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NOVEL OPTIMAL COORDINATED VOLTAGE CONTROL FOR DISTRIBUTION NETWORKS USING DIFFERENTIAL EVOLUTION TECHNIQUE

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Abstract. This paper investigates a Distributed Generators (DG) connected to distribution networks offering multiple benefits for grids and environments in the case of renewable sources used. Nevertheless, this task requires an appropriate planning and control strategy, if not several drawbacks can issue, including voltage rise problems and increased power losses. To overcome such disadvantages, this paper proposes a coordinated voltage control CVC method for distribution networks with multiple distributed generators. This new method is based on a differential evolution DE approach to obtain the optimal setting points for each control component. Furthermore this proposed method considers both of time-varying load demand and production, leading to not only an improvement in the voltage profile but also to optimally minimizing the active power loss.

Keywords. Optimal Coordinated Voltage Control (CVC), Distributed Generators (DG), Differential Evolution DE algorithm, active power loss minimization, On Load Tap Changing OLTC.

1. INTRODUCTION

Nowadays, distributed generation (DG) has become an important alternative to compensate for the increase of energy demand. DGs, such as solar and wind, are generally more environmentally friendly. Furthermore, by installing DGs close to consumer centres, the need to build new traditional generation plants (hydro-electric, thermal, nuclear) and new transmission lines can be reduced. Renewable distributed generators (DG) connected to grids offer multiple advantages, including active power loss reduction and voltage profile improvement, along with environmental benefits.

Generally, by limiting the amount of power injected into the grid, voltage rise and energy quality degradation may cause a reverse power flow (Heslop et al., 2014) [1]. In order to overcome the negative impacts of high active DG used, and to avoid power curtailment, various voltage control schemes involving DG production have been proposed. Mostly, voltage regulation in the presence of DG can be classified into two categories: Local control and Coordinated control, (Dragicevic et al., 2015) [2]. O'Gorman et al., 2008 [3] proposed an autonomous DG voltage control method. Distributed generators DG are also capable of intervening in the quality control process, as analyzed by Illindala et al., 2013 [4]. Dai et al., 2004 [5] and Kim et al., 2015 [6] investigated how DG phase inverter equipment can be applied to regulate active and reactive powers injected into the grid. Then DG can thus be used as a static VAR element. In such methods, control components, such as OLTCs, SVRs and

SCs, act individually and locally. Such approaches above usually interfere along with control equipment issuing excessive operations and although they solve most problems related to DG connection and management, the results in term of power line losses and varied voltage levels could be improved. With coordinated voltage control (CVC), DG control capabilities are coordinated between traditional control elements and DG power interfaces, as to maintain an optimal voltage profile and to minimize power losses. CVC for grids takes benefit of the control methods applied for transmission networks [7]. Several CVC approaches have been presented in the literature. In (Muttaqi et al., 2015) [8] and (Pachanapan et al., 2012) [9], the control zone and priority concept were introduced, as to ensure the control elements do not interfere with one another.

The use of evolutionary algorithms and meta-heuristic computation techniques has been proposed to optimally set each element involved in the control of the grids, including DG units. Thus, fuzzy logic is used to control the power factor of multiple synchronous generators [10] and is combined with CVC in (Ochoa et al., 2010) [11]. An optimization method for CVC and reactive power control with and without DG is presented by Viawan et al., 2008 [12]. A CVC method using intermittent PV generation is proposed by Paaso, 2014 [13]. In Daratha et al., 2015 [14], a centralized voltage control optimization problem is solved using robust optimization technique. However, when dealing with more control elements and grids, including distributed and unbalanced loads, it is preferred to address the network control via a multi-objective problem. Recently evolutionary algorithms are increasingly applied to solve such problems. Particle Swarm Optimization (PSO) in Sarmin et al. (2013) [15], Vlachogiannis et al. [16], Kim et al., 2015 [17], and Genetic Algorithm (GA) in Duong [18] have been applied. These works focus on various objectives, such as power loss reduction, voltage variation minimization, and so on. In Devaraj et al. [19], a GA technique is improved to solve the reactive power dispatch problem in a distribution network. Another modification of the GA is applied in Jeyadevi et al. [20] to solve a multi-objective problem and minimize the power losses in a DG system. Further, in Khatua et al., 2015 [21], the GA is combined with the Voltage-Stability Constrained Optimal Power Flow technique to solve a multi-objective problem, where wind generation is used to improve the voltage stability. Furthermore, other evolutionary algorithms, such as the Gravitational Search Algorithm (GSA) presented in (2016) [22], are successfully applied to solve the optimization problem of control elements and DG integration. Hybrid algorithms combining Fuzzy and GA (FGA), (2016) [23], is used to enhance optimization results. Related to the task of objective function implementation, various methods were proposed by Viawan et al. [24], Daratha et al., 2015 [25], Kulmala et al., 2014 [26], in which the objective function is configured to optimally minimize the active power losses and DG generation curtailment. Although, these works successfully address the CVC problem in unbalanced networks, they fall short when it comes to using more real scenarios, such as time-varying load demand and DG production. Moreover, they do not include objectives such as capacitor switching and OLTC operation reduction in the optimization problem.

