Experimental Determination of PV Inverter Response to Grid Phase Shift Events

Preprint

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Experimental Determination of PV Inverter Response to Grid Phase Shift Events

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Abstract—With the continued growth of renewable energy resources which interface to the electric grid via inverters, the understanding of such devices becomes ever more important to the safe and reliable operation of the bulk power system. This work investigates the specific response of a utility-scale PV inverter to grid voltage phase shift-type disturbances which sometimes occur during grid fault events. The role of the PV inverter's phase-locked-loop (PLL) is identified as important to modeling the response. Switching-level simulations of a utility-scale PV inverter with a modeled PLL show a characteristic response when phase shift disturbances require the PLL to track what appear as fast frequency changes. Additionally, in this work a full-scale laboratory testing was carried out using the Opal real time (RT) OP5142 real time simulator and a large grid simulator to create phase shift disturbances with a high degree of repeatability. A photovoltaic (PV) inverter was connected to a grid simulator, and phase shifts were instantaneously implemented on the simulated grid, the results of the currents were then obtained. The experimental results obtained were validated with simulation results obtained from MATLAB/Simulink.

Index Terms—DER, frequency response, harmonics, inverter, photovoltaics, T & D.

I. INTRODUCTION

The safe and reliable integration of renewable energy sources within the bulk electricity system is becoming ever more important as such sources continue to grow substantially every year. It is widely believed that the integration of renewables such as wind and solar can enable clean and reliable energy for human use both in developed and developing regions [1]-[3]. Wind and solar photovoltaics (PV) energy are both regularly interfaced to the ac electric grid via power electronic devices called inverters. As the amount of wind and PV energy increases in an electric grid it becomes ever more important to fully understand the expected response of such devices to abnormal voltage and frequency conditions which may be present on an electrical grid from time to time due to faults and other abnormal operating conditions. One existing uncertainty is how PV inverters respond to grid events whose dominating characteristic is a near instantaneous shift in the phase relationship of the grid voltages. This paper focuses on the results of an investigation into exactly such responses by first developing models to understand the most important factors relating to such phase shift responses and secondly, by completing laboratory testing to see how a commercially available PV inverter actually responds to phase shift disturbances. Section II of this paper describes the approach taken for PV inverter modeling including the response of the PV inverters grid synchronization control elements. Sections III

and IV present the methods and results from the completed simulations and laboratory experiments respectively. Section V. concludes the paper.

II. PV INVERTER MODELING AND GRID SYNCHRONIZATION

PV inverters are generally represented as constant PQ generators in current bulk system-level dynamic models, but during transient fault conditions they act as power-limited current sources. In addition to fundamental differences in fault current capability compared to traditional synchronous generators, PV inverters characteristic response to abnormal conditions is a strong function of the inverter controls implemented to protect the PV inverter itself but also to safely integrate to the interconnected grid. For example, a distribution-connected PV inverter would likely implement the requirements of the IEEE 1547-2003 standard which requires a PV inverter to disconnect within 2s of grid fault or if a utility island is created [4]. Grid-tied PV inverters also have the characteristics of tripping under grid events due to its settings. Disconnection or a dramatic reduction of real power delivered to the grid can occur during grid overvoltages and undervoltages, also during over/under frequencies [5]. As power systems experience rapidly changing frequency and voltage during faulted conditions or due to the loss or demand or generation, there is a growing expectation and additional grid requirements that a PV inverter is not expected to trip under these types of events to avoid exacerbating current bulk system contingencies and as to not reduce bulk system reliability. Hence, most PV inverters are designed to have voltage and frequency ride-through capabilities within a specified voltage and frequency range [6]. This work's focus on phase shift response originates from the fact that such phase shifts impact both the measured frequency and voltage and yet are characteristic of many real world faulted operation conditions (a phase-to-phase fault for instance) Grid-tied inverters (operating as current sources) must comply with certain requirements before they can be synchronized to the grid. These are:

1. The phase of the grid-tie inverter must be the same as the grid phase.
2. The frequency of the inverter must be the same as the grid.

