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Modern Distribution Management System and Voltage VAR Control

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Abstract

This paper describes modern Distribution Management System (DMS) and Voltage/VAR Control (VVC) as one of its important components. Importance of DMS with respect to latest changes such as renewable energy sources, distribution generation, demand-respond is significant for the complete power system stability and control. In this paper VVC, as one of the most important applications in DMS, is explained and analyzed. VVC uses power system control equipment and calculates new optimal operational state. Typical VVC objective function is minimization of system power losses, violations of bus voltage limits, feeder capacity limits or combinations of these. Changes of controllable devices are presented through their injected current used in current iteration method for power flow. Test of Voltage/VAR control is performed on modified IEEE13 test network and results show that proper adjustments of OLTC transformers, capacitors and DG significantly reducepower losses while satisfying all operation constraints.

1. INTRODUCTION

Growing concerns for the environmental problems have lead to increased integration and usage of renewable energy sources in the electricity grid. Renewable energy sources offer potentially infinite energy supply with low operating costs and minimal negative impacts on the environment. While Renewable Energy Resources (RES) have many advantages to offer, integration of renewable energy resources imposes several challenges for DN control. Some of the main factors that limit generation from RES are feeder's thermal capacity, system's fault levels, protection issues, reverse power flow capabilities of the distribution system, and steady state voltage rise problem [1]-[2].Compared to large power plants, RES have less capacity and they are usually integrated in lower grid levels to avoid expensive infrastructure investments. When connected to distribution network, RES can cause bidirectional power flow and seriously influence the operation of the whole grid. This calls for establishment of new operational and control strategies different from the one used for traditional unidirectional power flow in conventional distribution networks. In order to meet theserequirements, an efficient modelbased distribution management system (DMS) with improved operational and control strategies needs to be developed.This paper describes the most important components of modern DMS and explains set of functions and applications of each individual component. Moreover, paper presents calculation of voltage and reactive power control in distribution systems as one of the most important application in DMS.

There are many proposed solutions for Volt/VAR in the literature.Traditionally, control of voltage and reactive power in distribution systems is achieved using control devices such as on-load tap changers (OLTC) transformers and switched shunt capacitors [3]-[5]. The Multi-objective genetic algorithm (SPEA2) incremented by fuzzy logic is used in [6] to control automatic voltage regulators (AVRs) banks and capacitors in distribution systems for different load conditions, dealing with the combinatorial multi-objective optimization problem. Reference [7] presents a PSO-based (particle swarm optimization) optimization approach to find the optimal dispatch of a ULTC, substation capacitors, and feeder capacitors for volt/VAR control in a distribution system. Besides switched capacitors, reactive power can be regulated with distributed generators (DGs). If DG is installed on a certain feeder, the voltage of that point can rise since DG injects power at a certain point of the system and conventional operation of the voltage control needs to be modified to accommodate the presence of DG. This requires coordination between DG and other regulating equipment. In [1], coordination between voltage regulators and DGs is achieved locating RTUs at each DG, which communicate with each other. Using readings of these RTU, the voltage regulator controller can determine voltage levels and hence efficiently regulate the voltage of the feeder. Proper coordination among on-load tap-changer (OLTC), substation capacitors and feeder capacitors in the presence of Distributed Generation in [8] is achieved using combined local and remote control based on automated remote adjustment to the local control in order to keep the operating constraints fulfilled all the time. Voltage VAR control in distribution networks with DGs is also studied in [9]-[17]. This paperpresentscalculation of VVC in distribution systems with renewable energy based distributed generators. Method uses power flow calculation where all changes of control devices are treated as current injections. Algorithmseeks for optimal tap position for OLTC, switching position for capacitor and reactive power injection for DG which minimizes objective function and satisfy all physical limitations of thedistribution system.

Section2presents the modelof a modernDMSsystemand describes the interactionof the main components within the model. Section 3 provides detailed description of VVC methodandalgorithm defined in termsof the necessarymodifications needed for the proper handling ofRES. Section4verifiesand displays the resultsof the proposedalgorithm applied onmodifiedIEEE13testfeeder. Section5summarizes theconclusionsand recommendationsforfuture work.

