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Optimal voltage control strategies for day-ahead active distribution network operation

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ABSTRACT

The aim of this study is to develop a coordinated day-ahead voltage control strategy for an active distribution network. A framework comprising a synergy of real-time dynamic thermal rating (DTR) and coordinated voltage control (CVC) is proposed for solving the voltage quality and thermal limit problems associated with a high penetration level of distributed generation (DG) in an active distribution network. The CVC scheme involves solutions such as On-Load-Tap-Changers (OLTCs), active and reactive power control of DG units, and switchable shunt VAR compensation devices (SVCs). Loss minimization and voltage penalty objective functions in the CVC optimization problem are compared. A 147 bus test distribution network planned for an actual geographical location is used to evaluate the proposed DTR-based day-ahead CVC strategy. In this study, we have showed that the reactive power absorption/injection potential of DG units can play an important role in CVC. Moreover, the study demonstrates that real-time thermal rating boosts the utilization of reactive power resources in the distribution system. Finally, the study investigates the practicality of day-ahead active distribution network operation planning for CVC.

1. Introduction

In today's active distribution network there is an ever increasing penetration level of distributed generation (DG) driven by technical and policy forces. Among the various limiting factors inhibiting the further installations of DG units are feeder thermal capacity limits and the steady state voltage rise problem [1]. With regard to dealing with the voltage rise problem, reactive power contribution by DG units is one of the most commonly proposed approaches [2]. Wind turbines, for instance, by virtue of their power electronic converters, are able to control active and reactive power independently [3]. The voltage source inverter in PVs is also an interface that enables the control of reactive power. These non-dispatchable DG units, such as PV and wind, operate a significant fraction of their time much below their rated power, during which they can provide reactive power service. Nevertheless, the present grid code, for example in Finland, does not allow distributed generation to participate in distribution network voltage control in any way. Moreover, the currently used distribution network planning tools and procedures are not capable of taking active voltage control into account, as discussed in [4]. There are two possible explanations for the lack of a collective agreement on deploying DG units for voltage control in a distribution network. The first is the insufficient measurements and consequently the limited state estimation services in distribution networks. The second reason could be the absence of power flow constraints such as bottlenecks in many existing under-loaded distribution networks, which tends to have inhibited the deployment of real-time line and cable rating programs. Given the rapid development of active distribution networks, both aforementioned reasons are becoming obsolete. With the installation of automatic meter reading (AMR) devices, the accessibility of distribution network data has significantly increased in terms of resolution as well as clarity. Contradicting the second reason, the increasing installations of DG units are creating voltage level and capacity limit problems in today's distribution network. Hence, broad studies, with dependable control mechanisms for the coordinated operation of various types of voltage regulating options including DG units, are required. In addition, the formulation for the multi-objective optimization with coordinated voltage control involving DG units needs to be understandable and economical. An effective methodology for multi-objective DG operation for distribution system volt/var control during normal and emergency situation is therefore vital.

There have been numerous studies solving optimization problems for coordinated voltage control in distribution systems. Some

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studies considered the coordination of only two voltage control methods, while others investigated all the available methods, including the reactive power control of DG units. The study in [5] presents a coordination of OLTC and Static-var-Compensators (SVC) in an unbalanced distribution system. The proposed approach is a two-stage decision making procedure, where in stage one, an optimization problem of loss minimization is solved and in stage two, the minimization of switching due to economic and technical considerations is solved. Nevertheless, in [5] the DG units have been assumed to operate with unity power factor; no reactive power supply is considered from the DG units. In [6], coordination among multiple SVCs, OLTC and DG units is presented for an online voltage control in distribution systems. The synchronous machine-based renewable DG units are also involved in the voltage regulation, which minimized, according to [6], the total tap operation of SVRs. The method in [6] uses pseudo measurements for load and DG generation; however, it doesn't include the uncertainties involved with the measurements or uncertainties in the voltages from distribution state estimation. The study in [7] proposes a hierarchical rule based coordinated voltage control strategy involving OLTCs and DG units. In mitigating voltage problems, predefined steps tap changing steps, Q regulation of DG units and PQ regulation of DG units are initiated sequentially until the problem is alleviated. In the studies [4,8], the authors presented a method to enable distribution system operators to integrate the voltage level management potential of DG units in their network operation and planning principles. These studies are efforts to relate the vast optimization and rule-based coordinated voltage control theoretical studies to the practical conditions of the existing network. In [8], a planning procedure is proposed so that implementation in the currently used network planning tools is convenient.

