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Analysis and visualization method for understanding the voltage effect of distributed energy resources on the electric power system

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ABSTRACT

While adding distributed energy resources (DER) to a distribution circuit will affect numerous aspects of operation, bus voltage is a critical aspect that must be maintained within acceptable limits. It is therefore critical to: (1) quantify how DER installation will affect the voltage, (2) visualize the voltage change, and (3) predict the voltage change of the alternatives within the DER operational space. These three goals are achieved through the development of a simple voltage change potential (VCP) visualization method that can be determined using the basic characteristics of an inverter-based DER installation. The VCP results compare favorably with equivalent complete non-linear Matlab/Simulink™ models of DER implementation in distribution circuits at a fraction of the computational time. Calculation of VCP also enables a new control method that uses circuit information and simple equations to provide situation-dependent and optimal voltage regulation.

1. Introduction

Distribution systems are built to provide service locations with a voltage that is within a specified range by making assumptions on the direction, magnitude, and time-based characteristics of the real and reactive power load flow. DER can disrupt this process by (1) changing the load flow assumptions and directly creating over- or under-voltages, or (2) conflicting with the control of the utility voltage regulation equipment, such as capacitor banks and step voltage regulators. In the absence of other utility equipment, the first category could be addressed by allowing the DER to make local assumptions about power flow and counter adverse behavior, as shown in the analytical analysis of system voltage perturbations due to DG from [1] or the simulation-based simple circuit analysis in [2]. The added difficulty of the second category – potential fighting between DER and infrastructure – however, creates a complex challenge that limits the integration of high levels of DER in current distribution infrastructure. A report by GE CRD for NREL in 2003 investigated this problem by conducting a comprehensive study on generic distribution feeders to gain insight into the difficulties of integrating distributed generation (DG) into a distribution system [2]. There are a variety of over- and under-voltages in almost all of the cases and this work concludes that voltage regulation cannot be achieved without communications and control in distribution circuits [2]. While the GE/NREL work utilizes a worst-case approach of combining highest generation with lightest load, a stochastic load and generation model from Widen et al. indicates that voltage challenges are infrequent for high penetration residential PV installations under realistic operating scenarios [3]. Conti and Greco [4] examine this problem by assuming a centralized control for a distribution system with high penetrations of synchronous DG. The controller performs a dynamic load flow of the distribution system by using set system parameters as well as real-time utility operating data and DG information. Conti et al. also proposes a local control method in [5] that attempts to eliminate overvoltage problems in photo-voltaic (PV) installations by curtailing the real power if the local voltage exceeds a set limit.

Even if all customer loads are maintained within the allowable voltage limits, the integration of DER into the system can affect the voltage regulating equipment itself. DER could increase the number of times the capacitor bank must switch on and off, which would result in additional mechanical wear on the switch [6]. And Brady et al. describe a scenario where the increased system voltage would reduce the on time of capacitor banks and therefore increase the total import of reactive power from the rest of the electric power system [7].

2. Background

A distributed energy resource (DER) can provide power generation, energy storage, or energy conversion that is typically located near to the site of its use. The most common small generators and storage elements share an additional attribute – they are all inherently DC electricity-based resources. Fuel cells and solar

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photovoltaic generators create DC electricity directly, and micro-turbine generators (MTG) have a variable high frequency generator that rectifies to a DC bus. Electric energy storage elements, such as ultracapacitors and batteries are DC sources as well. Thus, while all of these DER have unique behavior and dynamics, they fundamentally connect to the rest of the electric power system in the same way – through a DC/AC inverter. In order to understand how such an inverter-based DER will affect the electric power system, each distribution element must be characterized and combined into a fully integrated feeder system model.

2.1. DER

The distributed generators considered herein include fuel cells (FC), micro-turbine generators, and solar PV. Wind turbines are not included as they are assumed to be interconnected at the transmission level. Fuel cells electrochemically react fuel and oxidant to produce electricity and heat. There are many types of fuel cells, but one categorization is by temperature – two low temperature fuel cell types, such as polymer electrolyte membrane (PEM), and two high temperature fuel cell types [8]. Some applications for the low temperature fuel cells include vehicles and back-up power/combined heat and power (CHP) applications [8]. High temperature fuel cells are well-suited to large, stationary, continuous power applications with CHP [9].

MTG are considered a more mature technology than fuel cells and solar PV because gas turbine technology has been used commercially for both stationary power and propulsion applications for decades. MTG are smaller-scale versions of these common systems that use a slightly different type of compressor in a power output size class that is suited for distributed power and heat generation (e.g., less than 1 MW) [10]. In general, an MTG can change power output, though with a limited dynamic ramp rate, such as 2 kW s^{-1} for the Capstone C60 MTG [11].