2. DISTRIBUTION MANAGEMENT SYSTEM

A Distribution Management System[18] is a collection of system components capable of collecting, organizing, displaying and analyzing real-time or near real-time electric distribution system information.Typically, real-time data is transferred to Power System Model (PSM) [19]-[20] using Supervisory Control and Data Acquisition (SCADA) [21]-[25] component.Data is visualized using single-line diagrams presented in very usable Graphical User Interface [26]-[33]. PSM is stored in a proprietary in-memory database and contains equipment parameters, topological, and real-time measurementdata. The topology is updated by set of tracing [34]-[35] routines. The real-time measurements are processed by Distribution System State Estimation (DSSE) component (DSSE) [36]-[47]. Albeit DSSE plays a role of load estimation in DMS, it is one of the most important components for Distribution Network Analysis (DNA). Power Flow (PF) [48]-[63] is another important component. PF is used by other components and for what-if scenarios. Voltage/VARcontrol(VVC) [1]-[17] within DMS is a component which is used to calculate optimal set of control actions while optimizing voltage violations, power losses and line limits. Since VVC does not change topology of the network, in some cases, VVC is not capable to find optimal operating state. Optimal Feeder Reconfiguration (OFR) [64]-[69] calculates optimal operating state using switches as control variables. Short Circuit Calculation (SCC) and Fault Location (FLOC) are used to analyze protective device settings and to locate faults [70]-[79].

Figure1shows the schematic of SCADA controlled VVC withits main components.

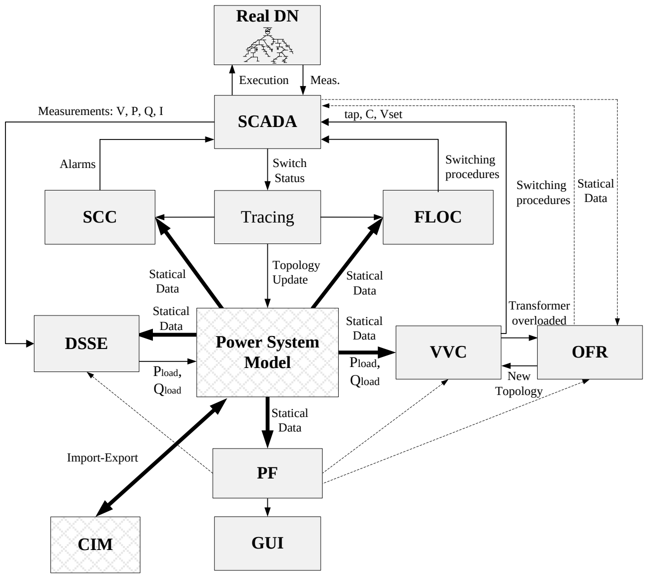

Figure1.Distribution Management System Control

3.VOLTAGE VAR CONTROL

The basic objective of VVC is to find suitable adjustments of the tap positions, capacitor status and DG reactive power injection for network model received from DSSE. To model the adjustments of these control devices, current iteration (CI) method can be used, where all changes of LTC position, capacitor status or DG reactive power injection, are represented as current source injections. In this way admittance matrix is constant and factorized once, and only vector of current injection is updated [15]. Current iteration method is explained in the following subsections.

3.1 Current iteration method for VVC

In current iteration method the branches are represented by an admittance matrix, expressed in a general form for N-node network as:

$$\mathrm{Y}=\begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1N} \\ \underline{Y}_{21} & \underline{Y}_{22} & \cdots & \underline{Y}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \underline{Y}_{N1} & \underline{Y}_{N2} & \cdots & \underline{Y}_{NN} \end{bmatrix} \quad (1)$$

Where $\underline{Y}_{pq}$ are admittances of the branches calculated using equivalent π model for given branch parameters. It is also easy to include constant node admittances $\underline{Y}_p$of capacitors or reactors connected to node p, or loads represented by constant impedance by adding $\underline{Y}_p$ to p-th diagonal element of admittance matrix Y. For a network with only PQ buses loads are treated as current source injections. If constant node admittances $\underline{Y}_p$of loads connected to node p are included in admittance matrix, the load current injections at the p-th bus can be expressed as:

$$I_{L_p}{}^{n}=\left(\frac{S_{L_p}}{\underline{V}_p{}^{n-1}}\right)^{*}+\underline{Y}_{L_p}\underline{V}_p{}^{n-1} \quad (2)$$

