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Optimal voltage control in distribution network in the presence of DGs

José Raúl Castro [a,b,*], Maarouf Saad [b], Serge Lefebvre [c], Dalal Asber [c], Laurent Lenoir [c]

[a] *Universidad Técnica Particular de Loja, Loja, Ecuador*
[b] *Ecole de technologie supérieure, 1100, rue Notre-Dame Ouest, Montréal H3C1K3, Canada*
[c] *Hydro-Quebec's Research Institute, IREQ, 1800, boul. Lionel-Boulet, Varennes, Québec J3X1S3, Canada*

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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.

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 [1–3] 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 [3–5].

Other researches [6,7] 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 [8]. In some networks, these devices are operated locally without wide coordination with the others. In [9,10], 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 [10]. 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 [9,10]: Objective 1: voltage deviation at pilot buses; Objective 2: reactive power production ratio deviation; and Objective 3: generators voltage deviation (OLTC + DGs).

In [11], 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 [10,12,13] 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.

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* Corresponding author at: Universidad Técnica Particular de Loja, San Cayetano Alto, Electrónica, Ext: 2516, Loja, Ecuador.

E-mail addresses: jrcastro@utpl.edu.ec (J.R. Castro), maarouf.saad@etsmtl.ca (M. Saad), lefebvre.serge@ireq.ca (S. Lefebvre), asber.dalal@ireq.ca (D. Asber), lenoir.laurent@ireq.ca (L. Lenoir).

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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 'Coordinated voltage control in distribution network' presents the coordinated voltage control in distribution network. The Pareto Multi-Objective optimization is explained in Section 'Pareto optimization'. The proposed approach on Optimal Coordinated Voltage Control is explained in Section 'Optimal Coordinated Voltage Control'. Section 'Case study' presents a case study and some results using the proposed approach. Finally, a conclusion is given in Section 'Conclusions'.

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 [10].

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) [10].

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:

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:

$$F_1 = \sum_{i\in P}\lambda_i\left[k(V_i^{ref} - V_i) - \sum_{k\in G} C_{i,k}^{V} \cdot \Delta V_k\right]^2 \tag{1}$$

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 k are weighting factor and regulator gain respectively.

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:

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

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 k are weighting factor and regulator gain respectively.

Voltage at generators

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

$$F_3 = \sum_{i\in G}\lambda_i^v\left[k(V_i^{ref} - V_i) - \Delta V_i\right]^2 \tag{3}$$

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 k are weighting factor and regulator gain respectively.

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 [10,14,15].

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 [16].

$$\begin{aligned} &V_i \in [V_i^{min}; V_i^{MAX}] && \text{for } i \in P \cup G \\ &|\Delta V_i| \leqslant \Delta V_i^{MAX} && \text{for } i \in G \end{aligned} \tag{4}$$

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 [1] an acceptable power factor for the DG is of ±0.91.

$$q^{ref} = \sum_{i\in G} Q_i \Big/ \sum_{i\in G} Q_i^{MAX} \tag{5}$$

where $|Q_i| \leqslant Q_i^{MAX}$

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 (6).

$$\lambda_i + \lambda_i^q + \lambda_i^v = 1 \tag{6}$$

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

The optimization problem (1)–(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 [17].

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.

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 [18,19].

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

Step 1: Compute $V_{bar} = \sum_{j=1}^{N} V_i$.
Step 2: Find $\Delta V_i = V_{bar} - V_i$.
Step 3: 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 1 shows the pilot bus selected.

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 [20]. 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 [21]:

$$\Delta V = V_1 - V_2 \approx \frac{R_L P_L + X_L Q_L}{V_2} \tag{7}$$

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 [21]:

$$\Delta V = V_1 - V_2 \approx \frac{R_L(P_L - P_{DG}) + X_L(Q_L - (\pm Q_{DG}))}{V_2} \tag{8}$$

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

Table 1
Pilot bus for IEEE 13 and IEEE 34 buses.

	IEEE 13	IEEE 34
Pilot bus	Bus 671	Bus 888

The extent of voltage regulation (ΔV) is limited by the number of positions and the step size between positions. In [22] the characteristics of our OLTCs are displayed.

Pareto optimization

Conversion of the multi-objective function into a single-objective function has several limitations [13,17]:

(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 (Fig. 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 [23]. 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 [24].

$$F = Min \sum_{j=1}^{N} \lambda_j f_j \tag{9}$$

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.

Optimal Coordinated Voltage Control (OCVC)

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 Eqs. (1) to (3), we see the three objectives on voltages on the pilot buses F1 and on reactive power F2 and voltages on the generation buses F3. Furthermore, Eq. (6) is responsible for maintaining an optimal relationship in the objectives.

