Operation of Parallel Grid-Connected PVs Due to an Islanding Event

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***Abstract*—The growing penetration of solar photovoltaic (PV) systems in power grids has increased the opportunity of these systems' exposure to different dynamics. The objective of this paper is to study and analyze the dynamics resulted from an accidental islanding event of a 30 MW grid connected PV system. The effect of voltage source converter (VSC) control switching and the influence of initial phase selection are discussed thoroughly. Different case studies are performed to test the system performance considering resistive and inductive loads. Moreover, the effect of the resulted dynamics on sensitive loads such as rotating machines is examined. Analysis are carried out based on electromagnetic transient (EMT) simulation results using MATLAB/SimPowerSystems.**

***Index Terms*—solar photovoltaic, grid following, grid forming, initial phase condition, islanding, parallel VSCs.**

I. INTRODUCTION

PV technology has been substantially implemented around the world over the past five years [1]. This large deployment has led to many dynamic issues related to solar energy grid integration systems. In the United States, specifically in South California, four different major disconnection events of power system connected PV resources have occurred over the past four years. In 2018, the Angles Forest and Palmdale Roost disturbance events caused the inverters of some grid connected PV systems to trip and lead to a total loss of around 3.3 GW of power [2]. In 2017, the Canyon 2 Fire caused transmission grid disturbances which resulted in the loss of nearly 1.6 GW of solar power generation [3]. In 2016, the Blue Cut Fire disturbance event resulted in the loss of 1.2 GW of solar PV resources [4]. Therefore, hypothetically creating, analyzing, and studying similar events is an important step towards improving the reliability of PV systems and power systems in general.

Different studies have been conducted regarding the PV system's performance while connecting to grid or serving load as a stand alone system. In [5], the effects of different kind of grid faults on a 10 MVA PV system are discussed and different system responses to reactive power support during faults are investigated. In [6], different island mode control strategies are identified for PVs and batteries working in a droop-controlled medium as standalone distributed generation units (DGs). Another method is proposed in [7] for power sharing between different DGs in islanding mode including PV units, where there is no need for communication between these units and other operating limitations.

The aforementioned studies investigated solar PV systems or DG systems in general, either in grid connected or island modes. The scope of this paper is to investigate system transients when an accidental islanding event occurs. In addition, unlike conventional microgrid where a battery has to be deployed for voltage and frequency control, a PV inverter will behave as a grid forming converter.

The proposed system consists of two parallel PV inverters that work based on grid following control mode under normal conditions. Due to an accidental islanding event, the PV system is isolated from the utility grid. As a result, one of the PV inverters takes the role of grid forming and the other inverter continues working in grid following mode and does not need to switch, since frequency and voltage are controlled by the first VSC. The process of tripping and control switching results in different dynamic responses of the system. The effect of the initial phase selection during control mode switching plays a big role in improving those dynamic responses [8]. Moreover, the effect of such dynamics on different loads varies based on the load type. For instance, in [8], it was pointed that rotating machines are greatly affected by such disturbance events. Thus, this paper also conducts sensitivity analysis of transients' effects on different load types.

The remaining contents of the paper are organized as follows. Section II describes the study system in details. Section III explains the VSC control modes used in this study in addition to the initial phase selection strategy. In Section IV, the event is described, different case studies are presented, and the EMT results are analyzed in each case. Finally, study is summarized and concluded in Section V.

II. STUDY SYSTEM

Figure 1 shows the diagram of the system used to study and analyse the accidental islanding event of the 30 MW PV system from the utility grid. Two PV arrays whith SunPower SPR-315E-WHT-D modules are used to deliver about 30 MW of power. Two stage topology is used to tie the PV arrays to the utility grid [9]. In this topology, the PV array is connected to a VSC through a DC/DC boost converter. Maximum Power Point Tracker (MPPT) with Perturb and Observe technique is used with both DC/DC boost converters to maintain the