where$\underline{S}_{L_p}$is complex load power, $\underline{Y}_{L_p}$ is the node shunt admittance, and n is the number of iteration. In each iteration, current source injections is a function of voltage from previous iteration. Current iteration method can be expressed as:

$$\begin{bmatrix}\underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1N}\\ \underline{Y}_{21} & \underline{Y}_{22} & \cdots & \underline{Y}_{2N}\\ \vdots & \vdots & \ddots & \vdots\\ \underline{Y}_{N1} & \underline{Y}_{N2} & \cdots & \underline{Y}_{NN}\end{bmatrix}\begin{bmatrix}\underline{V}_1\\ \underline{V}_2\\ \vdots\\ \underline{V}_N\end{bmatrix}=\begin{bmatrix}\underline{V}_{sl}\\ \underline{I}_2\\ \vdots\\ \underline{I}_N\end{bmatrix} \quad (3)$$

In this formulation the voltage updates, depend only on the parameters of the branch itself and injected current at one end of the branch.

$$[V]^{n}=[Y]^{-1}[I]^{n-1} \qquad (4)$$

Method iteratively calculates the voltage $\underline{V}_p{}^{n}$and only requires the value of the voltages in the previous iteration. Convergence requires that voltage values of the previous iteration are close to voltage values of the current iteration within some specified tolerance.

3.1.1 Modeling capacitors

In VVC control capacitors are used for generating reactive power as a response to reactive power demand. For a capacitor control, control variable is binary, where zero corresponds to the switched off status and value one corresponds to switched on status. The capacitor control can be either ganged where all phases are operated in unison and non-ganged where each phase is operated independently. In current iteration method capacitors are modeled with their injected currents:

$$\underline{I}_C=\underline{Y}_c\underline{V}_p \quad (5)$$

If capacitor is initially switched on, capacitor constant admittances are included in Y matrix. In this case, capacitor current $\underline{I}_C$is not included in vector of injected currents. Reactive power control with capacitors is achieved by changing the status of capacitors according to the Table 1.

TABLE 1. VAR CONTROL WITH CAPACITORS

Initial state	Next state	Y	I
On	On	$\underline{Y}_c$	0
On	Off	$\underline{Y}_c$	$-\underline{I}_C$
Off	On	0	$+\underline{I}_C$
Off	Off	0	0

In current injection vector current $+\underline{I}_C$ will be included if capacitor was initially switched off and the status is changed to“on”, and current $-\underline{I}_C$ if capacitor was initially switched on and the status is changed to“off”.

3.1.2 Modeling tap positions of LTC transformers

On-load tap-changer (OLTC) is a transformer with adjustable taps, which are moved to upper or lower positions to keep secondary bus voltages within the range. In VVC control, optimum tap position needs to provide objective function minimization. Figure 2 shows LTC transformer connected between buses p and q.

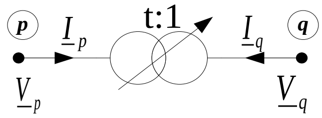

Figure 2. LTC transformer

By searching the optimum OLTC tap position, admittance matrix is changed for different tap values according to the equation (case from Figure 2):

$$Y=\begin{bmatrix}T\underline{Y}_{pp}T & \underline{Y}_{pq}T\\ T\underline{Y}_{qp} & \underline{Y}_{qq}\end{bmatrix} \qquad (6)$$

where$T$is matrix of tap positions for different phases:

$$T=\begin{bmatrix}t^{(0)} & 0 & 0\\ 0 & t^{(1)} & 0\\ 0 & 0 & t^{(2)}\end{bmatrix} \qquad (7)$$

In order to keep admittance matrix constant, initial tap value $T_{init}$is included in admittance matrix, while all other changes of tap positions$\Delta T$are modeled using fictitious current injections, and included in current injection vector for CI method:

$$\Delta I_{p_{LTC}}=\left(T^{-1}\underline{Y}_{pp}T^{-1}-\underline{Y}_{pp}\right)\underline{V}_p-\left(T^{-1}\underline{Y}_{pq}-\underline{Y}_{pq}\right)\underline{V}_q \quad (8)$$

$$\Delta I_{q_{LTC}}=\left(\underline{Y}_{qp}T^{-1}-\underline{Y}_{qp}\right)\underline{V}_p \quad (9)$$

If LTC is placed between nodes p and q (Figure 2), currents $\Delta I_{p_{LTC}}$ and $\Delta I_{q_{LTC}}$ are included in current injection vector for buses$p$ and$q$. In this way admittance matrix is constant, while tap changes are considered through current injections. For a tap changer, control variable ΔT is an integer that is changed by one in one direction (+1 or -1) until the optimum solution is found or until the limits are reached:

$$T_{min}\leq T\leq T_{max} (10)$$

where$T=T_{init}\pm\Delta T$. Tap changer control can be either ganged, where taps for all phases are moved to the same positions or non-ganged where each phase has different tap movement.