Fig. 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 = 100 s) is the input of the DG to the network. The second disturbance is the input of the large load on the pilot bus.

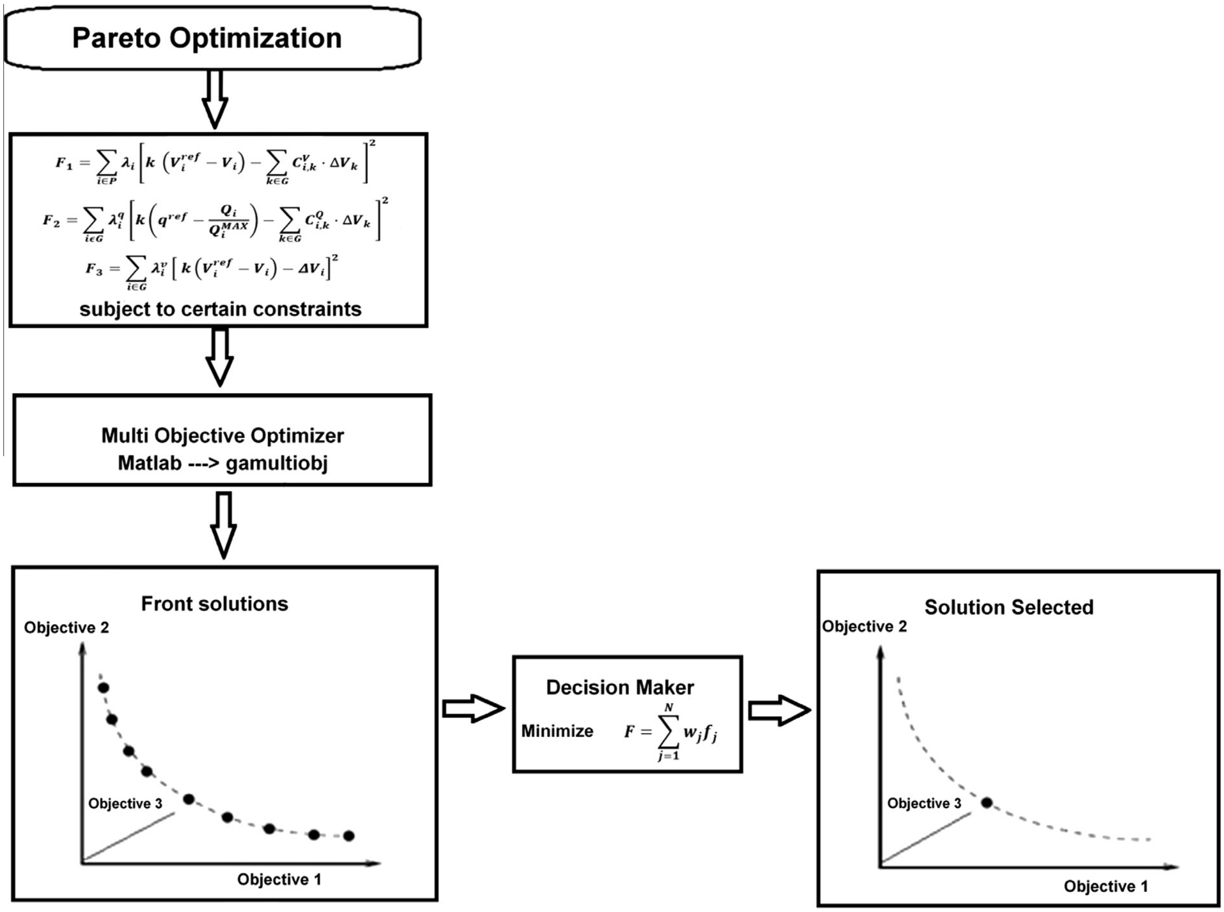

Fig. 1. Pareto optimization scheme for multi-objective function.