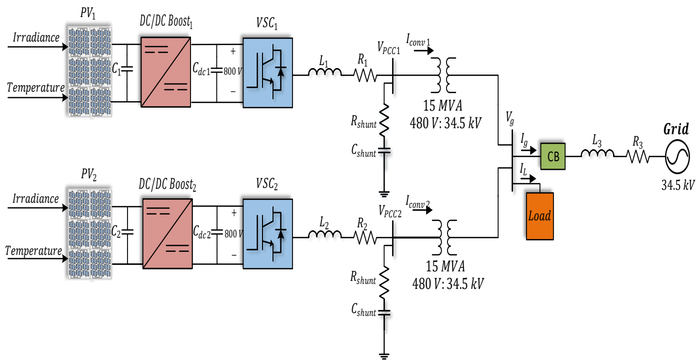


Fig. 1: Study system diagram.

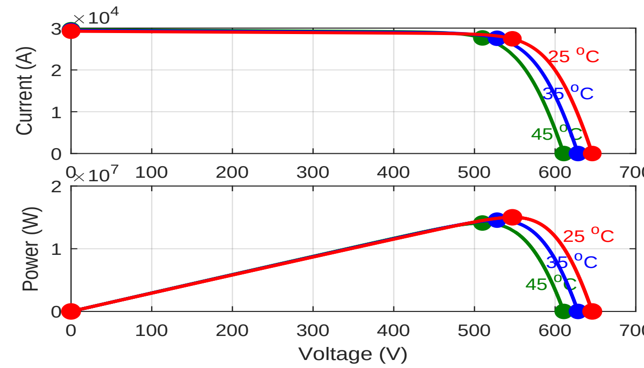


Fig. 2: I-V and P-V characteristics for 15 MW PV array.

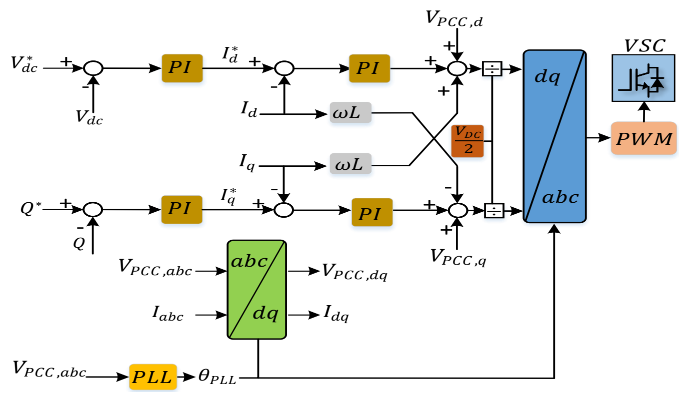


Fig. 3: VSC control in grid following mode.

voltages (V_{PV_1}) and (V_{PV_2}) at the value corresponding to the maximum power point. Figure 2 shows the I-V and P-V characteristics of each PV array at 1000 w/m2 irradiance and different temperatures.The DC/DC converters outputs are connected to two 15 MVA VSCs (VSC_1) and (VSC_2) through two dc-link busses of 800 V_{dc} each. each VSC converts the dc voltage to 480 V AC. The VSCs are then connected to a 34.5 kV utility grid through two 15 MVA step up transformers. For the purpose of reactive power compensation, two shunt capacitors each rated at 1.5 MVAR are employed. The grid is represented by a voltage source. Average models are assumed for both VSCs and DC/DC boost converters. Table I shows the system parameters and their values.

TABLE I: model parameters

Power Base	15 MW	R_1,R_2	0.003 pu
Voltage Base	480 V & 34.5 kV	X_{L1},X_{L2}	0.15 pu
C_{shunt}	1.5 MVAR	R_3	0.00255 pu
R_{shunt}	15 kW	X_{L3}	0.028 pu

III. VSC Control

As previously mentioned, two VSC control modes are used. The grid following mode is used for both VSCs as long as the PV system is connected to the utility grid. The grid forming mode is used to control VSC_1 after islanding event occures. Each control mode is explained as follows.