Solar PV has very different characteristics compared to an FC or MTG because it is based on an intermittent solar energy resource. While an FC or MTG will have a constant output and potential ability to manipulate output power, the maximum solar PV output is constantly changing in an uncontrollable manner. For a given temperature and solar irradiation level, there is a certain voltage that corresponds to the maximum power output of the cell. Advanced solar power controllers are designed to change the output voltage to achieve this maximum power point, but under certain circumstances it can be reduced to a lower value (if desired). Thus, in the absence of secondary energy storage, solar PV power is not controllable, but it is curtailable through manipulation of the cell voltage [5].

2.2. Power electronics

One characteristic shared by most distributed energy resources is that they rely on an inverter-based connection with the rest of the 3-phase AC electric power system. There are many types of inverters with various grid-connected behavior, although two main categories are multi-pulse inverters and pulse-width modulated (PWM) inverters [12]. In addition, there is interest in integrating a static synchronous compensator (STATCOM) capability into the inverter for use when the real power output is less than the rated inverter capacity. The STATCOM capability would enable the inverter to utilize spare capacity for the production or consumption reactive power as an ancillary service [13,14] or local power factor correction [15]. These additional functions increase the allowable operating modes of the inverter from just the generator-defined real power to the real power plus a reactive power capability that can produce benefits for the electric grid.

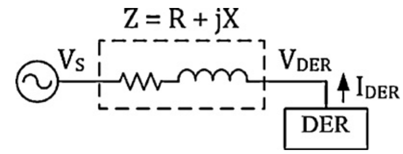

Fig. 1. Two bus circuit schematic for voltage linearization.

2.3. Modeling methodology

Each full nonlinear distribution system is modeled in Matlab/Simulink™ as described in [16]. The model includes a direct three-phase waveform-level simulation as well as a post-processing code to output quantitative parameters such as real/reactive power flows and rms voltage. Both levels of the model have been previously verified against analytical theory, literature data when available, and other commercial load-flow software programs such as PSCAD™ and PowerWorld™.

3. Analysis

3.1. Voltage change potential (VCP) method development

The VCP method is developed by first considering a linearization of a two-bus system. This simplification allows the DER real and reactive power to directly translate into the local voltage change. The voltage drop is calculated with the two-bus system that is presented in Fig. 1. The line impedance is defined as Z, which is the sum of line resistance (R) and reactance (X). The voltage drop ΔV_{DER} is the difference between the magnitude of the DER local voltage, V_{DER}, and the source voltage, V_S (Eq. (1)). The voltage at the DER location is calculated with Ohm's Law (Eq. (2)) using the DER current (I_{DER}), and the resulting voltage drop is defined in Eq. (3). The definition of apparent power, $S = P + jQ = VI^*$, can be used to rewrite I_{DER} as a function of the real and reactive power (P_{DER}, Q_{DER}), and substitute it into the expression for voltage drop (Eq. (3)) to produce Eq. (4). Further manipulation can separate the V_{DER} term into a real and imaginary part as presented in Eq. (5).

$$\Delta V_{DER} = |V_{DER}| - |V_S| \tag{1}$$

$$V_{DER} = V_S + I_{DER}Z \tag{2}$$

$$\Delta V_{DER} = |V_S + I_{DER}Z| - |V_S| \tag{3}$$

$$\Delta V = \left| V_S + \frac{(P_{DER} - jQ_{DER})}{V^*_{DER}}(R + jX) \right| - |V_S| \tag{4}$$

$$\Delta V = \left| V_S + \frac{(P_{DER}R + Q_{DER}X)}{V^*_{DER}} + \frac{j(P_{DER}X - Q_{DER}R)}{V^*_{DER}} \right| - |V_S| \tag{5}$$

In general, generators are considered to be constant P and Q sources, meaning that their real and reactive power output does not depend upon voltage – if the voltage changes, so will the current. Distributed generators will behave in a similar way. However, for the sake of linearization, the DER will instead be interpreted as a constant current source. This is a major, nontrivial assumption that is useful for effect visualization, but will heavily influence the accuracy of the results. The choice of standard DER voltage is another major factor in the subsequent results of the linear approximation. The local voltage is generally assumed to be between 0.95 p.u. and 1.05 p.u., so choosing a standard DER voltage of 1.0 p.u. should minimize the worst possible error. The source voltage is defined as the voltage reference with an angle of 0°, and it is also assumed that the voltage angle between V_S and V_{DER} is negligibly small. The magnitude of the voltage drop equation can then be calculated as