Development of a synchronverter for a grid connected photovoltaic system

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Abstract. As global population has grown exponentially since the past decade, the demand for a sustainable framework for cleaner, greener and stable energy production is becoming more important for a holistic society. Among multiple renewable energy sources, solar power is highly favoured to dominate the market due to improvements in solar energy conversion efficiency and reduction in production cost. Thus, many transmission grids will observe a high penetration of inverters as an interface between solar panels and the AC transmission grid. Consequently, inverter-dominated transmission grid will face issues with maintaining and achieving overall grid stability due to the characteristics of inverters which are composed of mainly solid state devices (SCR, MOSFETS or IGBTs). This is due mainly to the lack of rotational inertia, which is typically contributed and maintained by traditional synchronous generators when the stability of the transmission grid is disturbed. For this reason, conventional inverters can potentially be exploited to mimic the characteristics of synchronous generators to stabilize the transmission grid. Thus, this project is motivated to design a ‘smart’ inverter or synchronverter which can operate on islanded mode while integrated with solar panels. This project focuses on developing and prototyping a working three-phase inverter model using a Raspberry Pi microcontroller with Simulink support. Bipolar Sinusoidal Pulse Width Modulation (SPWM) technique is used to create the sinusoidal output waveform with a fixed frequency of 50Hz. The output waveform will also have a Total Harmonic Distortion (THD) of less than 5%. A Proportional-Integral (PI) controller is also implemented to ensure that amplitude and frequency of output sinusoidal remains constant. In this work, simulation of a three-phase inverter is done using Simulink (MATLAB) to validate the performance of the inverter (hardware prototype). The developed hardware prototype is experimentally tested by integrating with 1000W solar panels.

1. Introduction
The traditional transmission grid is commonly powered by synchronous generators that control the grid parameters and damps any unwanted oscillations. Recently, the penetration of renewable power sources, such as solar power, are given a higher priority due to cleaner energy production and cheaper photovoltaic (PV) solar panel manufacturing cost. But, solar panels generate Direct Current (DC) Power which incompatible with an Alternating Current (AC) grid, thus an inverter is required to integrate solar panels with transmission grids. Inverters differ from traditional synchronous generators because inverters are composed of solid state components, which means inverters do not possess mechanical inertial characteristics as exhibited by a rotational synchronous generators. This leads to
higher frequency instability as the transmission grids transition from a rotational-dominated system to an inverter dominated system. Thus, there is a strong need to develop a 'smart' inverter that is able to provide 'virtual inertia' for the grid during critical situations, synchronize with the grid without a PLL and predict the optimal entry points to inject real and reactive power.

Synchronverters are inverters that mimic synchronous generators. The basic groundwork that models the mechanical aspect of a synchronous generator has been developed [1]. Their work has proven that synchronization of a synchronverter is successful through simulation and experimentation with a low-voltage prototype. Their work shows that grid synchronization occurs smoothly, without any transients for grid frequencies that are lower and higher than the grid frequency (i.e. 50Hz in many countries). Synchronverters also exhibit pre-set real and reactive power tracking, with a response time of less than 1s. Their results show a sudden spike in frequency but stabilizes immediately after. P drooping and Q drooping methods also show spikes, which stabilizes immediately after. Furthermore, Weiss' and Zhong's work was adapted to develop PV Synchronverter that integrates with the grid [2]. Their work includes a MPPT to generate highest power output which is conditioned to be suitable for grid connection. But, their work was proven with MATLAB simulation, but lack experimental results. [3]

An improvement on the traditional Synchronverter technology is to improve the Synchronverter controller to include virtual impedance. Virtual filter inductance was increased by modifying the control algorithm to improve stability of the system. A virtual capacitor in series with the inverter outputs is also introduced to shunt DC components from entering the grid. Furthermore, an improved field current controller, which uses an anti-windup mechanism and the new formula for reactive power will improve stability of grid-connected synchronverter, but this improvement operates under a few assumptions. A comparison of performance of inductor and resistance values of 5 times greater than original and 25 times greater shows that a higher value will remove high-frequency fluctuations by 3 times when there is a dip in grid voltage and twice when there is a voltage drop across a phase. [4]

A traditional inverter or Synchronverter relies on a Phase Locked Loop (PLL) synchronizing unit to connect to the main grid. Improvement have been made to remove PLL units which allows Synchronverters to self-synchronise with the grid. This improves performance of the synchronverter and reduces computational burden on the control system. Experimental results shows that the synchronizing unit improves performance of real and active power control by 83% and 70% respectively. Frequency tracking of grids before and after connections also improved by 65%. Lastly, code size of control program reduced by 71.1% and average execution time is reduced by 19.2%. [5]