Based on results above-mentioned, this paper proposes an optimal coordinated voltage control CVC method to optimally minimize the power loss and voltage profile improvement in the presence of renewable DG. The proposed objective function optimally minimizes the active power losses, capacitor switching operations, and OLTC operation frequency, and optimally maximizes the DG power outputs. The results from the optimization process represent the optimal operation settings for DG units (active power and power factor), OLTCs and Shunt Capacitors (SC) operations for a 24-hour period. Furthermore, a differential evolution DE technique conducts the optimization calculation. It also includes a power factor control for the DG. The validity of the proposed method is proven using a load curve and a DG production curve for the photovoltaic PV distributed power plant, over an unbalanced distribution test network.

Then the main contributions presented in this paper include as follows:

- It provides a coordinated voltage control (CVC) method to fix all the optimal control settings for every control interface in the distribution network.
- It also provides an objective function that simplifies the method and reduces the complexity of the algorithm, including the number of Tap OLTC operations and capacitor switching (CS) as penalties.

The rest of this paper is organized as follows: The methodology is proposed in Section 2. In Section 3, different case studies are investigated. In Section 4, the simulation bench-mark test system and results using the new proposed DE-based CVC control application compared of a local Volt/Var control method are presented. Finally the conclusions are presented in Section 5.

2. METHODOLOGY

The purpose of voltage and reactive power control in a grid is principally to compensate for voltage drop along the feeders, and to reduce power losses. In a normal power system network with no DG connections at their feeders, feeder capacitors can compensate for the reactive power consumption and then boost the voltage level when it drops under imposed limits 0.03p.u. The OLTCs change their taps to restore the voltage level to the proper limits, (Vlachogiannis and stergaard, 2009) [27], based on voltage drop estimation from local measurements. When power injected to the network by DGs is greater than the power needed in the connection bus loads, this power goes to the substation, interfering with the configuration of control elements, and provokes excessive critical operations, which degrades the life expectancy and increases maintenance costs (Kim et al., 2015) [28]. In this paper, when a DG PV plant is connected to an end feeder, it can be supposed that the power interface is capable of controlling the reactive power QDG injection/absorption. In the case of voltage drop at the end of the feeder, DG can react faster than feeder capacitors in reactive power compensation. The DG interfaces cause DG units to act as a real and fast voltage and reactive control components in the distribution networks.

2.1. Optimization methodology

The coordinated voltage control CVC problem is formulated here as a nonlinear optimization problem of the form

$$\min F(x, u) \tag{1}$$

subjecting to

$$g(x, u) = 0, \tag{2}$$

$$h(x,u) \leq 0, \tag{3}$$

where F represents the objective function for the problem, x and u represent the dependent and independent variables respectively.

$$x = [V_1, ..., V_n, P_{Loss}^1, ..., P_{Loss}^L] \tag{4}$$

$$u = [P_{DG1}, ..., P_{DG1}, Q_{DG1}, ..., Q_{DGn}, Tap_{step}^m, Cap_s^m] \tag{5}$$

with P_{Loss}^L denotes the power loss at line L, Tap_{step}^m represents the tap position of the OLTC regulator for the m units installed on the network, and Cap_s^n, represents the capacitor state S: on/off of the n units present in the circuit. The objective function that defines the problem needs to include the following objectives: The first objective f_1 is to reduce the active power losses defined in (6). In order to maintain the voltage between the maximum and minimum boundaries the quadratic penalty function (QPF) $(V_{Li} - Vlim)^2$ is applied and considered in (8) as the 3^{rd} objective f_3, via investigating all the line voltages and upper and lower voltage limits (0.97 & 1.03 p.u.). Voltage has to be as close as possible to the rated voltage (1 p.u.), and then function $(V_{ref} - V_i)^2$ is used. This function is often called cumulative voltage deviation factor (CVD) and is considered in (7) as the 2^{nd} objective f_2. The mixed integer non-linear problem in (Kim et al., 2015), presents an objective function to limit the excessive taps and capacitor switching operations.