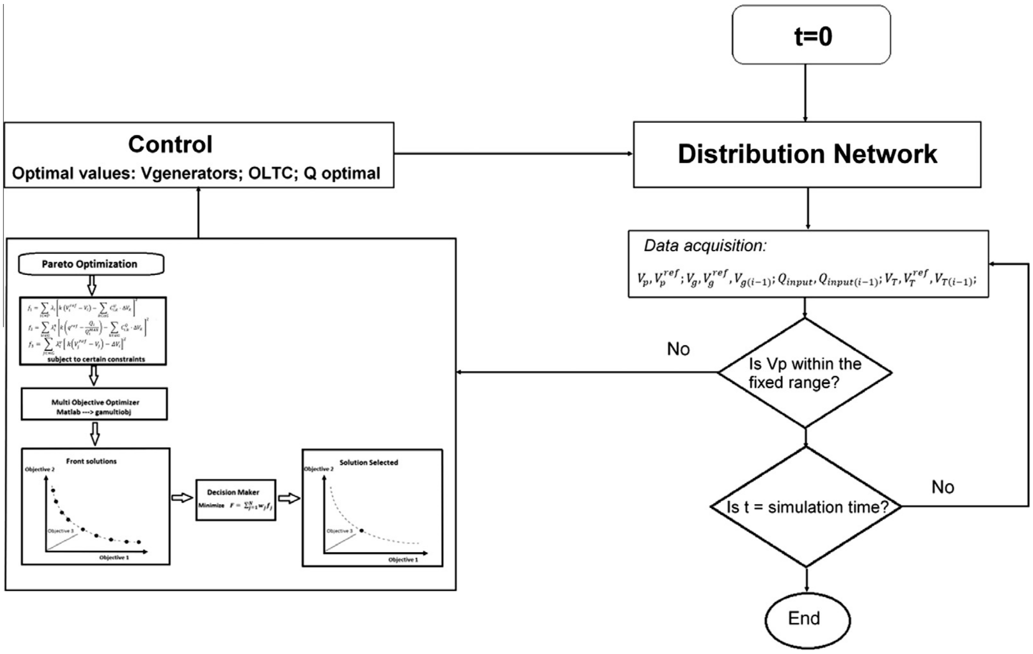

Fig. 2. Flow chart of the proposed algorithm.

Step 2. Analyze and complete the objective functions.

The objective functions are calculated from Eqs. (1) to (3) and the constraints (4)–(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 [25].

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 Eq. (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 Eq. (8), the voltage in the OLTC is calculated.

Step 5. With the data from step 4, OCVC calculates new values for the distribution network using the OpenDSS software [25].

Step 6. If the voltage values at the pilot bus is within the limits go to 7, if not, return to step 1.

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 [9,10] 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.

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 [26].

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, 50–60 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

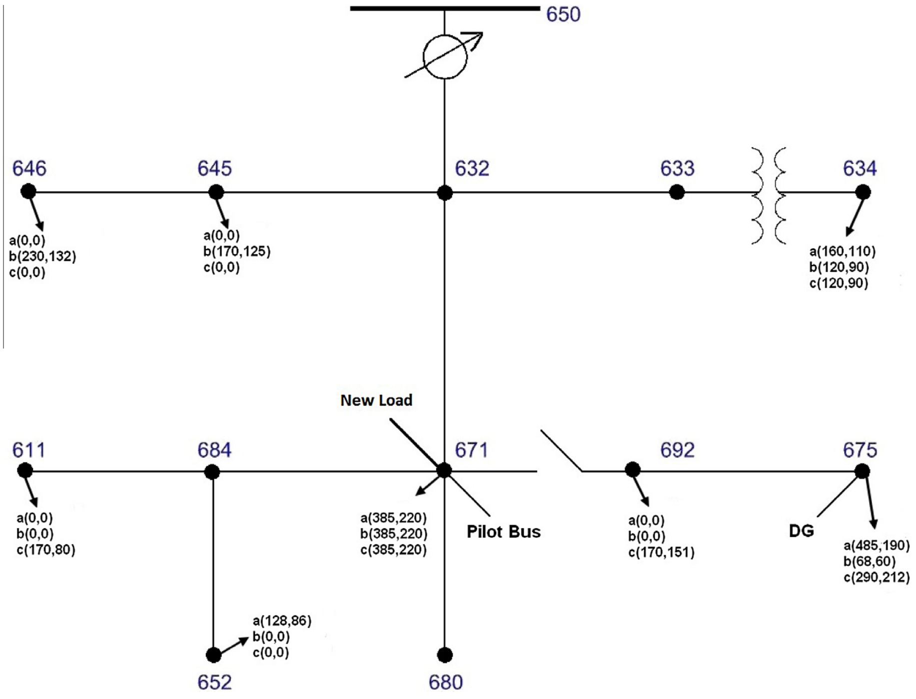

Fig. 3. Case study distribution network. IEEE 13 Node Test Feeder.

modernization efforts [25]. It can solve a very large distribution system in a very small CPU time. In addition, it is freely distributed by EPRI.

IEEE 13 Node Test Feeder

The diagram of the IEEE 13 Node Test Feeder used as a test system is given in Fig. 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 [26]. The network has an OLTC.

