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All-day coordinated optimal scheduling in distribution grids with PV penetration☆

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ABSTRACT

This paper presents an approach for the optimal scheduling of reactive power of photovoltaic (PV) inverters, tap position of on-load tap changers (OLTCs), and switch states of shunt capacitors (SCs) in distribution grids. The proposed method determines a day-ahead scheduling strategy containing continuous, discrete, and Boolean control variables. The optimization problem is formulated as a mixed-integer nonlinear programming (MINLP) problem with the objective of minimizing both the node voltage deviations and active power losses. The maximum allowable number of operations for OLTCs and SCs is constrained in predefined limits. Due to the operation limits of OLTCs and SCs, this multi-period optimal scheduling problem is time-coupled. The pattern search algorithm and the genetic algorithm are applied to solve the proposed optimization problem. Both the algorithms are improved with the multi-start framework for global optimization. The feasibility of the proposed method is examined on the modified IEEE 34-node test feeder and the modified IEEE 123-node test feeder. The performances of the proposed approach are verified in the case of forecast errors of PV generation and load demand.

1. Introduction

Due to the load demand increase and the concern over environmental consequences, more and more attention has been given to renewable energy sources e.g. solar power and wind power. In the USA, at the end of the first quarter of 2017, there was 44.7 GW of cumulative solar electric capacity [1]. The increasing penetration of distributed PV generation presents both challenges and opportunities for distribution networks [2]. Rapidly varying irradiance conditions can produce undesired voltage sags and swells, resulting in power quality degradation [3]. These voltage swings cause excessive operations of voltage regulation devices, such as OLTCs and SCs. This dramatic increase in the number of operation times can significantly shorten the life time of OLTC and SC devices [4]. At the same time, the coordination among PV generation, OLTCs and SCs can realize optimum voltage regulation and improve the performance of distribution networks [5].

1.1. Literature survey

OLTC transformers are well-known devices that can be used to correct the voltage fluctuation in low-voltage networks. A compensation-based OLTC voltage control algorithm is proposed in Ref. [6] by establishing a simple relation between power flow direction and a reference voltage setting point. However, in this paper, the problem associated with the overuse of OLTCs is not considered. In Ref. [7], a Volt/VAR control problem is formulated as a two-timescale optimization problem. The OLTCs and SCs can only be adjusted on a slow timescale (hourly), while PV inverters can be controlled on a fast scale. However, state-of-the-art OLTC and SC devices can react on a minute-scale. In addition to shunt capacitors, the PV inverters can be used to absorb or inject reactive power and so to control feeder voltage. In the presented approach inverter-based VAR control is used to follow the rapid fluctuation of the PV generation output. The goal of Ref. [8] is to address the voltage rise and reverse power flow issues by reactive power management based on PV inverter's capacity and sensitivity to the critical bus. However, the number of tap changer and shunt capacitor operations was not considered in this paper. The authors in Ref. [9] demonstrated – once more – that the addition of reactive control would increase the number of operations of OLTC. In Ref. [10], the proposed optimization scheme achieves to minimize the cost of grid losses, tap-position changes, PV inverters' operation and batteries' operation. However, minimize the operation of OLTCs may not be the

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Nomenclature

F	Objective function
i	Index of the node
j	Index of the branch
N^{br}	Total number of branches
N^{node}	Total number of nodes
PL	Active power losses
P_{pv}^t, Q_{pv}^t	Active power and reactive power output of the PV generation at the time t
Q_{PV}^L, Q_{PV}^U	The reactive power limit of the PV inverter
SC^t	Switch state of the SC at the time t
S_{pv}	Apparent power capacity of the PV inverter
t	Pre-decided time interval
Tap^U, Tap^L	The highest and lowest tap positions of the OLTC
Tap^t	Tap position of the OLTC at the time t
TTC	The total tap operations of OLTC within a day
TSC	The total switch operations of SC within a day
$TTC^{\max}$	The maximum total allowable tap operations of OLTC within a day
$TSC^{\max}$	The maximum total allowable switch operations of SC within a day
VD	Node voltage deviation
V_N	Nominal voltage
V_i	Voltage magnitude of node i
V^U, V^L	The prescribed voltage limits
$\boldsymbol{x}$	Design variables

primary objective of the cost function from the perspective of distribution network operations (DNOs).