In this paper the same factors are included with the following modifications proposed: To reduce the number of tap operation, a penalty $|Tap_{h1} - Tap_h|$, considered in (9) as the 4^{th} objective f_4, is imposed directly in the equation considering the last tap position h-1 instead of the next h+1 as stated in (Kim et al., 2015). Similarly the same type of penalty is imposed to the shunt capacitor switching $|C_{h1} - C_h|$, considered in (10) as the 5^{th} objective f_5. So on, the factor P_DG is included to increase the active power injection from the DG PV distributed generators and is considered in (11) as the 6^{th} objective f_6

$$f_1 = \sum\nolimits_{k=1}^{N} P_{L_i}, \tag{6}$$

$$f_2 = CVD = \sum\nolimits_{n=1}^{k} (V_{ref} - V_i)^2/k, \tag{7}$$

$$f_3 = QPF = \sum\nolimits_{i=1}^{N} \begin{cases} (V_i - V_{\min})^2; \ V_i \leq V_{\min} \\ 0; \ V_{\min} < V_i < V_{\max} \\ (V_i - V_{\max})^2; \ V_i \geq V_{\max}, \end{cases} \tag{8}$$

$$f_4 = |Tap_{h-1} - Tap_h|, \tag{9}$$

$$f_5 = |C_{h-1} - C_h|, \tag{10}$$

$$f_6 = P_{DG}. \tag{11}$$

Then, the objective function is defined as,

$$F = \min\{C_1 f_{1t} + C_2 f_{2t} + C_3 f_{3t} + C_4 f_{4t} + C_5 f_{5t} - C_6 f_{6t}\}, \ \forall t \in T. \tag{12}$$

The objective function (12) is then needed to satisfy the following constraints:

- P_{Loss} : Circuit active power loss,

- V_{ref} : Reference node voltage 1 p.u,
- V_n : Voltage at node n^{th},
- $V_{\min}^{n}$: Minimum voltage limit,
- $V_{\max}^{n}$: Maximum voltage limit,
- P_{DG}, Q_{DG} : Active and Reactive power output of DGi,
- PF_{DGi} : Denotes the power factor of DGi,
- $P_{DG}^{\min}$: Minimum limit for active power curtailment,
- $P_{DG}^{\max}$: Maximum limit for active power curtailment,
- $Q_{DG}^{\min}$: Minimum limit for reactive power injection,
- $Q_{DG}^{\max}$: Maximum limit for reactive power injection,
- $PF_{DG}^{\max}$: DGs Power factor maximum limit,
- $PF_{DG}^{\min}$: DGs Power factor minimum limit,
- Tap_h : OLTC tap position at time h.

Furthermore, $Tap_{h-1} - c$ and $Tap_{h1} + c$ represent a constraint that limits the tap changes during each hour. This constraint is included in the proposed algorithm. The number of tap movements is limited to C from the last set position. The objective of this restriction is to avoid having the OLTC play the principal role in the control operations. The value of the constant c determines the amount of control priority that the OLTC will have. By restricting the OLTC, the DG equipment and other control devices are required to actively participate in the voltage control actions.

By modifying the weights of each factor in objective function (12), an equilibrium state between losses minimization, voltage profile stability, and OLTC operations is to be eventually achieved. Then the proposed method solves the problem by optimally minimizing the objective function (12), with respect to the constraints (13) to (16), hence, attaining a set of optimal settings for the OLTC operation, active power and reactive power configurations for DGs, within a 24-hour planning horizon. These optimal settings will reduce the active power losses in the network, meanwhile maintaining an optimal voltage profile in all the network nodes. Fig 1 presents the flow chart for the proposed DE-based CVC approach.