3.1.3 Modeling Distributed Generators

Same as capacitors, distributed generators are used to generate reactive power and thus reduce the reactive power flow throughout the distribution networks. Unlike capacitors, which generate fixed amount of reactive power (status “on” or “off”) distributed generators can supply different amounts of reactive power (Figure 3).

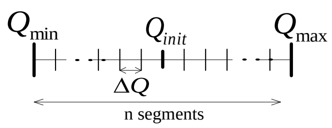

Figure 3. VAR control with distributed generators

Reactive power of distributed generator is given as:

$$Q=Q_{init}\pm\Delta Q \quad (11)$$

whereQ_{init} is initial value of reactive power which gives the initial injected current.

$$\underline{I}_{DG_{init}}=\left(\frac{P+jQ_{init}}{\underline{V}_p}\right)^* \quad (12)$$

In order to model the changes of reactive power injection from DGs during the VVC control, control variable ΔQ is defined:

$$\Delta Q=\frac{Q_{max}-Q_{min}}{n} \quad (13)$$

where$n$ is number of segments given in Figure 3. Control variable ΔQ defines changes of reactive power injection from initial reactive powerQ_{init}. Using the value ΔQ current is defined as:

$$\Delta\underline{I}_{DG}=\left(\frac{j\Delta Q}{\underline{V}_p}\right)^* \quad (14)$$

For CI method injected current from DG is:

$$\underline{I}_{DG}=\underline{I}_{DG_{init}}\pm\Delta\underline{I}_{DG}=\left(\frac{P+j(Q_{init}\pm\Delta Q)}{\underline{V}_p}\right)^* \quad (15)$$

3.1.4 CI algorithm

1. Form the network admittance matrix$Y$.
2. For flat start, all nodes' voltages are assumed to be 1+j0. Set iteration counter n to 0.
3. Calculate node currents (load, capacitor, LTC transformer, DG) and form node injected currents vector. Increment iteration counter by 1.
4. Calculate the new node voltages $[V]^n=[Y]^{-1}[I]^{n-1}$.
5. Calculate the maximum error between the new voltages and the voltages of the previous step. If the maximum error is less than or equal to the specified tolerance, stop the method, otherwise, go to step 3.

3.2 VVC algorithm

VVC algorithm attempts to find suitable adjustments of the tap positions, capacitor status and reactive power injection from DG in a way that minimizes power losses, voltage and currentviolations. Voltage and current violations are defined as deviations from desirable operating range. For voltage it is necessary that voltage is not lower or higher than its specified limits:

$$V_{p,min}\leq V_p\leq V_{p,max} \quad (16)$$

To avoid current violations, current cannot exceed its capacity constraint:

$$I_{pq}\leq I_{pq,max} \quad (17)$$

Constraints (16) and (17) form objective function by using penalties for their violations. Penalty functions for voltage and current violationsand power losses are included in objective function as:

$$f=\sum_p c_{V_{min}}\left(V_p-V_{min}\right)^2+c_{V_{max}}\left(V_{max}-V_p\right)^2 + \sum_{pq} c_{I_{max}}\left(I_{pq,max}-I_{pq}\right)^2+c_{P_L}P_{LOSS_{pq}} \quad (18)$$

where $c_{V_{i,min}} c_{V_{i,max}} c_{I_{ij,max}} c_{P_L}$ are penalties for minimum voltage violation, maximum voltage violation, maximum current limit violation and power losses, respectively. In order to find optimal equipment adjustment while minimizing objective function, VVC algorithm is divided in three parts: method which finds optimal status of capacitors, method which finds optimal reactive power injection from DG, method which finds optimal tap position for LTC transformers.

