Arani et Maddahi, 2013).

$$F = Min \sum_{j=1}^{N} \lambda_j f_j \tag{3.9}$$

Where: F is the minimum sum of the objectives of the set of solutions; N is the number of objectives; λ_j is the weight of the objective j; f_j is the objective j of the MO function.

OCVC includes the use of DM; in this study the fitness solution was used but various options are possible. The use of OCVC could be advantageous in relation to the development of a flexible system for network operator, by applying different settings at the decision stage, according to specific circumstances. Further research is needed on this topic.

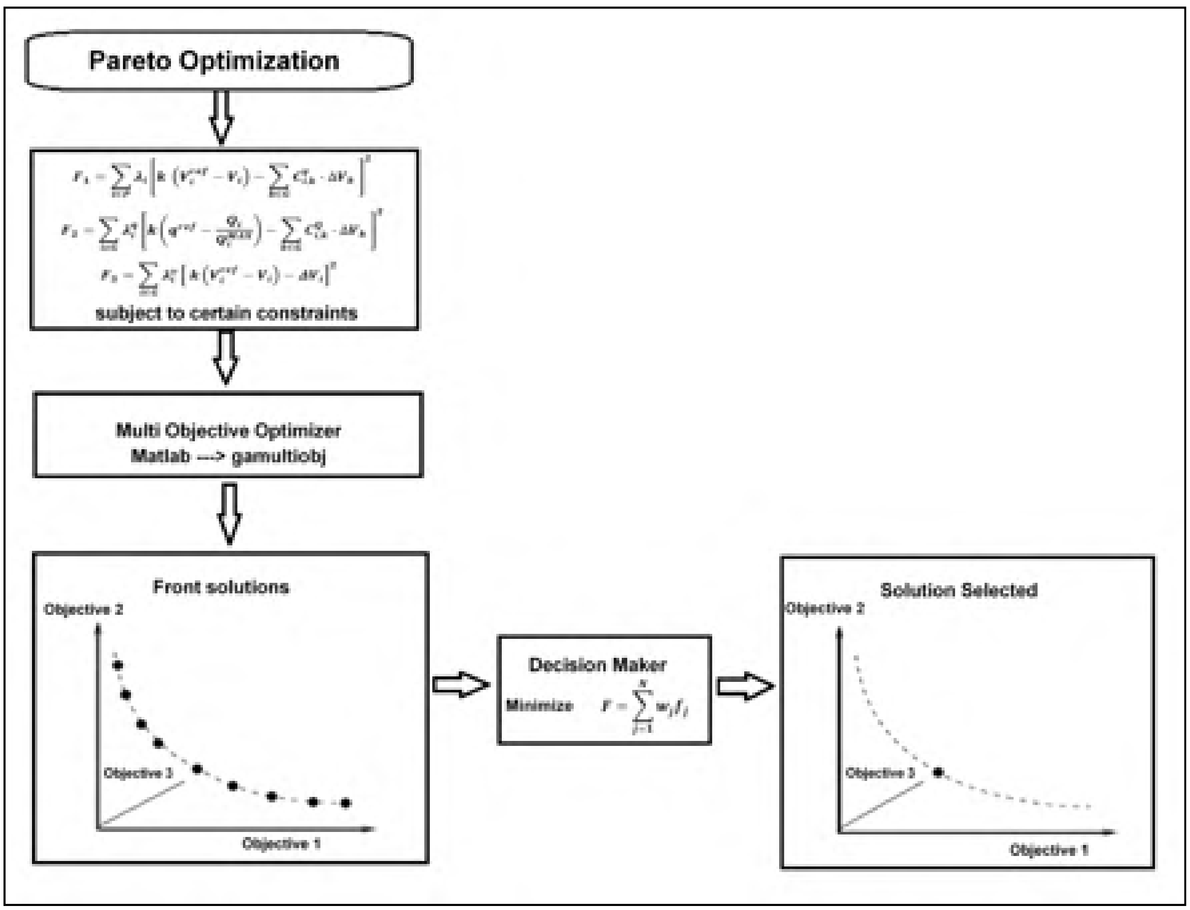

Figure 3.1 Pareto Optimization scheme for multi-objective function

3.4 Optimal Coordinated Voltage Control (OCVC)

3.4.1 Flowchart programming of OCVC

The priority for OCVC is to maintain the voltage within a specific range around the set point using all available resources in the network. From equations 3.1 to 3.3, we see the three objectives on voltages on the pilot buses F_1 and on reactive power F_2 and voltages on the generation buses F_3. Furthermore, equation (3.6) is responsible for maintaining an optimal relationship in the objectives.

Figure 3.2, shows the steps of the sequence of operations necessary for OCVC:

Step 1: Distribution Network

Define input variables; the algorithm acquires the network values. The network will have two disturbances. The first (t=100s) is the input of the DG to the network. The second disturbance is the input of the large load on the pilot bus.

Step 2: Analyze and complete the objective functions

The objective functions are calculated from equations (3.1) to (3.3) and the constraints (3.4) to (3.6). OCVC calculates the three weights corresponding to F1, F2 and F3.

The results of the distribution power flow namely bus voltages, line currents, real and reactive power are those which form the three objectives of the optimization problem. OpenDSS software performs this task (OpenDSS manual and reference guide).

Step 3: Pareto Optimization

When the voltage in the pilot bus is not around the set point, Pareto optimization finds a set of solutions (Pareto frontier) of the voltages at the pilot bus ($V_{P\_optimal}$), the reactive powers ($q_{ref\_optimal}$), and the voltages in the generator ($V_{g\_optimal}$).

Decision Maker (DM) calculates the fitness solution using equation (3.9).

Step 4: Control

According to the voltage at the pilot bus, the optimal reactive power and the voltage in the generator, the control action is executed. For this, a dynamic control of OLTC ensures compliance with the upper and lower voltages. In each time using equation (3.8), the voltage in the OLTC is calculated.

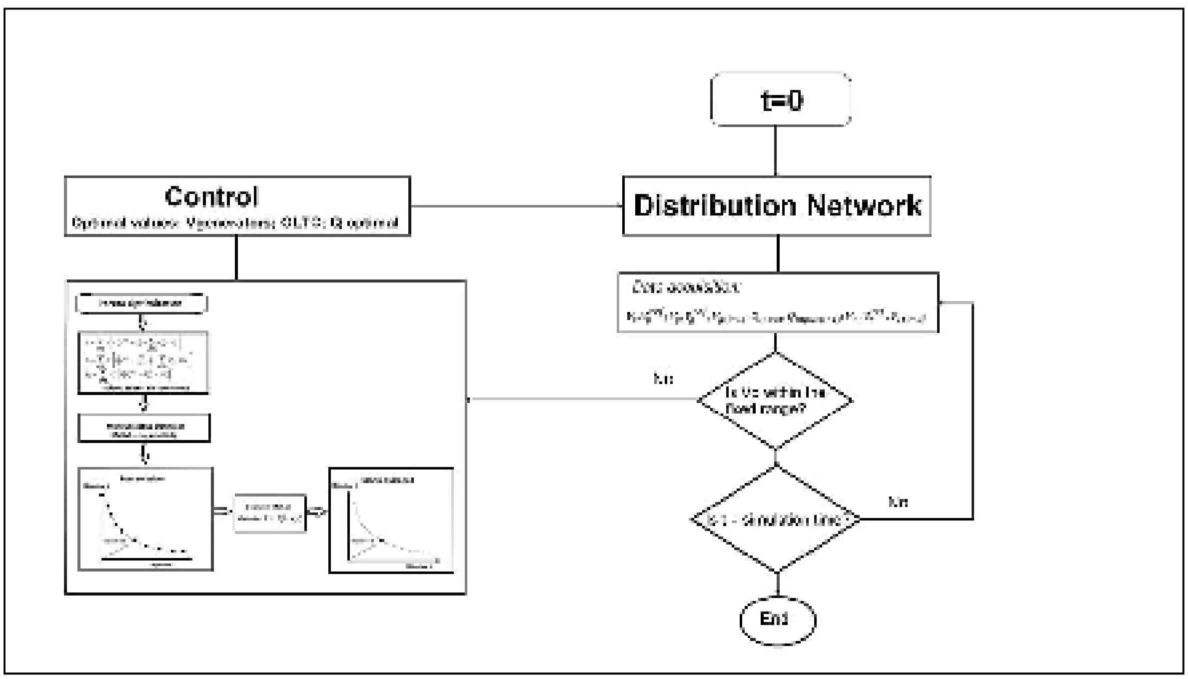

Figure 3.2 Flow chart of the proposed algorithm

Step 5: With the data from step 4, OCVC calculates new values for the distribution network using the OpenDSS software (OpenDSS manual and reference guide).

Step 6: If the voltage values at the pilot bus is within the limits go to 7, if not, return to step1.

Step 7: If the time reaches the limit of simulation go to 8, if not, return to step 2.

Step 8: End.

In OCVC, the three objectives are always competing. When the voltage in pilot bus is within the fixed range, the objective 1 decreases its value. Therefore, the objective 2 (reactive power) becomes more important. The weights are related to the optimization process and will be responsible to maintain this priority.

Conversely, when the voltage in pilot bus is outside the acceptable range, objective 1 and objective 3 increase the value and become the most important objectives. In this case, OCVC optimizes the voltage of the generators and OLTC available on the network.

When the voltage begins to be within the limits defined, OCVC changes the priority. The new objective is to reduce the losses. OCVC has the advantage of using all the available sources of reactive power in the network and calculates the optimum value and reduce the losses, so λ_i^q increases its value in MO function.

The difference between the methods (CVC) proposed by (Biserica et al., 2011; Richardot et al., 2006) and the proposed method is that OCVC solves all the different objectives of the optimization problem separately and that OCVC changes the weights all the time to achieve the objectives of the minimization of losses and maximization of all the reactive power sources.

3.5 Case study

Our analysis method has been implemented on two IEEE distribution test systems with unbalanced load. These are IEEE 13 node test feeder and 34 node test feeder. The first one, IEEE 13 node test feeder is small but good for test case. The second one, IEEE 34 node test feeder is an actual feeder located in Arizona (IEEE.org).

3.5.1 Implementation

OCVC was coded in Simulink of Matlab (R2014a) and OpenDSS (64 bits) software. Simulations carried out on a PC (Intel Core i7 2.9 GHz, 8 GB RAM) were delivered in around 30 s for the IEEE 13 Node, 50 to 60 s for the IEEE 34 Node Test Feeder.

The OpenDSS is an electrical power Distribution System Simulator (DSS) for supporting distributed resource integration and grid modernization efforts (OpenDSS manual and reference guide). It can solve a very large distribution system in a very small CPU time. In addition, it is freely distributed by EPRI.

3.5.2 IEEE 13 Node Test Feeder

The diagram of the IEEE 13 node test feeder used as a test system is given in figure 3.3. It corresponds to a simple primary distribution system. The values obtained for the voltages, currents, and power flows are very accurate compared with the values reported by the IEEE Distribution system analysis subcommittee (IEEE.org). The network has an OLTC.

The work performed by Anwar (Anwar et Pota, 2011) determines the appropriate size and proper allocation of the DG to reduce electric power losses. Then, one DG of 1200 kW in the 675 bus has been added in the network.

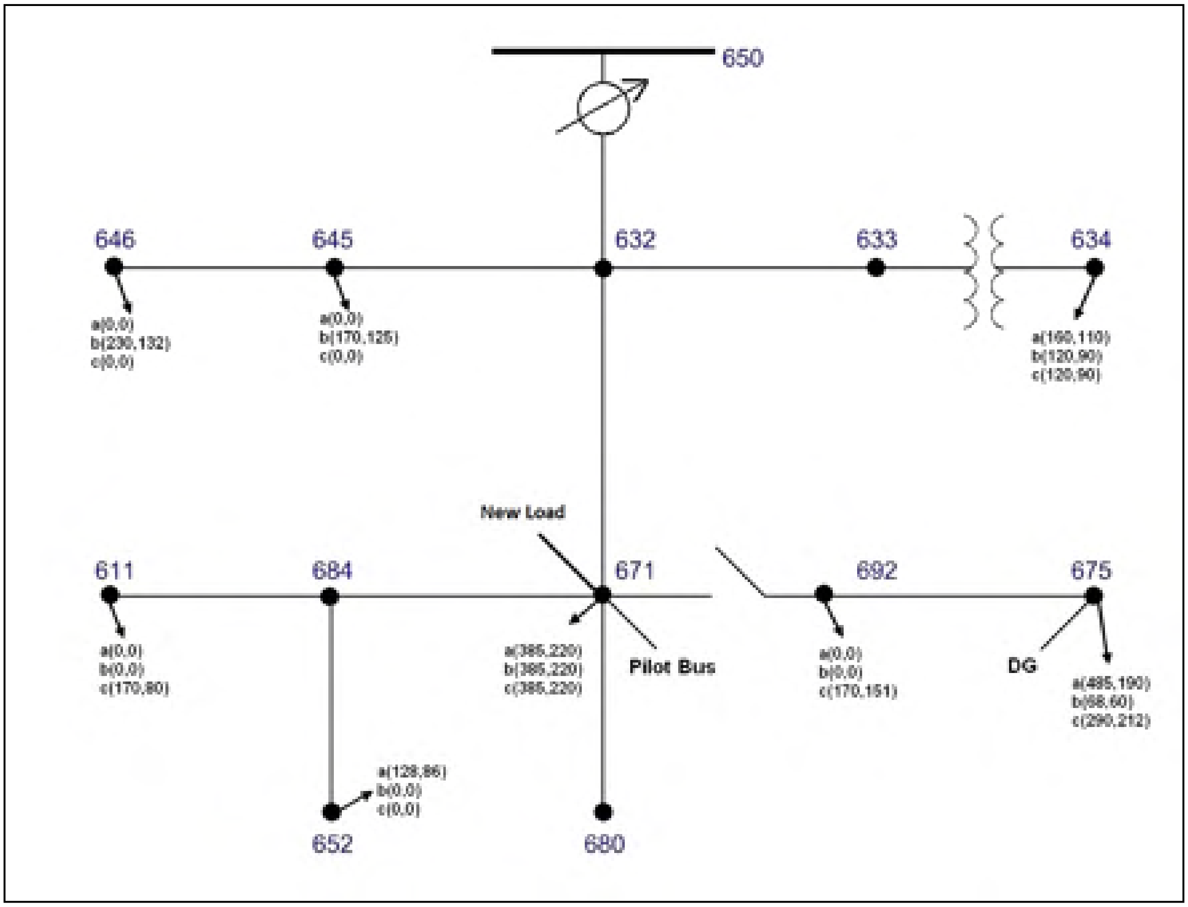

Figure 3.3 Case study distribution network IEEE 13 Node Test Feeder

Ahmidi proposed a multilevel approach for the optimal participation in reactive power balancing of wind farms connected to the network (Ahmidi et al., 2012). The PQ-diagram proposed by Ahmidi calculates the limits of reactive power of the DG, using the various European regulations. In this study, the standards from France are used which allow to use a power factor of ±0.91 and the variation of the operating voltage at DG is ±5% of its contractual voltage.

The simulation started with the initial loads of the distribution network. The total load in the distribution network is for phase 1: 1158 kW and 606 kVAr; for phase 2: 973 kW and 627 kVAr; and for phase 3: 1135 kW and 753 kVAr. Then a DG is added to the system (DG of 1290 kW, ± 0.91 pf) at the 675 bus (t= 100s). Finally, at t=350s, a new load is added to simulate a disturbance (New three phase balanced load in the 671 bus of 1200 kW and 800 kVAr). The simulation lasts 500 seconds.

3.5.2.1 OLTC: reference case

In this case, the only equipment used for the voltage control is the OLTC. This is the typical case of a distribution network currently. The DG and the new load in the network may appear like an overvoltage which OLTC will correct. The reactive power injected from the DG is zero in this case. Furthermore, the DG does not participate in the regulation of the voltage.

3.5.2.2 Coordination Voltage Control (Fixed weight)

The OLTC and DG are considered to control the voltage. In CVC, the weights factor of the MO function response to voltage deviation at the pilot bus.

When the pilot bus voltage is within the limits, the reactive power control is the priority. So, the weight factors are: $\lambda_i = 0.3;\ \lambda_i^q = 0.6\ \lambda_i^v = 0.1$. If the voltage in pilot bus is close to the limits, the reactive power is managed globally. The weight factors in this case are: $\lambda_i = 0.5;\ \lambda_i^q = 0.4\ \lambda_i^v = 0.1.$ Finally, when the voltage in pilot bus has exceeded the limits, the priority of CVC is to bring the voltage within the allowable limits. The weight factors are: $\lambda_i = 0.8;\ \lambda_i^q = 0.1\ \lambda_i^v = 0.1$ (Richardot et al., 2006).

3.5.2.3 Optimal Coordination Voltage Control (OCVC)

OCVC proposes a multilevel approach for optimal participation in reactive power balancing of DG connected to the distribution network. The weighting factors vary dynamically depending on: 1) the value of the voltage at the pilot bus, 2) the value of the voltage at the generator bus and 3) the value of reactive power available.

Table 3.2 Weight variation: Comparison between CVC and OCVC

	CVC			OCVC		
Time (s)	λ_i	λ_i^q	λ_i^v	λ_i	λ_i^q	λ_i^v
0-100	0.5 0.3	0.4 0.6	0.1 0.1	0.1009	0.5828	0.3169
110-340	0.5 0.3	0.4 0.6	0.1 0.1	0.1009	0.2967	0.6023
350-500	0.5 0.5 0.3	0.4 0.4 0.6	0.1 0.1 0.1	0.8	0.1	0.1

In Table 3.2, the variation of the weights is shown. When the voltage at the pilot bus is outside of the acceptable range, CVC usually gives the highest value to weight (λ_i). When the voltage is within the range around the set point, CVC gives higher priority to reactive power (λ_i^q). On the other hand, in OCVC, the weights vary according to availability of resources in the network. The optimal values of OCVC maintain the voltage at optimal values with lower losses.

The introduction of DG in distribution networks creates voltage quality problems (time=100s). Figure 3.4 shows the variation of the voltage (first disturbance).

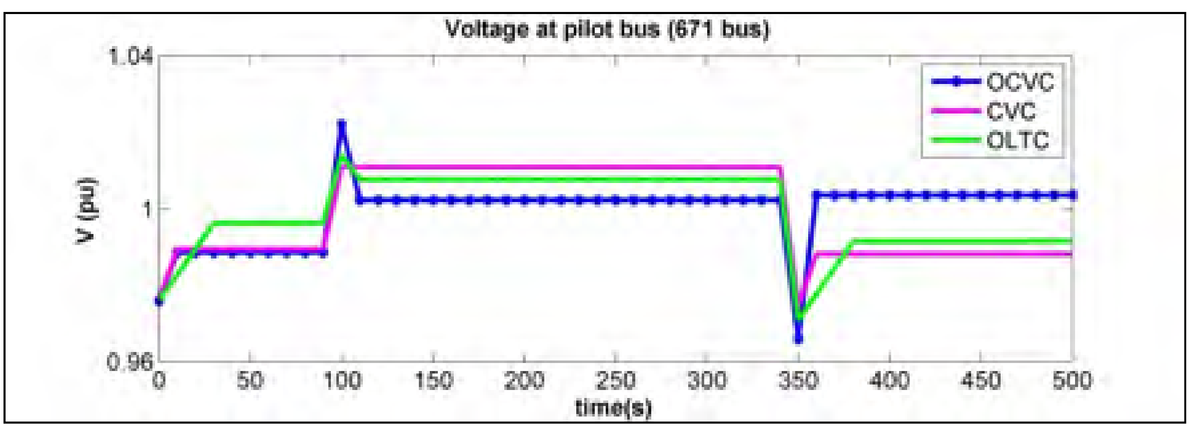

Figure 3.4 Voltage profile of the IEEE 13 Node Test Feeder on the pilot bus

At time t=350s, the second disturbance occurs in the network (new load). Figure 3.4 shows the voltage variation in the three methods used.

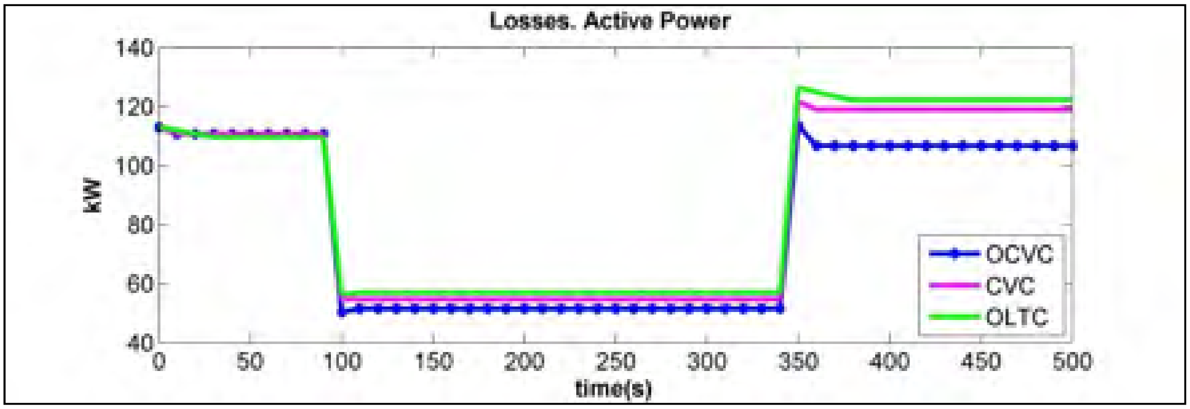

Figure 3.5 Active power losses in the IEEE 13 Node Test Feeder

The Joule losses are higher in the OLTC case due to the non-coordinated control of the DG and so, there are higher reactive power flows in the network (Figure 3.5). CVC has more losses than OLTC because the reactive power in the network is coordinated. The Joule losses are smaller in OCVC due to the optimal management of reactive power in the network. In this case, OCVC optimally coordinates the delivery of reactive power to obtain low losses.

The solution obtained of the three objectives in the multi objective function is the one that produces the smallest possible losses (Figure 3.6).