3. DEVELOPMENT OF RELEVANT SIMULATION CASES

3.1. DE technique implementation

To solve the optimization problem presented here, a DE optimization has been used. The DE technique is capable of solving multivariable nonlinear problems, obtaining the best global optimum solution. An initial population initializes the DE, and the objective function is evaluated for each solution (population). The algorithm continuously improves the population through crossover, mutation, and evaluation processes. When the DE reaches

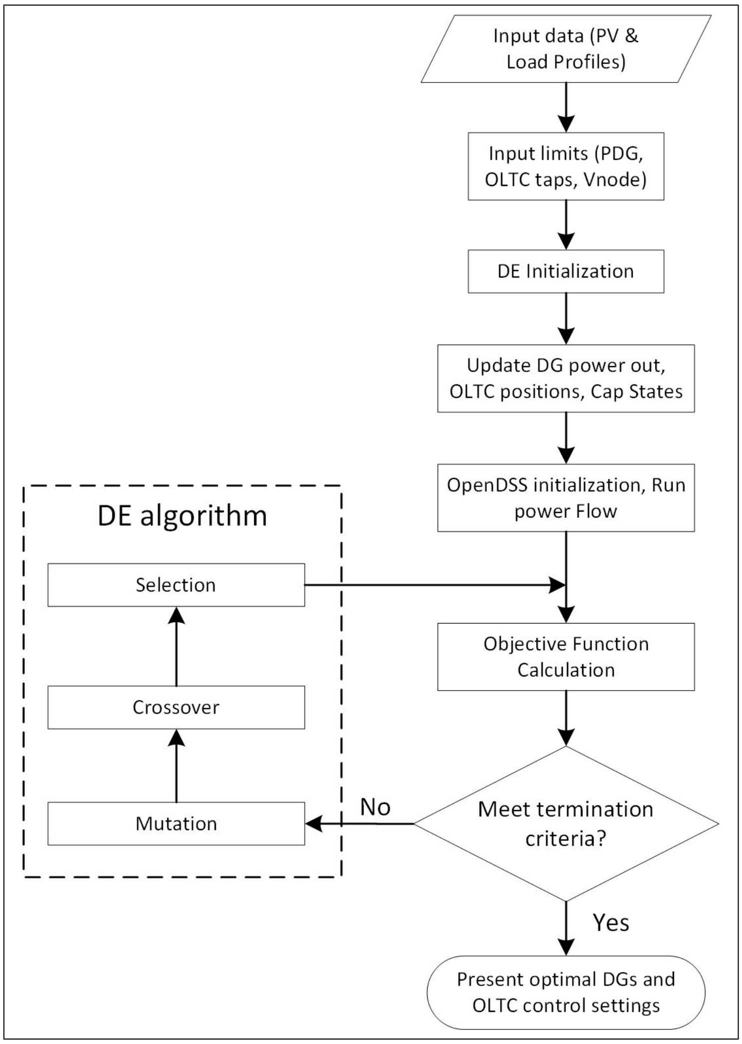

Figure 1. Flow chart of proposed DE-based CVC algorithm

the eventual criteria, it presents the optimal solution. In the proposed algorithm used in this work, the initial population is entered in integer format in order to reduce computation complexity. Due to the large number of variables (tap steps, power factor, active power, power factor and capacitor state), the initial population size is set to 60 individuals in order to increase the possibility of finding the optimal solution.

3.2. Simulation test system

The distribution system used to test the proposed method is the IEEE 13-Node Test Feeder. It is an unbalanced DG system with its specifications can be found in (Kersting, 1991). Solar PV was selected as the renewable generator source for testing the novel control approach. Two PV-based DGs are connected to the buses (680 and 671, respectively). In this paper, it is assumed that the power interface of the PV DG is able to dynamically inject or absorb the reactive power and to vary the amount of active power injection. In order to thoroughly verify the capabilities of the proposed method, a maximum power capacity of 1500 KW for each PV DG power unit is selected, which, in combination, represents the 88% of power penetration for the tested network. Both DG units vary according to the generation pattern shown in Fig. 2. The load demand profile for every load in the network is also presented in this Fig. 2 too. A novel algorithm to test the proposed method was