3.2.1 Method which finds optimal status of capacitors

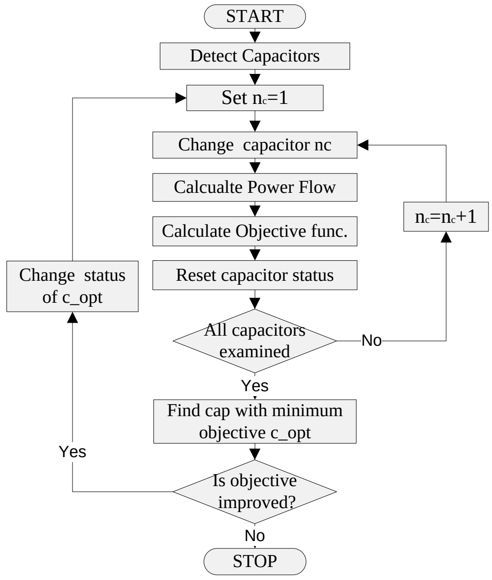

Figure 4.Algorithm for VAR control with capacitors

Method which finds optimal status of capacitorsis described with the following steps (Figure 4):

1. Detect all capacitors used for VAR regulation in selected distributed network.
2. Set capacitor counter $n_c$to first capacitor.
3. Change status of n_c capacitor.
4. Calculate power flow and check for any violations.
5. Form objective function from equation (18) which considers penalties for voltage violations, line current violations and power losses.
6. Reset capacitor status to status before changes.
7. If all capacitors are examined go to step 8. Otherwise, set $n_c=n_c+1$and repeat the steps 3-7 for all capacitors.
8. Find capacitor which gives minimum objective function. If this objective function is improved, change the status of that capacitor and repeat procedures from Step 2. If objective function is not improved, optimal capacitors statuses have been found and algorithm ends.

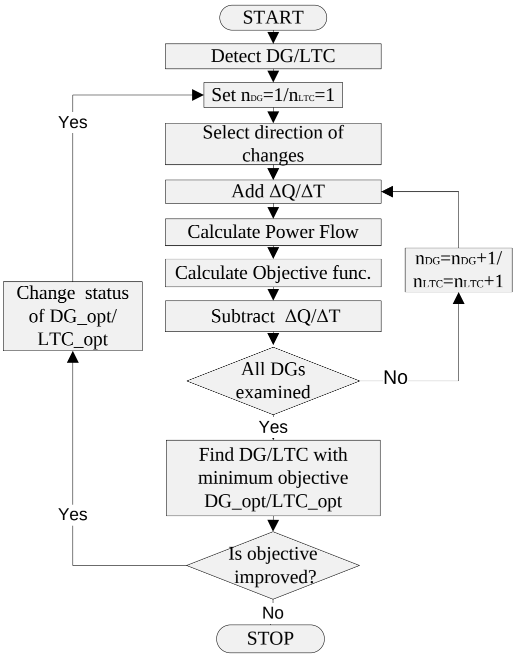

Figure 5.Algorithm for VAR control with distributed generators/voltage control with LTC

3.2.2 Method which finds optimal reactive powerinjection/tap positionfor DG/LTC

Method which finds optimal reactive power injection/tap position for DG/LTCis described with the following steps(Figure 5):

1. Detect all DGs/LTCs used for VVCcontrol in selected distributed network.
2. Set counter $n_{DG}/\ n_{LTC}$to first DG/LTC.
3. Find direction of changes and change $\Delta Q/\ \Delta T$one step in that direction:
$$Q^n = Q^{n-1} \pm \Delta Q$$
$$T^n = T^{n-1} \pm \Delta T$$
4. Calculate power flow and check for any violations.
5. Form objective function from equation (18) which considers penalties for voltage violations, line current violations and power losses.
6. Reset DG/LTC to initial status before changes.
7. If all DGs/LTCs are examined go to step 8. Otherwise, set $n_{DG} = n_{DG} + 1 / n_{LTC} = n_{LTC} + 1$and repeat the steps 3-7 for all DGs/LTCs.
8. Find DG/LTC which gives minimum objective function. If this objective function is improved, change the status of that DG/LTC and repeat procedures from Step 2. If objective function is not improved, optimal DG/LTC has been found and algorithm ends.

These three methodsare interconnectedin such a waythatthe optimalsolutionof one controllerinfluencesthe search for optimalsolution of othercontrollers. In other words, thealgorithmis executeduntil the change of any controllerdoes not affect any other controller. The overall VVC algorithm is given in Figure 6.

