An Adaptive Synchronverter for Ensuring Fault Ride Through Capability of Grid-Connected Solar Power System

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Abstract. In recent years, the grid-connected solar power system has grown tremendously because of its cost-effectiveness and environmental friendliness. However, its interface to the existing power grid introduces frequency and voltage instability due to its lack of rotating mass and inertia response, unlike a conventional synchronous machine. To alleviate the limitations, a novel adaptive synchronverter is proposed to equip with fault ride through in a grid-connected solar power system. It enables continuous electricity generation even under overloading, voltage sag or short circuit fault. MATLAB®/Simulink simulations are conducted, and it is validated by emulated hardware by Typhoon® Hardware-in-the-loop (HIL) 402 real-time simulation. The results validated that the fault ride through capability enables the synchronverter to stay connected in short periods of lower electric network voltage.

1. Introduction

As the solar energy grows significantly over the last decades, it gains momentum to replace the conventional synchronous machine (SM)-based power generation from coal, oil and gas [1]. The transition towards grid-connected solar power system is mainly driven by the sustainable development goal (SDG), reduction in solar panel cost and its technological maturity. However, the static inverter-based solar power system deteriorates the grid frequency and voltage stability because it does not have any rotating mass and inertial response like an SM [2]. Any fault such as overloading fault, short-circuiting, sudden load change and voltage sag may result in electricity shortage due to sudden frequency drop. Recent researches on synchronverter focus on the application of solar power system without considering the variation of input solar irradiance ($E_b$) and temperature ($T$). In other words, the real-world environment has not explored for the synchronverter. Typically, an ideal constant DC source is used to fetch to the input of inverter instead of a real solar array with varying solar irradiance and temperature. Plus, the capabilities of FRT with LVRT and HVRT for a synchronverter are not equipped yet. The continuity of electricity is not guaranteed under any voltage sag or swell faults.

To overcome the aforementioned limitations, a novel adaptive controller is proposed to control a synchronverter in interfacing solar power system with the existing power grid. It aims to emulate the inertial response of an SM by using an adaptive controller. By using mathematical modelling of a second-order SM swing equation [3], the controller is able to inject or absorb the active and reactive power according to the variable moment of inertia ($J$) and damping factor ($D_P$). To improve its operability and power continuity, fault-ride through (FRT) capability comprising of low-voltage ride...
through (LVRT) and high-voltage ride through (HVRT) is equipped with the proposed synchronverter. The novel contributions of this paper include the following:

1) A novel adaptive controller is proposed to adjust the moment of inertia \((J)\) and damping factor \((D_p)\) for the balance of transient speed and operating stability of a synchronverter

2) The equipment of fault ride through (FRT) capabilities comprising of low-voltage ride through (LVRT) and high-voltage ride through (HVRT) enables the synchronverter to continue electricity generation even under faults

3) The operation of the proposed synchronverter is assessed under dynamic weather with varying input solar irradiance \((E_r)\) and operating temperature \((T)\) to emulate the real-world environment.

The rest of the paper is organized as follows. Section 2 covers the overview of the synchronverter modelling, operating mechanism and its applicability. Section 3 presents the methodology of the proposed adaptive controller for synchronverter with varying \(J\) and \(D_p\) by equipping with FRT, following by the Section 4: Results and Discussion which presents extensive case studies from MATLAB/Simulink simulation results and validation by Typhoon HIL 402 emulated hardware results. Finally, Section 5 concludes the novelty and result findings of the paper with future directions.

2. The Operating Mechanism of a Synchronverter

This section covers and discusses the standard operating mechanism of a synchronverter in a grid-connected solar power system. As the name suggests, synchronverter or known as synchronous inverter, virtual synchronous machine (VSM), virtual synchronous generator (VSG) [4], cybersync and grid-tie inverter, is a specialized inverter (DC-AC converter) that mimics the dynamic behaviours of a conventional SM [5].