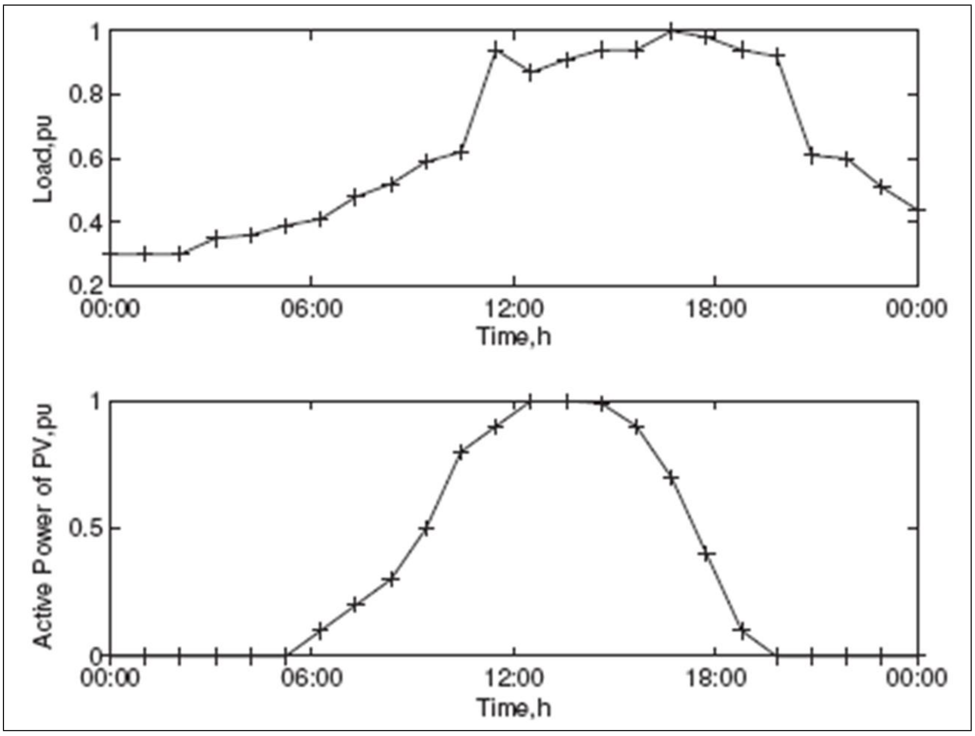

Figure 2. Daily system load and DG power production profiles

edited in MATLAB. This algorithm allows the execution of the DE, and interaction with the OpenDSS COM interface, (see EPRI, 2015). With each DE iteration, the OpenDSS software performs a power flow, for calculating the total circuit losses, voltage profile levels in each node, and the value of the objective function (12). The value of the objective function is then sent back to MATLAB to be processed with the DE technique. The solution presented for the DE is a vector containing the optimal settings for the OLTC taps position, the active and reactive power levels for the PV generators, and the on and off switching for the distribution capacitors.

Furthermore the weights for the objective function (12) are optimally established through differential evolution DE optimization technique. The results show that C_1 is set as 0.2, $C_2 = 0.2$, $C_3 = 0.1$, $C_4 = 0.2$, $C_5 = 0.2$, and $C_6 = 0.1$. Similarly, the constant c for the OLTC movement constraint is set to the value of ± 4.

4. SIMULATION RESULTS

Simulation results are obtained with MATLAB and OpenDSS in a co-simulation environment. The results from the proposed DE-based CVC method are verified with the IEEE 13-Node test Feeders bench-mark as follows.

In this bench-mark test, the IEEE 13-Node test Feeders is used with two PV generators connected to the distribution network, injecting 3000KW. Figure 3 shows the diagram of the IEEE 13-Node test Feeders and the two PV DG connections with following important notes,

- The PV DG generators are connected to the distribution system without any control interface. The OLTC tap changing and capacitor switching are controlled locally.
- The electronic interface of each PV generator had a Volt/Var control capability. Meanwhile OLTC and capacitor switching is locally controlled. Volt/VAr control is implemented directly in the OpenDSS script interface, with control settings based on the work reported in, (Kim et al., 2015).