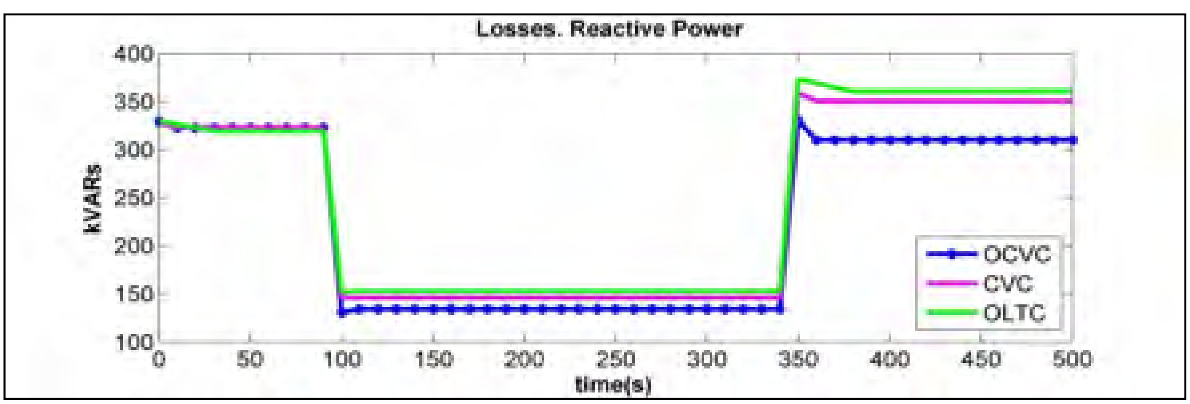

Figure 3.6 Reactive power losses in the IEEE 13 Node Test Feeder

3.5.3 IEEE 34 Node Test Feeder

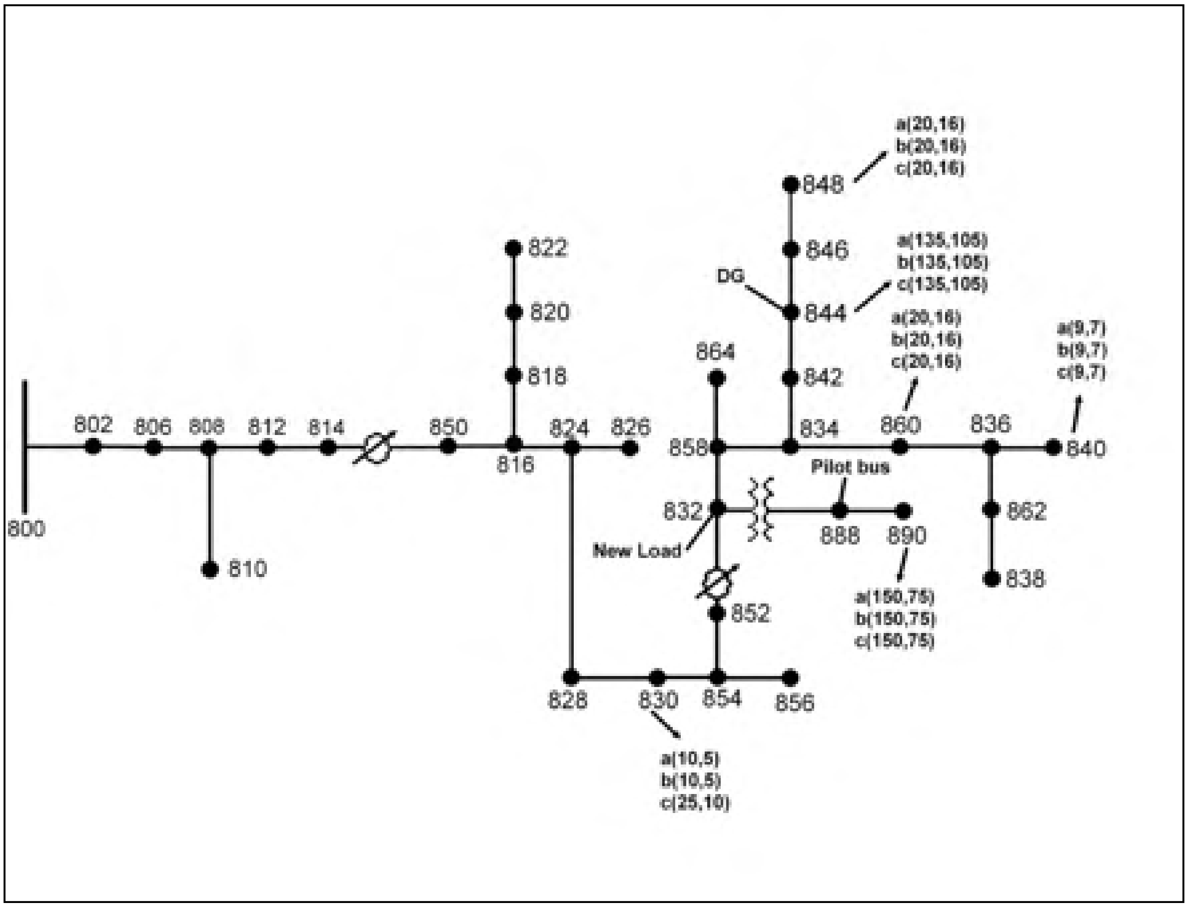

Figure 3.7 Case study distribution network. IEEE 34 Node Test Feeder

In Figure 3.7, we observe the diagram of the IEEE 34 node test feeder. The simulation started with the initial loads of the distribution network. The total spot loads for phase are: for phase 1: 344 kW and 224 kVAr; for phase 2: 344 kW and 224 kVAr; and for phase 3: 359 kW and 227 kVAr. The total distributed loads for phase are: for phase 1: 262 kW and 133 kVAr; for phase 2: 240 kW and 120 kVAr; and for phase 3: 220 kW and 114 kVAr (IEEE.org).

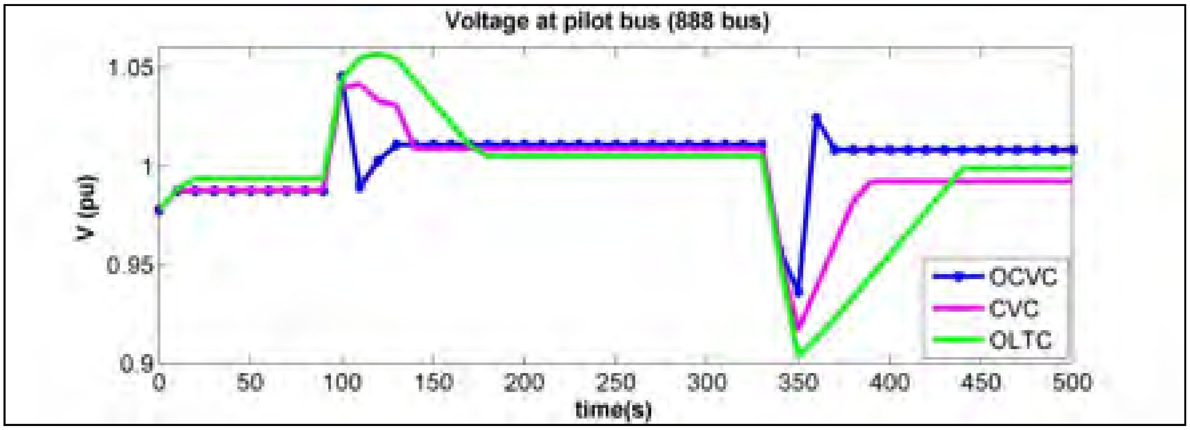

Figure 3.8 Voltage profile of the IEEE 34 Node Test Feeder on the pilot bus

At time t=100 s, one DG is added to the system (DG of 1150 kW, ± 0.91 pf) at the 844 bus, according to the work of (Anwar et Pota, 2011) to reduce losses in the network. The network absorbs 50% of the energy of the DG at t=100 s. At t=140 s, the DG will deliver full capacity. Finally, at t=350 s, a new load is added to simulate a disturbance (New three phase balanced load in the 832 bus of 1000 kW and 666 kVAr). The results are also compared with other techniques using CVC and OLTC.

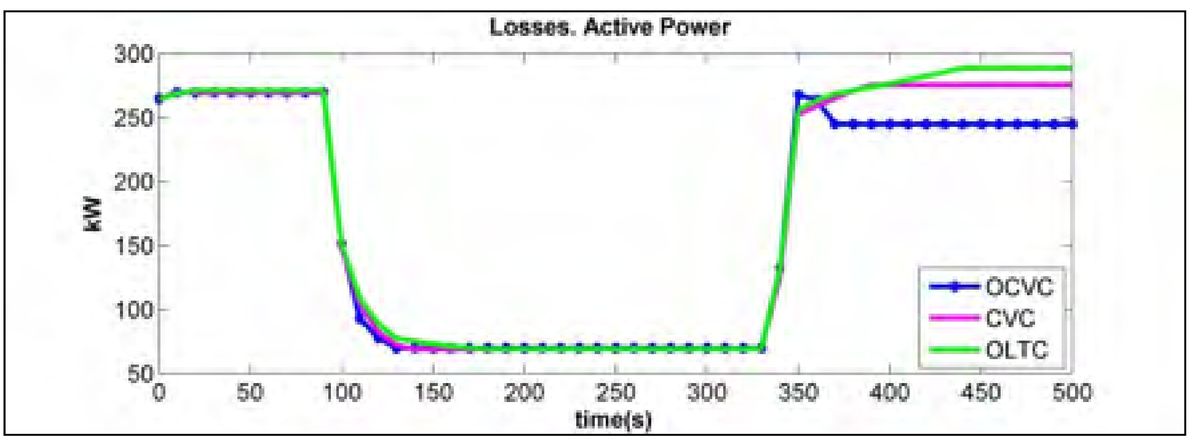

Figure 3.9 Active power losses in the IEEE 34 Node Test Feeder

In IEEE 34 Node Test Feeder, the impact of DG and the impact of a new load on the voltage variation in the pilot bus can be analyzed in Figure 3.8. In OCVC, the variation voltage can be controlled by the DG reactive power output. The impact of DG on losses is also dependent of the DG size and location. In Figure 3.9 and Figure 3.10, it can be seen that when the reactive power available is sufficient to compensate the reactive power demand, the DG operation does not have a significant effect on the distribution system losses.

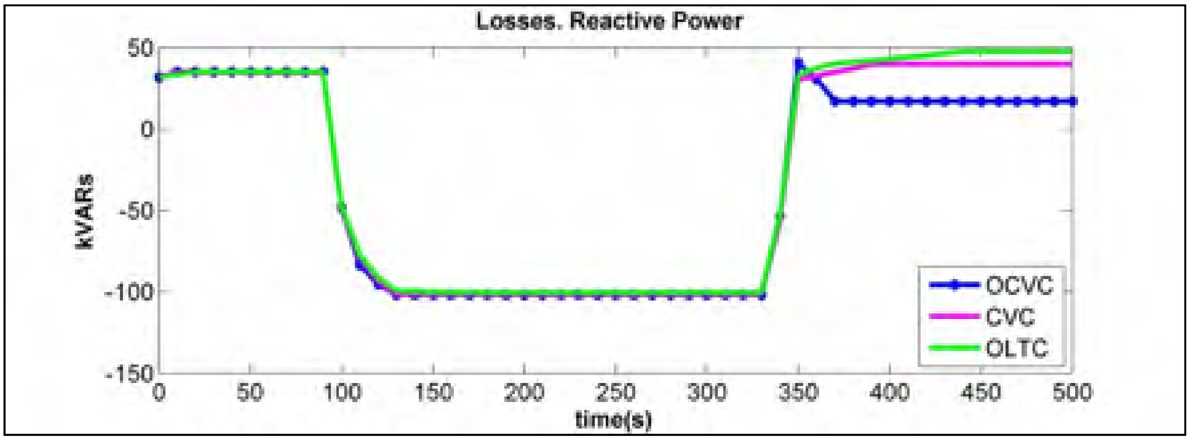

Figure 3.10 Reactive power losses in the IEEE 34 Node Test Feeder

3.6 Conclusions

In this paper, a new technique based on the Pareto frontier has been presented and applied to Multi-Objective optimization voltage problem. It has been proposed as multilevel optimization with the participation of active and reactive power of the DG connected to the distribution network. For this purpose, we used the Pareto frontier to solve all the different objectives of the Multi-Objective problem separately with dynamic weights.

The modern power system requires the generation of a set of optimal solutions (instead of a single solution) that would allow the operator (Decision Maker) to choose. Then, this new technique may be adapted to particular strategies, operating points, objectives and constraints.

OCVC performances are better than those of OLTC and CVC techniques. OCVC eliminates the entire voltage problem, including the DG's over-voltages. The voltage problem has been solved; the distribution network voltage profile stays in a fixed range around the set point values.

OCVC could be an interesting way to reduce or eliminate future investments in classical voltage and reactive power regulation.

This paper shows that the optimal integration of DG in distribution network can help to maintain the voltage within the limits and reduce losses.

CHAPTER 4

COORDINATED VOLTAGE CONTROL IN DISTRIBUTION NETWORK WITH THE PRESENCE OF DGs AND VARIABLE LOADS USING PARETO AND FUZZY LOGIC

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Abstract

This paper presents an efficient algorithm to solve the multi-objective (MO) voltage control problem in distribution networks. The proposed algorithm minimizes the following three objectives: voltage variation on pilot buses, reactive power production ratio deviation, and generator voltage deviation. This work leverages two optimization techniques: fuzzy logic to find the optimum value of the reactive power of the distributed generation (DG) and Pareto optimization to find the optimal value of the pilot bus voltage so that this produces lower losses under the constraints that the voltage remains within established limits. Variable loads and DGs are taken into account in this paper. The algorithm is tested on an IEEE 13-node test feeder and the results show the effectiveness of the proposed model.

Keywords: coordinated voltage control; distributed generation; on load tap changer; multi-objective voltage control; fuzzy logic

4.1 Introduction

Due to rapid industrialization and growth of residential and commercial sectors, the electrical energy requirements have increased significantly over the last decades. In this situation, renewable energy becomes a very important factor in the electrical distribution system. This type of generating unit is known as distributed generation (DG), and these generators will supply a large portion of demand and many of them will be directly connected to the distribution network. The DGs may trigger variations in voltage and can cause a change of direction in the power flow. The voltage rise depends on the amount of energy injected by the DG and, therefore, it is a limiting factor for the DG capacity. Many researchers have studied DGs and their impact on the voltage, the reduction of the losses in the active and reactive power, and the maximization of the DG capacity (Ahmidi et al., 2012; DeJesus et al., 2006; Habibi et al., 2013). In (Anwar et Pota, 2011) a minimization of loss was used to determine the optimum size and location of DG.

On the other hand, a review of the literature shows that many works have been done assuming that the loads in the electrical network are fixed. There are only a few works that use variable loads (Dehghani-Arani et Maddahi, 2013; Hong et al., 2015; Lopez et al., 2004; Queiroz et Lyra, 2009; Zidan et El-Saadany, 2012). In this paper, all the loads of the analyzed networks are varying in time to better reflect system operation. Three different models of load variation are utilized. Each model represents the measurements of the change in consumption of customers for 48 h (data provided by Hydro-Québec).

Coordinated voltage control (CVC) in distribution network adjusts the voltage in pilot buses. CVC uses the multi-objective problem to minimize the voltage variation at the pilot buses (Richardot et al., 2006). Several methods have been proposed to solve the optimization of the multi-objective (MO) voltage control problem. In (Richardot et al., 2006) a genetic algorithm (GA) was used to determine an optimal weighted solution of the MO problem. In (Knowles et Corne, 1999) a simpler evolution scheme for MO problems is proposed; this algorithm uses the local search for the generation of new candidate solutions.

Some researchers (Ngatchou et al., 2005; Richardot et al., 2006; Soroudi et al., 2011) solve the MO voltage control problem converting the objectives into a single objective (SO) function; in this case, the objective is to find the solution that minimizes or maximizes this single objective. The optimization solution results in a single value that represents a compromise among all the objectives (Ngatchou et al., 2005).

Other researchers (Deb et al., 2002; Ngatchou et al., 2005; Xiyi et al., 2013) work with the objectives of the MO problem separately, resulting in a set of solutions called the Pareto frontier. This causes the difficulty to find an optimal solution since there is no a single solution. Therefore, a decision-maker (DM) is necessary to choose the most appropriate solution. This feature is useful because it provides a better understanding of the system because all the objectives are explored. This method leads to find the weighted minimum of the objectives. Thus, the constraints and criteria specified of each objective are important to find the Pareto frontier.

Electrical power systems are very difficult to control with traditional methods due to highly complex and nonlinear behaviors. Fuzzy logic can overcome these difficulties. In (Barin et al., 2008; Loetamonphong et al., 2002) a fuzzy logic technique was introduced to solve the optimal values of MO voltage control problem. The solution set is usually not a singleton set. The problem requires the objectives functions to be linear and it also requires the value of the minimal solutions of the system. To solve this problem, fuzzy logic can be used closely with other optimization technique (Gao et al., 2014).

Previous methods adequately solved the problem of MO voltage control problem using DGs in distribution networks obtaining optimum values of voltage and reactive power (Ahmidi et al., 2012; Anwar et Pota, 2011; Barin et al., 2008; Gaonkar et Pillai, 2010; Ghatee et Hashemi, 2009; Kiprakis et Wallace, 2004; Maciel et Padilha-Feltrin, 2009; Richardot et al., 2006; Viawan et Karlsson, 2008). There is no research that calculates the value of the reactive power of the DG using the optimal values of the MO voltage control problem in distribution network with variable and unbalanced loads.

To overcome the problems cited above, this paper proposes a new method called coordinated voltage control using Pareto and fuzzy logic (CVCPF). This technique finds the optimal values of the MO voltage control problem and finds the optimal value of reactive power of the DG. CVCPF maintains the voltage of the buses into the established limits, minimize the losses of the network, and minimizes the voltage variation in the pilot bus. This new method is tested on an IEEE 13-node test feeder using variables and unbalanced loads.

CVCPF uses Pareto optimization for solving the MO voltage control problem; the objectives of the MO problem are resolved separately. This paper uses fuzzy logic to find the optimal reactive power of DG to inject in distribution system. Fuzzy logic analyzes the voltage difference (ΔV) between the reference voltage (V_{pref}) and the optimal voltage of pilot bus ($V_{pOptimo}$) to find the reactive power of DG that minimizes voltage error.

The original contributions of this paper consist basically in combining the following:

1) variables and unbalanced loads with DGs in distribution network are investigated;
2) CVCPF uses two optimization techniques. Pareto Optimization to find the optimal voltage and fuzzy logic to calculate the optimal value of reactive power of DG;
3) CVCPF uses the reactive power of DG as a control variable to minimize the voltage variation;
4) the objectives of the MO voltage control problem are resolved separately.

The rest of this paper is organized as follows: Section 4.2 presents the classical CVC. Section 4.3 presents coordinated voltage control using Pareto and fuzzy approach (CVCPF). Simulation results are presented in Section 4.4 and, finally, in Section 4.5 the conclusions are given.

4.2 Coordinated Voltage Control (CVC)

Richardot et al. in (Richardot et al., 2006) demonstrated that CVC for transmission networks can be successfully applied to a distribution network. Based on this work, it is presented in the following subsections the optimization model considered in this paper.

4.2.1 Objectives Function

The voltage variation at the pilot buses, the reactive power production, and the generator's voltage deviations are coupled variables and are tied together. Any increase or decrease in voltage at pilot buses will increase or decrease the reactive power production and generator voltage respectively. These objectives are modelled as follows:

4.2.1.1 Voltage at Pilot Bus

The first objective is to minimize the variation in voltage at the pilot buses. In a mathematical form, the objective can be written as follows:

$$F_1 = \sum_{i \in P} \lambda_i \left[\kappa \left(V_i^{ref} - V_i \right) - \sum_{k \in G} C_{i,k}^{V} \cdot \Delta V_k \right]^2 \tag{4.1}$$

where: P and Q are the sets of pilot and generator buses indices; V_i^{ref}, V_i and ΔV_k are set-point voltage, actual voltage and voltage deviation at bus *i*, i.e., the difference of voltage values between two computing steps; $C_{i,k}^{V}$ is the sensitivity matrix coefficient linking the voltage variation at bus *i* and bus *k*, respectively, λ_i and κ weighting factor and regulator gain, respectively.

4.2.1.2 Reactive Power

The second objective is the management of the reactive power. This objective is modelled as follows:

$$F_2 = \sum_{i \in G} \lambda_i^q \left[\kappa \left(q^{ref} - \frac{Q_i}{Q_i^{MAX}} \right) - \sum_{k \in G} C_{i,k}^Q \cdot \Delta V_k \right]^2 \tag{4.2}$$

where: *G* is the set of generator buses indices; Q_i and Q_i^{MAX} are actual and maximum reactive power generations at bus *i*; $q^{ref} = \sum_{i \in G} Q_i / \sum_{i \in G} Q_i^{MAX}$ is the uniform set-point reactive power value within the regulated area; $C_{i,k}^Q$ is sensitivity matrix coefficients linking, respectively, voltage variation at bus *i* and bus *k*. λ_i^q and κ are weighting factor and regulator gain, respectively.

4.2.1.3 Voltage at Generators

The third objective is the minimization of the generator's voltage deviations. The mathematical model is as follows:

$$F_3 = \sum_{i \in G} \lambda_i^v \left[\kappa \left(V_i^{ref} - V_i \right) - \Delta V_i \right]^2 \tag{4.3}$$

where: G is the set of generator buses indices; V_i^{ref}, V_i and ΔV_i are the set-point voltage, actual voltage and voltage deviation, respectively, at the bus *i*, i.e., the difference of voltage values between two computing steps. λ_i^v and κ are weighting factor and regulator gain, respectively.

4.2.2 Constraints

The constraints are presented as follows:

4.2.2.1 Reactive Power Constraint

In this work, one of the main objectives is to control the production of the reactive power of the DG. In (Ahmidi et al., 2012) an acceptable power factor is of ±0.91.

$$q^{ref} = \sum_{i \in G} Q_i / \sum_{i \in G} Q_i^{MAX} \tag{4.4}$$

where: $|Q_i| \leq Q_i^{max}$.

4.2.2.2 Technical Compliance Voltage

The compliance of constraints of voltage on the pilot and generator buses is used to determine the safe operation values. In distribution networks an acceptable steady voltage range is considered within ±3% of the operating voltage at DG (Masters, 2002):

$$\begin{gathered} V_i \in \left[V_i^{min}; V_i^{MAX}\right] \, for \; i \in P \cup G \\ |\Delta V_i| \leq \Delta V_i^{MAX} \, for \; i \in G \end{gathered} \tag{4.5}$$

4.2.2.3 Weights Constraints

The weights of the objectives are important because they give priority to an objective that depends on the conditions of operation. For example, if the voltage on the pilot bus is outside of the limits, the weight for this objective will be higher than the other two; however, these weights are related as described in relation Equation (4.6):

$$\lambda_i + \lambda_i^q + \lambda_i^v = 1 \tag{4.6}$$

$\lambda_i, \lambda_i^q, \lambda_i^v$ are weighting factors for bus *i*.

4.3 Coordinated Voltage Control Using Pareto and Fuzzy Logic (CVCPF)

This section presents the Pareto optimization to find the optimal voltage on the pilot bus and the determination of reactive power of DG using a fuzzy approach.

4.3.1 Pareto Optimization

The classical methods consist of converting the MO problem into a single objective (SO) problem. The solution of this SO problem yield a single result that depend of the selection of the weights. On the other hand, Pareto optimization optimizes all objectives separately.