2.1. The Mathematical Modelling of an SM

A synchronverter is a grid-friendly inverter based on the mathematical modelling of an SM [6]. The optimized DC output from solar array by maximum power point tracking (MPPT) DC-DC converter is fed to the input of inverter. The emulation of the inertial response of an SM is synthesized by the controller of synchronverter model [7]. It aims to adjust active power \((P)\) and reactive power \((Q)\) during the frequency and voltage fluctuation respectively [8]. At the output of synchronverter, a LC filter is used to attenuate the current and voltage ripples. The grid current and voltage are the major feedback measurements used for the synchronverter to regulate \(P\) and \(Q\) [9]. The output of the controller is a control signal \((e)\) to drive the PWM of switching devices [10]. The generated reference signals \(e_a, e_v\) and \(e_r\) represent the back EMF generated by moment of imaginary rotor. The general frequency and voltage droop are described mathematically by swing equation (1) and (2) respectively.

\[
P_{set} - P - D_P(\omega_r - \omega) = J\omega \frac{d\omega}{dt} \tag{1}
\]

\[
Q_{set} + D_q(v_r - v) - Q = K\frac{dE}{dt} \tag{2}
\]

The three essential equations that emulate the dynamic characteristic of a synchronous generator are defined in equations (3)-(5). The equation (6) that defines the frequency droop. The equation (7) that defines the voltage droop.

\[
e = \dot{\theta} M_f i_f \sin \theta \tag{3}
\]

\[
Q = -\dot{\theta} M_f i_f < i, \cos \dot{\theta} > \tag{4}
\]

\[
T_e = M_f i_f < i, \sin \dot{\theta} > \tag{5}
\]

\[
\dot{\theta} = \frac{1}{J_\phi} [T_m - T_e + D_p (\dot{\theta}_r - \dot{\theta})] \tag{6}
\]

\[
M_{bf} = \frac{1}{K_s} [Q_{SET} - Q + D_q (V_r - V_m)] \tag{7}
\]
2.2. The Fault-ride Through Capability
The fault-ride through (FRT) is a requirement for grid code to ensure the continuous connection of distributed generation (DG). The large fault inrush current threatens the safety of synchronverter, which possibly results in power electronic device faulty [11]. The protection system based on FRT is used to equip synchronverter with transient fault characteristic. The FRT capability is crucial for synchronverter to ensure the solar power system remains connected to the grid for a short transition time even under voltage sag or swell. It helps the stability of grid voltage and frequency during the public grid faults, apart from the ordinary features of synchronverter.

3. The Proposed Adaptive Controller for Synchronverter with FRT
This section presents the proposed adaptive controller for the synchronverter with FRT capabilities in grid-connected solar power system. The proposed synchronverter is equipped with the varying moment of inertia ($J$) and damping factor ($D_P$) to balance the need for transient speed and stability. The manipulation of $J$ and $D_P$ depends on the frequency measurement feedback. Low voltage ride through (LVRT) enables the solar power system to stay connected with the load during any transient fault by injecting reactive power ($Q$) to the power grid using the proposed synchronverter. The solar array used in the simulation and emulated hardware is a dynamic model with varying irradiance and temperature inputs. It is used to simulate the dynamic weather from the real-world environment. The point of common coupling (PCC) is connected to the power grid and resistive load. Table 1 presents the parameters of the proposed synchronverter.

| Parameter                  | Symbol | Value (Unit) |
|----------------------------|--------|--------------|
| Nominal active power       | $P_n$  | 10000W       |
| Nominal reactive power     | $Q_n$  | 10000VAr     |
| Filter inductance          | $L_f$  | 18.4mH       |
| Filter capacitance         | $C_f$  | 1μF          |
| Nominal frequency          | $f_n$  | 50Hz         |
| Switching frequency        | $f_s$  | 10kHz        |
| Frequency droop            | $\Delta f$ | 4% over 100% $\Delta P$ |
| Moment of inertia          | $J$    | 0.1 – 0.5 Kgm$^2$ |
| Damping coefficient (friction factor) | $D_P$ | 200-1000 Nms/ rad |
| Resistive load             | $R_{LOAD}$ | 1.2kW (80Ω) |
| Nominal AC angular speed   | $\omega_n$ | 314.16 rad/s |

4. Simulation and Emulated Hardware Results with Discussion
This chapter presents the extensive MATLAB/ Simulink simulation and Typhoon HIL 402 emulated hardware real-time simulation results. To validate the effectiveness and feasibility of the proposed adaptive synchronverter in a grid-connected solar power system, MATLAB/ Simulink simulation is configured and setup. After the simulation, an emulated hardware real-time simulation based on Typhoon HIL 402 is also executed to validate the simulation results.

4.1. MATLAB/ Simulink Simulation
The proposed synchronverter is modelled in MATLAB/ Simulink simulation R2020a to study its dynamic behaviour. As illustrated in Figure 1, the simulation environment is a grid-connected solar power system with a resistive load. The proposed synchronverter controller used two feedback
measurements, namely $V_{ABC}$ and $I_{ABC}$, which are the three-phase voltage and current at PCC. The output is the PWM to drive the switching devices of IGBT.