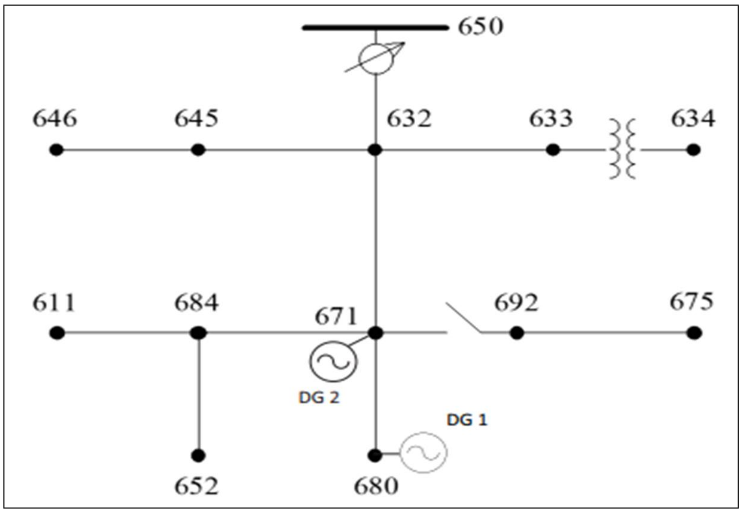

Figure 3. Diagram of the IEEE 13 Node test Feeders and the two PV DG connections

4.1. Impact on total circuit power losses by applying the proposed CVC method

Connecting the two PV DG systems to bus 680 and bus 671 had a direct impact on the power losses. The total capacity of the generators is chosen to keep the same total power losses the network experienced before the DG connections. Nevertheless, the purpose here is to let the proposed CVC method perform an optimal minimization of active power losses, as compared to the two benchmarks presented earlier. Fig. 4 shows the network losses for the 13-node test system. The simulation uses the 24-hour load demand and DG patterns installed in Fig. 2.

Fig. 4 illustrates the total circuit Losses resulting through three cases:

1) The 1st Case relates to no control case.

2) The 2nd Case relates to use local control and Volt/Var control.

3) The 3rd Case applies the proposed DE-based CVC control approach.

It is obvious to see that, in case with the proposed DE-based CVC method, active power losses present the best results. This coordination permits the dynamic variation of the power injected from the PV-based DG generator according to the load variation. The OLTC planning is determined by the CVC, avoiding the use of the voltage estimator, which could be interfered for the reversed power from the distributed generators.

4.2. Impact of applying the proposed CVC method on the voltage regulation

Distributed generators connected to a distribution system could cause voltage rises at the connected buses. This phenomenon is incremented when the load profile is much lower than the DG power production at those buses. In Fig. 5, the voltage profile level at the bus 681 is shown. This voltage profile allows us to observe the impact of proposed CVC method on voltage variation. The voltage in all the network buses is maintained between the maximum and minimum boundaries (0.03 p.u.) by applying the optimal settings to the voltage control devices. Moreover, a comparison is made with no control and local control, respectively. As to confirm the advantage of CVC over other techniques in voltage regulation, Table 1 shows the cumulative voltage deviation (CVD) at bus 681, calculated using function (7), for each control technique, as well as the active power and reactive power losses for each scenario. This data is obtained for 24 hours, and the results show that the proposed DE-based CVC method presents the best behaviour in all the scenarios.

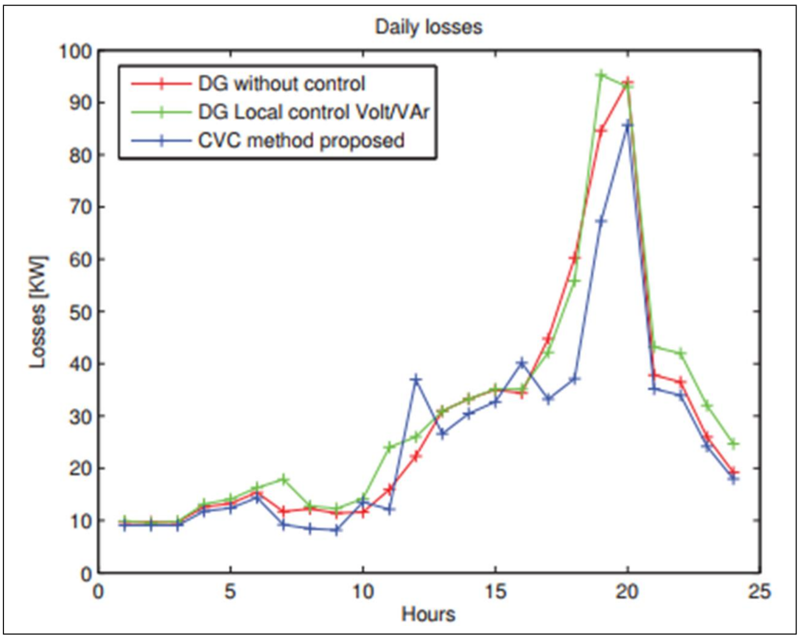

Figure 4. Daily network losses with CVC application and the two comparison scenarios

