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Optimal reactive power control of DGs for voltage regulation of MV distribution systems using sensitivity analysis method and PSO algorithm

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ABSTRACT

This paper addresses the problem of reactive power control of distributed generation (DG) units in the medium voltage (MV) distribution systems to maintain the system voltages within the predefined limits. An efficient approach for the load flow calculation is used here which is based on the topological structure of the network. It has been formulated for the radial distribution systems. A direct voltage sensitivity analysis method is developed in this paper which is also based on the topological structure of the network and independent of the network operating points. Thus, the sensitivity matrix is calculated once with the load flow program and it is used in all the system working conditions. The problem of DGs reactive power control is formulated as an optimization problem which uses the sensitivity analysis for linearizing the system around its operating points. The objective of the optimization problem is to return the system voltages inside the permitted range by using the reactive power of DGs in an optimal way. The optimal solutions are obtained by implementing particle swarm optimization (PSO) algorithm. Then, the results are verified by running a load flow considering new values of DGs reactive power. The procedure is repeated as long as a voltage violation is observed. Simulation results reveal that the proposed algorithm is capable of keeping the system voltages within the permitted limits.

Introduction

During the recent years, the conventional structure of electrical power systems has been changed by the presence of distributed generation units (DGs). Previously, the electric power was generated in large generating stations at a small number of locations (called central generation). In these stations, voltage was stepped up to high voltage (HV) to be transmitted through HV transmission networks. The voltage was then stepped down to medium voltage (MV) and low voltage and distributed through radial distribution networks to the end users. In recent years, there has been a considerable growth in the amount of decentralized generation connected to the distribution systems. As a result, currently, power systems are in a state of transition from the conventional systems with unidirectional power flows to the active networks with bi-directional power flows. Therefore, new technical challenges have emerged for distribution system operators (DSOs) [1].

Presence of distributed generation units alters the conventional voltage regulation schemes of distribution systems. In the conventional distribution feeder (without DG units), voltage decreases toward end of the feeder, as the impedance of lines causes a voltage drop. Thus, the biggest voltage drop happens at the end of the feeder based on the amount of loads demand. With the presence of DG, if its power exceeds the local demand of loads, the power flow direction will be inversed and a voltage rise will appear at the DG-connected bus.

Traditionally, DSOs have managed their system at the planning stage based on the fit and forget policy using deterministic load flow studies (considering the critical cases) in order to meet the loads demand and to verify lines capacity and voltage regulation issues. With DG units, as their output power varies during the day, the uncertainty in distribution system management is increased and the safe operation of the system becomes more complicated. In this situation, implementing an on-line voltage control system based on the active network management policy becomes more crucial.

Theoretically, different methods can be applied for voltage regulation of distribution systems but the most applicable methods

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are based on using on-load tap changer (OLTC) mechanism of the transformer, reactive power compensation and curtailment of DG active power. In [1], coordination of the OLTC action and the reactive power changes provided by distribution STATCOM has been studied. The problem of reactive power control of DGs for voltage regulation of the radial distribution systems by using a new voltage sensitivity analysis method has been addressed in [2]. The proposed algorithm acts on a single generator that has the biggest effect on the voltage of the violated bus. A method for voltage regulation of MV distribution systems based on the generation curtailment of DGs active power has been presented in [3]. The generation curtailment is done using the voltage sensitivity factors extracted from Jacobian matrix. Also, an algorithm for short term scheduling of distribution systems including day-ahead scheduler and intra-day control system has been developed in [4]. It is formulated as a non-linear optimization problem that is linearized by the use of the sensitivity coefficients obtained from the load flow calculations. A centralized voltage control scheme based on the model predictive control (MPC) and using the sensitivity indexes has been investigated in [5]. A coordinated scheme to minimize the cost of the system operation in terms of cost of the energy losses, cost of the curtailed energy and cost of the reactive power support while maintaining the system limits has been formulated as an optimal power flow (OPF) algorithm in [6]. In [7], a hierarchical three-layer control scheme has been developed for the control of active and reactive powers of DGs using the MPC and OPF algorithms. Authors in [8] have presented a new method called the experimental design method for the optimal positioning, sizing and eventually for the real time control of the system voltages in the MV grids.