A. Grid Following Mode

The grid following control mode has been documented in some textbooks, e.g., [9], [10]. Three main components are controlled in this scheme: the DC-link voltage, the VSC output reactive power and the output current. Figure 3 shows the control block diagram. The control is designed based on dq reference frame and consists of two loops. Inner current control loop to control the VSC output current and protect it against high currents. The outer loop $d-axis$ is used to regulate the dc-link voltage at the desired value. The outer loop $q-axis$ is used to control the VSC output reactive power. The Phase Lock Loop (PLL) is used to track the phase of the voltage on the PCC bus and use it in the abc and dq transformation and the generation of (PWM) signals [8].

B. Grid Forming Mode

The grid forming control mode has also been documented in some books, e.g., [10], [11]. This strategy is used when the VSC is working in islanding mode and aims to control voltage at the PCC bus and maintain the frequency at the desired value, since it is no longer supported by the grid. Figure 4 shows the control block diagram. The control design is based on dq reference frame and consists of two loops. The inner loop is exactly the same as in the grid following mode where current is controlled for VSC protection. The outer loop is used to control the voltage at the PCC bus. Unlike the grid following mode, the PLL is not used to track the phase of the voltage on the PCC bus. Instead, the phase is generated by a voltage-controlled oscillator (VCO) whose input is the desired frequency value to guarantee that the VSC output frequency is controlled. The output of the VCO is used in the abc and dq transformation and the generation of the (PWM) signals [8].

C. Initial Phase Shift Selection

When the switching from grid following to grid forming control happens, the source of θ changes from the PLL to the VCO. This switching process can cause some high transients in the system if there is a mismatch between the initial value of the VCO output θ and the value of the PLL output θ_{PLL} at the time of switching. Therefore, setting an initial value of the VCO output that is equal to the value of the PLL when switching occurs, will guarantee smooth transient behavior.

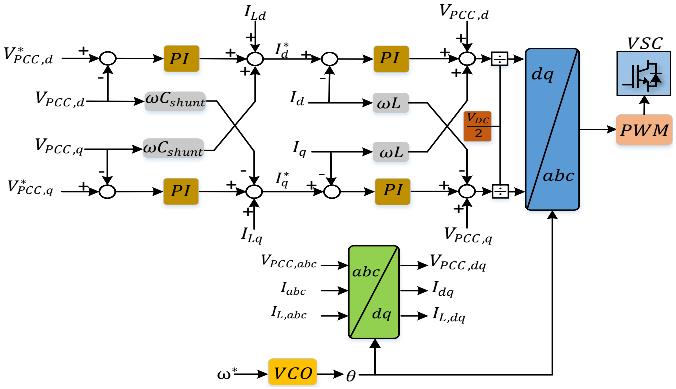


Fig. 4: VSC control in grid forming mode.

Figure 5 shows the schematic diagram of initial phase shift selection when switching the VSC control mode from grid following to grid forming [8].

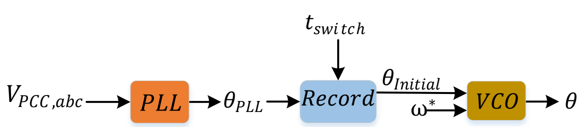


Fig. 5: Initial phase shift selection process.

IV. Event Description and Simulation

As stated earlier, the 30 MW grid connected PV system is built and simulated using MATLAB/SimPowerSystems. The PVs are assumed to be operating at a constant 1000 w/m^2 irradiance and a temperature of 25 C^o.