Table 1. Cumulative voltage deviation (CVD) and Power Losses for the different control scenarios

	Network without DG installed	DG with no control	DG Volt/Var local control	DG CVC proposed control
Active Losses [MW]	1.21	0.692	0.743	0.619
Reactive Losses [MW]	3.51	1.83	1.98	1.63
CVD factor	1.3337	1.2267	1.1071	1.0663

4.3. Impact on the OLTC and capacitor operations by applying the proposed CVC method

The proposed coordinated voltage CVC control includes an expression $|Tap_{h1}Tap_h|$ in the objective function, which limits the number of actions the OLTC performs along with each control iteration. This expression is included in order to balance the control actions of each element. Fig. 6 shows the result of the OLTC operations in each scenario. It is easy to see that the tap changes realized with the proposed CVC method do not increase significantly.

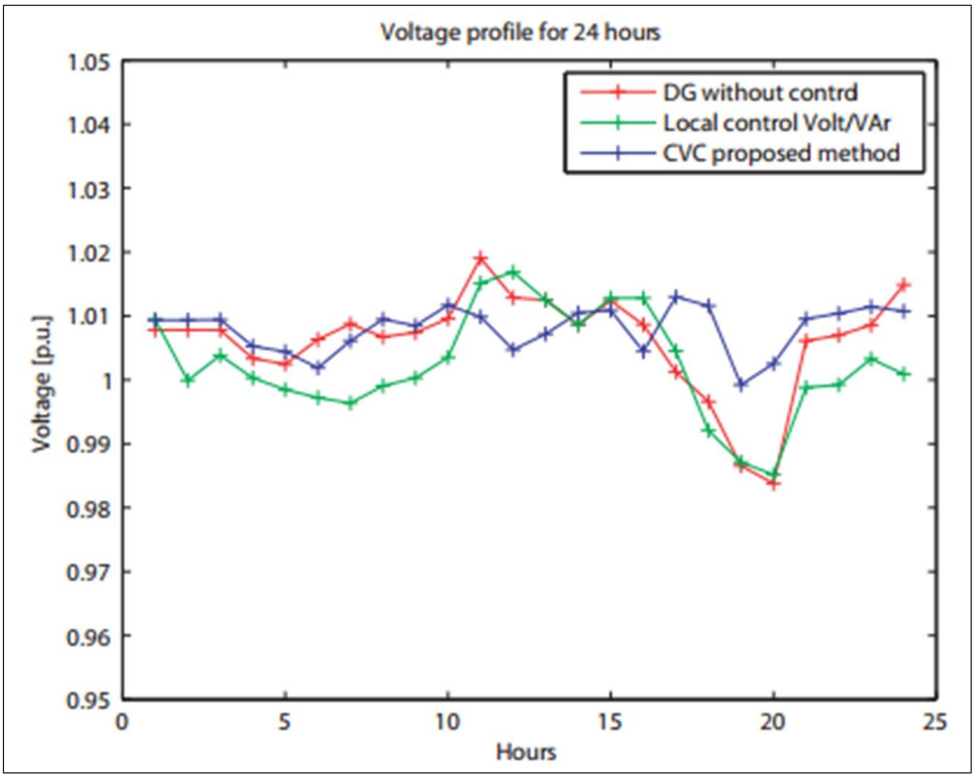

Figure 5. Daily voltage profile comparison at bus 680, from phase A - with the proposed DE-based CVC method and the two comparative scenarios