The response of an inverter to grid events is potentially influenced by many factors and systems such as frequency and voltage measurement methods, inverter current limiting protection circuitry and control, dc bus voltage control, and, of course, the specific design

of the inverter including the design of the output filter. Often an inverter is synchronized to the grid using a phase-locked loop (PLL). The PLL also likely plays an important role in frequency measurement as the oscillator inherent in a PLL would likely make a reliable grid frequency measurement source for supervisory functions like frequency ride-through control logic. Modeling efforts for this work have focused on accurate modeling of a PLL in the PV inverter model as to elucidate the role such circuitry/code play in PV inverters response to phase shifts.

Three-phase systems are synchronized to the grid using the phase-locked loops (PLL). The three-phase voltage signal is transformed to two-axis d-q components using park's transformation, and the frequency, ω and phase, ϕ components are utilized as reference signals in the PLL. A PLL consists of a voltage controlled oscillator (VCO), phase detector (PD), and a low-pass filter as shown in Fig. 1.

Previous research regarding PLLs in power systems is vast but few, if any, work characterizing and modeling the PLLs response specifically for PV inverter. Still, a number of previous works show the importance of PLL design and performance for grid synchronization. PLLs have also been employed in rectifier circuits in [7], where a novel digital PLL was proposed to realize a faster convergence of the system using the ratio of d-q voltages as the parameter of interest. However, synchronous reference frame PLL (SRF-PLL) are normally being adopted for the interconnection of three-phase systems [8][9]. They were used to detect system islanding in [10] based on virtual impedance that was added to the circuit. The virtual impedance provided a sufficient frequency deviation that was needed to detect islanding when the frequency of the resonant tank matches the grid frequency. An analysis of the middle frequency resonance in doubly fed induction generator (DFIG) considering PLL was investigated in [11]. However, this paper presents the characteristic response of grid-tied PLL-based PV inverters to grid disturbances using laboratory evaluation of utility scale (500 kW) hardware components.

Figure 1. Block diagram of the PLL.

A. Mathematical Model of the PLL

The output signal, u_f (shown in Fig. 1), of the loop filter determines the angular frequency, ω_2 , at which the VCO oscillates. The angular frequency, ω_2 is given by;

$$\omega_2(t) = \omega_o + K_o u_f(t) \quad (1)$$

where ω_o is the center angular frequency of the VCO and K_o is the VCO gain in $\text{rads}^{-1}\text{V}^{-1}$.

The output of the PD is proportional to the phase error, ϕ_e and is given as

$$u_d(t) = K_d \phi_e \quad (2)$$

where K_o represents the gain of the PD in V/rad .

The phase signal, $\phi_1(t)$ can be a constant, linear or quadratic function of time depending on the signal at which it is excited [12]. As shown in Fig. 2, the three-phase ac signals are transformed to a two-axis vector using the park transformation technique. This produced the direct-axis component, v_d and the quadrature-axis component, v_q in the form of dc quantities. The quadrature-axis component, v_q , is used as the reference signal, $u_1(t)$ with an angular frequency of $\omega_1(t)$.

The phase signals carried by the input of the PLL can be represented as;

$$u_1(t) = U_{10} \sin[\omega_1 t + \phi_1(t)] \quad (3)$$

The output is represented as a square wave signal written as;

$$u_2(t) = U_{20} \sin[\omega_2 t + \phi_2(t)] \quad (4)$$

where U_{10} and U_{20} are the amplitudes, ω_1 and ω_2 are the angular frequencies, ϕ_1 and ϕ_2 are the phases.