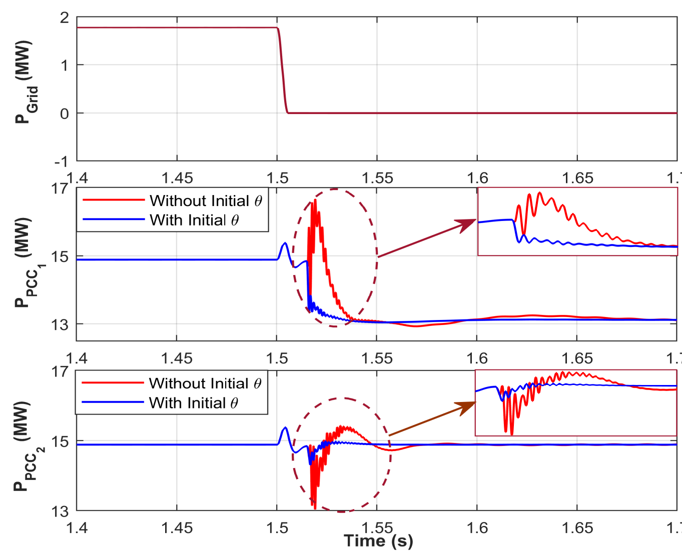
The simulation starts with both VSCs working in grid following mode. At $t = 1.5$ s, the main circuit breaker connecting the PV system to the utility grid is tripped. After tripping, the PVs are supposed to supply a local load as a stand alone system. At $t = 1.515$ s, the island mode is detected and the control of VSC_1 switches to grid forming mode to maintain constant voltage and frequency while VSC_2 stays in the grid connected mode. The reason behind assuming such short detection time is that the PV system was delivering power to the grid prior to islanding which means that there was a mismatch between the power delivered to load and the total generated power by the PV system. This could lead to a fast and large deviation in voltage or frequency from nominal values and causes VSCs to trip [12].

The following case studies, the islanding event is performed considering different load types. For each case, results are presented twice to show the effect of the initial phase selection on the transients resulted from VSC control switching.

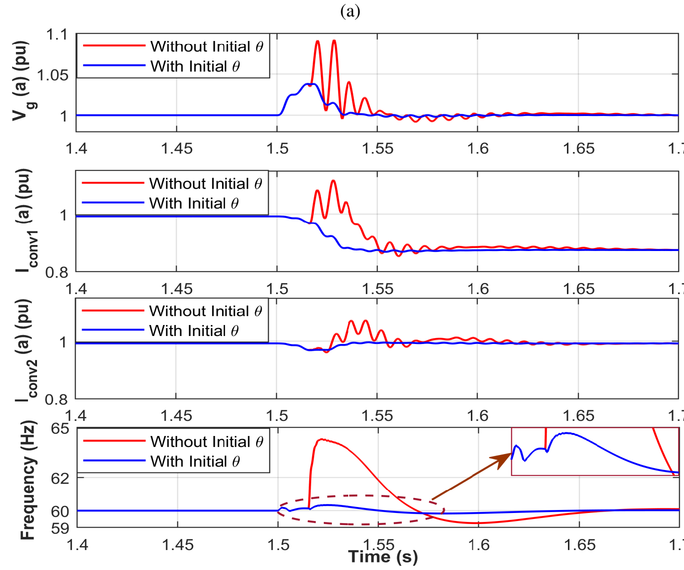
A. Case 1: Pure Resistive Load

In this case, a total load of 28 MW is connected to the PV system at the grid bus. The load consumes around 94% and the remaining 6% is sent to the utility grid. Figure (6a) shows the results of the active power delivered to grid, at PCC_1 and at PCC_2. Figure (6b) shows the results of the voltage magnitude at the grid bus, magnitudes of I_{conv1} and I_{conv2}, and the frequency taken from the PLL output. All of the results are shown with and without initial phase shift selection prior to, during and following the disconnection event. Since VSC_2 control is not switched and its power stays controlled at the maximum value, VSC_1 power drops down to 13 MW to pick up the remaining load demand. The output currents waveforms behaves similarly to the output power with a big difference in transients with and without initial phase shift selection. Therefore, VSC_1 behaves as a slack converter to provide, within its capability, whatever power is remaining to supply the load.

The effect of the initial phase shift selection is reflected when switching happens at $t = 1.515$ s. Substantial difference in the transient behavior of all results. However, this is because of the large phase difference at switching time between the



(a)



(b)

Fig. 6: Case 1: VSC_1 and VSC_2 AC side results.

value of θ_{PLL} and $\theta_{initial}$ of the VCO output which is set to zero by default. Therefore, the initial phase selection strategy is extremely important in maintaining rated values of the system within the acceptable range during accidental islanding events. For example, as shown in Figure (6b), the frequency of the system reached around 64 Hz which of course will cause the VSCs to trip. However, after implementing the initial phase shift strategy, the frequency deviated within ± 0.3 Hz which is acceptable as per IEEE-Standard 446-1995.