Figure 4.1 shows that Pareto optimization calculates a set of solutions called the Pareto frontier, which can optimize the maximum possible number of objectives. In this work, we use Matlab to find the minimum of multiple functions using a genetic algorithm and obtain the Pareto frontier subject to the linear equalities $\mathrm{Aeq} \times \mathrm{x} = \mathrm{beq}$. All objectives and constraints are changing in the real-time set considering the actual needs and capabilities. This Pareto frontier is obtained by using the dominance relationship among different solutions.

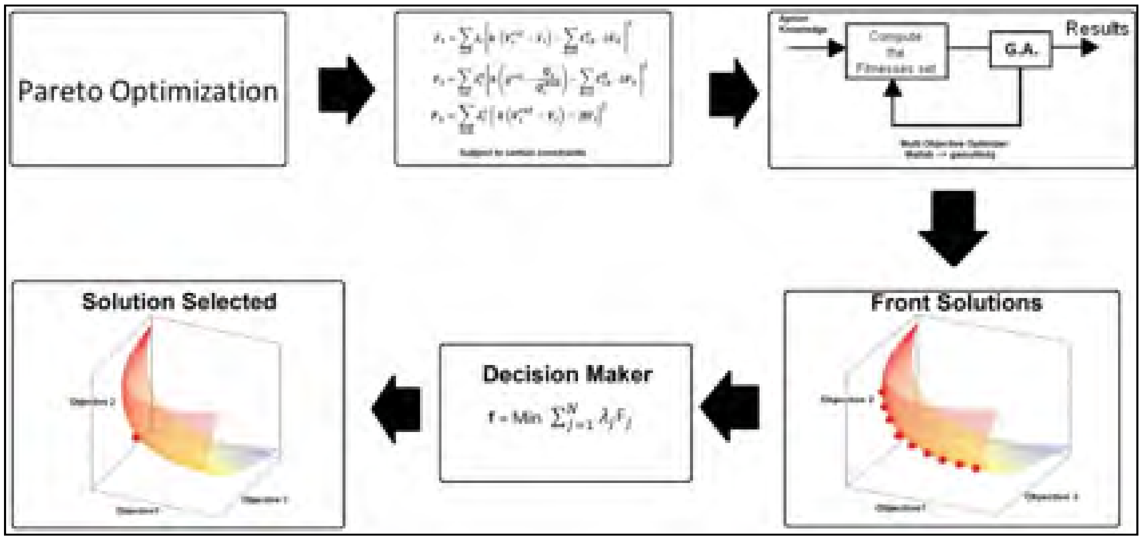

Figure 4.1 Pareto optimization scheme for a multi-objective problem

The algorithm needs to choose only one solution to this set of solutions using a new condition decision-maker (DM) (Dehghani-Arani et Maddahi, 2013).

For each set of solutions, the decision-maker (DM) calculates the minimum of the sum of the three objectives; the set of solutions that have the minimum is selected:

$$f = Min \sum_{j=1}^{N} \lambda_j F_j \tag{4.7}$$

where: f is the minimum sum of the objectives of the set of solutions. N is the number of objectives. λ_j is the weight of the objective j. F_j is the objective j of the MO voltage control problem.

4.3.2 Fuzzy Logic

Fuzzy logic is an extension of traditional Boolean relations where the system is not characterized by simple binary values but a range of truths from 0 to 1. The input and output of the system are “somehow” related (Ghatee et Hashemi, 2009). Fuzzy logic is increasingly utilized in distribution networks.

Two of the most important types of fuzzy control are: the Mamdani and Sugeno models. The Mamdani model allows expressing the available prior knowledge of the system, whereas the Sugeno model simplifies the calculations of the output. The Sugeno output can be either linear or constant and the final output is a weighted average of each rule’s output; so, its process does not require defuzzification. It works well with optimization and adaptive techniques and has a guaranteed continuity of output surface. Finally, the Sugeno model is well suited to mathematical analysis (Takagi et Sugeno, 1985).

In this work, the Sugeno model will be used and its mathematical model has the following form:

$$If\ input\ 1 = x\ , then\ the\ Output\ is\ z = c \tag{4.8}$$

In a zero-order model, the output level *z* is a constant (a=0). Each output z_i of each rule has a weight w_i (Soroudi et al., 2011):

$$w_i = min\ F_1(x) \tag{4.9}$$

Where $F_1(x)$ are the membership functions for input 1 (Takagi et Sugeno, 1985). The average estimate is then given by the equation:

$$Final\ output = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \tag{4.10}$$

CVCPF uses fuzzy logic to calculate the optimal reactive power of DG. Figure 4.2 shows the fuzzy logic reactive power controller. The input signal is the error (ΔV). This error (ΔV) is varying over the range [$\Delta V_{\min}$, Zero and $\Delta V_{\max}$] where

$\Delta V_{\min}$ = -0.05 (p.u.) and ΔV_{max} = +0.05 (p.u.)

The output of the fuzzy logic is the variation of the reactive power. The output of the controller is the voltage variation. The PID generates an output based on the difference between the power factor calculated by fuzzy logic and output power factor of the network. The three linguistic labels define voltage: Low, Normal, and High. The input membership (Gaussian) functions are shown in Figure 4.3.

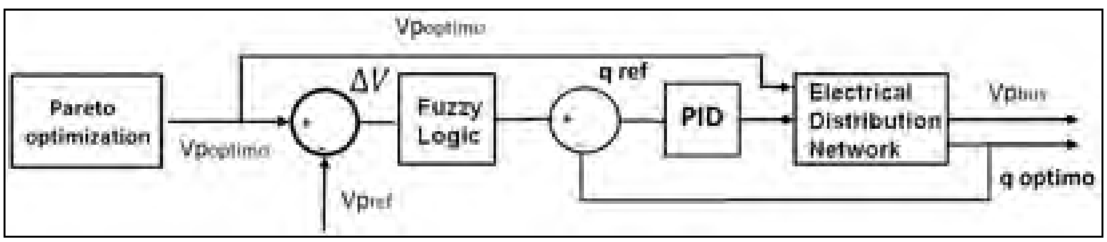

Figure 4.2 Fuzzy logic reactive power factor controller

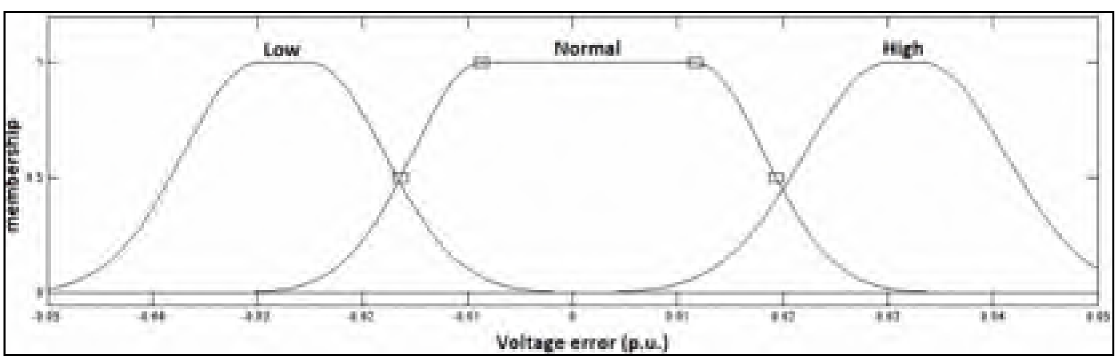

Figure 4.3 Input fuzzy membership functions

4.3.3 Design of Reactive Power of DG

In this work, this model is a single-input and single output (SISO) controller (Figure 4.2). Using relation Equation (4.8):

$$If\ input\ 1 = \Delta V, then\ Output\ is\ z = c \tag{4.11}$$

The set of fuzzy rules are as follows:

$$\begin{aligned} &IF\ (\Delta V = Low)\ THEN\ u_1 = PF_{min} \\ &IF\ (\Delta V = Normal)\ THEN\ u_2 = PF_{nom} \\ &IF\ (\Delta V = High)\ THEN\ u_3 = PF_{max} \end{aligned} \tag{4.12}$$

The advantage of the Sugeno model is that the output can be found using the average estimate formula (Takagi et Sugeno, 1985).

$$PF_{ref} = \frac{\sum_{i=1}^{3} w_i u_i}{\sum_{i=1}^{3} w_i} \tag{4.13}$$

where: u_1, u_2, u_3 are the outputs of the respective fuzzy rules.
$w_i = \min F_1(x)$ when $F_1(x)$ is the membership function for input 1.

4.3.4 Solution Algorithm

The algorithm flow chart is illustrated in Figure 4.4. The steps followed to solve the MO voltage control problem are as follows:

Step 1: System Data: Define input variables; the algorithm acquires the network values.

Step 2: Analyze and complete the objective functions. The objective functions are calculated from Equations (4.1) to (4.3) and the constraints Equations (4.4) to (4.6). CVCPF calculates the three weights corresponding to F1, F2, and F3 and finds a set of solutions (Pareto frontier).

Step 3: Decision-maker (DM) calculates the fitness solution.

Step 4: Fuzzy logic

Figure 4 shows the step 4. The error (ΔV) is calculated:

$$\Delta V = Vp_{ref} - Vp_{optimo} \tag{4.14}$$

Determination of the rules: Equation (4.12) shows the rules.

Determination of the output stage: The final output is computed according to Equation (4.13). Finally, the reactive power of DG is:

$$\begin{gathered} Ang = \operatorname{acos}(PF) \\ Q_{DG} = (Active\ power\ of\ DG) \times \tan(Ang) \end{gathered} \tag{4.15}$$

Determination of the optimal reactive power reference: The reactive power is computed using Equation (4.4):

$$q^{ref} = \sum_{\mathrm{i} \in \mathrm{G}} Q_{DGi} / \sum_{\mathrm{i} \in \mathrm{G}} Q_i^{MAX} \tag{4.16}$$

Finally, the PID removes the error of the power factor.

Step 5: Control: According to the voltage at the pilot bus and the optimal reactive power reference, the control action is calculated on the OLTC and the PF of the DG.

Step 6: With the data from step 5, CVCPF calculates new values for the distribution network using the OpenDSS program (OpenDSS manual and reference guide).

Step 7: If voltage values at the pilot buses, reactive power reference, and voltage at generators are within the limits go to step 8; if not, return to step 1.

Step 8: End.

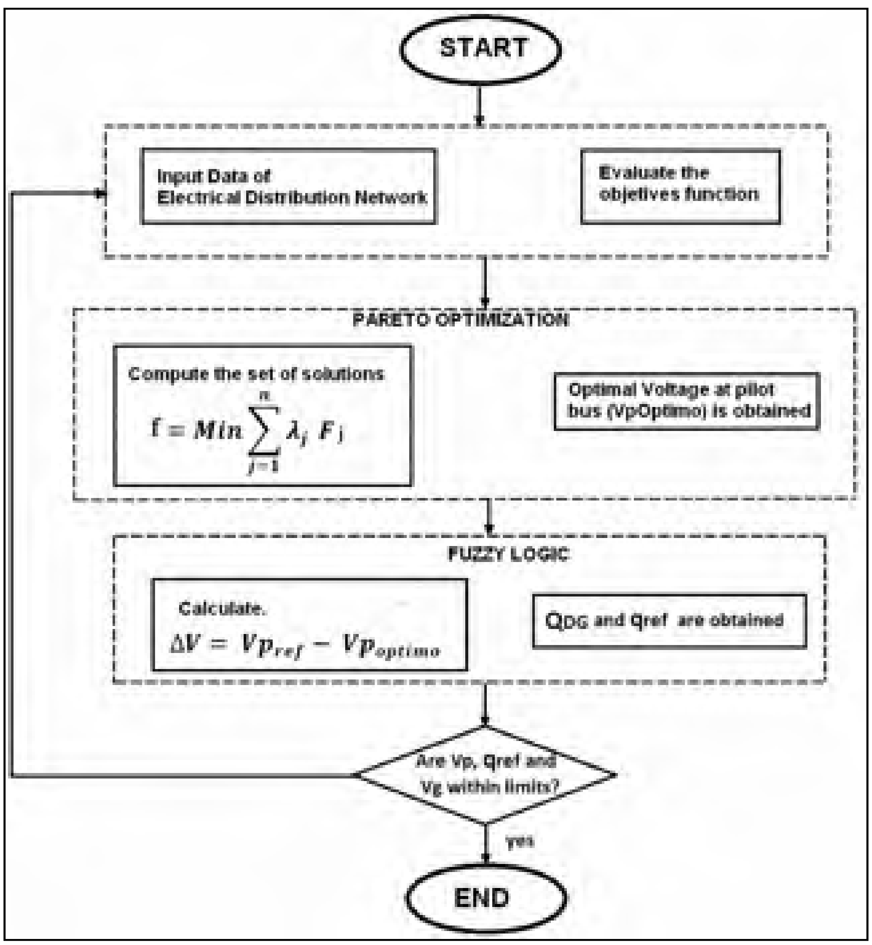

Figure 4.4 Flow chart of the proposed algorithm

4.3.5 Case Study

The proposed method is tested on IEEE13 Node Test Feeder shown in Figure 4.5, 4.16 kV distribution network. The technical data of the network is given in (Kersting, 2001). In this work, for Case 1, 2, and 3 only a DG with 1.290 kW connected at the 675 bus is considered (Anwar et Pota, 2011). For Case 4, this work uses three DGs.

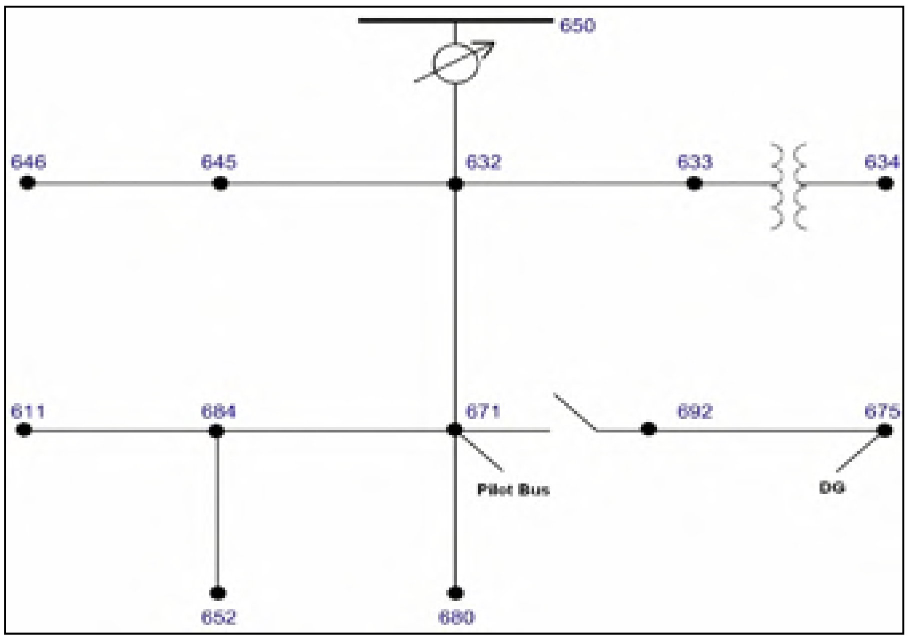

Figure 4.5 IEEE 13 Node Test Feeder

Table 4.1 shows the default unbalanced loads values for the network IEEE 13 (fixed values). In the second column of the Table 4.1, the three basic loads are displayed. (1) Constant Impedance Load Model (Constant Z); (2) Constant Current Load Model (Constant I); and (3) Constant Power Load Model (Constant PQ). In this study, three different cases are analyzed where variable loads are added to the fixed network loads; each case represents the measurements of typical change in consumption of customers in a 48 h horizon (data provided by Hydro-Québec). Table 4.2 shows the cable line configuration for an IEEE 13 node test feeder. Figure 4.6 shows these three cases on the pilot bus in active power (bus 671).

Table 4.1 Spot Load Data for IEEE 13

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	**1158**	**606**	**973**	**627**	**1135**	**753**

Table 4.2 Cable line configuration for IEEE 13 node test feeder

Node	R (Mile)	X (Mile)	Distance	Config.	X/R Ratio
650–632	0.3465	1.0179	0.378	601	2.9376
632–633	0.7526	1.1814	0.094	602	1.5697
632–645	1.3294	1.3471	0.094	603	1.0133
632–671	0.3465	1.0179	0.378	601	2.9376
645–646	1.3294	1.3471	0.056	603	1.0133
671–684	1.3238	1.3569	0.056	604	1.0250
671–680	0.3465	1.0179	0.189	601	2.9376
692–675	0.7982	0.4463	0.094	606	0.5591
684–611	1.3292	1.3475	0.056	605	1.0137
684–652	1.3425	0.5124	0.151	607	0.3816
671–692				Switch	
633–634	1.10%	2%		XFM-1	

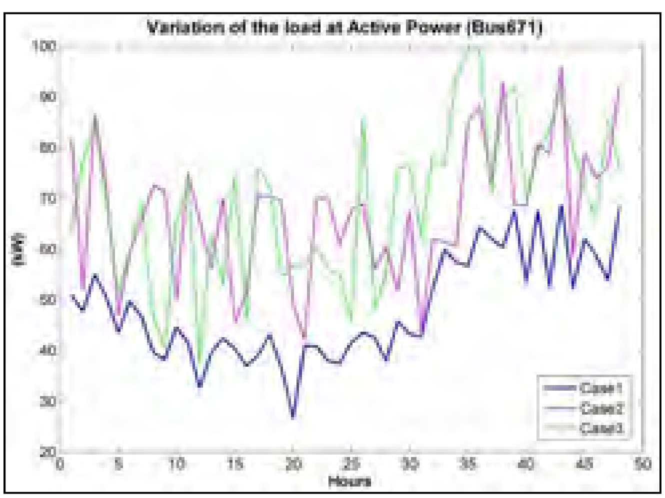

Figure 4.6 Variation of the load in kW at bus 671

In Figure 4.6 and in the Table 4.3, we can see the maximum load variations. Case 1 is 16.27 and 16.49 kW at hours 42 to 43 and 43 to 44, respectively; Case 2 is 34.28 and 37.38 kW at hours 2 to 3 and 43 to 44, respectively; and Case 3 is 39.66 and 37.73 kW at hours 25 to 26 and 26 to 27, respectively.

Table 4.3 Maximum load variation in Case 1, 2 and 3

Case 1 (kW)			**Case 2 (kW)**			**Case 3 (kW)**		
Hour	**Bus 671**	**Variation**	**Hour**	**Bus 671**	**Variation**	**Hour**	**Bus 671**	**Variation**
43	68.69	16.27	3	86.38	34.28	26	85.59	39.66
44	52.20	16.49	44	58.62	37.38	27	47.86	37.73

4.4 Simulation Results

The proposed method (CVCPF) is compared with two other methods (OLTC and OCVC).
In the method OLTC, the only equipment used for the voltage control is the OLTC. This is the typical case of a distribution network nowadays. The connection of DG and the variable load will fundamentally alter the feeder voltage profile then the OLTC performs control voltage. The reactive power injected from the DG is zero in this method; furthermore, the DG does not participate in the regulation of the voltage.

Optimal Coordinated Voltage Control (OCVC) proposes a solution for the MO voltage control problem using only Pareto optimization. This method proposes a balanced participation in the reactive power of DG connected to the distribution network. In OCVC, the weighting factors vary dynamically depending on: (1) the value of the voltage at the pilot bus, (2) the value of the voltage at the bus generator, and (3) the value of the reactive power available (Richardot et al., 2006).

The difference between CVCPF and OCVC is that CVCPF uses two techniques to calculate the optimum values. OCVC uses only Pareto to get the optimum values whereas CVCPF uses Pareto and fuzzy logic. To calculate the reactive power given by DG, CVCPF uses fuzzy logic according to the optimum values given by Pareto. The effect of reactive power of

DG on the voltage profile and the variable load in the network is shown in Figures 4.7–4.9. In all three cases, the reactive power input of CVCPF and OCVC are almost equal. The difference is the voltage variation; in the CVCPF method it is lower than in the other methods (Table 4.3).

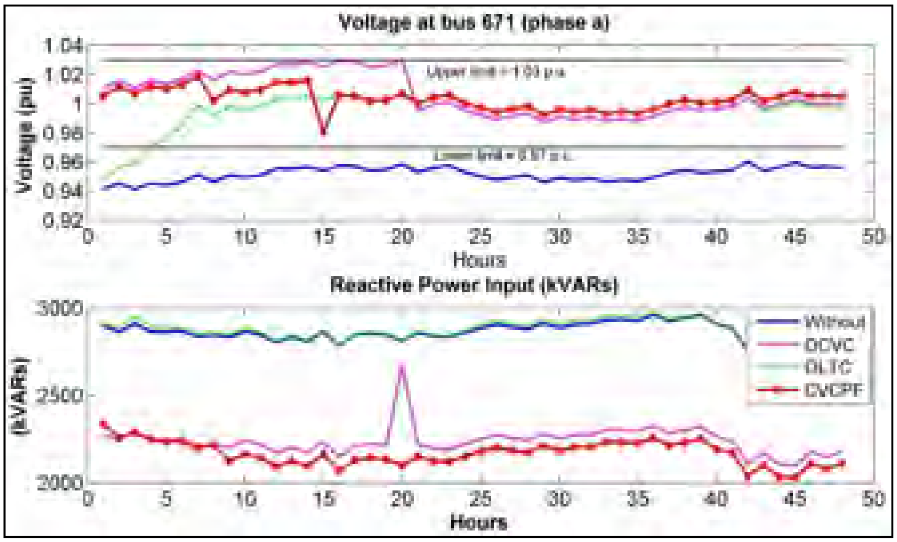

Figure 4.7 Voltage at bus 671 (phase a) with respect to reactive power input. Case 1

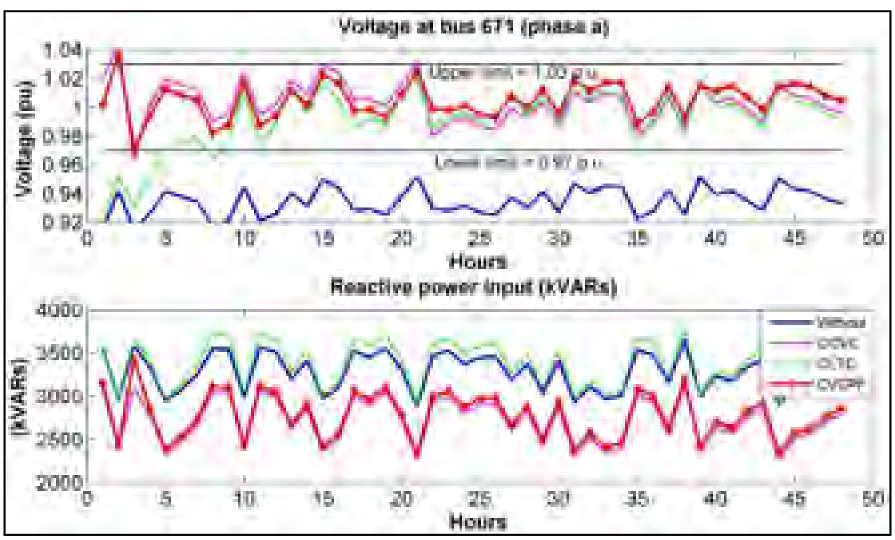

Figure 4.8 Voltage at bus 671 (phase a) with respect to reactive power input. Case 2

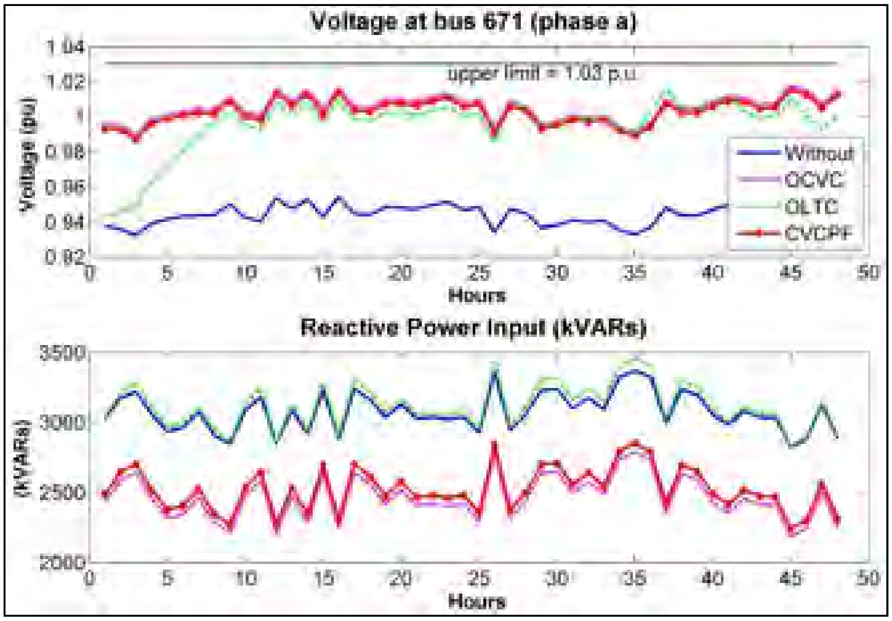

Figure 4.9 Voltage at bus 671(phase a) with respect to reactive power input. Case 3

For the case study, the constraints of Equations (4.4) and (4.5) will be:

$$|Q_i| \leq DG\ (kW) \times (\pm 0.91) \tag{4.17}$$

$$V_i \in [0.97; 1.03]\ for\ i \in P \cup G \tag{4.18}$$

In the method "without", the network does not perform any voltage control. The DG and variable loads cause voltage variations.