Further improvements have been introduced to develop a Synchronverter that restricts its frequency and voltage to a given range. This improvement is parameterized and ensures that the Synchronverter is always stable and converges to a unique equilibrium, provided power exchange at the terminal is kept within this area. The proposed work assumes a stiff grid to derive the existence condition of an equilibrium point. Simulations have shown that frequency and voltage remains in tight bounds even with the effect of grid voltage variation. [6]

Improvements on Synchronverters has been largely focused on control algorithm of the original strategy. The current system also heavily depends on the current status of the main grid for connection conditions. With the improvements on data collection units, a database of grid conditions can be generated and stored over long periods of time. Thus, there is a potential to study and develop prediction models to improve Synchronverter operations. Artificial Intelligence (AI) is a useful tool to study and develop models which is able to evolve the current Synchronverter system to better predict faults conditions and failure. But, there has been minimal research on applying AI control methods to develop and evolve the current Synchronverter control. With a proper AI control method, the Synchronverter will be better able to predict changes in the grid and respond appropriately.

Thus, we are motivated to develop a low-cost, low-voltage, 3-phase inverter that is able to integrate with the grid and control real and reactive power flow from DC sources. The inverter will be controlled by a Raspberry Pi with MATLAB Simulink, and be integrated with solar panels. The output of the inverter will be a 50Hz sine wave with a total harmonic distortion (THD) of less than 5%.
voltage ripple of less than 10% and current ripple of less than 5%. Response time of closed loop system will be less than 1 second for any sudden changes in reference wave.

The rest of the paper will be organized as follows. Section 2 will review the working principles of Synchronverter control Section 3 will discuss the methodology of this report. The results will be presented and discussed in Section 4 and the report is concluded in Section 5.

2. Working Principle of a Synchronverter
Synchronverter is an inverter that mimics the inherit characteristics of a synchronous generator. The Synchronverter will also inherit the advantages and disadvantages of a synchronous generator, but a Synchronverter can dynamically select physical parameters, such as inertia, friction coefficient, field inductance and mutual inductances. This means that the synchronverter can mimic and enhance any mechanical losses experienced by a normal synchronous generator. Most synchronverter technology have similar designs and operations, based on the work of Zhong and Weiss [1]. But, there have been improvements on the original designs over the years. For example, self-synchronisation without PLLs [7], improved stability with virtual capacitors, virtual inductors and anti-windup [4] and introducing bounded voltage and frequency ranges to improve stability [6]

![Figure 1. Three-Phase Inverter Layout.](image)

The power part or the electronic components of a synchronverter is shown in figure 1. The schematic diagram shows a three-phase inverter, with a switching circuit that is controlled and composed of power transistors (e.g. MOSFETs) which is filtered with a LCL filter and connected to the grid via a circuit breaker. PWM signals which are generated by control unit of the synchronverter controls the operational state of the transistors.
The Synchronverter controller scheme is shown in figure 2. The control scheme incorporates both frequency drooping and voltage drooping techniques to regulate real and reactive power respectively. The proposed control scheme also relies on a PLL for the amplitude detector as shown in Figure 2. A PLL is still required to measure grid parameters which is transmitted to the Amplitude Detection block as shown in figure 2.

Real power reference are defined by $P_{set}$, which varies in proportion to the load. Frequency droop method attempts to reduce error between virtual angular speed, $\dot{\theta}$ with nominal angular frequency of grid, $\theta_r$ (which would normally be equal to nominal angular frequency of the grid $\theta_r$). The error is multiplied with the damping factor, $D_p$, and summed with the difference between mechanical torque, $T_m$, and electrical torque, $T_e$. $\dot{\theta} = \frac{\partial}{\partial \theta} M_f i_f \sin \theta$

Reactive power reference, defined by $Q_{set}$, also has similar regulation methods with voltage drooping techniques. The difference between reference voltage, $V_r$, and amplitude, $V_m$, of the feedback voltage, $V_f$, (which would normally be grid voltage), is amplified with the voltage drooping coefficient, $D_q$. This value is subtracted from difference between $Q_{set}$ and reactive power, $Q$.

![Synchronverter Control Scheme Layout](image)

**Figure 2.** Synchronverter Control Scheme Layout.

\[
T_e = -M_f i_f \left( i, \frac{\delta}{\delta \theta} \cos \theta \right) = M_f i_f \left( i, \frac{\delta}{\delta \theta} s \sin \theta \right) \\
e = \dot{\theta} M_f i_f \sin \theta \\
P = \dot{\theta} M_f i_f \left( i, s \sin \theta \right), Q = -\dot{\theta} M_f i_f \left( i, \cos \theta \right)
\]

Constants in equation (1), (2) and (3) are defined below:

\[
i = \text{Stator Phase Current} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}
\]

\[M_f = \text{Mutual Inductance}, T_e = \text{Electromagnetic Torque}\]

\[
c \cos \theta = \begin{bmatrix} \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix}, s \sin \theta = \begin{bmatrix} \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix}
\]

\[e = \text{Electromotive Force} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}\]
(calculated from equation (3), is passed to an integrator to generate armature reaction, $M_{dr}$, which is then passed to equations (1-3) to generate PWM signals.