Regarding the DC side of both converters, Figure (7a) shows the DC link voltages and the duty cycle for the DC/DC boost$_1$ converter. Figure (7b) shows both PV arrays' voltages and currents. The DC side ratings of VSC$_2$ does not change as a result of the disconnection event since its control continues in the grid following mode and VSC$_1$ control is responsible to form that grid to maintain constant voltage and frequency. Therefore, PV$_2$ array continues to work at MPP and the DC-link voltage stays regulated at the value of 800 V.

For VSC$_1$, its dc-link performance is influenced by how PV$_2$ array is operating after islanding event occurs where it does not operate at its maximum power point tracking (MPPT) mode anymore because of the reduced power demand. Therefore, MPPT can not be implemented. Instead, the PV operates at a higher voltage and lower current values. Recalling Figure 2, and by looking at Figure (7b), the operating point is on the right side of P-V and I-V curves. Moreover, since there is no regulation on the DC-link voltage when VSC$_1$ switches to grid forming mode, its value increases with the increasing PV voltage until the duty cycle reaches a new equilibrium value or a limit (0.4 is a limit for the dc/dc converter duty cycle control). At $t = 1.5$ s, when the circuit breaker trips, there is a voltage drop before the control mode switching occurs and PV array responds to the new operating conditions.

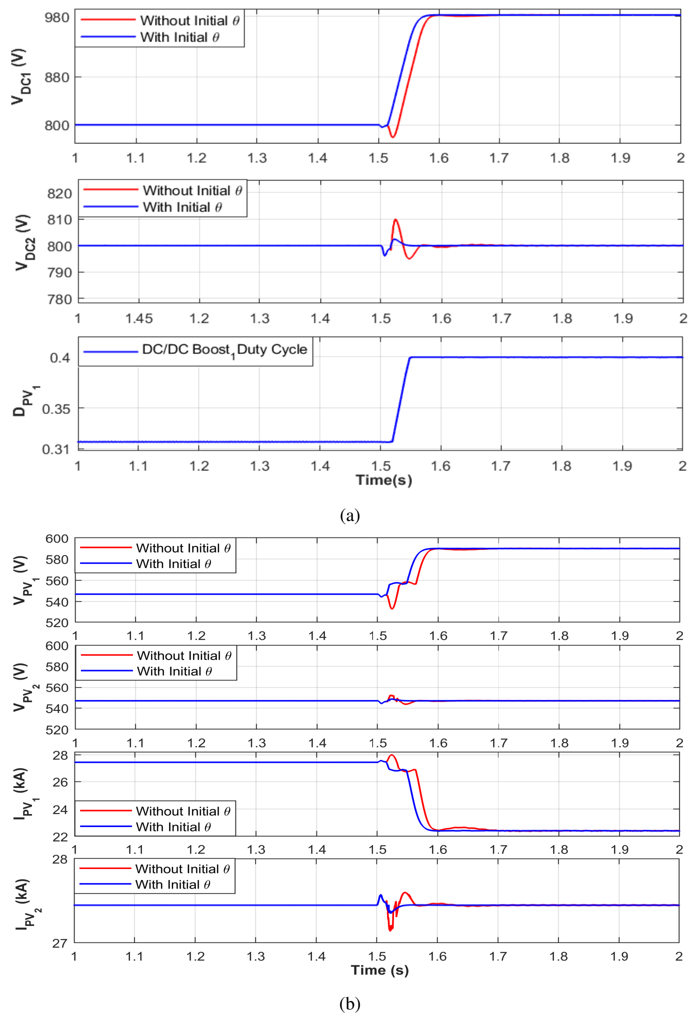


Fig. 7: VSC$_1$ and VSC$_2$ DC side results, (case1).

B. Case 2: Adding an Inductive Load

In this case, an inductive load of 1 MVAR is connected in addition to the previous resistive load to examine the system way of picking up this extra type of load. In general, the system takes a similar transient behavior to the previously discussed case with some differences in magnitudes. However, there are significant transient in reactive power. Figure 8 shows the waveforms of reactive power coming from the grid, at PCC$_1$ and at PCC$_2$. In addition, the magnitude of the voltage at the grid bus, VSCs' currents and the frequency taken from the PLL output are shown to compare their values with the values in the previous case.