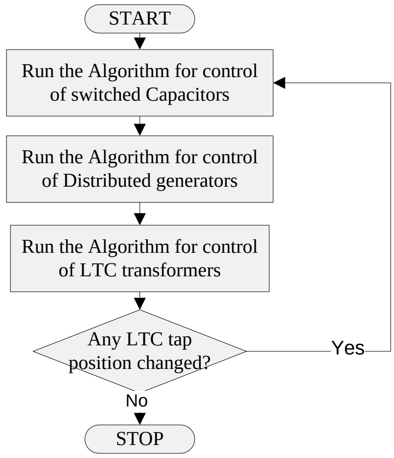

Figure 6.VVC algorithm

4. RESULTS

VVC algorithm is tested on modified IEEE13 test network. The network comprises of 33 buses, 32 branches, 20 loads and control devices: 2 LTC transformers, 5 capacitors and 2 DGs. Shunt capacitors are installed at several locations to compensate reactive power flow, improve the voltage profile and reduce the real power losses. There are 4 Y-connected capacitors installed at bus 645, 675, 611 and 633', and one Δ-connected capacitor installed at bus 646'. Reactive power control with DG is performed using DGs connected at bus 633 and 675'. Voltage control is achieved with two substation transformers installed with LTC to keep the bus voltage close to the specified value.

Objective function from equation (18) takes into account violations ofvoltage limits, current limits and power losses using penalty for their violations. Usually 5% margins around nominal voltage values are defined as voltage limits. This means that voltage values greater than 1.05 (p.u) or less than 0.95 (p.u) are considered in objective function using penalties for their violations. Current violations are defined as violation of predefined capacity of each line. By changing the values of penalty factors, it is possible to change the priority of how the constraints are satisfied. Higher penalty factor gives priority to that constraint, and minimizes its violations.To illustrate theeffects of grading penalty factors in objective function, three different cases are considered:

Case 1. Voltage and current violations have same penalties
Case 2. Voltage violations are given higher penalty factor
Case 3. Current violations are given higher penalty factor

Table 2 and 3 summarize the results for three VVC cases above. Results for three cases are also compared with basic case without application of VVC optimization. Table 2 displays total number of voltage violations, total number of current violations,objectivefunction for all voltage violations and objective for all current violations. As it can be seen from Table 2 basic case gives maximum number of both voltage and current violations. In Case 1, VVC optimization with equal penalty for voltage and currentlimits violation decreases total number of voltage violations to 7 and total number of currentviolations to 14. In Case 2, violations of voltages have been significantly reduced since priority is given to removal of this violations. Number of current violations is same as in Case 1, but the violations are greater, which is indicated by calculated objective. Objective is increased from 0.020049 in Case 1 to 0.200554 in Case 2. In Case 3, current violations need to be minimized, as they are given higher penalty factor.When compared to other cases, results confirm that Case 3 gives the smallest objective for current violations (0.006567), as expected.

TABLE 2. VIOLATIONS OF VOLTAGE AND CURRENT LIMITS

Results	Base Case	Case1	Case2	Case3
No: Voltage	36	7	5	10
No: Current	72	14	14	14
Obj: Voltage	5.72875	0.004332	0.000751	0.048503
Obj: Current	22.5644	0.020049	0.200554	0.006567

Table 3 compares results for power losses and total objective calculated for all three cases. Results are also compared with the basic case before VVC application. Obtained results show that voltage and reactive power control can beimproved by setting up convenient penalty factor. Usually, higher penalty factors are given to larger deviations in order to ensure that system will be moved away from this value which can cause undesirable situation.

TABLE 3. POWER LOSSES AND TOTAL OBJECTIVE FOR DIFFERENT CASES

Objective	Base Case	Case1	Case2	Case3
Power loss[kW]	50.2180	36.5196	36.5952	36.4091
Total Objective	78.5111	36.5439	36.7965	36.4641

5. CONCLUSIONS

This paper presents VVC optimization approach used to find the optimal dispatch of LTC, capacitors, and DG in a distribution system. The objective is minimization of the system power losses, minimum and maximum bus voltages violations and violations of maximum current limits. A modified IEEE13-bus test system is used to demonstrate the effectiveness of the proposed method. Results illustrate how VVC algorithm with different types of objective function can be used to improve bus voltage profiles and current levels.

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