In the literature, in [3–6], the sensitivity matrix extracted from Jacobian matrix is used which is not constant and it changes with respect to the network operating point. Also, the sensitivity method based on the Jacobian matrix suffers from inaccuracies because it should incorporate the variation of load powers with voltage, which is not well known in practice [5]. In this paper, a direct approach is presented to obtain the voltage sensitivity coefficients based on the topological structure of the network. The proposed sensitivity method is independent of the network operating points and has a simple theory and structure. Finally, in this work, a centralized voltage control method is developed to optimally manage the reactive power of DG units using PSO algorithm and the proposed sensitivity approach. The main objective of this work is to return the system voltages inside the permitted limits while minimizing the reactive power changes of DG units.

Voltage control problem in the new distribution systems

The electric power networks have traditionally been operated in a passive mode where the power generated by large power plants was delivered to the customers through distribution networks. Thus, the flow of power was from the higher toward the lower voltage levels. Recently, in the emerging electric networks, distributed generation units are expected to play an increasing role. With the introduction of the DGs, the power flows may be reversed. The distribution network is no longer a passive circuit supplying loads but an active system with the power flow and voltage determined by the DGs as well as the loads. When a DG injects active power at a certain point of the system, the voltage of that node can be raised. This fact is explained as follows. Consider the radial system shown in Fig. 1.

In case of no DG, the power flow between nodes 1 and 2 (P_{12} and Q_{12}) is equal to the load demand at bus 2 ($P_L + jQ_L$). The voltage drop in per unit at bus 2 can be given approximately by [9,10]

$$V_1 - V_2 = P_{12}r_{12} + Q_{12}x_{12} \tag{1}$$

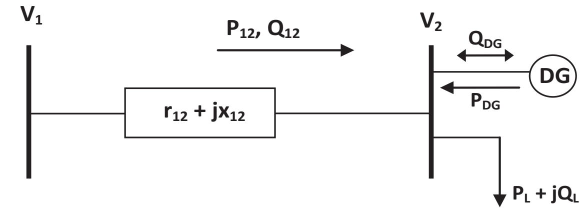

Fig. 1. Part of a distribution system.

where r_{12} and x_{12} are the resistance and reactance of the line between nodes 1 and 2. Now, if the DG injects power at node 2, the power flow between nodes 1 and 2 is changed. In this case, (1) must be modified as

$$V_1 - V_2 = (P_L - P_{DG})r_{12} + (Q_L \pm Q_{DG})x_{12} \tag{2}$$

where P_{DG} and Q_{DG} are active and reactive powers of the DG unit. Based on (2), when active power of the DG increases, the term $P_L - P_{DG}$ can become sufficiently negative so that the right side of (2) becomes negative that means V_2 is greater than V_1. So the injection of DG power can cause a voltage rise problem, especially, when the x/r ratio is low that is the case in the distribution systems. As it can be observed, the amount of voltage variations depends on the amount of DGs active and reactive powers, demand of loads and impedance of the system lines. Due to the fact that demand of loads and DGs active power are changing during the day, both voltage rise and voltage drop problems are possible to occur. The voltage control problem is known as one of the biggest obstacles for increasing the integration of DG units in distribution grids. If this problem can be solved efficiently, then higher DG levels could be allowed to be installed on the feeders.

Reactive power compensation

Reactive power compensation is a useful method for voltage regulation of distribution systems. Traditionally in distribution systems, capacitor banks have been used to keep the power factor close to 1 and to compensate voltage drop in the heavy load situations. In the DG-connected distribution systems, as we must deal with both voltage drop and voltage rise problems, we need a source of reactive power with the ability to work in both inductive and capacitive modes (see (2)).

The needed reactive power of the system can be provided by synchronous machine-based DG units that are able to adjust their output reactive power in order to affect the system voltages. Conventional control systems for reactive power control of synchronous machines are automatic power factor control (APFC) system and automatic voltage regulation (AVR) system [11]. In the automatic power factor control mode, the reactive power of DG follows any variation of the active power of DG. Therefore, the P_{DG}/Q_{DG} ratio is maintained constant in order to keep the system voltage within the limits. This method is not applicable in voltage regulation of distribution systems with a low ratio of x/r. Also, it is not an effective approach as the load power variations of the system are not taken into consideration. In the automatic voltage control mode, the difference between the actual bus voltage and a set reference voltage defines the needed reactive power of the system. This action can be explained by a droop characteristic that shows the relationship of the needed reactive power of DG in accordance with the voltage of the system. In [12], a new voltage control method has been proposed which combines the advantages of AVR and APFC control systems. The above-mentioned reactive power control methods are based on the local control of DGs unit.

In case of doubly-fed induction generators (DFIGs), reactive power compensation is possible through control of rotor current