Case 1:

In Figure 4.7, we can see that when the voltage reaches the upper limit allowed, the Objective 1 of the MO voltage control problem is the priority (Equation (4.1)). The voltage at hour 20 (OCVC line) reaches the maximum allowed value; OCVC maintains the voltage close to the reference value. Objective 2 of the MO voltage control problem is not the priority (Equation (4.2)), so the reactive power of the DG decreases and the reactive power input increases.

From hour 21, the profile voltages are similar. However, in CVCPF the voltage is close to one (1 p.u.). Reactive power input is similar in these two methods. In the hours 43 and 44 (maximum load variations), the variation of voltage in reactive power is similar in the CVCPF and OCVC methods.

Case 2:

At hours 3 and 44 (maximum load variations) of Figure 4.8 and Table 4.4, the voltage variation in CVCPF is smaller than in the other methods. At hour 3, OLTC has a lower variation than CVCPF but the voltage on the bus 671 is not within the limits (Figure 4.8). In the hours 3, 22, 39, and 44, we can see that each time that the CVCPF line crosses the OCVC line; the voltage variation in CVCPF is smaller than the other methods. Additionally, at this time, the reactive power input between CVCPF and OCVC is almost similar. So, CVCPF used DG reactive power to reduce the voltage variation.

Table 4.4 Maximum load variation in Case 1, 2 and 3

Case 2				
	Hour	Variation (V p.u.)		
		CVCPF	OCVC	OLTC
Maximum load variation	3	0.065	0.081	0.033
	44	0.016	0.026	0.033
Line crosses	3	0.065	0.081	0.033
	22	0.026	0.053	0.033
	39	0.021	0.032	0.038
	44	0.016	0.026	0.033
OCVC variation is higher than 0,025 V	3	0.065	0.081	0.033
	4	0.023	0.039	0.024
	10	0.028	0.029	0.036
	11	0.028	0.029	0.036
	22	0.026	0.053	0.033
	35	0.028	0.029	0.029
	39	0.021	0.032	0.038
	44	0.016	0.026	0.033

When the voltage variation on the method OCVC is higher than 0.025 p.u. (Table 4.4), the voltage in CVCPF is lower. This can be observed at the hours 3, 4, 10, 11, 22, 35, 39, and 44. At these hours, there is a small difference between the reactive power input of CVCPF and OCVC. Fuzzy logic is better suited to voltage changes caused by the variation of the load. Therefore, fuzzy logic achieves a more efficient management of reactive power.

Case 3:

At hours 26 and 27 (maximum load variations) of Figure 4.9, the voltage variation in CVCPF is similar than in the other methods. In all the time, voltage variations in CVCPF and OCVC have not exceeded the value of 0.025 p.u. Similarly, the reactive power input for CVCPF and OCVC are similar.

The losses of active and reactive power for CVCPF and OCVC are always lower than other proposed methods (Figure 4.10).

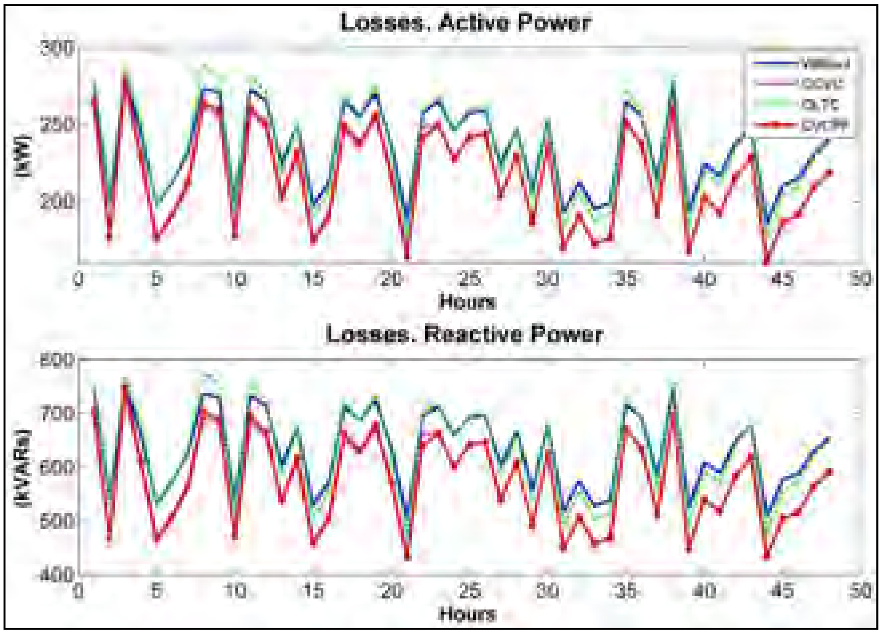

Figure 4.10 Losses. Active and reactive power for Case 2

Figure 4.11 shows the reactive power delivered by the DG for Case 3 using CVCPF and OCVC methods. The reactive power varies according to the needs of the network. Then, the reactive power of the DG helps the distribution network to maintain a stable voltage and reduce loss.

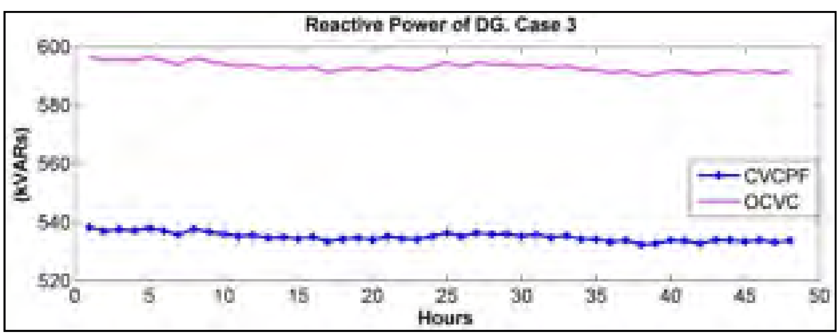

Figure 4.11 Reactive power generated by the DG for Case 3
with CVCPF and OCVC methods

For the simulation, the OpenDSS and Matlab programs are used. We have used OpenDSS for unbalanced load flow. The method uses an OpenDSS server to communicate with Matlab; thus, OpenDSS data and Matlab can work together.

Case 4.

The IEEE 13 Node Test Feeder has three DGs. The DG1 is located on the bus 675 and has a capacity of 360 kW. The DG2 is located on the bus 671 and has a capacity of 630 kW. Finally, The DG3 is located on the bus 632 and has a capacity of 300 kW (Khushalani et Schulz, 2006). Variable load 1 is used in this case.

The Figure 4.12 shows that the voltage at the pilot bus is always within the limits. However, in CVCPF the voltage variation is less.

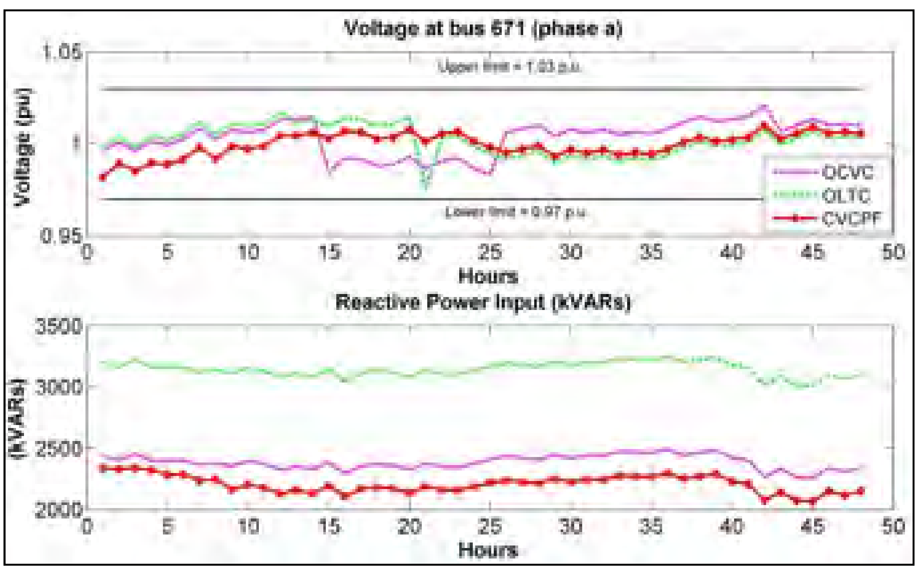

Figure 4.12 Voltage at pilot bus with respect to reactive power input. Case 4

4.5 Conclusions

A new algorithm, called CVCPF, for resolving the MO voltage control problem in distribution networks is presented. The three objectives considered in this paper are: voltage at pilot bus, management of the reactive power and voltage in generators. CVCPF uses a combination of optimization techniques (Pareto optimization and fuzzy logic) to find the optimal values for the MO voltage control problem.

The performance of the CVCPF is evaluated on an IEEE 13 node test feeder. Variables and unbalanced loads are used, based on real consumption data, over a time window of 48 h. Three such profiles are used in the study, varying in the amount of the load. The results are compared with those obtained from the methods OCVC and OLTC as well as from the case of no voltage control.

This work demonstrates that CVCPF reduces the voltage variation more than the other methods.

This work shows also that optimal integration of the DGs in the distribution network helps to maintain stable voltage and to reduce loss.

CVCPF includes the use of decision-maker; in this study the fitness solution was used but various options are possible. The use of CVCPF could be advantageous with respect to the development of a flexible system for network operators, by applying different settings at the decision stage, according to specific circumstances. Further research is needed on this topic.

Acknowledgments

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CHAPTER 5

POWER FACTOR COMPUTATION OF DISTRIBUTED GENERATION USING MULTI-OBJECTIVE OPTIMIZATION

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Abstract

Increased Distributed Generation (DG) conventional distribution networks with unbalanced loads require new control strategies to optimize the use of available resource assets. This paper presents a new technique to demonstrate the benefits of using the reactive power of the DGs in distribution networks with variable and unbalanced loads. The problem is formulated as a multi-objective optimization model that minimizes reactive power losses with the minimization of the variations of the voltage on the pilot bus using : Pareto Optimality, used to find the optimal value of the pilot bus voltage, and Fuzzy-PI controller, used to find the optimal power factor of the DGs. The proposed technique is applied to the IEEE 13 and 123-node test feeders with different and real cases of variable loads. The results demonstrate the efficiency of the proposed approach and its significant impact on loss minimization.

Keywords: Distributed generation (DG); Multi-objective optimization; distribution network; energy loss; optimal power factor; optimal size.

5.1 Introduction

Demand for electricity is growing rapidly. To satisfy this demand, the electrical networks has become highly complex due to the large number of buses present, as well as the large variety of production systems in use; these include those related to renewable energy in general, which today, play a very important role in electrical distribution systems.

The generating units connected to the distribution network are known as Distributed Generations (DGs), and they can meet a large proportion of demand. However, DGs may trigger voltage deviation and changes in the power flow direction. Voltage deviation is function of the energy injected by the DGs, and therefore constitutes a limiting factor for their capacity. Traditionally, DGs have been integrated into the distribution network as passive circuits; their power factor (PF) depends on technical decisions made at certain given times, and may lead to undesirable levels of absorption of reactive power from the transmission network, as well as to voltage problems (Ochoa et al., 2011). Knowledge of the characteristics of the distribution network, of load variation and of the DG type is required to specify the capacity of the reactive power (or voltage support) (Kolenc et al., 2012; Li et al., 2013). In most European countries, the permissible power factor (PF) range for DGs is ±0.95. However, countries such as Spain allow the reactive power of DGs to be delivered according to network requirements (Grid, 2010). Moreover, DGs can yield several additional benefits, such as loss reduction, voltage enhancement, reliability improvement and network upgrade deferral. The DGs are integrated into the network, act as spinning reserves, and provide reactive power support, loss compensation, frequency control, and other rapid response services (Anwar et Pota, 2011; Barin et al., 2008; Dehghani-Arani et Maddahi, 2013; Hung et Mithulananthan, 2014; Hung. et al., 2013; Kiprakis et Wallace, 2004; Maciel et Padilha-Feltrin, 2009).

As the volumes of DGs increases, however, so do some associated problems. One of these is the disequilibrium between energy supply and demand. Generally, in a distribution network, loads usually change with time, while the network uses available resources to attempt to maintain the voltage within permissible limits (Hung et Mithulananthan, 2014; Ren et al., 2010; Zhang. et al., 2015). The direct and indirect cost of power supply quality, reliability, and energy losses of the DGs is presented by (Muttaqi et al., 2016). Many researchers (Aghaei et al., 2014; Esmaili, 2013; Griffin et al., 2000; Khalesi et Haghifam, 2009; Li et al., 2013; Nara et al., 2001; Ren et al., 2010; Richardot et al., 2006) usually employ a multi-objective optimization problem (MOP) in dealing with the latter problem. (Niknam et al., 2011) presents an efficient new MO fuzzy self-adaptive particle swarm optimization (MNFSAPSO) to solve the MOP, considering the minimization of power loss and voltage deviations. In (Richardot et al., 2006), the three objectives of the MOP are: 1) minimization of the voltage deviation on pilot buses; 2) minimization of reactive power production ratio deviation; and 3) minimization of generators' voltage deviation. The authors convert MOP models into a simple objective problem (SOP). The optimal solution gives a single value, which represents a compromise between all objectives, and requires a priori knowledge about the relative importance of the objectives and the limits of the constraints under consideration. The MOP allows precise reactive power management to maintain the voltage within permissible limits.

The importance of working with DGs that are capable of delivering both active and reactive power in a distribution network is illustrated in (Ahmidi et al., 2012; Duong et al., 2010; Moghimi et al., 2013; Thong et al., 2007). In (Ahmidi et al., 2012; Thong et al., 2007), the DGs are considered as negative loads that play an active role in the power system's control and operation.

Previous methods adequately solved the problem of finding an optimum location and size for DGs in a distribution network. However, the majority of existing works convert the MOP into SOPs. Furthermore, there is no solution that considers reactive power losses as an objective of the MOP.

To overcome the above problems, our paper proposes a new technique called "DG with optimal variable power factor" (VPF). In our previous works (Castro et al., 2016a; Castro et al., 2016b), the MOP had three objectives; in the first work, we proposed Pareto optimization for solving the MOP separately, and in the second paper, we proposed Pareto optimization and Fuzzy-PID for solving the MOP. In this paper, and based on these previous works, we consider the MOP with only two objectives, where the reactive power of the DGs minimizes the voltage deviation on the pilot bus and the losses in the network. Three cases are evaluated: 1) the adoption of fixed values of the DGs with a variable power factor in real time and variable loads, 2) the implementation of variable values of the DGs with a variable power factor in real time and variable loads, and 3) analysis of losses and voltage using only OLTC (On-Load Tap Changer). The VPF is tested on 1) the IEEE 13-node test feeder using a DG with variable and unbalanced loads, and 2) the IEEE 123-node test feeder using four DGs with variable and unbalanced loads.

Pareto Optimality and Fuzzy-PI are used in VPF for solving the MOP problem and for defining the optimal active and reactive powers values of the DGs. The two objectives of the multi-objective optimization problem are solved separately. The original contributions of this paper consist essentially in combining the following:

1) it presents a new MO function, where the reactive power losses and voltage regulation have been incorporated as objective functions considering DGs;
2) it proposes a new multi-objective algorithm based on Pareto optimality and Fuzzy-PI;
3) it applies real and variable loads and illustrates the impact of variable and fixed DGs on distribution networks.

The rest of this paper is organized as follows: Section 5.2 presents the mathematical formulation of the problem using MOP and Optimization techniques. Section 5.3 presents the proposed solution approach. In section 5.4, the case studies used are given and simulation results are presented. Finally, in section 5.5, the conclusions are presented.

5.2 Problem formulation and optimization

In this work, different variable loads are analyzed. The variable loads are added to the fixed network loads of the IEEE 13 and 123-node test feeders, and load represents a typical change in consumption by customers in a 48-hour horizon (Data provided by Hydro-Québec).

In order to investigate the impact of the DGs on the voltage on a pilot bus and the losses in distribution networks with variable and unbalanced loads, three cases are evaluated:

Case 1: Variable Demand and Variable DGs (VDGs+VL): The active and reactive powers of the DG need to be optimized.

Case 2: Variable Demand (DGs+VL): The reactive power of the fixed DG is optimized.

Case 3: OLTC: Analysis of losses and voltage using only OLTC (On-Load Tap Changer).

Conventional (passive) networks operate DGs with fixed PF values over all load conditions. Conversely, VPF may vary the OLTC or the PF of the DGs (active network). To facilitate understanding of how the control system reduces losses, a number of variables and constraints are incorporated into the VPF. Here, the Coordinated Voltage Control (CVC) and the minimization of reactive power losses are implemented with the main objective of finding the optimal size of the DGs allowing loss reduction while maintaining the voltage within acceptable limits.

5.2.1 Multi-Objective Problem (MOP)

The MOP model aims to support the decisions of planners respecting the selection of the levels of operation of the DGs throughout the planning period (Ren et al., 2010). The objectives are modelled as follows:

5.2.1.1 Coordinated Voltage Control (CVC)

The first objective is to minimize the variation in voltage on the pilot buses. In mathematical form, the objective can be written as follows (Richardot et al., 2006):

$$F_1 = \sum_{i \in P} \lambda_i \left[\kappa \left(V_i^{ref} - V_i \right) - \sum_{k \in G} C_{i,k}^{V} \cdot \Delta V_k \right]^2 \tag{5.1}$$

Where P and Q are the sets of pilot and generator bus indices; V_i^{ref}, V_i are the set point voltage, and the measured voltage on bus *i* respectively, and ΔV_k, is the voltage deviation on generator bus *k*, i.e., the difference in voltage values between two iterations; $C_{i,k}^{V}$ is the sensitivity matrix coefficient linking the voltage deviation on buses *i* and *k*, respectively, and λ_i is a desired weighting coefficient.

5.2.1.2 Active and reactive power of the DGs

The second objective is loss reduction management. (Abu-Mouti et El-Hawary, 2011; Anwar et Pota, 2011; Esmaili, 2013; Young-Jin et al., 2013) present an optimized algorithm using sensitivity factors. If the DG size varies from Q_{DGi1} to Q_{DGi2} to then the reactive power loss varies from Q_{li1} to Q_{li2}, respectively. The sensitivity factor is stated as follows:

$$F_2 = \frac{dQloss}{dQ_{DGi}} = \sum_{i \in DG} \lambda_i^q \left(\frac{Ql_{i1} - Ql_{i2}}{Q_{DGi1} - Q_{DGi2}} \right) \tag{5.2}$$

where $Ql_{i1} - Ql_{i2}$ corresponds to the change in reactive power loss; $Q_{DGi1} - Q_{DGi2}$ is the change in DG reactive power from time 1 to 2; and λ_i^q is a weighting coefficient.

The power factor (PF) of the DGs is given by (5.3)

$$PF_{DGi} = \frac{P_{DGi}}{\sqrt{P_{DGi}^2 + Q_{DGi}^2}} \tag{5.3}$$

where P_{DGi} and Q_{DGi} are the active and reactive power of DG_i, and PF_{DG} is the power factor of DG.

Assuming

$$a = (sign)\tan(cos^{-1}(PF_{DG})) \tag{5.4}$$

The reactive power output of the DGs is expressed by (5.5)

$$Q_{DGi} = aP_{DGi} \tag{5.5}$$

in which

sign = $+1$ DG injecting reactive power;

sign = -1 DG consuming reactive power;

From (5.2), (5.3), (5.4), and (5.5), the reactive power loss can be rewritten as:

$$F_2 = \frac{dQloss}{dQ_{DGi}} = \sum_{i \in DG} \lambda_i^q \left(\frac{Ql_{i1} - Ql_{i2}}{a(P_{DGi1} - P_{DGi2})} \right) \tag{5.6}$$

where $\mathrm{P_{DGi}} \leq \mathrm{P_{DGi}^{MAX}}$ and $P_{DGi1} - P_{DGi2}$ is the variation of the DG size.

5.2.2 Main Constraints

Three categories of constraints are observed, and they relate to: 1) the power factor of the DGs, 2) the constraints of the voltage on the pilot bus, and 3) the weights of the objectives.