Virtual inertia is introduced by altering $D_{qr}$, which is designed to cater to grid requirements [8]. Real and reactive power can be changed over time to meet the changes in load requirements. Output voltage and frequency of the synchronverter can also be adjusted to meet load requirements or for protection setting purposes.

3. Methodology

The closed-loop setup for a three-phase inverter is shown in figure 3. The solver used was ode23tb with a max step size of 1μs. The DC input voltage is fixed at 30V.

PI controller gain is tuned using the Zigler-Nichols method [9]. The initial proportional gain was selected and adjusted until the output amplitude matches the reference. This allows us to adjust the integral gain to ensure that the inverter output matches the reference with different load types.

The switching frequency was selected given that a higher switching frequency will push harmonic frequencies to a higher value. This allows design of the low-pass filter circuit to utilise capacitor and inductors with smaller capacity. A sinusoidal signal with a frequency of 50Hz is used as the reference voltage and the triangular wave frequency was set to be 200 times the reference signal frequency which is 10kHz. The cut-off frequency which is the product of the switching frequency and signal frequency approximates to 707Hz is used to design the low pass filter. The cut-off frequency is much higher than the reference signal frequency, which makes it easier to filter higher frequency components.

![Figure 3. Simulink Layout for Closed-Loop Three-Phase Inverter Simulation.](image-url)
The inverter prototype, shown in figure 4, which is powered by a DC power supply supplying 31.3V. The Raspberry Pi microcontroller measure voltage and current from the sensors and generate a PWM signal which is transmitted to the gate drivers. The gate drivers then determine the on-off state of the Power MOSFETs. The Simulink layout which generates the PWM signal is shown in figure 5. Since Raspberry Pi does not have on-board Analogue-to-Digital Converter (ADC), an external device with Serial Peripheral Interface (SPI) is utilised.

4. Results
This section presents measurements from both simulation results and Synchronverter hardware prototype. Results shown presents the Synchronverter output for different load types. Figure 6 shows simulation results of the output from a three-phase inverter based on the Simulink layout shown in Figure 3.
It is observed that phase voltage waveforms are 120° shifted from each other in figure 6. Peak voltages are maintained for 3 cycles, with minimal distortion to their signals. Voltage ripple is kept to a minimum and THD values are approximately 2%, which meets our targeted requirements.

As shown in Figure 7, the output voltage is similar to the reference voltage under different load conditions. There is minimal distortion shown for resistive loads, capacitive loads and resistive and reactive loads. But, purely inductive loads shows slight distortion due to the filter circuit. The proportional gain is slightly altered to maintain output stability as shown in Table 1.

### Table 1. Power Load Requirement for all Simulation Cases.

| Scenario             | Real Power Load (W) | Reactive Power Load (VAR) | Proportional Gain | Integral Gain |
|----------------------|---------------------|---------------------------|-------------------|---------------|
| Resistive Load       | 5                   | 0                         | 2                 | 0.01          |
| Inductive Load       | 0                   | -5                        | 0.5               | 0.01          |
| Capacitive Load      | 0                   | 5                         | 2                 | 0.01          |
| Resistive and Reactive Loads | 2.5             | 2.5                       | 2                 | 0.01          |

Next, the inverter prototype is developed as shown in Figure 4 and the output is probed and recorded with an oscilloscope. The results shown in Figure 8 is replotted via MATLAB and analysed.
Figure 8. Inverter Operation in Real-time.

The results shown in figure 8 shows the three-phase voltage output from the inverter hardware. The results have slight distortion, while the signal waveform is maintained continuously. The amplitude of the signal reaches its target with the PI controller, but the signal frequency has dropped to 2.5Hz, which is a huge drop from the expected 50Hz.

The THD for the signal waveform shown in Figure 8 is -3.0977dB or 62.3897%, which is much higher than the targeted THD tolerance. The high THD value is due to the low frequency of the output signal. Thus, THD calculations includes higher order harmonics multiples of the fundamental frequency (i.e. harmonics at 5Hz, 7.5Hz, 10Hz, etc.) . These higher order harmonics may also contain low-frequency noise which deterioates signal quality, thus resulting in a higher THD value.

A limitation on the current setup with Simulink and Raspberry Pi is the long computational time required to generate the PWM. This is mostly due to Simulink attempting to improve calcualtion accuracy and thus results in slower operational output. Future works will include attempting to increase computational time which allows for higher switching frequencies and better inverter signal output. Reducing computational time will also better integrate the Synchronverter algorithm through Simulink.

5. Conclusion
This paper has presented a simulation of a three-phase inverter and shown that a hardware prototype is feasible to be developed with a microcontroller and Simulink. Therefore, Synchronverter control can be easily established with Simulink to control the output of the inverter which can be interfaced with an islanded grid.

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