Some papers focus more on the optimization technique rather than on the power grid adaptability of the solution. The Optimal Power Flow (OPF) problem is first proposed in Ref. [11]. The OPF problem concerns the problem of determining bus voltages and generator power levels to minimize a cost function. It can be formulated as a constrained non-convex optimization problem which can be solved by several algorithms [12]. In Ref. [13], the Volt/Var optimization problem is solved via mixed integer linear programming. In Ref. [14], the optimal reactive power dispatch problem was formed as a multi-objective optimal problem and solved by Gravitational Search Algorithm (GSA). The efficiency of GSA is improved by a random generation and self-adaptive parameter tuning scheme. In Ref. [15], a coordination strategy to minimize the total number of tap operations is proposed. The primal-dual interior point method is applied to solve this optimization problem. However, the interior-point method is not suitable to solve non-convex problems because the global optimum is not guaranteed. The authors in Ref. [16] present a systematic approach to determine the active and reactive power set points for PV inverters. The sparsity-promoting regularization methods and semidefinite relaxation techniques are applied to reformulate the original non-convex and NP-hard problem. In Ref. [17], the authors point out that for most MINLP problems a global optimum can hardly be ensured. For complex problems with a large number of variables, the calculation time can also be a problem. A short-term two-stage scheduling in distribution network was proposed to minimize the sum of costs of generation units. In Ref. [18], the backtracking search optimizer algorithm is applied to solve the reactive power dispatch problem. However, only a single time-point is considered in the optimization problem. In Ref. [19], a decentralized method based on fuzzy logic is proposed, and the gradient descent algorithm is applied to optimize each distributed generation (DG) unit separately. The performance is compared with a centralized voltage control which is solved with particle swarm optimization. The proposed method can find the near-optimal solution, but the mutual interactions between DGs are not considered.

1.2. Our contribution

In this paper, we present a multi-period optimal scheduling that considers the coordination of the PV inverters, OLTCs, and SCs. The objective is formulated as a bi-objective function to minimize both node voltage deviations and energy losses while keeping the number of intraday OLTC and SC operations under a predefined value. The Edgeworth–Pareto optimization [20] is applied to properly determining the importance weights of the objective functions. To be able to impose the constraints on the maximum number of OLTC and SC operations per day, we considered a 24-h window rather than a single time point as in Ref. [18]. Due to the presence of the operation limits of OLTCs and SCs, the proposed problem is time-coupled [21]. The direct search algorithms, i.e., the pattern search algorithm and genetic algorithm are proposed to solve this MINLP problem. They are derivative-free methods [22] in the sense that they can solve optimization problems when the derivatives of the objective function are not available or have a stochastic nature. In contrast to the linearization or semidefinite programming (SDP) relaxation [23], when evaluating the objective function we decided to treat the load flow calculation process as a black-box, this approach ensures an easy applicability of the proposed approach to a generic network but at the same time rule out the use of analytical approaches. Both the algorithms are improved with the multi-start framework and parallel computing to guarantee global optimality within reasonable computational time. To verify the proposed method, the IEEE 34-node test feeder and the IEEE 123-node test feeder are modified to include time-varying load demand and PV generation with variable output. A Monte Carlo-based probabilistic load flow simulation is applied to evaluate the robustness of the day-ahead

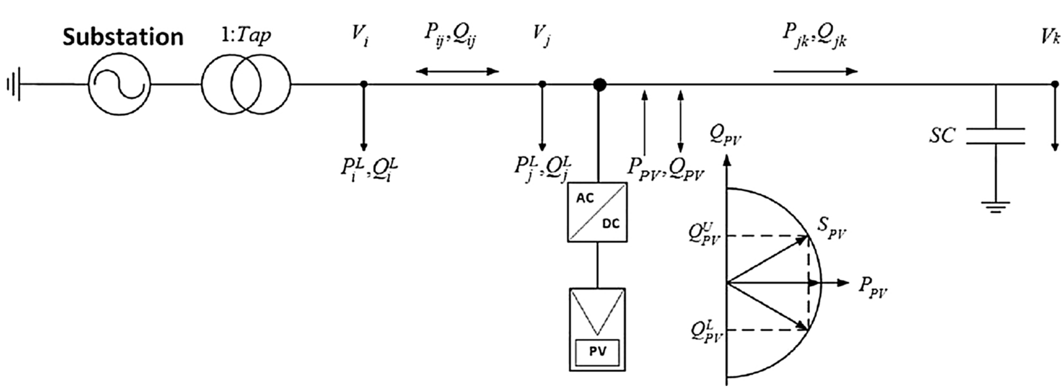

Fig. 1. Single-line diagram of a simplified radial distribution feeder with a PV plant, a shunt capacitor bank and an on-load tap changer.