The coordination between substation voltage and DG reactive power is claimed to be the least cost method in [4], which used statistical distribution planning to select voltage control strategy. In the statistical planning, one year load and production curves were used to conduct load flows which can then be used to evaluate the costs of different control strategies [4]. Nevertheless, the rule-based procedures in [4,8] do not investigate the costs of the optimal coordination of different voltage control strategies. A comprehensive voltage control strategy among OLTCs, substation switched capacitors and feeder-switched capacitors is presented in [9]. The study also investigated the impact of DG units on the control strategies, in which they found that a constant voltage operation of DG units is beneficial for a significant reduction in OLTC operation. In [9], however, the DG is set to generate constant active power, which is not possible in the case of PVs and Wind, ruling out the possibility of PQ control of DG.

The study in [10] proposes a simple DG local reactive power control with occasional communication with distribution network operators (DNO). The proposed approach aims to guarantee that active power generation does not cause voltage rise. With an objective function that minimizes DG curtailment and voltage violations, the study in [11] proposes a comprehensive centralized voltage constraint management approach. Provided that the VCM problems are formulated properly, the MINLP solvers generally provide an acceptably fast solution, as most distribution systems are equipped with a relatively small number of discrete control means [11]. In [11], the transfer of DG between feeders using only remotely controlled switches only occurs when the DG curtailment cost exceeds the cost of switching.

There are only a few studies (such as [12,13]) which tackle the real-time management of voltage and thermal constraints local to DG connection. The decentralized approach in [12] aims to avoid extensive sensing and communications, where the thermal constraint is managed by setting a constant line capacity threshold which triggers the trimming of wind generation if violated. A centralized management of thermal constraints, while inhibiting violation of voltage limits, is presented in [13] by employing remotely controlled switches to reduce the DG curtailment. The study claims that the additional degree of freedom provided by remotely controlled network switches leads to less DG curtailment. However, as in [12], in [13] the thermal limits of all lines are set to a constant value.

In practice, both the capacity threshold and DG generation fluctuates a lot, following weather variations in real-time. Hence, dynamic thermal rating is proposed in this study to manage voltage level and network losses while the real-time line thermal limit is being respected in the constraint. In addition, in this study OLTCs, DG units and SVCs are coordinated in addressing the voltage and thermal constraints in an active distribution network.

The purpose of this study is to provide a CVC strategy for the day-ahead operation of an active distribution network with updated network capacity using real-time thermal rating (RTTR). The CVC involves tap changing transformers, switchable static VAR compensators and DG units. The day-ahead control strategies use day-ahead forecasts of load, weather variables and DG generation. Voltage penalty function and network loss minimization objectives are compared in solving the CVC problem involving DG units.

The limitations of the method proposed in this study are mostly associated with uncertainties in load and weather variable forecasts. Further, the execution complexity due to inconsistencies between the planned day-ahead settings of voltage control devices and their intraday local measurement-based closed loop operation pose a challenge. Nevertheless, with the development of network operation planning from day-ahead to hour- and minute-ahead planning, the inaccuracies are likely to become less significant.

Section 2 reviews the various voltage regulating mechanisms and discusses the reactive power potential of DG. In Section 3, a brief discussion of the real-time thermal rating (RTTR) method employed in this study is presented. The subsequent section, Section 4, presents the CVC formulation, which incorporates the DG Q/V droop control variables and network component ratings. In this section, the loss minimization and voltage deviation penalty function based objectives are also discussed. In Section 5, the test active distribution network and the load and weather variables utilized in the analysis are presented. Section 5 also discusses the main observations of the analysis while Section 6 briefly discusses practical concerns related to communicating control set-points. The last section, Section 7, summarizes the main findings of this study.

2. Voltage control methods

There are two typical voltage level problems in distribution systems. The short-term problem, which lasts for not more than a minute, and the long-term problem, where the voltage level remains outside the ±10% limit for more than 1 min. Over voltage and under voltage events require proper management that utilizes the dependencies of voltage and other variables, such as active and reactive load and generation, as shown in Fig. 1 and (1). The voltage at busbar 2 in Fig. 1 can be approximated as

$$V_2 \approx V_1 + \frac{R(P_G - P_L) + (\pm Q_G - Q_L \pm Q_C)X}{V_2} \tag{1}$$

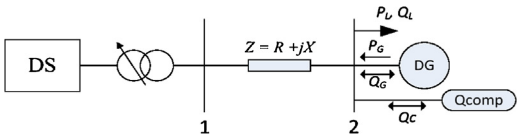

Fig. 1. A simple illustration of voltage dependency in distribution network [14].