5.2.2.1 Power factor constraints

One of the main objectives of this work is to control the production of reactive power in the presence of DGs. To obtain the power factor of the DGs that minimizes (5.6), the former becomes a variable of the optimization problem, and is constrained by the reactive powers corresponding to the limits (Ochoa et al., 2011):

$$|Ql_i| \leq Ql_i^{MAX} \tag{5.7}$$

5.2.2.2 Voltage constraints

Compliance with voltage constraints on the pilot bus is used to determine the safe operation values. In distribution networks, an acceptable steady state voltage range is considered to be within ±3% of the nominal voltage (Masters, 2002).

$$\begin{gathered} V_i \in \left[V_i^{min}; V_i^{MAX}\right] \ for \ \ i \in P \cup G \\ |\Delta V_i| \leq \Delta V_i^{MAX} \ \ for \ \ i \in G \end{gathered} \tag{5.8}$$

5.2.2.3 Weight constraints

The weights of the objectives are important because they give priority to an objective that depends on the operating conditions. For example, if the voltage on the pilot bus falls outside the limits, the weight for this objective becomes much greater than for the other. These weights are related, as shown in relation (5.9):

$$\lambda_i + \lambda_i^q = 1 \tag{5.9}$$

where λ_i, λ_i^q are weighting coefficients for bus *i*.

5.2.3 Optimization techniques

This section presents the Pareto optimization and Fuzzy-PI approach used to find the optimal size and power factor of the DGs.

5.2.3.1 Pareto optimization

The Pareto optimization finds a set of solutions constituting what is known as the Pareto frontier, which can optimize the two objectives (figure 5.1). The Genetic algorithm (GA), a global optimization technique, is used to find the optimal solution.

GA emulates the biological evolution process. An initial population of individuals representing different solutions is evolving to find optimal solutions. The fittest individuals are evaluated and selected from the current population. These are the values that solve the optimization problem of the objective function. Each individual is mutated to form a new generation using crossover operations (Ouyang et Pano, 2015). It is important to maintain population diversity to ensure convergence to an optimal Pareto frontier (Deb et al., 2002). The Pareto frontier is obtained by using the dominance relationship between different solutions (Fu et al., 2015).

The algorithm needs to choose only one solution among the set of solutions, using a Decision Maker (DM) (Dehghani-Arani et Maddahi, 2013; Ngatchou et al., 2005). For each set of solutions, the DM calculates the minimum of the reactive power losses. The set of solutions having the minimum DM is selected:

$$DM = Min \sum_{i \in DG} \lambda_i^q \left(\frac{Ql_{i1} - Ql_{i2}}{a(P_{DGi1} - P_{DGi2})} \right) \tag{5.10}$$

where DM is the minimum of the second objective of the set of solutions; $Ql_{i1} - Ql_{i2}$ corresponds to the change in reactive power loss; $P_{DGi1} - P_{DGi2}$ is the change in active power of DG from time 1 to time 2; and λ_i^q is a weighting factor.

5.2.3.2 Fuzzy-PI controller

The Fuzzy-PI controller uses the Pareto optimal values to find the appropriate reactive power values that can deliver the DGs.

The controller, as shown in Figure 5.2, has two inputs and one single output. The voltage deviation (ΔV) and its derivate are the inputs. The input membership functions are Low, Normal, and High (Figure 5.3) (Pitalúa-Díaz et al., 2015). The output signal Fuzzy-PI controller is the optimal reactive power of the DGs.

The Fuzzy-PI controller has the advantage of not having a specific operating point. The rules evaluate the tendency of the error signals to determine whether to increase or decrease the control variable.

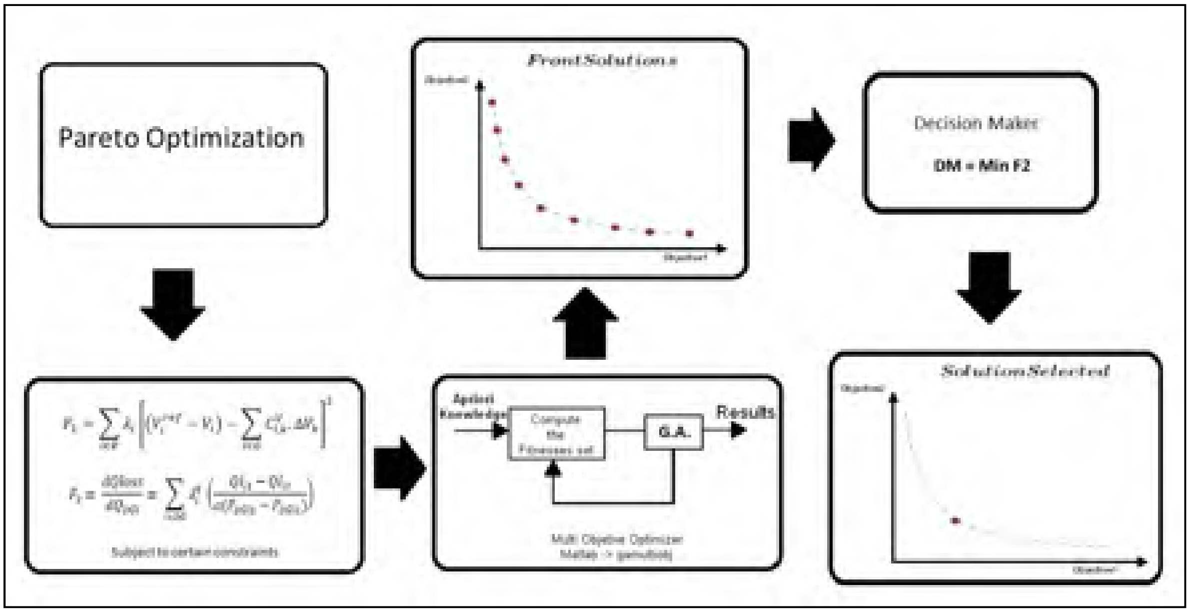

Figure 5.1 Pareto optimization scheme for MOP

There are two different types of fuzzy control available, namely, Mamdani and Sugeno, and they differ mainly in the fuzzy control rule application. The Sugeno type is used in this work because, the final output is the weighted average of each rule output, and as a result, it does not therefore require a defuzzification process (Gaonkar et Pillai, 2010) (Takagi et Sugeno, 1985).

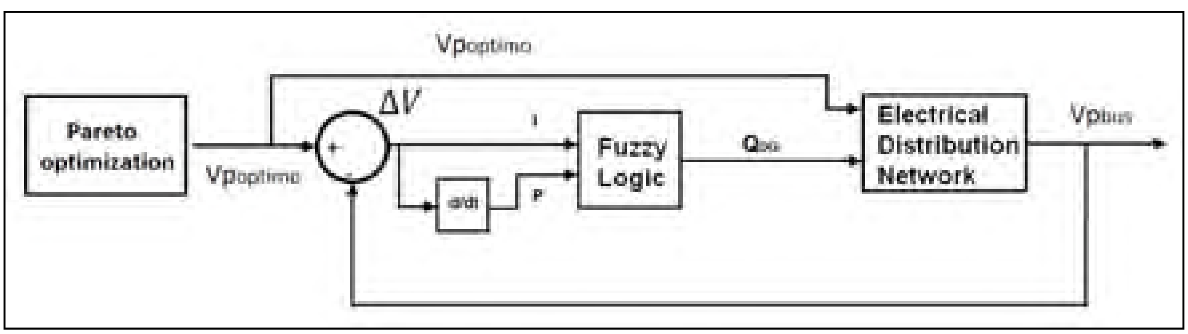

Figure 5.2 Scheme of a Fuzzy-PI controller

Based on the input and output membership functions, nine linguistic labels are possible. Equation (5.11) shows the set of IF-THEN rules used in the rule-based system.

$$\begin{aligned}
&\text{IF } \left(V_{p\ bus\ i1} - V_{p\ bus\ i2} = \text{Low}\right) \text{ and Vvc is low THEN } \mathrm{u}_1 = \mathrm{PF}_{\mathrm{min}} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{Low}\right) \text{ and Vvc is normal THEN } \mathrm{u}_2 = \mathrm{PF}_{\mathrm{nom}} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{Low}\right) \text{ and Vvc is high THEN } \mathrm{u}_3 = \mathrm{PF}_{max} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{Normal}\right) \text{ and Vvc is low THEN } \mathrm{u}_4 = \mathrm{PF}_{\mathrm{nom}} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{Normal}\right) \text{and Vvc is normal THEN } \mathrm{u}_5 = \mathrm{PF}_{\mathrm{nom}} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{Normal}\right) \text{ and Vvc is high THEN } \mathrm{u}_6 = \mathrm{PF}_{max} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{High}\right) \text{ and Vvc is low THEN } \mathrm{u}_7 = \mathrm{PF}_{max} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{High}\right) \text{ and Vvc is normal THEN } \mathrm{u}_8 = \mathrm{PF}_{max} \\
&\text{IF } \left(V_{pbus\ i1} - V_{p\ bus\ i2} = \text{High}\right) \text{ and Vvc is high THEN } \mathrm{u}_9 = \mathrm{PF}_{max}
\end{aligned} \tag{5.11}$$

The output can be found using the weighted average formula (Takagi et Sugeno, 1985):

$$\mathrm{PF}_{\mathrm{ref}} = \frac{\sum_{\mathrm{i}=1}^{9} \mathrm{w_i u_i}}{\sum_{\mathrm{i}=1}^{9} \mathrm{w_i}} \tag{5.12}$$

where $\mathrm{u_i}$ is the value of the output member for the $i-th$ rule; and $\mathrm{w_i}$ is the output membership value for the $i-th$ rule.

From Equations (5.4) and (5.5), the reactive power of the DGs can be rewritten as:

$$\begin{aligned}
&\theta = cos^{-1}\left(PF_{ref}\right) \\
&Q_{DGi} = (P_{DGi}) * \tan(\theta) \\
&\theta_G^- \leq \theta_{G,i} \leq \theta_G^+
\end{aligned} \tag{5.13}$$

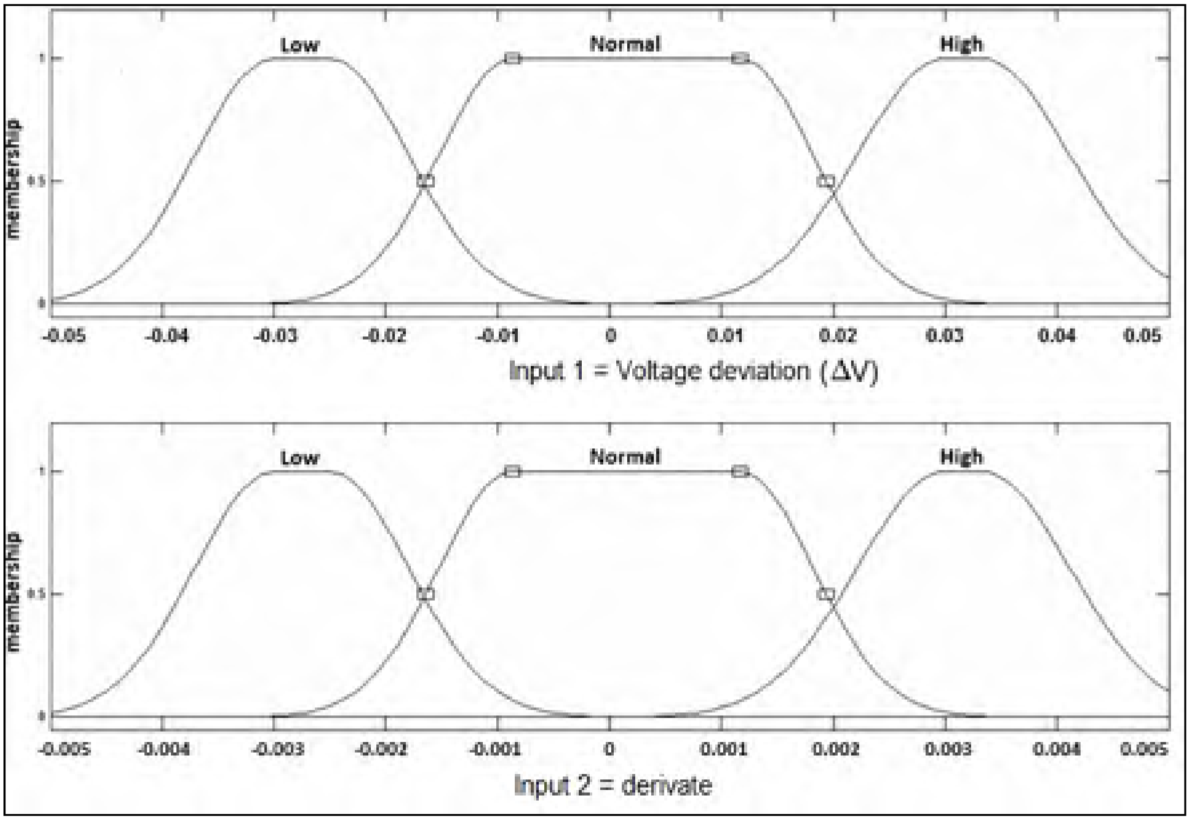

Figure 5.3 a) Fuzzy set for input voltage deviation;
b) Fuzzy set for input voltage deviation change

Figure 5.2 depicts the Fuzzy-PI controller block, in which a closed-loop control system is embedded. The process (Electrical Distribution Network) output (Voltage on pilot bus) is denoted by $V_{P\ bus}$; its inputs are denoted by the optimal voltage on the pilot bus $V_{P\ optimo}$ and the reference input of the fuzzy controller is denoted by the Reactive power of the DGs (Q_{DGi}).

5.3 Proposed Solution

Figure 5.4 presents the steps of the sequence of operations necessary for VPF to find the optimal voltage on the pilot bus and power factor of the DGs using the proposed approach:

Step 1: Input Data: The input of the variables to Equations (5.1) and (5.6) of the optimization problem are defined. The data network is provided using OpenDSS software (OpenDSS manual and reference guide).

Step 2: Pareto optimization: Matlab is used to solve Equations (5.1) and (5.6) with constraints (5.7) to (5.9). The algorithm calculates the two weights (λ_i and λ_i^q) corresponding to the functions F1 and F2, and finds a set of solutions (Pareto frontier). (Figure 5.1)

Step 3: The Decision Maker (DM) finds the solution set that minimizes the second function. The set of solutions selected gives the optimal values of the two functions. So, the optimal voltage for the pilot bus is selected. While the variation of the load has an impact on the pilot bus voltage, the reactive powers of the DGs can however help reduce this voltage deviation.

Step 4: Fuzzy-PI Controller: Equation (5.11) determines the rules. The final output is computed according to Equation (5.12). Finally, the reactive powers of the DGs are calculated using Equation (5.13)

Step 5: Control: The control action is executed according to the voltage on the pilot bus and the optimal reactive and active powers of the DGs.

OLTC should adjust its tap to reach the optimal voltage value found in Step 3. At each time step, the voltage in the OLTC is treated as a variable. The upper and lower voltages and the maximum and minimum variations of active and reactive power are respected.

Step 6: With the data from Step 5 and the new values of the load (variable load), the OpenDSS program calculates the power flow of the distribution network (OpenDSS manual and reference guide).

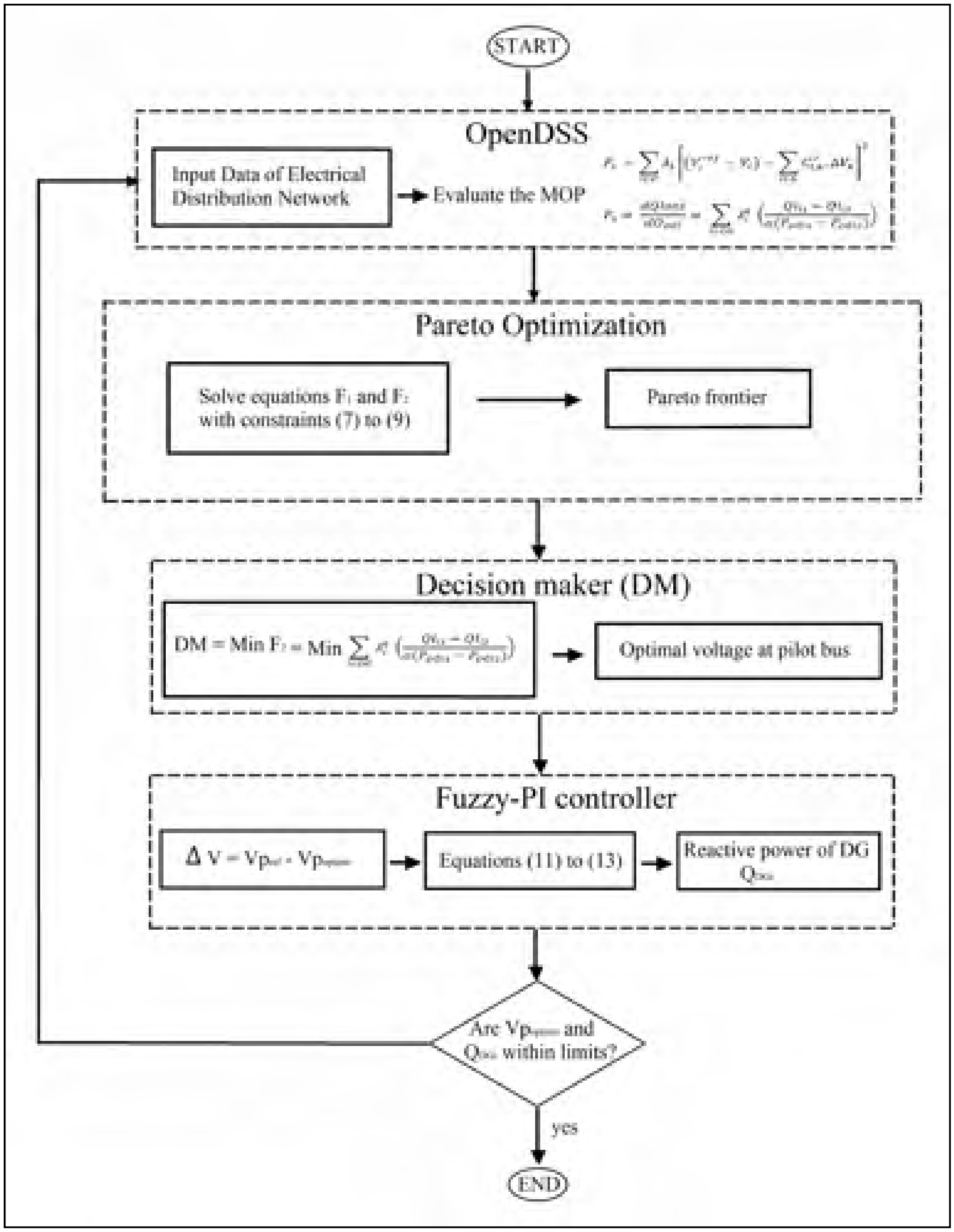

Figure 5.4 Flow chart of the proposed algorithm

Step 7: If the voltage values on the pilot buses and the reactive and active power of the DGs are within acceptable limits, the program ends; otherwise, using the voltage values on the pilot bus and the reactive power of DG, GOTO Step 1.

5.4 Case Study

5.4.1 IEEE 13-node test feeder

In the IEEE 13-node test feeder, only a DG connected on bus 675 is considered (Anwar et Pota, 2011). The DG size is calculated for a network with variable and unbalanced loads. To demonstrate the new technique, a simplified version of the network was studied with only a single DG unit connected (Figure 5.5).

Table 5.1 shows the spot load data for the IEEE 13-node test feeder. In the second column, the three basic loads are displayed: (1) Constant Impedance Load Model (Constant Z), (2) Constant Current Load Model (Constant I), and (3) Constant Power Load Model (Constant PQ)

Table 5.1 Spot Load Data for IEEE 13

Node	**Load Model**	**Ph-1 kW**	**Ph-1 kVAr**	**Ph-2 kW**	**Ph-2 kVAr**	**Ph-3 kW**	**Ph-3 kVAr**
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	**1158**	**606**	**973**	**627**	**1135**	**753**

Table 5.2 displays the cable line configuration for an IEEE 13-node test feeder, while Table 5.3 shows the test feeder's Transformer data. Furthermore, the frequency is 60 Hz and the base voltage is 115kV.

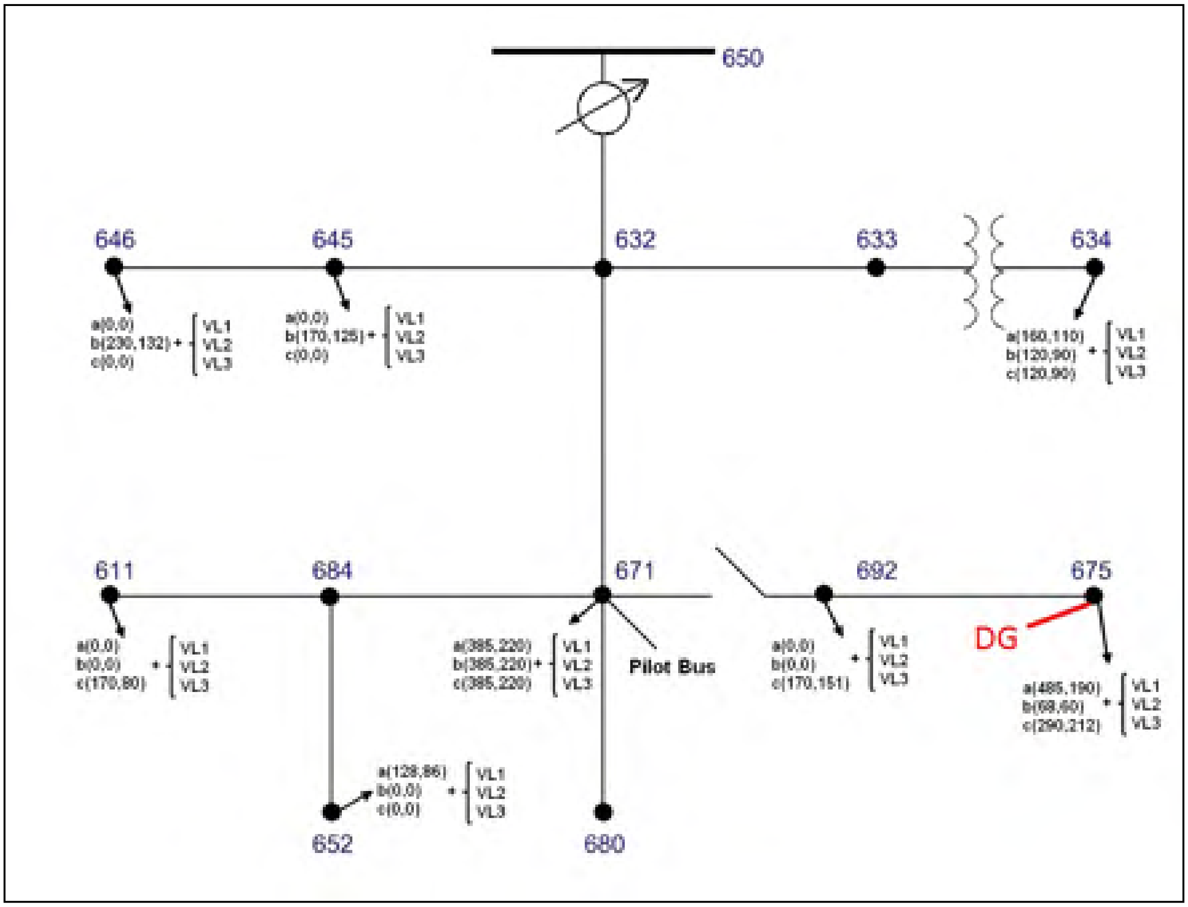

Figure 5.5 IEEE 13-node test feeder with variable and unbalanced load

5.4.1.1 Simulations results

Figure 5.5 shows that the variation of the load is different in each bus. The network's technical data are given in (Kersting, 2001). In this study, three variable loads (VL1, VL2 and VL3) are added to the fixed load of the study network (Figure 5.6).