The work performed by Anwar and Pota [3] 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.

Ahmidi proposed a multilevel approach for the optimal participation in reactive power balancing of wind farms connected to the network [1]. 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 ($t = 100$ s). Finally, at $t = 350$ s, 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 s.

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.

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: $\lambda_i = 0.8; \lambda_i^q = 0.1; \lambda_i^v = 0.1$ [10].

Optimal Coordinated 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.

In Table 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 = 100 s). Fig. 4 shows the variation of the voltage (first disturbance).

At time $t = 350$ s, the second disturbance occurs in the network (new load). Fig. 4 shows the voltage variation in the three methods used.

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 (Fig. 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 (Fig. 6).

Table 2
Weight variation: Comparison between CVC and OCVC for IEEE 13 Node Test Feeder.

Time (s)	CVC			OCVC		
	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

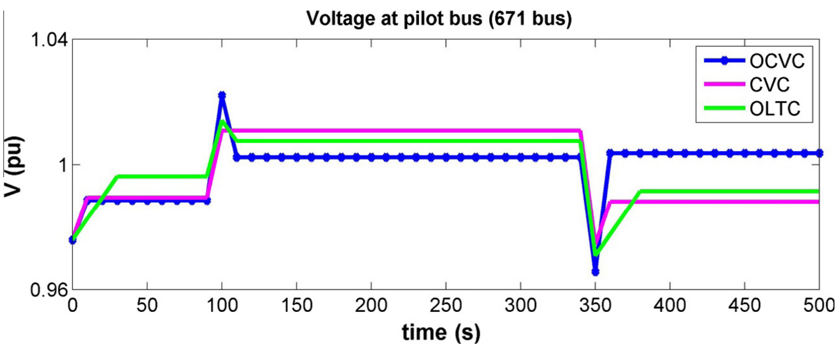

Fig. 4. Voltage profile of the IEEE 13 Node Test Feeder on the pilot bus.

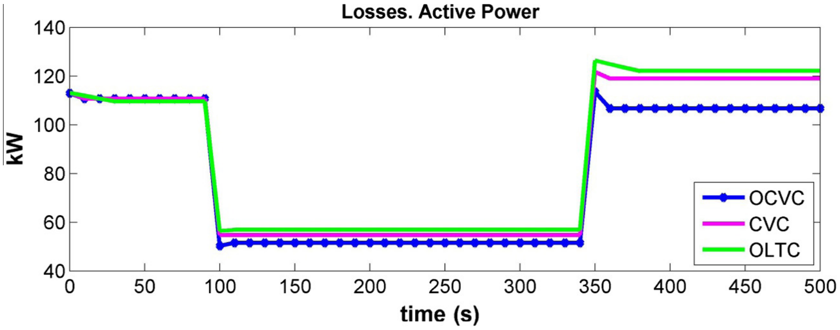

Fig. 5. Active power losses in the IEEE 13 Node Test Feeder.

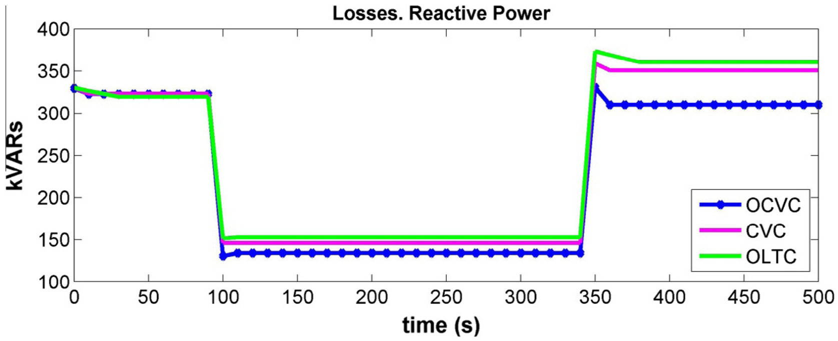

Fig. 6. Reactive power losses in the IEEE 13 Node Test Feeder.

IEEE 34 Node Test Feeder

In Fig. 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 [26].

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 [3] 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.

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 Fig. 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 Figs. 9 and 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.

