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Review

The transient-state effect of the reactive power control of photovoltaic systems on a distribution network

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ABSTRACT

Despite of their small capacity, distributed generation (DG) systems can cause an increase in feeder voltage when they produce power into a distribution system if not appropriately controlled. To prevent such an increase in voltage, the state-of-the-art inverter can adjust reactive power, referred to as Volt/Var control. Furthermore, such an inverter-based DG system has been continuously connected to a large distribution network. Thus, the objective of this study is to present an optimal reactive power control method for DG systems, particularly photovoltaic (PV) systems, in the steady state. The second objective of this study is to analyze the transient-state response of a sufficiently large distribution network integrated by high-capacity PV systems able to control reactive power. The large network can be more efficiently developed by a steady-state power-flow analysis program, or OpenDSS based on text editors, than a transient-state analysis program based on graphical editors. Therefore, this study proposes a method that imports the feeder models developed in OpenDSS into a transient-state power systems analysis program, or DIgSILENT. That is, the proposed method models a sufficiently large actual distribution network with thousands of nodes and high-capacity PV systems able to control reactive power. Then, this study examines transient-state dynamics of the feeders. From the steady- and transient-state analyses, this study found that high-capacity PV systems with the capability of Volt/Var control could mitigate an increase in voltage caused by their power injection to the feeder and they could regulate the voltage of a bus to which they are connected within a set voltage range if they are optimally controlled.

1. Introduction

To reduce the energy dependence on the conventional generators, various distributed generation (DG) systems have been connected to a distribution network. When they produce power, they can increase feeder voltage because of their reverse power flow, if they are not appropriately controlled. Therefore, during the last a few decades, many researchers have examined the transient-state response of a distribution network that hosts such a DG system [2]. For example, some studies solved electromagnetic transient-state problems of a distribution network [3,4]. Furthermore, available simulation methods and tools for transient-state analyses were overviewed in [5]. Since these studies did not present the detailed modeling of a specific power system component, one study proposed an analytical method for the transient-state analysis of induction motor, lighting, and resistor loads by their power balance equations [6]. Another study presented a detailed model of photovoltaic (PV) and wind systems [7]. Using Power Systems Computer Aided Design (PSCAD), the transient-state model of a grid-connected microturbine system was presented in [8]. Grid-connected inverters were also modeled in [9,10].

While the previous studies have modeled various power systems components for transient-state analyses, they did not compare simulation results to actual measurement. Thus, after comparing simulation results to actual measurement values, one study claimed that short-circuit studies simulated in the transient state could provide an accurate understanding of feeder dynamics [11,12].

Meanwhile, since the previous studies did not examine the transient-state response of a distribution network that hosts DG systems, several studies simulated a distribution network integrated by DG systems such as wind, solar PV, hydropower, gas turbines, diesel engines, and induction generators [13–20]. For example, a distribution network that hosts a hybrid DG system such as a wind turbine, PV, and hydro power was analyzed by Digital Simulation and Electrical Network Calculation Program (DIgSILENT) [13]. The transient-state behaviors of a small test feeder were analyzed by the nonlinear models of gas, diesel turbine, and excitation systems implemented in Simulink of MATLAB

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Nomenclature

DC	direct current
DG	distributed generation
D_i	the droop value of photovoltaic (PV) system i in percent
$\Delta I_{q,i,a}^{(k)}$	the current injected to phase a of bus i at the kth iteration
$\delta_{V,i,a}^{(k)}$	the voltage angle of phase a of bus i at the kth iteration
ΔV_i	the deviation from the setting voltage of bus i or a bus to which PV system i is connected
MPPT	maximum power point tracking
OLTC	on-load tap changing
pf_i	the power factor limit of bus i (e.g., either leading or lagging 0.9 or higher [1])
PI	proportional integral (controller)
PV	photovoltaic
PF	power factor
$P_{min,i}$ and $P_{max,i}$	the minimum and maximum active power of PV system i, respectively
$P_{PV,i}^{(k)}$ and $Q_{PV,i}^{(k)}$	the active and reactive power output of PV system i at the kth iteration
Q_i	the reactive power generation output of PV system i
$Q_{min,i}$ and $Q_{max,i}$	the minimum and maximum reactive power of PV system i, respectively
$Q_{setpoint,i}$	the set value of the reactive power output of PV system i
Sign (ΔV)	$+1$ if $\Delta V > 0$, otherwise -1
$S_{nom,i}$	the nominal power of PV system i
SVC	static var compensator
V_i	the terminal voltage of a bus to which PV system i is connected
$V_{pos,i}^{(k)}$	the positive-sequence voltage of bus i at the kth iteration
$V_{setpoint,i}$	the positive-sequence setting voltage of a bus to which PV system i is connected
$Z_{bus,i}$	the ith diagonal element of the positive-sequence impedance matrix