Replacing equation (6) by its Fourier series gives,

$$u_2(t) = U_{20} \left[\frac{4}{\pi} \cos(\omega_2 t + \phi_2) + \frac{4}{3\pi} \cos(3\omega_2 t + \phi_2) + \dots \right] \quad (5)$$

For the PD output, u_d , we have

$$u_d(t) = u_1(t) \cdot u_2(t) = U_{10} U_{20} \sin(\omega_1 t + \phi_1) \cdot \left[\frac{4}{\pi} \cos(\omega_2 t + \phi_2) + \frac{4}{3\pi} \cos(3\omega_2 t + \phi_2) + \dots \right] \quad (6)$$

When the PLL is locked, the frequencies ω_1 and ω_2 are identical, and $u_d(t)$ becomes,

$$u_d(t) = U_{10} U_{20} \left[\frac{2}{\pi} \sin \phi_e \dots \right] \quad (7)$$

The higher order terms have been filtered out.

$$\text{By setting } K_d = \frac{2U_{10} U_{20}}{\pi} \quad (8)$$

$$u_d(t) \approx K_d \sin \phi_e \quad (9)$$

When the phase error is very small, the sine function can be replaced by its argument, and we have

$$u_d(t) \approx K_d \phi_e \quad (10)$$

This equation represents the linearized model of the phase detector. The above equations were used to design a PLL for simulation of a three-phase PV inverter as detailed in the next section.

III. SIMULATION METHODS AND RESULTS

Simulation were carried out in MATLAB/Simulink to determine the expected response of a utility-scale PV inverter to grid voltage phase shift disturbances. In the model, an array of 40 parallel by 10 series 1Soltech 1Sth-215-P 215 W PV panels with an irradiance level of 1000 Wm^{-2} and a temperature of 25°C were connected to the grid using a switching-level model of a three-phase inverter which included a detailed model of a PLL for PV inverter grid

synchronization. The PV inverter model used in shown in Fig. 2. A maximum power point tracking (MPPT) perturb & observe (P&O) algorithm was implemented on the dc-dc interface between the PV and the inverter to model the realistic behavior of PV inverters as they continuously track the MPPT. The inverter was driven by a sinusoidal pulse width modulated (SPWM) signal at a switching frequency of 2.1 kHz. The simulation was executed, and instantaneous grid voltage phase shifts of 15°, 30°, and 60° were injected 1.5 s after the start of the simulation (which began in steady-state). The results obtained are presented in Figs. 3 through 8 for phase shifts of 15°, 30°, and 60°. Whenever a phase shift occurs, there is a significant reduction of the three-phase voltages, as well as reduction of current supplied to the grid in all the phases. It was observed that the impact of phase shift on the voltages and currents increased as the phase shift value increases. Figure 7 shows a situation of nearly complete voltage collapse a couple of cycles after the phase shift event; similar result was also observed with the phase currents in Fig. 8. The simulated results were tested under resistive load conditions (i.e. no stiff grid connection) thus there is a very predictable relationship between each phase voltage and current.

Figure 2. PV inverter model.

Figure 3. Three-phase voltages, V_a , V_b , V_c , when the phase shift is 15°.

Figure 4. Three-phase currents, I_a , I_b , I_c , when the phase shift is 15°.

Figure 5. Three-phase voltages, V_a , V_b , V_c , when the phase shift is 30°.

Figure 6. Three-phase currents, I_a , I_b , I_c , when the phase shift is 30°.

Figure 7. Three-phase voltages, V_a , V_b , V_c , when the phase shift is 60°.

Figure 8. Three-phase currents, I_a , I_b , I_c , when the phase shift is 60° .

IV. EXPERIMENTAL METHODS AND RESULTS

The experiment was set-up using a grid simulator, 500 kW utility-scale PV inverter, PV simulator, connecting cables, current sensors, oscilloscope, computer, and the OpalRT real-time simulator. The OpalRT is a Simulink-compatible real-time simulator. Phase shifts were implemented using the transport delay block, clock, and switch blocks in the Simulink library. The current sensors were used to measure the current flowing from the inverter to the grid via the oscilloscope. The grid reference voltages, generated by the OpalRT – effectively being used as a highly configurable signal generator – and the resulting grid voltages, supplied by the grid simulator, were also measured on the oscilloscope. Phase shifts of 15° , 30° , and 60° were subjected to the grid voltage (all three phases) after a period of normal grid operation sufficient to startup the PV inverter and have the system settle to a steady-state operating point equivalent to the conditions shown in Table 1. The OpalRT was also used to supply a trigger signal to the oscilloscope to capture the PV inverters response to the phase shifts.