5.4.1.2 Variable load 1

Figure 5.6 shows the first total variable load (VL1), and Figure 5.7b shows a decrease in losses that are achieved using an optimal DG, without exceeding the voltage limits. It can be seen that the losses are almost similar between case 1 and case 2. In both cases, the voltage is within acceptable limits because the VPF method uses the abilities of the MOP, which controls the voltage on the pilot bus.

In Figure 5.7a, with the presence of DG, the reactive power input from the transmission network (negative sign) is lower in cases 1 and 2. In Case 2 using fixed a DG, the variation in reactive power input is less than the variation in Case 1.

Table 5.2 Cable lines configuration for IEEE 13-node test feeder

Node	**R (mile)**	**X (mile)**	**Distance**	**Config.**	**X/R ratio**
650-632	0.3465	1.0179	0.378	601	1.11043636
632-633	0.7526	1.1814	0.094	602	0.14755727
632-645	1.3294	1.3471	0.094	603	0.09525154
632-671	0.3465	1.0179	0.378	601	1.11043636
645-646	1.3294	1.3471	0.056	603	0.0567456
671-684	1.3238	1.3569	0.056	604	0.05740021
671-680	0.3465	1.0179	0.189	601	0.55521818
692-675	0.7982	0.4463	0.094	606	0.05255851
684-611	1.3292	1.3475	0.056	605	0.05677099
684-652	1.3425	0.5124	0.151	607	0.05763307
671-692				Switch	
633-634	1.10%	2%		XFM-1	

Table 5.3 Transformer data for IEEE 13-node test feeder

	KVA	**kV-high**	**kV-low**
Substation	5000	115 - Delta	4.16 Wye
XFM-1	500	4.16 - Wye	0.48 Wye

VPF and OLTC maintain the voltage within acceptable limits (Figure 8b), with the difference being in the voltage deviation, which is lower in VPF. Figure 8a shows an increased production of reactive power of the DG in Case 2 (DG +VL). This is because the control variable is the PF of the DG. However, in case 1, VPF can control the active power and PF of the DG.

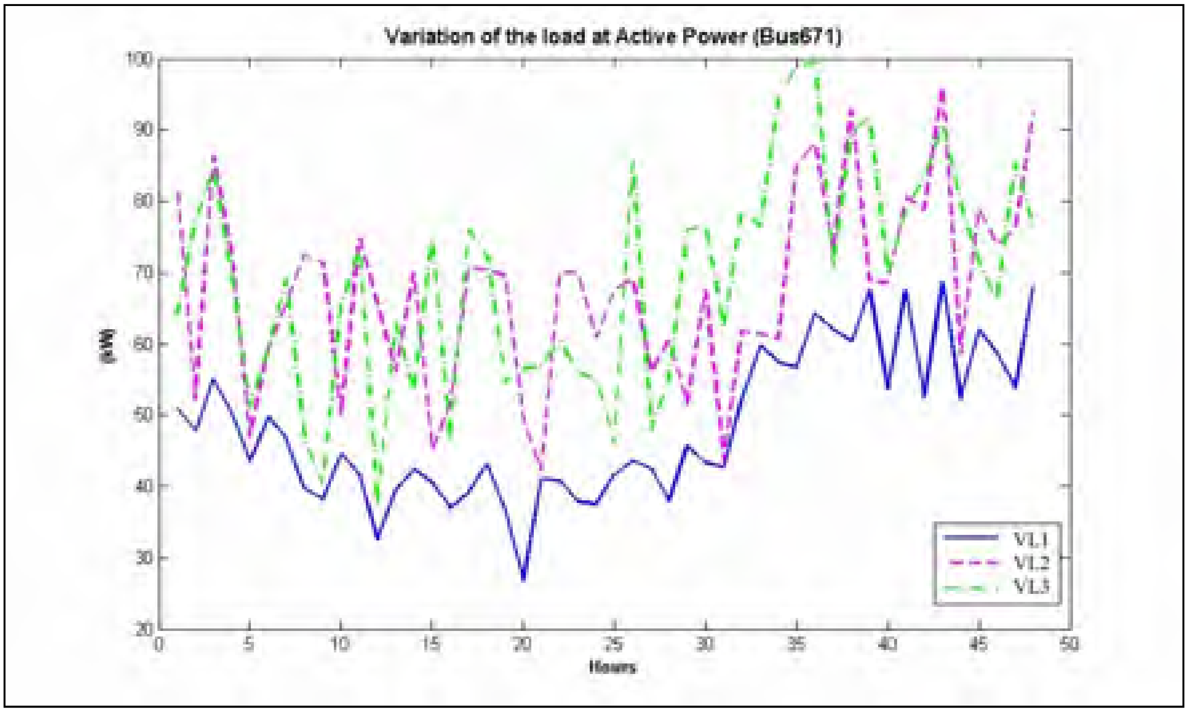

Figure 5.6 Total variable load (VL1, VL2, VL3)

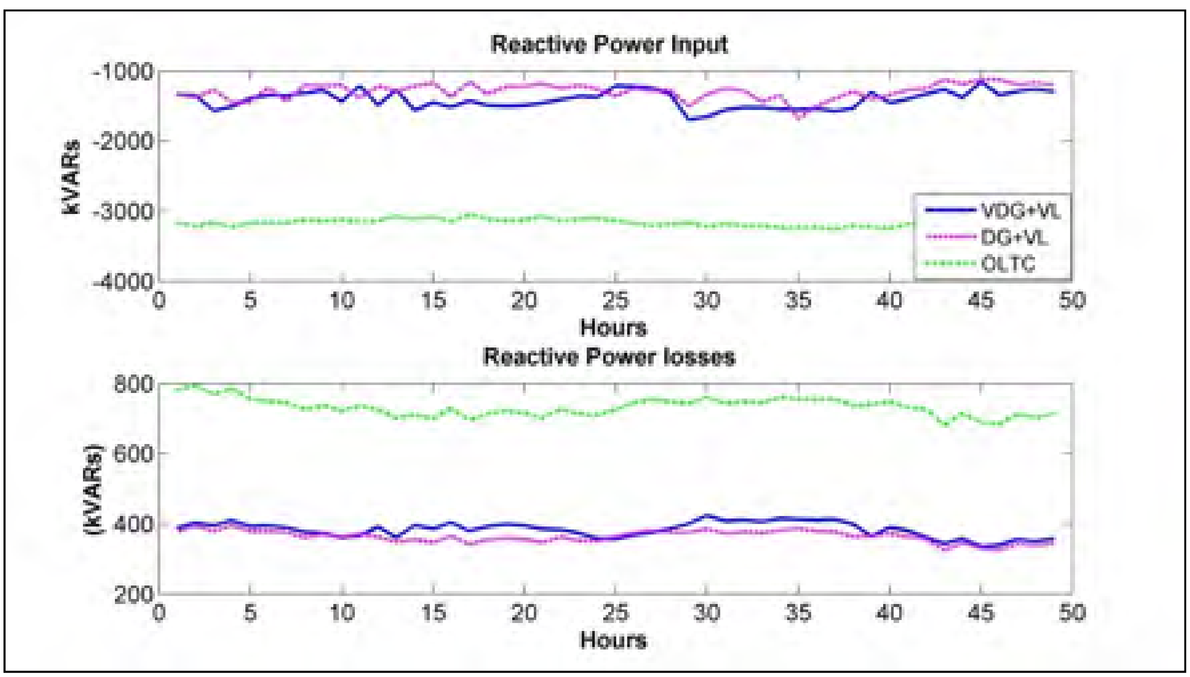

Figure 5.7 a) Active power input;
b) Reactive power losses. Variable load 1

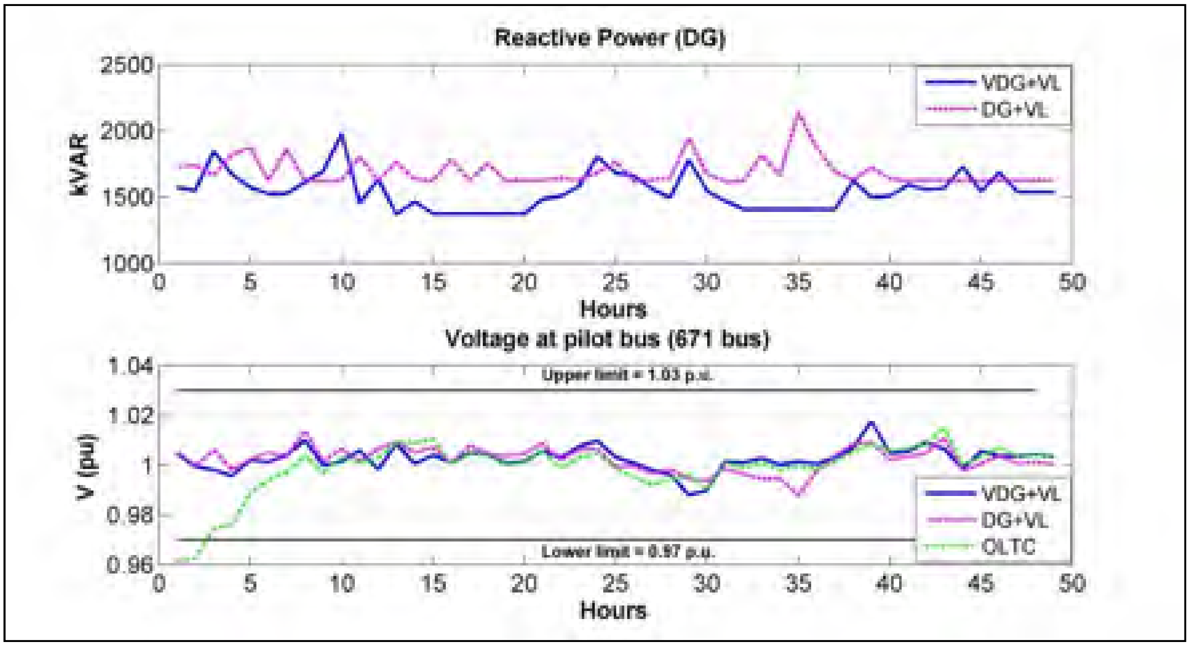

Figure 5.8 a) Reactive power of DG;
b) Voltage on pilot bus 671 with VL1

5.4.1.3 Variable load 2

Figure 5.6 shows the second variable load 2 (VL2). Figures 5.8b and 5.9b show that the voltage deviation on the pilot bus with VL2 is higher than with VL1. However, the 3 methods are able to maintain the voltage within acceptable limits.

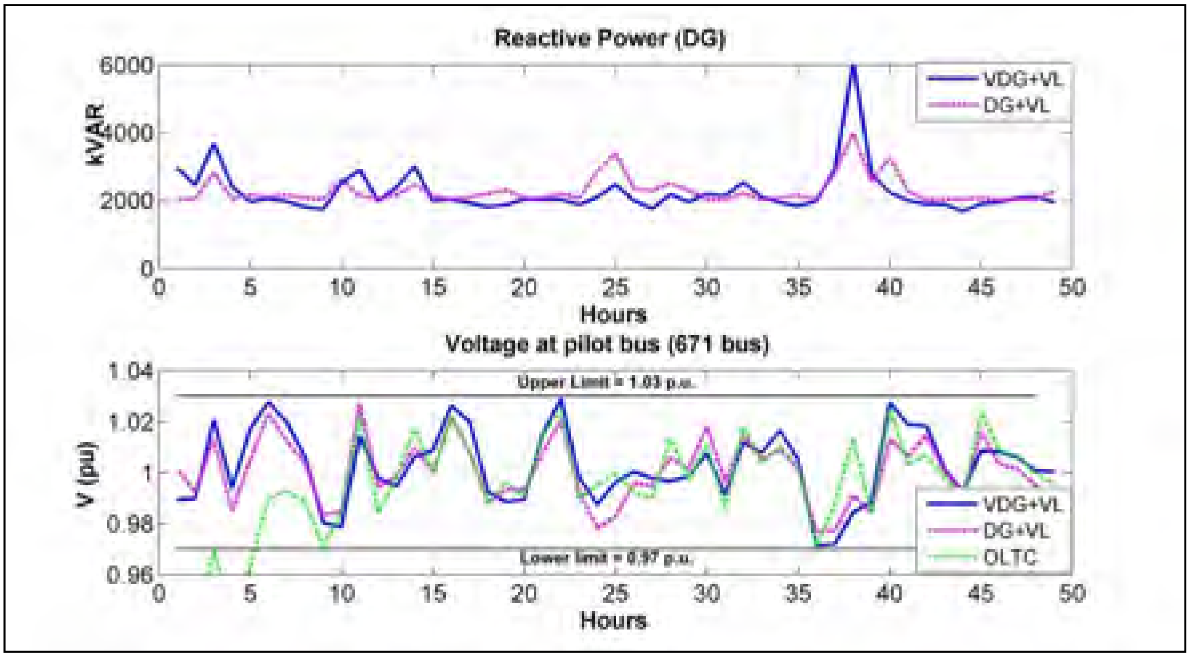

Figure 5.9 a) Reactive power of the DG;
b) Voltage on pilot bus 671 with VL2

To reduce losses and maintain the voltage within the desired limits, VPF in case 1 controls the active and reactive powers of the DG. On the other hand, VPF in case 2 only controls the reactive power of the DG by reducing the losses and maintaining the voltage within acceptable limits.

Large load variations (VL2) cause variations in reactive power generation. In Figure 5.9a, the reactive power generated by a variable and a fixed DG is shown. VPF maintains the voltage of the pilot bus within permissible limits using an optimal injection of the reactive power of DG.

5.4.1.4 Comparison of results

In our previous first work, we proposed a new technique called Optimal Coordinated Voltage Control (OCVC) (Castro et al., 2016a). OCVC is capable of coordinating different areas of the distribution network, including all sources of active and reactive power. OCVC uses Pareto optimization to solve the MOP.

In our second work (Castro et al., 2016b), Pareto optimization and Fuzzy-PID find the optimal values of the reactive power of DG to minimize losses and reduce voltage deviation. This technique, called the Coordinated Voltage Control using Pareto and Fuzzy (CVCPF) approach, is tested on an IEEE 13-node test feeder using variables and unbalanced loads.

When the voltage deviation on the method OCVC is higher than 0.025 p.u. (Table 4), the voltage in CVCPF is lower. Similarly, the voltage in VPF (VDG+VL and DG+VL) is lower, except at hour 39, when VPF requires a more reactive power of DG (Figure 5.9a) due to a strong decrease in load (Figure 5.6).

Table 5.4 Voltage deviation. OCVC, CVCPF, and VPF methods

Variable Load 2				
			VPF	
Hour	OCVC	CVCPF	VDG+VL (Case 1)	DG+VL (Case 2)
3	0.081	0.065	0.028	0.028
4	0.039	0.023	0.023	0.020
10	0.029	0.028	0.026	0.032
11	0.029	0.028	0.017	0.032
22	0.053	0.026	0.031	0.028
35	0.029	0.028	0.034	0.025
39	0.032	0.021	0.039	0.029
44	0.026	0.016	0.016	0.024

5.4.1.5 Variable load 3

Figure 5.6 shows the third total variable load (VL3), and Figure 5.11b shows voltage deviation on pilot bus 671. Similar to cases 1 case 2 and case 3 is able to maintain the voltage within the desired limits. The reactive power input and the reactive power loss are almost similar (Figures 5.10a and 5.10 b) for cases 1 and 2. A side benefit of minimizing the reactive power input of the network using VPF is the reduction of losses it entails, as compared to OLTC (Figure 10b).

VPF minimizes the reactive power losses, optimizes the reactive power of DG, and maintains the voltage on the pilot bus within limits.

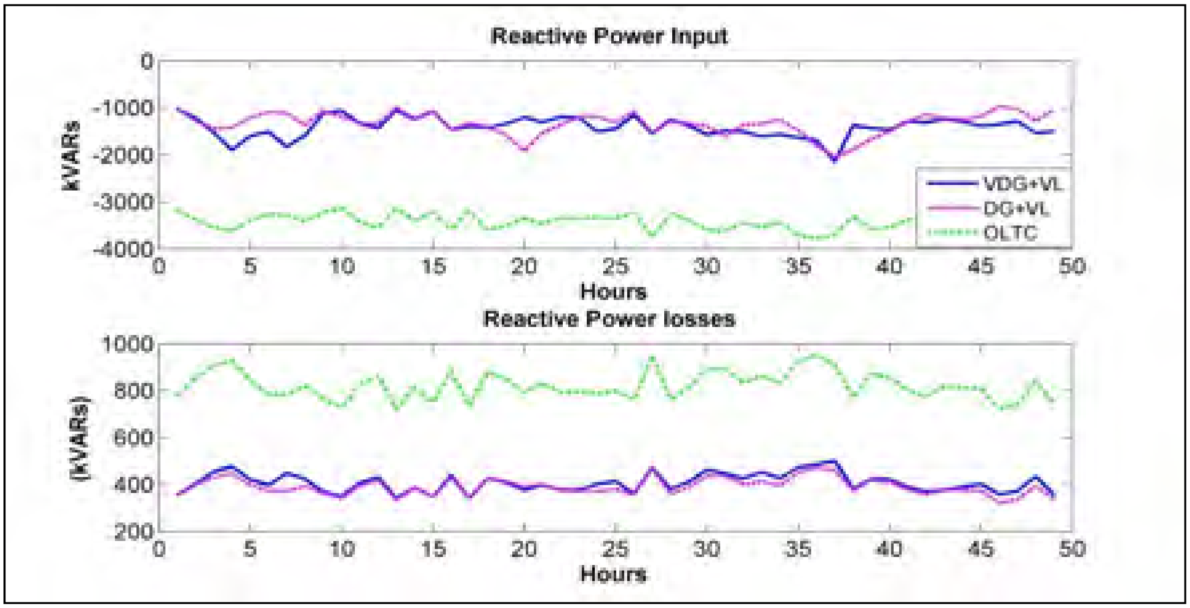

Figure 5.10 a) Active power input;
b) Reactive power losses. Variable load 3

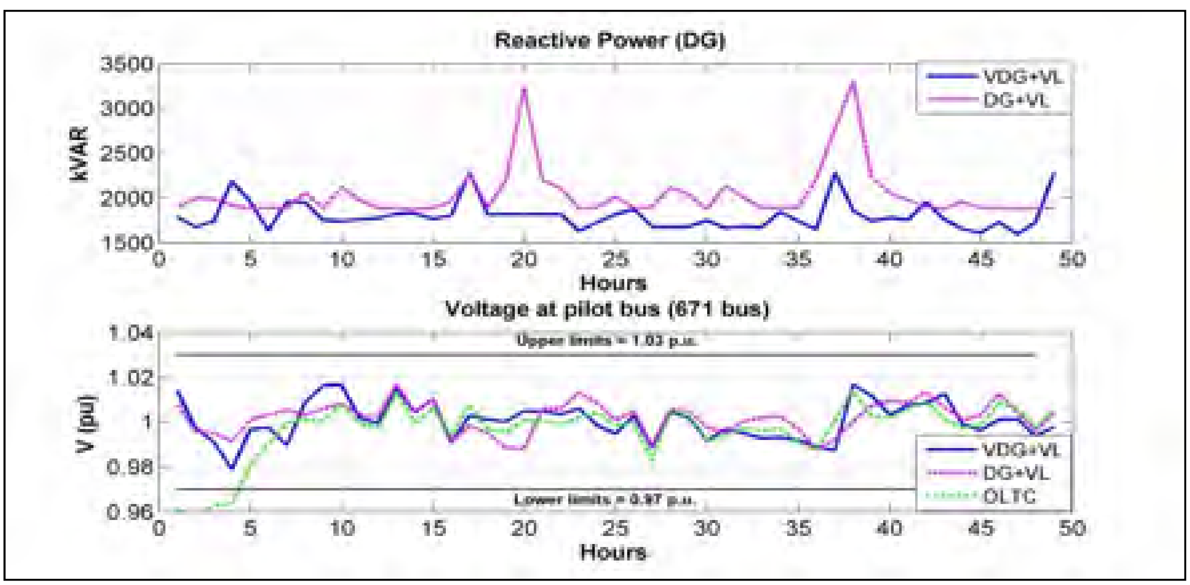

Figure 5.11 a) Reactive power of the DG;
b) Voltage on pilot bus 671 with VL3

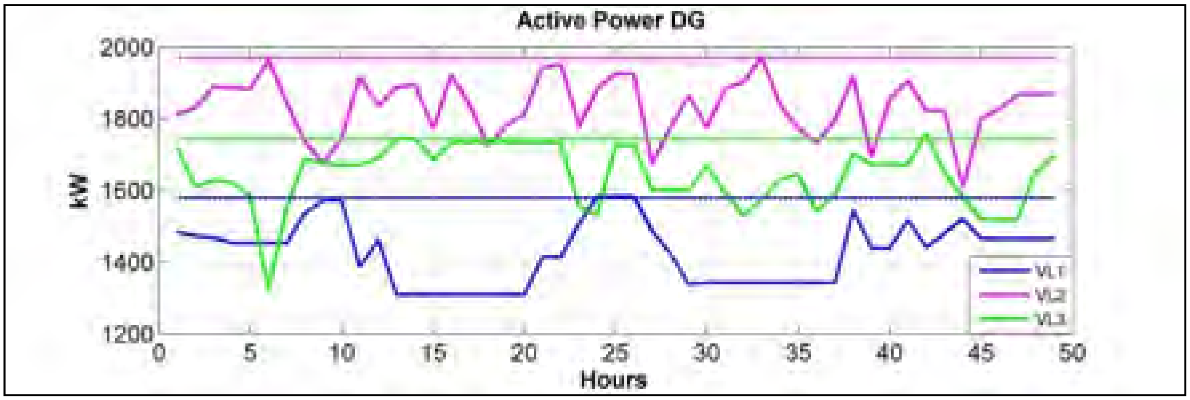

Figure 5.12 Size of the active power of the DG (Variable loads VL1, VL2 and VL3)

Figure 5.12 shows the sizes of the DGs (fixed and variable) for each variable load.