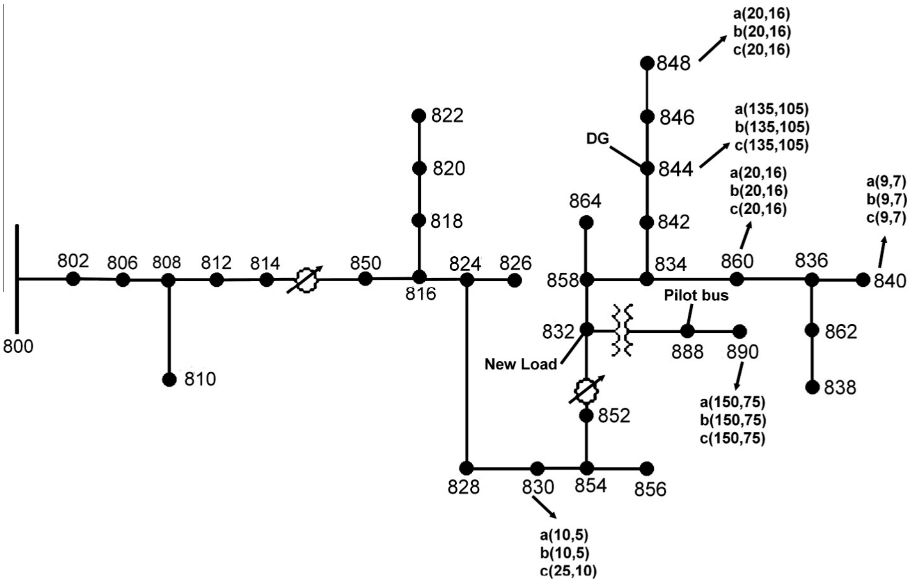

Fig. 7. Case study distribution network. IEEE 34 Node Test Feeder.

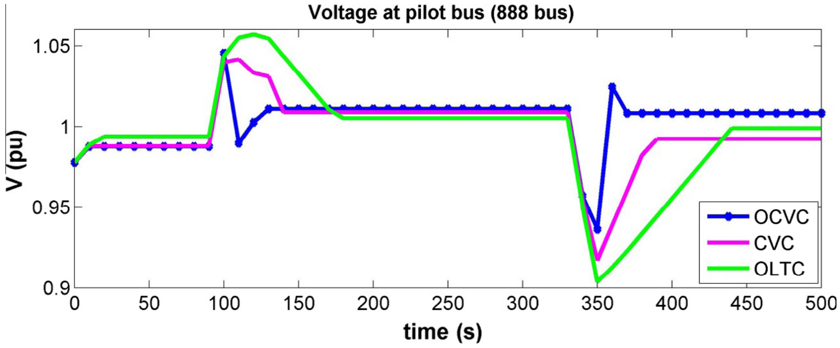

Fig. 8. Voltage profile of the IEEE 34 Node Test Feeder on the pilot bus (bus 888).

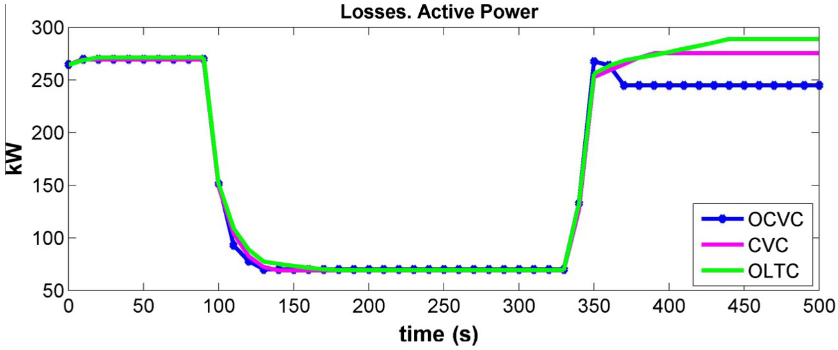

Fig. 9. Active power losses in the IEEE 34 Node Test Feeder.

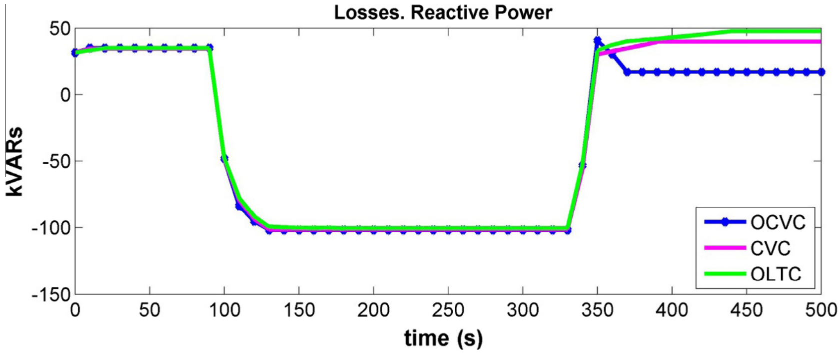

Fig. 10. Reactive power losses in the IEEE 34 Node Test Feeder.

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.

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