The grid operational model used for this experiment was built using Simulink and some RT lab blocks such as the OpComm, OpCtrl and the OP5142 EX Analog Out blocks. As mentioned above the OpalRT system was used as a configurable signal generator in a open loop fashion. The grid conditions (voltage and frequency) were normal at all times with the exception of the phase shifts subjected during the laboratory experiments. The grid model was compiled, loaded, and built in the RT lab before hardware execution at a sample rate of 200 μ s. Figure 9 shows the basics of the OpalRT and oscilloscope setup. All laboratory testing was completed at NREL's Energy System Integration Facility (ESIF) in Golden, CO.

TABLE 1. PARAMETERS OF THE EXPERIMENTAL PV INVERTER AND THE GRID SIMULATOR.

Parameters	Values
PV inverter dc power	176 kW
Grid simulator phase voltages	277 V
Grid frequency	60 Hz
Sample rate	200 μ s

Figure 9. A view of the laboratory experimental set-up.

The outcomes of the experiments are presented in the figures below. A screenshot of the results obtained from the oscilloscope are presented in Figures 10, 11, 12, and 13. The three-phase voltages are at the top, while the three-phase currents are at the bottom. Phase A (V_a), phase B (V_b), and phase C (V_c) voltages are the purple, red and yellow lines respectively. The first three channels, and the next three channels are the same as expected, and they represent the reference phase voltages measured from the OpalRT analog output and the actual grid voltages supplied by the grid simulator respectively. Phase A (I_a), phase B (I_b), and phase C (I_c) currents are the pink, green and purple lines respectively on the last three channels.

Figure 10. Three-phase voltages and currents at zero phase shift.

Figure 11. Three phase voltages and currents when phase shift is 15°.

Figure 12. Three phase voltages and currents when phase shift is 30°.

Figure 13. Three phase voltages and currents when phase shift is 60°.

Figures 10, 11, 12 and 13 are the laboratory results under a normal operating condition, and phase shifts of 15°, 30°, and 60° respectively. Whenever a phase shift occurs, there is an instantaneous collapse of the three-phase voltages, and a reduction of current supplied to the grid in all the phases. This is also the same for the simulation results except that the voltages maintained a nearly constant voltage with little distortions after the event due to the low impedance (stiff) grid connection in the experimental setup. For the experimental cases, the values of the three-phase currents in Figures 11 and 12 shows a tracking of the current magnitude and phase mainly with the action of the PV inverter controllers and PLL, but this is characterized with periodic current spikes and distortions. In both the simulation and experimental cases, the distortion was minimal at 15°, and stability was quickly achieved after a few seconds. A case of inverter tripping was observed in the laboratory as shown in Fig. 13. The inverter went offline and the output current went to zero shortly after the phase shift of 60°. This is validated by the simulation results of Figure 8, where the output current collapses to near zero immediately after the phase shift event

V. CONCLUSION

This work was able to evaluate PV inverter responses to phase shift grid events both through simulation and laboratory testing. Phase shift events were studied as such shifts are often observed during power system fault conditions. The experimental work was informed by simulation results obtained from MATLAB/Simulink. Periodic increases and decreases in the PV inverters voltages and currents magnitudes were obtained during phase shift events when the PLL is attempting to maintain phase synchronization. These results provide insight into the expected behavior of PV inverters under a variety of faulted grid scenarios. Additionally, this work provides an initial view of how the PLL response of individual PV inverters may need to be considered when modeling the expected response of PV inverters. Utilities can better manage or mitigate against the probable response that could result from grid-tied PV inverters.

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