5.4.2 IEEE 123-node test feeder

In the IEEE 123-node test feeder, four DGs are connected at buses 76, 67, 57 and 98 (Dahal et Salehfar, 2013). The DGs' sizes are calculated using VPF for a network with variable and unbalanced loads. Figure 5.13 shows the location of the four DGs.

Figure 5.14a shows the total variation load (VL) added to the fixed load of the network. Figure 5.14b shows the variation load on the pilot bus (bus 99). The variation load is on the 91 spot loads of the IEEE 123-node test feeder.

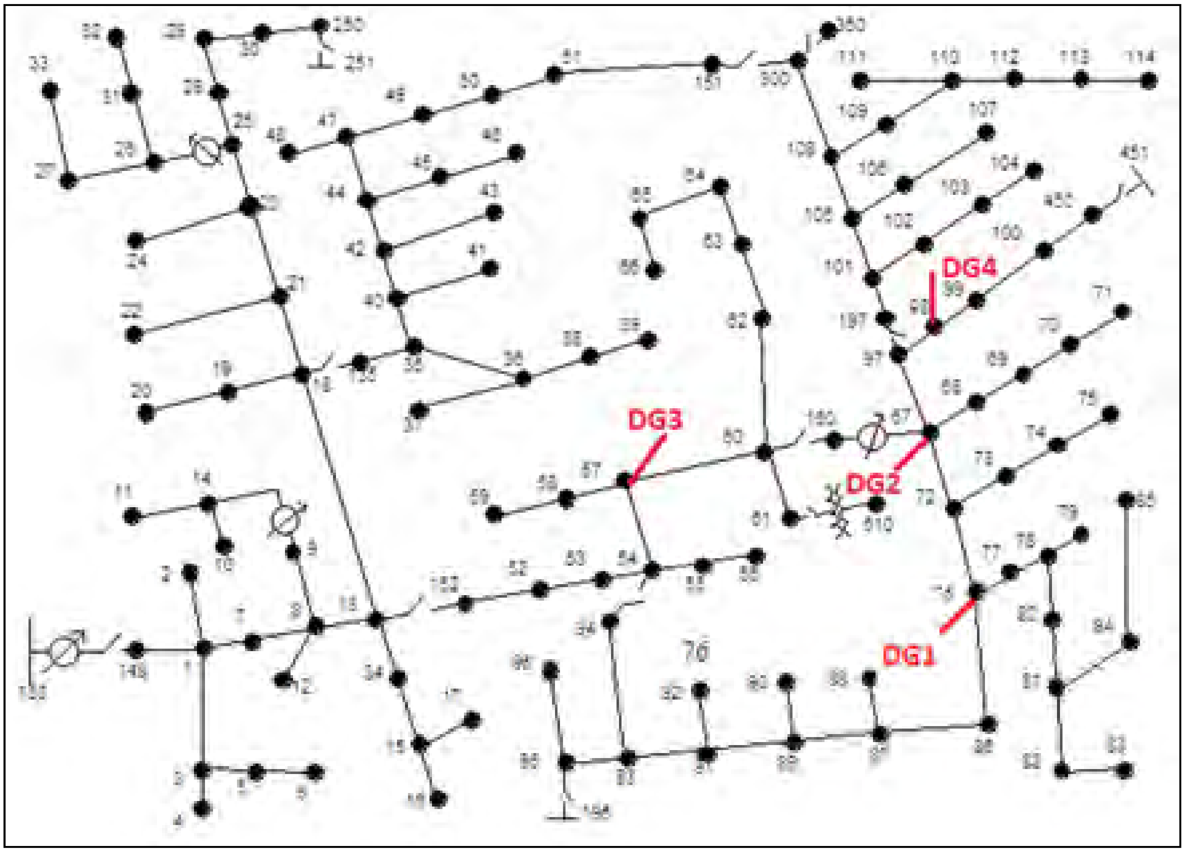

Figure 5.13 IEEE 123-node test feeder with variable and unbalanced load

Figure 5.15a shows the graphs of the reactive power input (negative sign) needed by the network. VPF optimizes the reactive power supplied by the DGs, which reduces the reactive power input. When the active powers of the DGs are fixed, the variation of power factor (PF) is the only control element. This is observed in the variation curves of the reactive power input using variable and fixed DGs. When VPF optimizes the reactive power supplied by variable DGs, the reactive power input has a lower variation. Reactive power losses are lower when VPF optimizes the DGs (Figure 5.15b).

Figure 5.16c shows the voltage deviation on the pilot bus. The three methods are able to maintain the voltage within acceptable limits. In Figure 5.16a, VPF optimizes the delivery of the reactive power of the four variable DGs. Figure 5.16b shows the delivery of reactive power with four fixed DGs. Figure 5.16a shows that the variation of the reactive power supply is lower when the active power of DGs is variable.

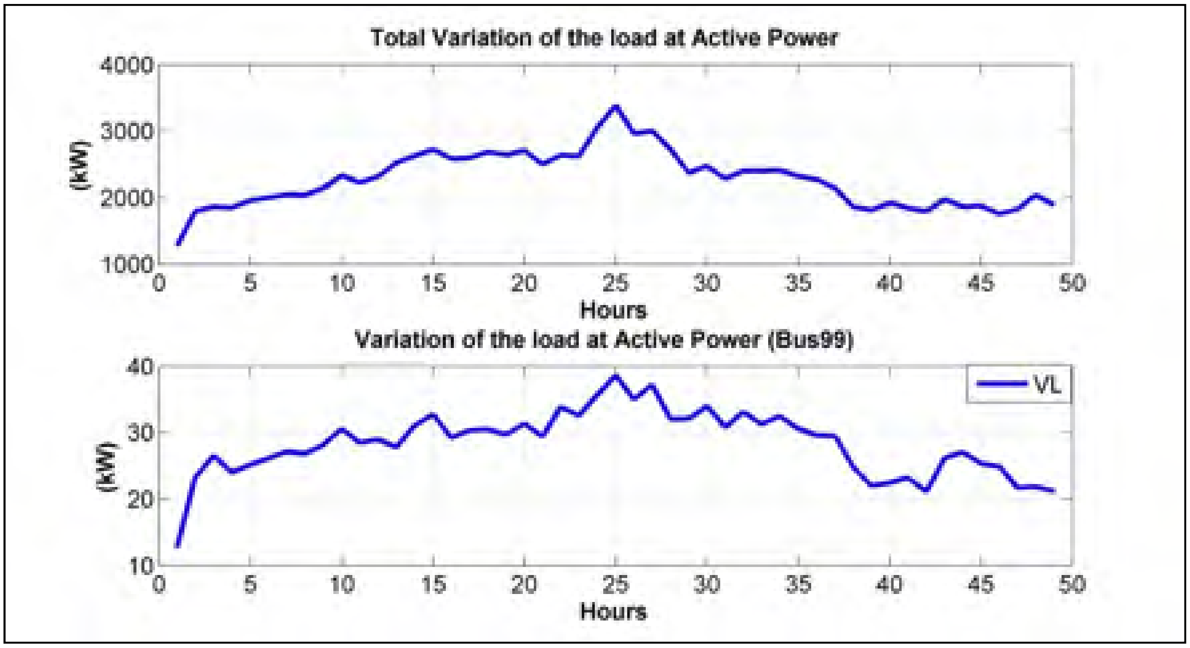

Figure 5.14 a) Total variable load;
b) Variable load on bus 99

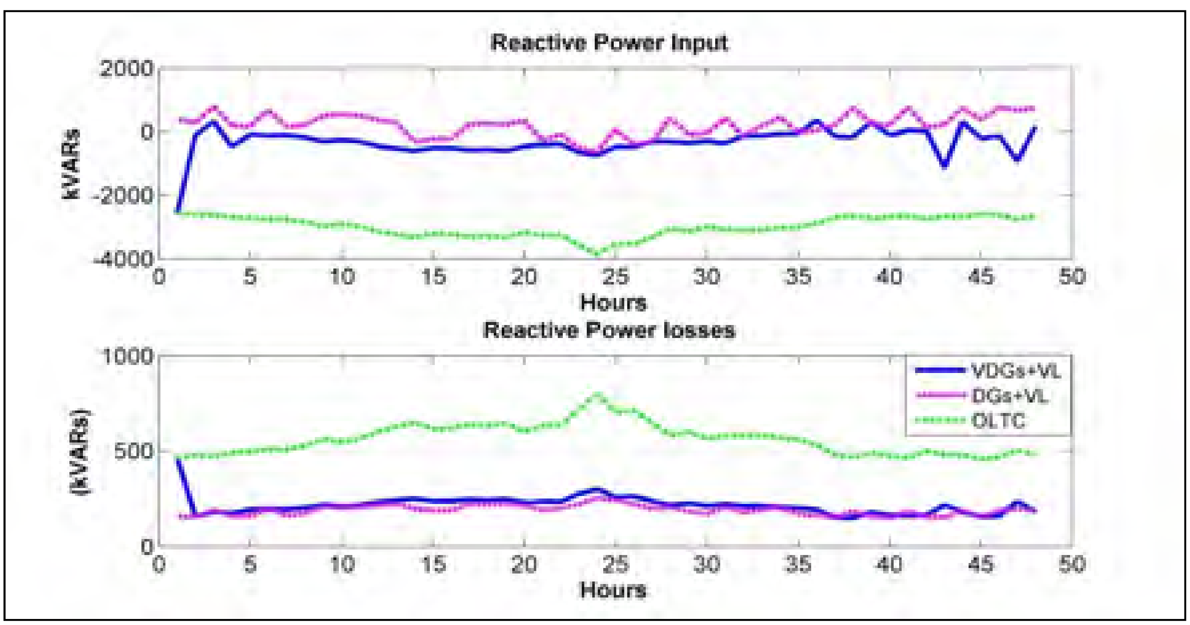

Figure 5.15 a) Active power input;
b) Reactive power losses for IEEE 123

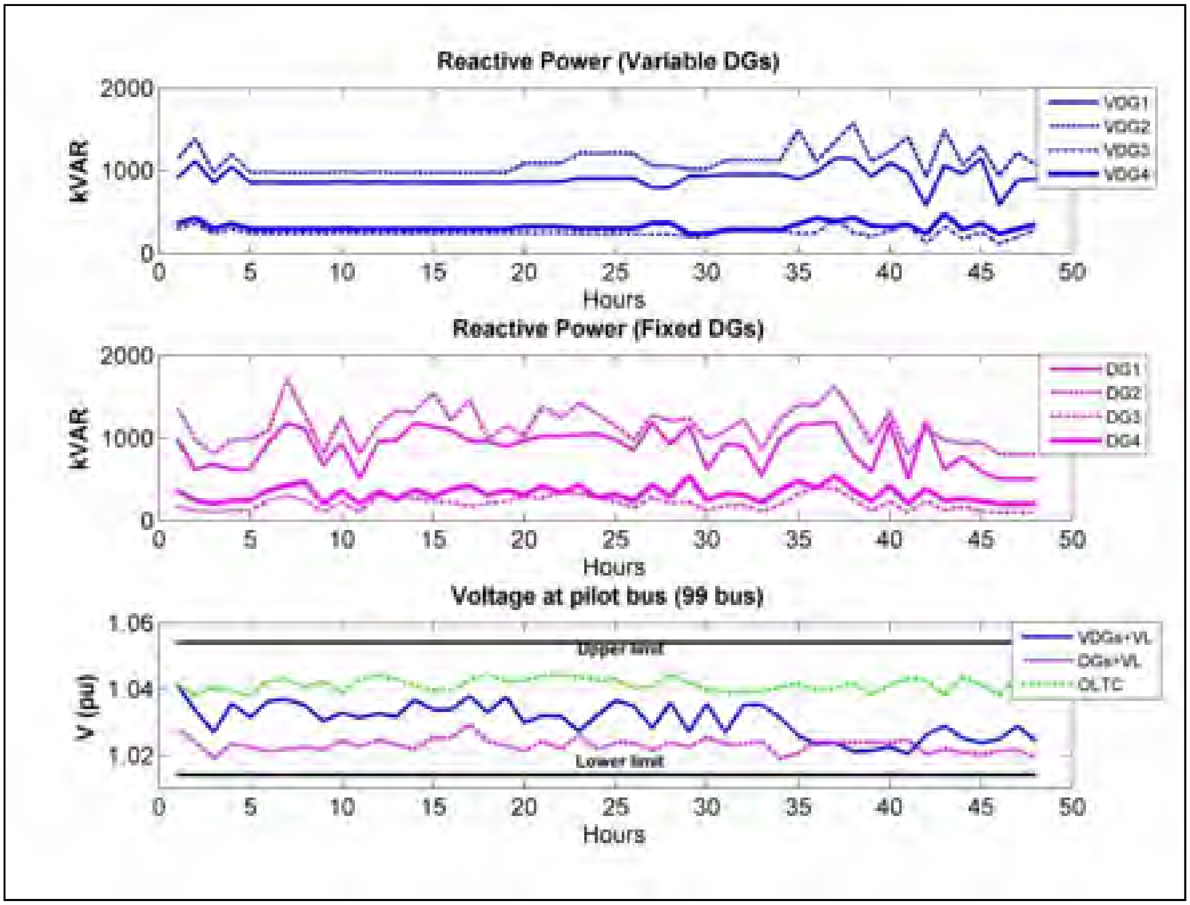

Figure 5.16 a) Reactive power of the DGs;
b) Reactive power of the fixed DG;
c) Voltage on pilot bus

5.4.3 Implementation

VPF was coded in Matlab (R2014a) and OpenDSS (64-bit) software. For the IEEE 13-node test feeder, simulations were carried out on a PC (Intel Core i7 2.90 GHz, 8 GB RAM). Case 1 (Variable demand and Variable DG) needs about 90 to 120 s of CPU time, Case 2 (Variable Demand) needs about 55 s of CPU time, and Case 3 (only OLTC) needs about 35 s of CPU time. For the IEEE 123-node test feeder and four DGs, about 180 to 200 s of CPU time is required.

Table 5.5 Computation Performance; OCVC, CVCPF, and VPF methods

		VPF	
OCVC	**CVCPF**	**VDG+VL**	**DG+VL**
50-60s	280-300s	90-100s	55s

Table 5 shows the times required to perform the simulations

5.4.4 Analysis of Results and Discussions

Case 1 and Case 2 in the IEEE 13 and 123-node test feeders are analyzed using the proposed VPF technique. When variable DGs are used, VPF determines the optimal size and optimal power factor of each DG in each time period. Similarly, VPF constantly calculates the PF of the DG when using fixed DGs. In VPF, relation (9) varies dynamically, depending on: 1) the value of the voltage on the pilot bus, and 2) the optimal value of the power factor of the DGs.

VPF demonstrates the benefits of an active network by constantly analyzing the reactive power losses. The main advantage of the proposed technique is its capacity to respond not only to different states of demand, but also to the variability of the DGs and of the voltage.

Finally, in the OLTC method, the only equipment used for voltage control is the OLTC.

5.5 Conclusions

A new technique called VPF is presented. The technique illustrates the benefits of the optimal use of the reactive power of DGs in distribution networks. VPF was employed to analyze the problem using: 1) an IEEE 13-node test feeder with three different load demands, and 2) an IEEE 123-node test feeder with four DGs.

VPF uses optimization techniques to find optimal voltage values on pilot buses and the power factor of DG. An active control of the power factor capabilities of the DGs and the real-time control of on-load tap changers (OLTC) are used by VPF.

Acknowledgments

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CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

In the coming years, distributed generation (DG) will be a challenge in the distribution network. In this problematic, our interest in this thesis is related to: the voltage on the buses, the reactive power injection and power losses. This dissertation proposes through new techniques the optimal coordination of the reactive power in the different areas of the distribution network to improve voltage regulation, and reduce losses using DGs on distribution networks with variable and unbalanced loads.

In this thesis, the primary objective of this work is the intelligent distribution voltage control using the optimal participation of reactive power of a DG at variable and unbalanced distribution network. The secondary objectives are as follows:

1) Investigate the impact of DG on losses and voltage profile

This objective was accomplished using a new technique called Optimal Coordinated Voltage Control (OCVC). OCVC uses Pareto optimization to find an optimal participation of reactive power of all devices available in the network. After validating effectiveness of the proposed method on IEEE 13-node test feeder and IEEE 34-node test feeder with the initial loads, it was then validated adding a DG in the network. Finally, the proposed method was also validated adding a new load to simulate a disturbance. Pareto optimization was implemented in simulink of Matlab and the distribution power flow was simulated using open source software called OpenDSS. Results from the proposed method shows that the optimal integration of DG in distribution networks can help to maintain the voltage within the limits and reduce losses.

2) Improve and minimize the voltage variation in distribution network using DGs

This objective was accomplished by two optimization techniques: PID-Fuzzy Logic to find the optimum value of the reactive power of the DG and Pareto optimization to find the optimal value of the pilot bus voltage so that minimize the voltage variation in distribution network. Coordinated Voltage Control using Pareto and Fuzzy logic (CVCPF) was proposed by combining the optimization techniques. The proposed method was validated on IEEE 13-node test feeder. Variables and unbalanced are used, based on real consumption, over a time window of 48 hours. The results are compared with those obtained from the methods OCVC and OLTC as well as from the case of no voltage control. The robustness of the proposed method was demonstrated using three DGs simultaneously. Results from the proposed method show that the optimal integration of DG in distribution network can help to minimize the voltage variation and reduce losses.

3) Investigate the impact of variable and fixed DGs in distribution network

This objective was accomplished by implementation a new multi-objective model that minimizes reactive power losses with the minimization of the variation of the voltage on the pilot bus. DG with variable power factor (VPF) uses Fuzzy-PI controller according to the optimal values given by Pareto, and calculates the power factor of the DGs. The proposed method (VPF) was validated on IEEE 13 and 123-node test feeder with different and real cases of variables loads and four DGs. These networks were analyzed from two perspectives; the first with variable DGs, changing according to demand variations, and the second with fixed DGs. The results are compared with those obtained from the method OLTC as well as from the case of fixed and variable DGs. Result from the proposed method shows that VPF allows to optimize the DGs of the distribution network to maintain the voltage within permissible limits and reduce reactive power losses.

6.2 Conclusions

The work of this thesis is to study the impact of DGs in distribution networks. The new methods, a MO problem focusing on voltage profile improvement, power loss reduction and voltage stability was formulated to find the optimal participation of DG.

Firstly, the methodology used is a comparative analysis. We have proposed a new method for solving the MO problem. The results of this method have been verified with others two methods used in distribution networks.

The results have resulted in the following conclusions:

- The optimal participation of active and reactive power of DGs connected to the distribution network.
- Solve all the different objectives of the multi-objective problem separately with dynamic weights.
- Eliminate the entire voltage problem, including the DG's over-voltages.
- The method OCVC could be interesting way to reduce or eliminate future investments in voltage control and reactive power regulation.

Secondly, an efficient algorithm to solve the multi-objective voltage control problem is presented. Fuzzy logic to calculate the optimal reactive power of DG and the PID generates a solution based on the difference between the power factor calculated by fuzzy logic and the output power factor of the network. The results of Pareto and PID-Fuzzy Logic with DGs have resulted in the following conclusions:

- The reduction of the voltage variation more than other methods is demonstrated.
- The optimal integration of DGs in distribution networks helps to maintain stable voltage and to reduce losses.

- CVCPF could be advantageous for network operators by the development of flexible systems.

Thirdly, an experimental design methodology was used to demonstrate the benefits of using the reactive power of the variables and fixed DGs in distribution network. The problem was formulated as multi-objective problem with two objectives. The first objective was to minimize the variation voltage and the second objective was the management of the loss reduction. The results of Pareto and Fuzzy-PI controller have resulted in the following conclusions:

- The reduction of the voltage variation and the losses on distribution networks using DGs is demonstrated.
- The benefits that the better use of reactive power of DGs on distribution network.
- The advantages of optimizing the multi-objective problem with Pareto and Fuzzy-PI controller.
- The use of fixed and variable DGs on distribution network.

6.3 Recommendations for future work

Although the work presented in this thesis provides methods and results for DGs integration on distribution network, it can be extended in the following research directions.

- Variable Decision Maker (DM) to choose a set of solutions according to distribution network conditions.
- The impact of DGs on economic resources. One objective of the multi-objective problem should be the cost of implementation, the maintenance costs and the cost of connection.
- The impact of DGs on the frequency, voltage stabilization and reactive power regulations should be addressed carefully.
- Reactive power compensation in single-phase.

- To use the methods proposed to determine the best location of the DG in distribution network.

APPENDIX I

IEEE 13-node Test Feeder

Table-A I-1 Line Segment Data

Node A	Node B	Length(ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Table-A I-2 Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Table-A I-3 Capacitor Data

Node	Ph-A kVAr	Ph-B kVAr	Ph-C kVAr
675	200	200	200
611			100
Total	200	200	300

Table-A I-4 Regulator Data

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	50		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Voltage Level:	122	122	122

Table-A I-5 Spot Load Data

Node	**Load Model**	**Ph-1 kW**	**Ph-1 kVAr**	**Ph-2 kW**	**Ph-2 kVAr**	**Ph-3 kW**	**Ph-3 kVAr**
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

IEEE 34-node Test Feeder

Table-A I-6 Overhead line Configurations

Config.	Phasing	Phase ACSR	Neutral ACSR	Spacing ID
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

Table-A I-7 Overhead line Configurations

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2500	69 - D	24.9 -Gr. W	1	8
XFM -1	500	24.9 - Gr.W	4.16 - Gr. W	1,9	4,08

Table-A I-8 Spot Loads

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-4 kVAr
860	Y-PQ	20	16	20	16	20	16
840	Y-I	9	7	9	7	9	7
844	Y-Z	135	105	135	105	135	105
848	D-PQ	20	16	20	16	20	16
890	D-I	150	75	150	75	150	75
830	D-Z	10	5	10	5	25	10
Total		344	224	344	224	359	229

Table-A I-9 Shunt Capacitors

Node	Ph-A kVAr	Ph-B kVAr	Ph-C kVAr
844	100	100	100
848	150	150	150
Total	250	250	250

Table-A I-10 Regulator Data

Regulator ID:	1		
Line Segment:	814 - 850		
Location:	814		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2,7	2,7	2,7
X - Setting:	1,6	1,6	1,6
Volltage Level:	122	122	122
Regulator ID:	2		
Line Segment:	852 - 832		
Location:	852		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2,5	2,5	2,5
X - Setting:	1,5	1,5	1,5
Volltage Level:	124	124	124

IEEE 123-node Test Feeder

Table A I-11 Overhead Line Configurations (Config.)

