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An optimal reactive power control method for distribution network with soft normally-open points and controlled air-conditioning loads

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ABSTRACT

The paper proposes an optimal reactive power control method for distribution systems with soft normally-open points (SNOP) and considering the direct load control (DLC) of thermostatically controlled air-conditioning loads. The starting voltage constraints of aggregate air-conditioning loads connected into a distribution network is studied according to the direct control mode and the starting characteristic of air-conditioning load. Using the flexible regulating capacity of power flow of SNOP, an optimal model of reactive power flow for distribution systems with SNOP is established to meet the voltage quality of sensitive loads and the starting requirements of aggregate air-conditioning loads. In the model, the load balancing commands of different DLC aggregators, the on/off status of thermostatically controlled air conditioner, the power regulating command of SNOP, the voltage adjusting and reactive power compensation devices are comprehensively controlled in the constraints of reduction balance and starting voltage of air-conditioning loads, as well as the conventional network and voltage constraints. And a multi-objective functions are developed for the objectives of solving the low-voltage problems, minimizing the comfort impacts on users of air-conditioning and minimizing the active power loss of distribution systems. Finally, the simulation results of a practical 53-bus 10 kV distribution system demonstrate the accuracy and effectiveness of the proposed method.

1. Introduction

Load demands of distribution systems usually maintains at a high level in the summer and the winter, because of seasonal temperatures in a longtime. Because of the heavy load condition of distribution networks, the low-voltage problems are widely occurring and influencing the power supplying quality of consumers [1]. For urban areas, the maximum air-conditioning loads can reach 30–40% of the peak load in a day [2,3]. For example, it is estimated that air-conditioning loads are in a proportion of 43% in 2016 and shows an increasing trend in recent years in Chengdu, China. Thus, the demand-side management (DSM) of aggregate air-conditioning loads is introduced to encourage clients to decrease the power usage during peak load periods by Electric Power Research Institute (EPRI) [4]. There are many methods to engage clients in DSM, including pricing-based approaches (time-of-use pricing, critical-peak pricing, peak-time rebate, and real-time pricing) as well as direct load control (DLC) [5–8]. The DLC programs are mostly applied when the system is in an extreme event (such as high production costs, low system reliability) to provide the ability of power balance and frequency regulation by shedding partial loads. And the air-conditioning loads have a large amount of capacity for heat storage, which have potentials for power load regulations by direct load control (DLC) conducted by electric power companies [8]. To alleviate the low-voltage problems in the distribution network in the heavy load conditions, the DLC of thermostatically controlled air-conditioning loads is an effective measure for shifting and averting the peak load [9–11] when a reasonable cycle control is implemented for the air-conditioning loads in the power scheduling procedure.

Active control of power flows and voltages by power electronic device is an alternative measure to address the low-voltage problems of distribution networks [12,13]. Soft normally-open points (SNOP) are power electronic devices replacing normally-open switches connecting the adjacent feeders. The concept of SNOP is proposed in [14] to enhance the flexibility of current distribution networks by little equipment or infrastructure upgrades. There are three types of topologies can be adopted for the SNOP, including back-to-back voltage source converter (VSC), unified power flow controller, and static series synchronous compensator [15–18]. The control modes of SNOP employed back-to-back VSC are analyzed during the normal operation condition and the fault isolation and supply restoration under grid fault condition

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in [16]. To make use of the potential capability of SNOP, the operational benefits of a distribution network with SNOP is quantified in [17], and then an optimal method to determine the siting and sizing of SNOP is presented in [18]. The SNOP is able to improve the controllability of distribution system by reconfiguring the network and regulate active and reactive power flows between feeders, and the reactive powers at both sides of SNOP are regulated independently. Due to the bus voltage of distribution network can be changed by controlling the active and reactive power flows, the SNOP is applied to increase the penetration of distributed generation in [19,20]. The SNOP can also isolate the voltage disturbance on one feeder from the other feeder [21], thus the operation strategy of SNOP plays a key role to enhance the security and efficiency of distribution network [20]. The existing studies have investigated the optimal operation of SNOP in distribution networks. However, the operating strategy of the network both with SNOP and DLC has not been studied. The coordination of SNOP and DLC is more effective to enhance the voltage quality of distribution feeders with the heavy air-conditioning loads.

In the cycle control of DLC, the air-conditioning loads have to be started up or shut down back and forth, when the room temperature goes up and down. In particular, the high reactive power consumption of air conditioners in starting procedure may cause voltage collapse of the network. If the voltage does not satisfy the starting requirement, these air-conditioning loads cannot be started up in this cycle [22,23]. By the active power regulation and reactive power compensation of SNOP, the starting voltage constraint of air conditioners can be effectively relieved in the cycle control. The introduction of SNOP can guarantee the security of the cycle control of air-conditioning loads in distribution networks, and also can improve the load balancing level between different distribution feeders. In [9,10], the cycle control of air-conditioning loads is adopted to mitigate the unbalance between power supply and demand in the presence of renewable power generation, and the distributed model predictive control scheme is proposed to control the aggregate air-conditioning loads for the ancillary load balancing service in [24]. The Refs. [16,25–27] indicate that the DLC of aggregate loads and the power control of SNOP are both the distributed flexible resources in smart distribution networks, while the existing studies do not develop the utilization potential of SNOP to support the voltage control of distribution network with the DLC air-conditioning loads. In addition, the critical starting voltage of air-conditioning loads is a key indicator to assess their starting processes during the cycle control [28]. The critical starting voltage should be incorporated into the DLC of air-conditioning loads to determine whether the air conditioners are successfully started up.