Initially, when the system is connected to the grid, the reactive load is fed from the grid, since both converters are set to provide zero reactive power while in grid following mode. However, when the islanding event occurs the reactive load is picked up by VSC$_1$ only since the control mode of VSC$_2$ does not change as a result of this event.

Moreover, the initial phase selection still has a great effect on the transient due to switching the VSC$_1$ control. For the active power and the DC side results for both converters, the system acts almost similar to the previous case with small differences in transients' values.

C. Case 3: Effects on Rotating Machine Load

Transients due to any interruption or switching event is not healthy for the power system, especially for sensitive loads. In fact, high transients can lead to severe oscillations on machine rated values such as torque, speed, or currents. Therefore, to illustrate this case, a low rated induction motor (IM) was connected in parallel to the 28 MW load to test its performance due to control mode switching of VSC$_1$ with and without initial phase selection control. The motor is rated at 3 hp, 220 V and 1725 rpm. During normal conditions, the total delivered power to the IM is 2.315 kW of real power and 1.945 KVAR of reactive power. As in Case 2, before switching, the real power demand is delivered by both PVs and the reactive power is delivered by the grid since both VSCs are regulated at zero reactive power. After switching, the reactive power demand is picked up by VSC$_1$ and the real power demand continues to be provided by both PVs where PV$_2$ provide its maximum and PV$_1$ provides whatever remaining demand within its capabilities. Figure 9 shows the effect of

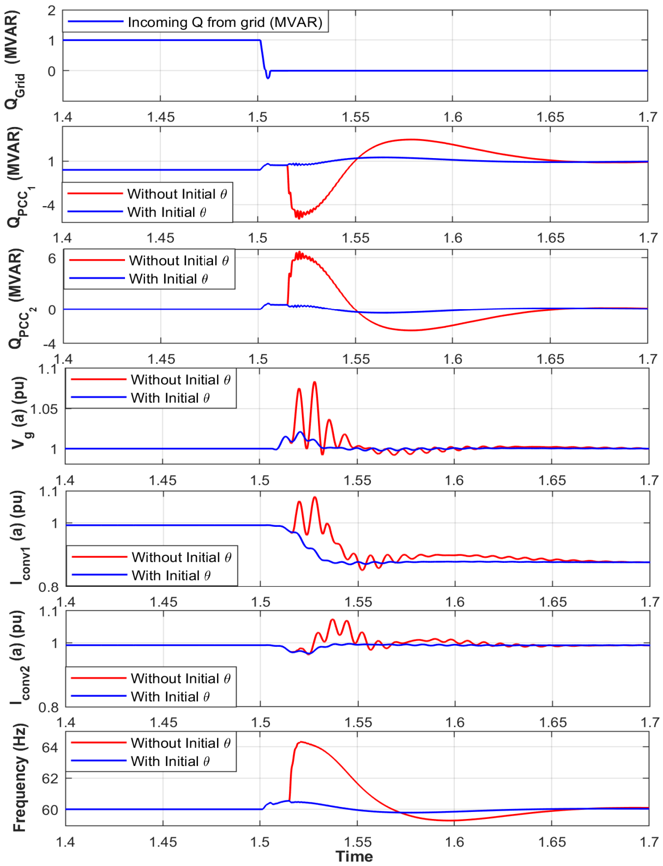


Fig. 8: Case 2 results.

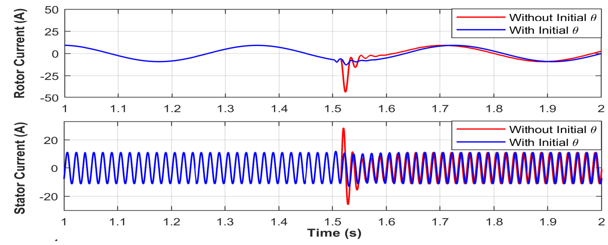


Fig. 9: IM rotor and stator currents.