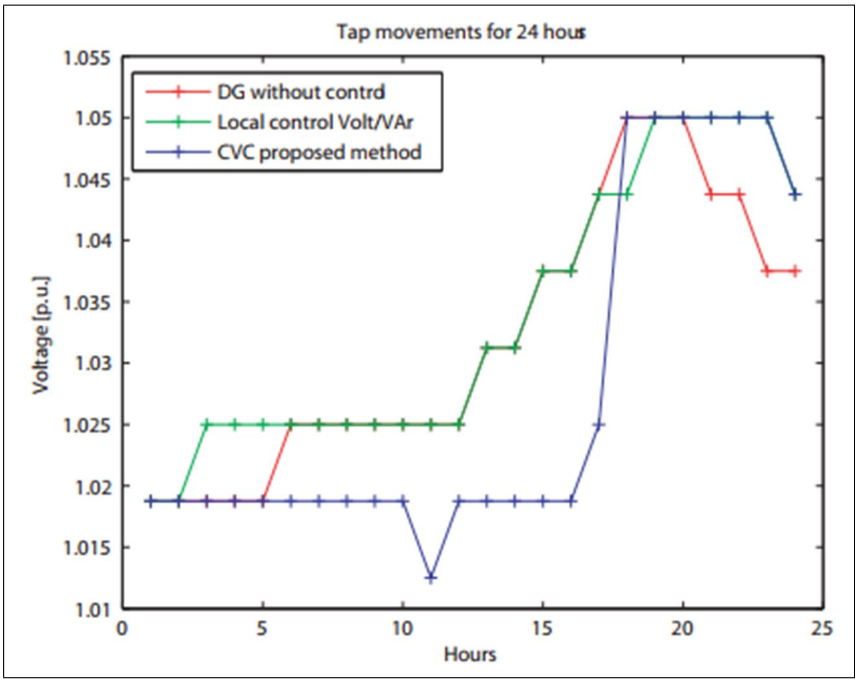

Figure 6. Result of OLTC tap movements for 24 hours, with proposed CVC and the two comparative scenarios

Furthermore, in this particular case study, capacitor switching does not present major state variations during the 24-hour planning period covered. The algorithm determines that both system capacitors are maintained in the ON position for each hour as shown in Fig.7.

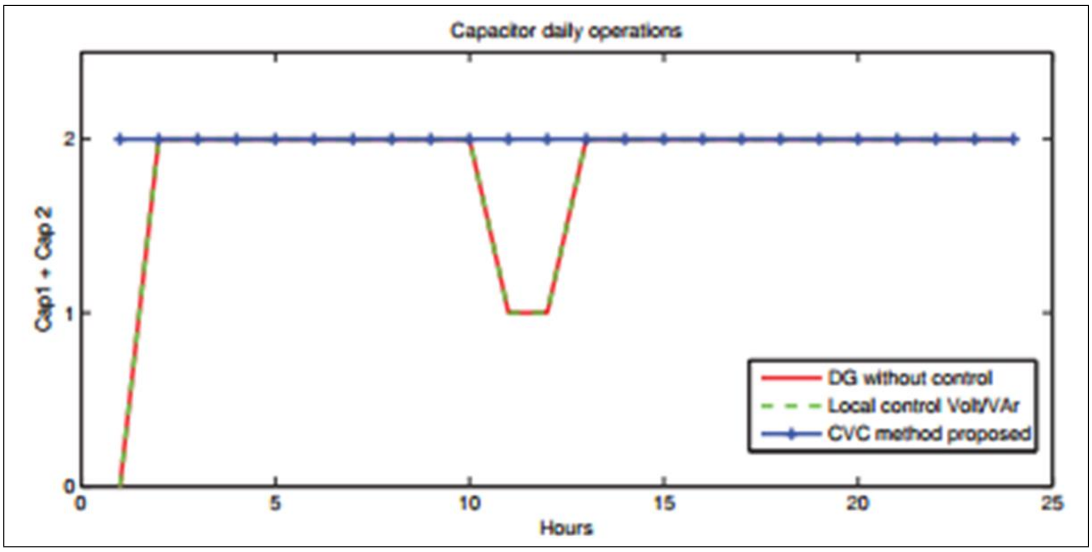

Figure 7. Capacitors status for 24 hours with proposed CVC

5. CONCLUSIONS

In this paper, a newly proposed coordinated voltage control CVC method for distribution networks with multiple DG connections has been presented. The proposed CVC method is designed to obtain the optimal settings for the control devices from an optimization problem. The designed algorithm used a DE technique in co-simulation with OpenDSS software. The results show a satisfactory voltage control and loss reduction, demonstrating the effectiveness of the proposed method. The use of the time-varying load profile and DG generation patterns shows that the proposed algorithm can be used in real implementations, helping to increase reliability and DG integration in distribution networks.

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