Config.	Phasing	Phase Cond.	Neutral Cond.	Spacing
		ACSR	ACSR	ID
1	A B C N	336,400 26/7	4/0 6/1	500
2	C A B N	336,400 26/7	4/0 6/1	500
3	B C A N	336,400 26/7	4/0 6/1	500
4	C B A N	336,400 26/7	4/0 6/1	500
5	B A C N	336,400 26/7	4/0 6/1	500
6	A C B N	336,400 26/7	4/0 6/1	500
7	A C N	336,400 26/7	4/0 6/1	505
8	A B N	336,400 26/7	4/0 6/1	505
9	A N	1/0	1/0	510
10	B N	1/0	1/0	510
11	C N	1/0	1/0	510

Table A I-12 Underground Line Configuration (Config.)

Config.	Phasing	Cable	Spacing ID
12	A B C	1/0 AA, CN	515

TableA I-13 Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation	5.000	115 - D	4.16 Gr-W	1	8
XFM - 1	150	4.16 - D	.480 - D	1,27	2,72

Table A I-14 Line Segment Data

Node A	Node B	Length (ft.)	Config.	Node A	Node B	Length (ft.)	Config.
1	2	175	10	42	43	500	10
1	3	250	11	42	44	200	1
1	7	300	1	44	45	200	9
3	4	200	11	44	47	250	1
3	5	325	11	45	46	300	9
5	6	250	11	47	48	150	4
7	8	200	1	47	49	250	4
8	12	225	10	49	50	250	4
8	9	225	9	50	51	250	4
8	13	300	1	52	53	200	1
9	14	425	9	53	54	125	1
13	34	150	11	54	55	275	1
13	18	825	2	54	57	350	3
14	11	250	9	55	56	275	1
14	10	250	9	57	58	250	10
15	16	375	11	57	60	750	3
15	17	350	11	58	59	250	10
18	19	250	9	60	61	550	5
18	21	300	2	60	62	250	12
19	20	325	9	62	63	175	12
21	22	525	10	63	64	350	12
21	23	250	2	64	65	425	12
23	24	550	11	65	66	325	12
23	25	275	2	67	68	200	9
25	26	350	7	67	72	275	3
25	28	200	2	67	97	250	3
26	27	275	7	68	69	275	9
26	31	225	11	69	70	325	9
27	33	500	9	70	71	275	9
28	29	300	2	72	73	275	11
29	30	350	2	72	76	200	3
30	250	200	2	73	74	350	11
31	32	300	11	74	75	400	11
34	15	100	11	76	77	400	6
35	36	650	8	76	86	700	3
35	40	250	1	77	78	100	6

Table A I-15 Line Segment Data (continued from Table 14)

Node A	**Node B**	**Length (ft.)**	**Config.**	**Node A**	**Node B**	**Length (ft.)**	**Config.**
36	37	300	9	78	79	225	6
36	38	250	10	78	80	475	6
38	39	325	10	80	81	475	6
40	41	325	11	81	82	250	6
40	42	250	1	81	84	675	11
82	83	250	6	102	103	325	11
84	85	475	11	103	104	700	11
86	87	450	6	105	106	225	10
87	88	175	9	105	108	325	3
87	89	275	6	106	107	575	10
89	90	225	10	108	109	450	9
89	91	225	6	108	300	1000	3
91	92	300	11	109	110	300	9
91	93	225	6	110	111	575	9
93	94	275	9	110	112	125	9
93	95	300	6	112	113	525	9
95	96	200	10	113	114	325	9
97	98	275	3	135	35	375	4
98	99	550	3	149	1	400	1
99	100	300	3	152	52	400	1
100	450	800	3	160	67	350	6
101	102	225	11	197	101	250	3
101	105	275	3				

Table A I-16 Shunt Capacitor Data

Node	**Ph-A**	**Ph-B**	**Ph-C**
	kVAr	**kVAr**	**kVAr**
83	200	200	200
88	50		
90		50	
92			50
Total	250	250	250

Table A I-17 Three Phase Switch Data

Node A	**Node B**	**Normal**	**Node A**	**Node B**	**Normal**
13	152	closed	250	251	open
18	135	closed	450	451	open
60	160	closed	54	94	open
61	610	closed	151	300	open
97	197	closed	300	350	open
150	149	closed			

Table A I-18 Regulator Data

Regulator ID:	1	Regulator ID:	3		
Line Segment:	150 - 149	Line Segment:	25 - 26		
Location:	150	Location:	25		
Phases:	A-B-C	Phases:	A-C		
Connection:	3-Ph, Wye	Connection:	2-Ph,L-G		
Monitoring Phase:	A	Monitoring Phase:	A & C		
Bandwidth:	2.0 volts	Bandwidth:	1		
PT Ratio:	20	PT Ratio:	20		
Primary CT Rating:	700	Primary CT Rating:	50		
Compensator:	Ph-A	Compenator:	Ph-A	Ph-C	
R - Setting:	3	R - Setting:	0,4	0,4	
X - Setting:	7,5	X - Setting:	0,4	0,4	
Voltage Level:	120	Voltage Level:	120	120	
Regulator ID:	2	Regulator ID:	4		
Line Segment:	9 - 14	Line Segment:	160 - 67		
Location:	9	Location:	160		
Phases:	A	Phases:	A-B-C		
Connection:	1-Ph, L-G	Connection:	3-Ph, LG		
Monitoring Phase:	A	Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts	Bandwidth:	2		
PT Ratio:	20	PT Ratio:	20		
Primary CT Rating:	50	Primary CT Rating:	300		
Compensator:	Ph-A	Compensator:	Ph-A	Ph-B	Ph-C
R - Setting:	0,4	R - Setting:	0,6	1,4	0,2
X - Setting:	0,4	X - Setting:	1,3	2,6	1,4
Voltage Level:	120	Voltage Level:	124	124	124

Table A I-19 Spot Load Data

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-4 kVAr
1	Y-PQ	40	20	0	0	0	0
2	Y-PQ	0	0	20	10	0	0
4	Y-PQ	0	0	0	0	40	20
5	Y-I	0	0	0	0	20	10
6	Y-Z	0	0	0	0	40	20
7	Y-PQ	20	10	0	0	0	0
9	Y-PQ	40	20	0	0	0	0
10	Y-I	20	10	0	0	0	0
11	Y-Z	40	20	0	0	0	0
12	Y-PQ	0	0	20	10	0	0
16	Y-PQ	0	0	0	0	40	20
17	Y-PQ	0	0	0	0	20	10
19	Y-PQ	40	20	0	0	0	0
20	Y-I	40	20	0	0	0	0
22	Y-Z	0	0	40	20	0	0
24	Y-PQ	0	0	0	0	40	20
28	Y-I	40	20	0	0	0	0
29	Y-Z	40	20	0	0	0	0
30	Y-PQ	0	0	0	0	40	20
31	Y-PQ	0	0	0	0	20	10
32	Y-PQ	0	0	0	0	20	10
33	Y-I	40	20	0	0	0	0
34	Y-Z	0	0	0	0	40	20
35	D-PQ	40	20	0	0	0	0
37	Y-Z	40	20	0	0	0	0
38	Y-I	0	0	20	10	0	0
39	Y-PQ	0	0	20	10	0	0
41	Y-PQ	0	0	0	0	20	10
42	Y-PQ	20	10	0	0	0	0
43	Y-Z	0	0	40	20	0	0
45	Y-I	20	10	0	0	0	0
46	Y-PQ	20	10	0	0	0	0
47	Y-I	35	25	35	25	35	25
48	Y-Z	70	50	70	50	70	50
49	Y-PQ	35	25	70	50	35	25

Table A I-20 Spot Load Data (Continued from Table 19)

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-4 kVAr
50	Y-PQ	0	0	0	0	40	20
51	Y-PQ	20	10	0	0	0	0
52	Y-PQ	40	20	0	0	0	0
53	Y-PQ	40	20	0	0	0	0
55	Y-Z	20	10	0	0	0	0
56	Y-PQ	0	0	20	10	0	0
58	Y-I	0	0	20	10	0	0
59	Y-PQ	0	0	20	10	0	0
60	Y-PQ	20	10	0	0	0	0
62	Y-Z	0	0	0	0	40	20
63	Y-PQ	40	20	0	0	0	0
64	Y-I	0	0	75	35	0	0
65	D-Z	35	25	35	25	70	50
66	Y-PQ	0	0	0	0	75	35
68	Y-PQ	20	10	0	0	0	0
69	Y-PQ	40	20	0	0	0	0
70	Y-PQ	20	10	0	0	0	0
71	Y-PQ	40	20	0	0	0	0
73	Y-PQ	0	0	0	0	40	20
74	Y-Z	0	0	0	0	40	20
75	Y-PQ	0	0	0	0	40	20
76	D-I	105	80	70	50	70	50
77	Y-PQ	0	0	40	20	0	0
79	Y-Z	40	20	0	0	0	0
80	Y-PQ	0	0	40	20	0	0
82	Y-PQ	40	20	0	0	0	0
83	Y-PQ	0	0	0	0	20	10
84	Y-PQ	0	0	0	0	20	10
85	Y-PQ	0	0	0	0	40	20
86	Y-PQ	0	0	20	10	0	0
87	Y-PQ	0	0	40	20	0	0
88	Y-PQ	40	20	0	0	0	0
90	Y-I	0	0	40	20	0	0
92	Y-PQ	0	0	0	0	40	20

Table A I-21 Spot Load Data (Continued from Table 20)

Node	**Load Model**	**Ph-1 kW**	**Ph-1 kVAr**	**Ph-2 kW**	**Ph-2 kVAr**	**Ph-3 kW**	**Ph-4 kVAr**
94	Y-PQ	40	20	0	0	0	0
95	Y-PQ	0	0	20	10	0	0
96	Y-PQ	0	0	20	10	0	0
98	Y-PQ	40	20	0	0	0	0
99	Y-PQ	0	0	40	20	0	0
100	Y-Z	0	0	0	0	40	20
102	Y-PQ	0	0	0	0	20	10
103	Y-PQ	0	0	0	0	40	20
104	Y-PQ	0	0	0	0	40	20
106	Y-PQ	0	0	40	20	0	0
107	Y-PQ	0	0	40	20	0	0
109	Y-PQ	40	20	0	0	0	0
111	Y-PQ	20	10	0	0	0	0
112	Y-I	20	10	0	0	0	0
113	Y-Z	40	20	0	0	0	0
114	Y-PQ	20	10	0	0	0	0
Total		1420	775	915	515	1155	635

APPENDIX II

OpenDSS codes

```
!Lines of code for IEEE-node test feeder
Clear

!File name
new circuit.IEEE13

!Base voltage
~ basekv=115 pu=1.0001 phases=3 bus1=SourceBus
~ Angle=30
~ MVAsc3=20000 MVASC1=21000

!SUB TRANSFORMER DEFINITION
New Transformer.Sub Phases=3 Windings=2   XHL=(8 1000 /)
~ wdg=1 bus=SourceBus   conn=delta  kv=115  kva=5000   %r=(.5 1000 /)  XHT=4
~ wdg=2 bus=650           conn=wye    kv=4.16  kva=5000   %r=(.5 1000 /)   XLT=4

! FEEDER 1-PHASE VOLTAGE REGULATORS
! Define low-impedance 2-wdg transformer

New Transformer.Reg1 phases=1 XHL=0.01 kVAs=[1666 1666]
~ Buses=[650.1 RG60.1] kVs=[2.4  2.4] %LoadLoss=0.01
new regcontrol.Reg1  transformer=Reg1 winding=2  vreg=122  band=2  ptratio=20
ctprim=700  R=3   X=9

New Transformer.Reg2 phases=1 XHL=0.01 kVAs=[1666 1666]
~ Buses=[650.2 RG60.2] kVs=[2.4  2.4] %LoadLoss=0.01
new regcontrol.Reg2  transformer=Reg2 winding=2  vreg=122  band=2  ptratio=20
ctprim=700  R=3   X=9

New Transformer.Reg3 phases=1 XHL=0.01 kVAs=[1666 1666]
~ Buses=[650.3 RG60.3] kVs=[2.4  2.4] %LoadLoss=0.01
new regcontrol.Reg3  transformer=Reg3 winding=2  vreg=122  band=2  ptratio=20
ctprim=700  R=3   X=9


!TRANSFORMER DEFINITION
New Transformer.XFM1  Phases=3   Windings=2  XHL=2
~ wdg=1 bus=633       conn=Wye kv=4.16    kva=500    %r=.55     XHT=1
~ wdg=2 bus=634       conn=Wye kv=0.480    kva=500    %r=.55   XLT=1
```

```
!LINE CODES
!File with data network lines
redirect IEEELineCodes.dss

New linecode.mtx601 nphases=3 BaseFreq=60
~ rmatrix = (0.3465 | 0.1560 0.3375 | 0.1580 0.1535 0.3414 )
~ xmatrix = (1.0179 | 0.5017 1.0478 | 0.4236 0.3849 1.0348 )
~ units=mi
New linecode.mtx602 nphases=3 BaseFreq=60
~ rmatrix = (0.7526 | 0.1580 0.7475 | 0.1560 0.1535 0.7436 )
~ xmatrix = (1.1814 | 0.4236 1.1983 | 0.5017 0.3849 1.2112 )
~ units=mi
New linecode.mtx603 nphases=2 BaseFreq=60
~ rmatrix = (1.3238 | 0.2066 1.3294 )
~ xmatrix = (1.3569 | 0.4591 1.3471 )
~ units=mi
New linecode.mtx604 nphases=2 BaseFreq=60
~ rmatrix = (1.3238 | 0.2066 1.3294 )
~ xmatrix = (1.3569 | 0.4591 1.3471 )
~ units=mi
New linecode.mtx605 nphases=1 BaseFreq=60
~ rmatrix = (1.3292 )
~ xmatrix = (1.3475 )
~ units=mi
New linecode.mtx606 nphases=3 BaseFreq=60
~ rmatrix = (0.7982 | 0.3192 0.7891 | 0.2849 0.3192 0.7982 )
~ xmatrix = (0.4463 | 0.0328 0.4041 | -0.0143 0.0328 0.4463 )
~ Cmatrix = [257 | 0 257 | 0 0 257]
~ units=mi
New linecode.mtx607 nphases=1 BaseFreq=60
~ rmatrix = (1.3425 )
~ xmatrix = (0.5124 )
~ cmatrix = [236]
~ units=mi


!LOAD DEFINITIONS

New Load.671 Bus1=671.1.2.3  Phases=3 Conn=Delta Model=1 kV=4.16   kW=1155
kvar=660
New Load.634a Bus1=634.1     Phases=1 Conn=Wye  Model=1 kV=0.277  kW=160
kvar=110
```

New Load.634b Bus1=634.2 Phases=1 Conn=Wye Model=1 kV=0.277 kW=120 kvar=90
New Load.634c Bus1=634.3 Phases=1 Conn=Wye Model=1 kV=0.277 kW=120 kvar=90
New Load.645 Bus1=645.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=170 kvar=125
New Load.646 Bus1=646.2.3 Phases=1 Conn=Delta Model=2 kV=4.16 kW=230 kvar=132
New Load.692 Bus1=692.3.1 Phases=1 Conn=Delta Model=5 kV=4.16 kW=170 kvar=151
New Load.675a Bus1=675.1 Phases=1 Conn=Wye Model=1 kV=2.4 kW=485 kvar=190
New Load.675b Bus1=675.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=68 kvar=60
New Load.675c Bus1=675.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=290 kvar=212
New Load.611 Bus1=611.3 Phases=1 Conn=Wye Model=5 kV=2.4 kW=170 kvar=80
New Load.652 Bus1=652.1 Phases=1 Conn=Wye Model=2 kV=2.4 kW=128 kvar=86
New Load.670a Bus1=670.1 Phases=1 Conn=Wye Model=1 kV=2.4 kW=17 kvar=10
New Load.670b Bus1=670.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=66 kvar=38
New Load.670c Bus1=670.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=117 kvar=68

!CAPACITOR DEFINITIONS
New Capacitor.Cap1 Bus1=675 phases=3 kVAR=600 kV=4.16
New Capacitor.Cap2 Bus1=611.3 phases=1 kVAR=100 kV=2.4

!Bus 670 is the concentrated point load of the distributed load on line 632 to 671 located at 1/3 the distance from node 632

!LINE DEFINITIONS
New Line.650632 Phases=3 Bus1=RG60.1.2.3 Bus2=632.1.2.3 LineCode=mtx601 Length=2000 units=ft
New Line.632670 Phases=3 Bus1=632.1.2.3 Bus2=670.1.2.3 LineCode=mtx601 Length=667 units=ft
New Line.670671 Phases=3 Bus1=670.1.2.3 Bus2=671.1.2.3 LineCode=mtx601 Length=1333 units=ft
New Line.671680 Phases=3 Bus1=671.1.2.3 Bus2=680.1.2.3 LineCode=mtx601 Length=1000 units=ft
New Line.632633 Phases=3 Bus1=632.1.2.3 Bus2=633.1.2.3 LineCode=mtx602 Length=500 units=ft
New Line.632645 Phases=2 Bus1=632.3.2 Bus2=645.3.2 LineCode=mtx603 Length=500 units=ft
New Line.645646 Phases=2 Bus1=645.3.2 Bus2=646.3.2 LineCode=mtx603 Length=300 units=ft
New Line.692675 Phases=3 Bus1=692.1.2.3 Bus2=675.1.2.3 LineCode=mtx606 Length=500 units=ft

```
New Line.671684    Phases=2 Bus1=671.1.3     Bus2=684.1.3    LineCode=mtx604
Length=300  units=ft
New Line.684611    Phases=1 Bus1=684.3       Bus2=611.3      LineCode=mtx605
Length=300  units=ft
New Line.684652    Phases=1 Bus1=684.1       Bus2=652.1      LineCode=mtx607
Length=800  units=ft

!SWITCH DEFINITIONS
New Line.671692    Phases=3 Bus1=671   Bus2=692  Switch=y  r1=1e-4 r0=1e-4 x1=0.000
x0=0.000 c1=0.000 c0=0.000

Set Voltagebases=[115, 4.16, .48]

!Transformer.Reg1.Taps=[1.0 1.0625]
!Transformer.Reg2.Taps=[1.0 1.0500]
!Transformer.Reg3.Taps=[1.0 1.06875]
Set Controlmode=ON

! Instruction to calculate the flow
calcv

! File with distance of lines
BusCoords IEEE13Node_BusXY.csv

//Show Voltages LN Nodes   ! Instruction for display bus Voltage
// Show Currents Elem      ! Instruction for display bus Currents
// Show Powers kVA Elem    ! Instruction for display kVA for elements
// Show Losses             ! Instruction for display power losses
//Show Taps                ! Instruction for display the data of taps of OLTC

Solve                      ! Instruction to solve the power flow of the network.
End
```

Generally, the code that represents the case study is saved to file as: "*master.dss*". The master file needs the following two files:

1) IEEELineCodes.dss

```
! These are for the IEEE 13-node test feeder. The file contains the characteristic of the
network lines.

New linecode.601 nphases=3 BaseFreq=60
```

~ rmatrix = [0.065625 | 0.029545455 0.063920455 | 0.029924242 0.02907197 0.064659091]
~ xmatrix = [0.192784091 | 0.095018939 0.19844697 | 0.080227273 0.072897727 0.195984848]
~ cmatrix = [3.164838036 | -1.002632425 2.993981593 | -0.632736516 -0.372608713 2.832670203]

New linecode.602 nphases=3 BaseFreq=60
~ rmatrix = [0.142537879 | 0.029924242 0.14157197 | 0.029545455 0.02907197 0.140833333]
~ xmatrix = [0.22375 | 0.080227273 0.226950758 | 0.095018939 0.072897727 0.229393939]
~ cmatrix = [2.863013423 | -0.543414918 2.602031589 | -0.8492585 -0.330962141 2.725162768]

New linecode.603 nphases=2 BaseFreq=60
~ rmatrix = [0.251780303 | 0.039128788 0.250719697]
~ xmatrix = [0.255132576 | 0.086950758 0.256988636]
~ cmatrix = [2.366017603 | -0.452083836 2.343963508]

New linecode.604 nphases=2 BaseFreq=60
~ rmatrix = [0.250719697 | 0.039128788 0.251780303]
~ xmatrix = [0.256988636 | 0.086950758 0.255132576]
~ cmatrix = [2.343963508 | -0.452083836 2.366017603]
New linecode.605 nphases=1 BaseFreq=60
~ rmatrix = [0.251742424]
~ xmatrix = [0.255208333]
~ cmatrix = [2.270366128]

New linecode.606 nphases=3 BaseFreq=60
~ rmatrix = [0.151174242 | 0.060454545 0.149450758 | 0.053958333 0.060454545 0.151174242]
~ xmatrix = [0.084526515 | 0.006212121 0.076534091 | -0.002708333 0.006212121 0.084526515]
~ cmatrix = [48.67459408 | 0 48.67459408 | 0 0 48.67459408]

New linecode.607 nphases=1 BaseFreq=60
~ rmatrix = [0.254261364]
~ xmatrix = [0.097045455]
~ cmatrix = [44.70661522]

2) BusCoords IEEE13Node_BusXY.csv

```
! These are for the IEEE 13-node test feeder. The file contains the distance of the lines.

SourceBus, 200, 400
650, 200, 350
RG60, 200, 300
646, 0, 250
645, 100,250
632, 200, 250
633, 350, 250
634, 400, 250
670, 200, 200
611, 0, 100
684, 100, 100
671, 200, 100
692, 250, 100
675, 400, 100
652, 100, 0
680, 200, 0
```

ANNEXE I

REFERENCES OF ARTICLES PUBLISHED

Castro, José Raúl, Maarouf Saad, Serge Lefebvre, Dalal Asber et Laurent Lenoir. 2016a. « Optimal voltage control in distribution network in the presence of DGs ». *International Journal of Electrical Power & Energy Systems,* vol. 78, p. 239-247.

Castro, José, Maarouf Saad, Serge Lefebvre, Dalal Asber et Laurent Lenoir. 2016b. « Coordinated Voltage Control in Distribution Network with the Presence of DGs and Variable Loads Using Pareto and Fuzzy Logic ». *Energies,* vol. 9, nº 2, p. 107.

REFERENCES OF ARTICLES SUMMITED

Castro, José, Maarouf Saad, Serge Lefebvre, Dalal Asber et Laurent Lenoir. “Power factor computation of distributed generation usin multi-objective optimization”. It is submitted to the *International Journal of Electrical Power & Energy Systems*.

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Castro, José, Maarouf Saad, Serge Lefebvre, Dalal Asber et Laurent Lenoir. « Optimal Voltage Control in Distribution Network » CIGRE-481 Canada conference. International Center. Toronto, Ontario, September 22-24, 2014.

Castro, José, Maarouf Saad, Serge Lefebvre, Dalal Asber et Laurent Lenoir. “ Optimo Control de Voltaje en redes de Distribución con Generadores distribuidos” INER. Congreso I+D+i en Sostenibilidad Energética. Diciembre 2015.

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