To satisfy the voltage control requirements of distribution network with DLC and SNOP in consideration of the starting processes of air-conditioning loads, this paper proposes an analytical method to calculate the critical starting voltage of aggregate air-conditioning loads according to DLC control mode and the starting voltage characteristic. In the constraints of voltage quality of sensitive loads and starting voltage of air-conditioning loads, an optimal reactive power control method for a distribution system is established by using SNOP and the other voltage adjusting and reactive power compensation devices. The method is a collaborative integrated solution for demand responses and voltage quality enhancements. The proposed technique is verified by simulation results of a practical 53-bus 10 kV distribution system.

2. Critical starting voltage of air conditioning load

For the resource of demand response of air-conditioning loads with heat storage capacity, the DLC cycle control can be applied to provide load balancing service. In Fig. 1(a), the DLC aggregate has n controlled air-conditioning loads (D_1, D_2, …, D_n), and the aggregate is in charge of the loads in a same feeder. According to the dispatching commands of an electric power company, the aggregate determine the on/off status of air conditioner in the DLC cycle control for load shedding [11]. Fig. 1(b) shows the cycle control of air conditioners when $n = 10$, which can be numbered from 1 to 10 (corresponding to the 1st to 10th air conditioners) in the small square box. If the room temperature drops to the lower setting $T_{\min}$, the relevant air conditioner will be off status which is the gray box. When the room temperature rises to $T_{\max}$, the air conditioner needs to be started up corresponding to the on status of white box.

In a control cycle from 0 to t_{on}, the on status duration of an air conditioner is t_{on}-t_{off}. The starting characteristic of air conditioner can be represented by an induction motor [23,28], in which the starting electromagnetic torque is proportional to the square of the applied voltage. When the supply voltage is connected to the stator of an induction motor, a rotating magnetic field is produced, and the rotor starts rotating. During the starting process, the rotor speed rises from zero to the rated speed due to the driving electromagnetic torque is larger than the braking mechanical torque, and then the induction motor will operate at an equilibrium point that the electromagnetic torque is equal to the mechanical torque [29]. At the starting time of air conditioner, the rotor slip is unity, and the starting current is very large. The corresponding reactive power is closed to 4–6 times the rated power of air-conditioning loads, which will result in a sharp voltage drop at the connected point of air conditioners. The critical starting voltage is the minimum condition of the starting of air conditioners. Once the terminal voltage is lower than the critical starting voltage, there are no equilibrium points between the electromagnetic torque and the mechanical torque. And then the electromagnetic torque is always lower than the mechanical torque, so that the speed of air conditioner cannot be accelerated to the rated speed, and the air-conditioning load will fail to start. When the terminal voltage is larger than the critical starting voltage, the motor speed can be accelerated for the successful startup of air-conditioning load. Thus the DLC cycle control of air-conditioning loads will keep working when the terminal voltage satisfies the minimum condition of the starting of air conditioners; otherwise the DLC will fail. The critical starting voltage has to be determined to judge whether the system voltage meeting the starting conditions of air-conditioning loads.

The power demand during the starting of air conditioner is mainly from a compressor which has the similar dynamic voltage characteristic with induction motor. Fig. 2 shows the electromagnetic and mechanical torques-speed curves of an air-conditioning load where the parameters are in [28]. When the starting voltage is high enough, there are intersection points (stable equilibrium points) between the curves of electromagnetic torque T_{e} and mechanical torque T_{m}. In this case, the motor speed ω_{r} can be accelerated to the equilibrium point after the starting process [29]. If the terminal voltage is lower than the critical starting voltage, there are no intersection points between the curves of T_{e} and T_{m}. The mechanical torque is still higher than the electromagnetic torque under different speeds, so the motor cannot run steadily on the normal equilibrium state.

The mechanical torque T_{m} of air-conditioning load is proportional to the square of the rotor speed ω_{r} [23], and the electromagnetic torque T_{e} is in terms of the rotor speed ω_{r} and the terminal voltage U in Fig. 2. The critical starting voltage U_{cr} can be got by $T_{\text{e}}(\omega_{\text{rmax}}, U_{\text{cr}}) = T_{\text{m}}(\omega_{\text{rmax}})$, where ω_{rmax} is the rotor speed corresponding to the maximum electromagnetic torque. For the case in consideration of the network impedance, $U_{\text{cr}} = 0.95$ pu. However, there are still stable equilibrium points between T_{e} and T_{m} when $U = 0.95$ pu in the case without the network impedance that meets the starting requirement of air conditioner. Thus, it is needed to consider the network impedance to determine the critical starting voltage.

Using the equivalent circuit of induction motor as an air-conditioning load, the equivalent circuit of an aggregator with n controlled air-conditioning loads is shown in Fig. 3. U_i is the voltage at the connecting point of aggregator; R_{k} and X_{k} ($k = 1, 2, \ldots, n$) are the line resistance and reactance; R_{sk}, R_{rk}, X_{sk} and X_{rk} are stator-side and rotor-side resistance and reactance of k^{th} air-conditioning load; X_{mk} is the

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