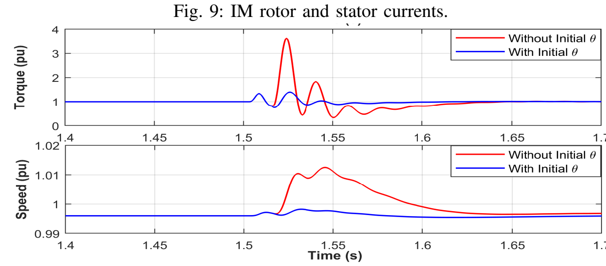


Fig. 10: IM torque and speed.

interruption and control mode switching on the rotor and stator currents. Obviously, the initial phase shift selection made a huge difference in the rotor and stator currents' reaction to the event. For instance, the initial phase of zero degree caused the rotor current to oscillate to around 150% of its peak value compared to a very small change in case of selected initial phase. Another effect of the disconnection and switching event is shown in Figure 10. The torque is greatly affected by the initial phase selection. A 2.5 pu transient in the torque is very damaging to the motor and lead to life shortening [13]. On the other hand, the speed of the motor showed a very small deviation from its nominal value compared to the case where there is no initial phase control.

V. Conclusion

This paper studies the dynamic response of a 30 MW grid connected PV system due to an accidental islanding event. The operation of two parallel inverters is examined during the islanding event, with one working in grid following mode while the other switching from grid following to grid forming. The effect of initial phase selection when switching between two control modes is presented and the results show the importance of this selection strategy and how the system dynamic response accordingly improved. The study takes into consideration different types of load and show the effect of this event on sensitive loads such as rotating machines.

References

[1] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power and Energy Magazine*, vol. 15, no. 2, pp. 61–73, 2017.

[2] Joint NERC and WECC Staff, "April and may 2018 fault induced solar photovoltaic resource interruption disturbances report southern california events: April 20, 2018 and may 11, 2018," January 2019.

[3] ——, "900 mw fault induced solar photovoltaic resource interruption disturbance report southern california event: October 9, 2017," February 2018.

[4] NERC, "1,200 mw fault induced solar photovoltaic resource interruption disturbance report southern california 8/16/2016 event," June, 2017.

[5] M. Mirhosseini and V. G. Agelidis, "Performance of large-scale grid-connected photovoltaic system under various fault conditions," in *2013 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, 2013, pp. 1775–1780.

[6] H. Mahmood, D. Michaelson, and J. Jiang, "Strategies for independent deployment and autonomous control of pv and battery units in islanded microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 3, pp. 742–755, 2015.

[7] Y. Karimi, H. Oraee, M. S. Golsorkhi, and J. M. Guerrero, "Decentralized method for load sharing and power management in a pv/battery hybrid source islanded microgrid," *IEEE Transactions on Power Electronics*, vol. 32, no. 5, pp. 3525–3535, 2017.

[8] L. Xu, Z. Miao, and L. Fan, "Control of a back-to-back vsc system from grid-connection to islanded mode in microgrids," in *IEEE 2011 EnergyTech*. IEEE, 2011, pp. 1–6.

[9] Y. Yang, K. Kim, F. Blaabjerg, and A. Sangwongwanich, *Advances in Grid-Connected Photovoltaic Power Conversion Systems*. Elsevier Science, 2018. [Online]. Available: https://books.google.com/books?id=vKNPDwAAQBAJ

[10] A. Yazdani and R. Iravani, *Voltage-sourced converters in power systems*. Wiley Online Library, 2010, vol. 34.

[11] L. Fan, *Control and Dynamics in Power Systems and Micrograds*. CRC Press, 2017. [Online]. Available: https://doi.org/10.1201/9781315269542

[12] H. Karimi, H. Nikkhajoei, and R. Iravani, "Control of an electronically-coupled distributed resource unit subsequent to an islanding event," *IEEE Transactions on Power Delivery*, vol. 23, no. 1, pp. 493–501, 2008.

[13] J. C. Gomez, M. M. Morcos, C. A. Reineri, and G. N. Campetelli, "Behavior of induction motor due to voltage sags and short interruptions," *IEEE Transactions on Power Delivery*, vol. 17, no. 2, pp. 434–440, 2002.