[14]. The transient-state impact of a fault event on the actual distribution system with synchronous generators designed in Simulink of MATLAB was examined in [15]. Recently, one study investigated the transient-state response of a 10 kV distribution system with induction, diesel, and microturbine generators after a fault [16]. Another study generated a fault on a 154/22.9 kV substation modeled by the Electromagnetic Transient Program (EMTP) and examined the restoration characteristics of the system [17]. In 2012, one study examined the transient-state response of a real distribution network and the self-healing methods of the network using EMTP-Restructured Version (EMTP-RV) [18]. More recently, a 230/24 kV substation network with PV plants was modeled by EMTP Real-Time Digital Simulator (RTDS) and RSCAD [19]. A Nigerian 330 kV distribution system was modeled by DIgSILENT and the eigenvalue analysis of the system was presented in [20].

While the previous studies have focused on feeder dynamics caused by short-circuit events, some studies have examined the transient-state response to switching events of DG systems, which are not triggered by a short circuit. For example, the effect of switching events of DG systems on the IEEE 13-bus test feeder was analyzed by Fourier and wavelet transform [21]. One study also examined the islanding operation of a microgrid system after the switching events of DG systems [22]. Another study investigated the transient-state islanding operation of a distribution network that hosts fuel cells, battery systems, and a wind turbine after switching events [23].

The previous studies, however, have examined only either short-circuit events on a relatively small distribution network or transient-state responses to a switching event (which is not triggered by a short circuit). That is, Volt/Var control was not taken into account. Thus, some studies have presented various methods and algorithms on Volt/Var control in the steady state [24–28] and active power control methods [29–33]. Moreover, a transient-state active and reactive power control method of a hybrid system that consists of PV, wind, and storage systems was also modeled in [34]. However, these studies, [24–34], did not apply the active and reactive power constraints for the optimal Volt/Var control method of high-capacity DG systems upon voltage regulation. Thus, the first objective of this study is to present an optimal reactive power control method for high-capacity PV systems that takes the active and reactive power constraints into account for voltage regulation in the steady state. Moreover, none of the previous studies examined voltage variation when DG systems inject reactive power into the large distribution network with thousands of nodes in the transient state. Thus, the second objective of this study is to analyze the transient-state response of a sufficiently large actual distribution network (e.g., with thousands of or more nodes) integrated by high-capacity PV systems able to control reactive power.

This paper is organized as follows: Section 2 presents the problem statement. Section 3 describes the Volt/Var control of a DG system and the method that imports a large steady-state feeder model into DIgSILENT. Section 4 introduces case studies that verify the proposed method and discusses the simulation results. Finally, Section 5 provides the conclusions and contributions of this study.

2. Problem statement

Present regulations recommend that DG systems maintain their terminal bus voltage within 0.95 to 1.05 p.u., which corresponds to ANSI C84.1-2011 Range A, when producing power into a distribution feeder [35]. However, if either a distribution network is lightly loaded or a relatively high-capacity PV system injects power into the feeder, the system may experience an increase in overvoltage (e.g., equal or higher than 1.05 p.u.) [36]. To prevent such an overvoltage problem, the state-of-the-art inverter-based DG systems connected to the grid, particularly PV systems in this study, are able to control reactive power, which is well-known as Volt/Var control and management. However, since either clustered or scattered PV systems have continuously been connected to a large distribution network (e.g., having thousands of nodes), a study on such an overvoltage problem should take a large distribution network into account. Thus, one study examined the steady-state response of a sufficiently large distribution network (e.g., with approximately 4200 nodes) that hosts high-capacity PV systems able to control reactive power [36]. However, none of the previous studies applied the active and reactive power constraints for the optimal Volt/Var control method upon voltage regulation in the steady state. Thus, this study initially presents an optimal Volt/Var control method with the active and reactive power constraints and examines the effect of the proposed method on voltage regulation in the steady state.

The large network can be more efficiently modeled by a steady-state power-flow analysis program, or OpenDSS based on text editors, than a transient-state analysis program based on graphical editors. Furthermore, it is not feasible to draw thousands of power system components on the graphical editor. Thus, one study imported a small feeder into DIgSILENT [37]. But the study did not present the detailed method that imports feeders to DIgSILENT and verify the method for an actual large distribution feeder with PV systems. Therefore, this study proposes a method that imports the large feeder models developed in OpenDSS into a transient-state analysis program, or DIgSILENT. That is, using DIgSILENT, it develops a transient-state feeder model of a large actual distribution network with thousands of nodes. Then, high-capacity PV systems able to control Volt/Var are added to the feeder model. Thus, the model can be used for analyzing the effect of various