The DC link voltage from the output of solar array under dynamic weather is illustrated in Figure 2. The variation of irradiance and temperature contributes to the noises and sudden dip from $t = 0.5s$ to $1.5s$, indicating there is the occurrence of partial shading condition (PSC) whereby the irradiance has been reduced. Figure 3 presents the operating frequency of the synchronverter under dynamic weather. From $t=1$ to $t=2$, due to overloading and sudden voltage drop of DC link due to PSC, the frequency of synchronverter drops to 49.95Hz by -0.1%. At $t=3s$ and $8s$, there are underloading occurrences which caused the frequency to increase to 50.12Hz by +0.24%. It indicates that the dynamic weather and loading condition is the affecting factor to the variation of frequency, and thereby it affects the stability of frequency at the AC power grid.

In response to the frequency variation, the synchronverter acts as a buffering device to intelligently manipulate the voltage and current for the injection or absorption of active power and reactive power. Figure 4 depicts the voltage and current outputs at PCC. During there is overloading, the active power is injected to ensure the frequency back to the nominal value at 50Hz, as shown in Figure 5. It is because when there is an occurrence of overloading, more active power is required to drive the additional load, hence if there is no active power injection, the frequency will drop and thereby causing power instability issue at AC power grid. On the contrary, the reactive power $(Q)$ injection is observed in Figure 6 by synchronverter, to reduce the voltage swell at $t = 3s$ and $t = 7s$. 

![Figure 1. The MATLAB/Simulink simulation.](image1)

![Figure 2. DC link voltage of solar array output under dynamic weather.](image2)

![Figure 3. The frequency output of synchronverter at PCC.](image3)
4.2. Typhoon HIL 402

In order to validate and verify the simulation result, Typhoon HIL 402 is used to emulate the real-time hardware result as presented in Figure 7 (a). The emulated supervisory control and data acquisition (SCADA) control panel is used to control, manipulate and observe the emulated hardware, as illustrated in Figure 7 (b). Figure 8 presents the non-linearity of I-V and P-V curves of the solar array.

![Figure 4. AC voltage and current outputs of synchronverter at PCC.](image1)

![Figure 5. The active power (P) output of the synchronverter at PCC.](image2)

![Figure 6. The reactive power (Q) output of the synchronverter at PCC.](image3)

(a) The schematic of Typhoon HIL real-time simulation and (b) The control panel of SCADA for HIL real-time simulation.
Figure 8. The characteristic curves of: (a) I-V and P-V in Simulink and (b) I-V and P-V in HIL.

As illustrated in Figure 9 (a), the LVRT capability of synchronverter is demonstrated by ensuring the continuity of electricity. At t = 5.5s, there is an emulated voltage sag fault. However, the synchronverter recovers back to its normal operation. The results showed that the synchronverter stay connected and supportive during the transient fault. On the contrary, in Figure 9 (b), the HVRT capability of synchronverter is presented. There is a voltage swell occurred at t = 4s, but the synchronverter is able to contain the fault and continuously provide the AC electricity to the grid. Even though the LVRT and HVRT are not able to recover back to its maximum nominal output value, the results indicated that the synchronverter is able to recover back and at least stay connected with minimum voltage support to the grid. Figure 10 (a) and (b) shows the injection and absorption of reactive power (Q) to support the voltage sag and swell respectively. Overall, the proposed synchronverter is able to demonstrate FRT capability while operating as a normal synchronverter to ensure power stability.

Figure 9. The current, voltage, DC link current and grid voltage at the PCC under: (a) voltage sag and (b) voltage swell.

Figure 10. The reactive power response of synchronverter under: (a) voltage sag and (b) voltage swell.
5. Conclusion

This paper presents an adaptive synchronverter with FRT capabilities to interface the solar power system with the power system. Both MATLAB®/Simulink simulation results and Typhoon® HIL 402 emulated real-time hardware results show mutual validation for the effectiveness of the proposed synchronverter. The FRT capabilities ensure the continuity of electricity while preserving the inertia response for power stability. In the future, virtual inertia (VI) will be the standardized ancillary service for the modern power system, especially in the high penetration of renewable energy sources (RES). Future synchronverter should be smarter and support FRT capabilities. The synchronverter acts as an important grid-interfacing device to harmonize and synchronize all sources and load that involve the bidirectional AC-DC or DC-AC conversion. The future areas include electric vehicle (EV), vehicle-to-grid (V2G), energy storage system (ESS) comprises of battery, supercapacitor and ultracapacitor, wind and solar energy integration and high voltage direct current (HVDC).

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