A PWM Controller of a Full Bridge Single-Phase Synchronous Inverter for Micro-Grid System

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Abstract. Nowadays, microgrid system technology is becoming popular for small area power management systems. It is essential to be less harmonic-distortion and high efficiency of the inverter for microgrid applications. Pulse width modulation (PWM) controller is a conventional switching control technique which is suitable to use in the microgrid connected power inverter system. The control method and algorithm of this technique are challenging, and different approaches are required to avoid the complexity for a customized solution of the microgrid application. This paper proposes a comparative analysis of different controller and their operational methods. A PWM controller is used to reduce the ripple voltage noise while a continuous current mode provides a small output ripple which gives steady-state error as zero on fundamental and cutoff frequency. To reduce the ripple current, higher frequency harmonic distortion, switching loss and phase noise, LC low pass filter is used on either side of input and output terminals. The proposed inverter is designed by MATLAB 2016a simulation software. A balanced load resistance (RL = 20.5 Ω) of star configuration and a dual input DC voltage of ± 35V are considered. In this design, the circuit parameters, the fundamental frequency of 50 Hz, the PWM duty cycle of 95%, the cutoff frequency of the switching controller of 33 kHz are considered. The inverter in this paper exhibits THD of 0.44% and overall efficiency approximately of 98%. The proposed inverter is expected to be suitable for microgrid applications.

1. Introduction
The microgrid connected inverter can be found as both half-bridge and full-bridge configurations. While the voltage and current range are a small one cover, usually utilized in uninterruptible power supplies, high-power static power topologies, short-long distance transmission and distribution systems, islanding systems and power supply systems [1]. A half-bridge inverter (voltage source) generates an output of the square wave signal for a resistive load with single-phase. The resistive load is connected to the two-capacitor midpoint [2]. The inverters have simple switching technique to operate at much lower frequency compared to others inverter. On the other hand, a single phase full bridge inverter comprises of a couple of terminals which are connected with two IGBT switches. The parallel freewheeling diode is connected to each IGBT to pass the current in terms of different loads [3]. Additional diodes are employed to direct the load current when resistive-inductive loads are used. These diodes deliver an alternative way to deliver the inductive current is directed by these additional diodes when turn ‘OFF’ condition is occurred. A typical inverter control strategy is a sine-triangle, pulse width modulation (SPWM) control [4]. By SPWM control, the inverter of the semiconductor
switch regulated in funding for an analysis of a sinusoidal wave signal and a triangular switching signal. The sinusoidal regulated waveform secures the required fundamental frequency through the output. Meanwhile, the triangular waveform builds the switching frequency of the circuit [5]. The proportion between the frequencies of the sinusoid and the triangle wave also is indicated because of the alteration percentage of the frequency. However, the reference waveform might be available in a completely different form to suit the inverter topology, for example, sine wave and twisted sine wave. A sinusoidal waveform may be utilized for PWM as a part of input DC to output AC inverter wherever it is utilized to form the AC voltage to be near to a sine wave [6].

The PWM could be a technique that is described by the generation of steady amplitude pulse by adjusting the duty cycle through balancing the pulse length of time. A PWM controller simply involves the generation of both carrier signals, and a reference signal which is sustained into the comparator devices and created by logical and absolute output is provided [7]. The referred signal (output frequency) may be a square wave. The carrier signal could also be a triangular wave into the frequency completely more observable rather than the reference signal. These signals are utilized as a part of the primary PWM control techniques such as the single, multiple and sinusoidal PWM system. The single PWM has generated a standard output gate pulse every one-half cycle. The output signal has modified by unsteady the size of the pulse [8]. The reference signal between a rectangular reference signal and a triangular reference is twisted by the gate signal. The two signs are approximately equivalent to the frequency. Multiple modulation systems around various quantities of pulses every one-half cycle and all pulses are of equal size. The output signals have created through matching a reference which is a rectangular and triangular references wave. The reference signal frequency generated the carrier frequency and output frequency [9]. Whereas, the sinusoidal modulation approach is the smaller size of pulse output for every half cycle and the individual pulses are measured. This size of every single pulse shifts by 180° out of phase with the measured sinusoidal wave.

The current controllers can reduce the harmonics on the output filter inductors while the voltage controller must decrease the harmonic voltage on the capacitors. However, the harmonics of the current and voltage that result from PWM switching can be lowered not by a controller but by a lowpass LC output filter [10]. The LC filters decrease outcome can improve by reducing the filter cutoff frequency compared to the inverter switching frequency. But, the cutoff frequency has confined the inverter control bandwidth. Improving the bandwidth is significant not only for inverter system operation, but also for specific voltage restitution without a phase delay at maximum harmonics. Therefore, there is a trade-off between the control bandwidth and the reduction effect in the design of the output LC filter [11].

This paper has proposed a PWM based, full bridge single phase PSI for transformer fewer microgrid systems to improve switching loss and minimize the attenuation effect. Although, considering the LC lowpass filter are used to decrease the ripple current exceed problem without reducing the damping performance of the inverter systems. Based on the study, a new controller design method that assurance steady state control methods and that reduces the switching loss and ripple current has proposed. This technique improves the switching loss and decreases the switching delay. In turn, the controller response in transient condition is further improved by this technique.

2. Design of single-phase H-bridge PSI systems
The planned single-phase PSI circuit is presented in figure 1. Here, the output terminal voltage of the bridge, \( V_a \) and \( V_b \) are proportionally related to the DC input voltage and the inverter duty cycle. The voltage can have any value of \(+V_{DC}\), \(0\) or \(-V_{DC}\) which is determined by the controlling signal of switches. It is noteworthy that the switches in a leg cannot be turned on simultaneously in order to prevent short circuit across the DC source. Precisely controlling the switch is the primary challenge; therefore, PWM technique is used to create the proper gate signal which has done by controlling the phase of an output signal with a specific frequency.
Figure 1. Block diagram of a PSI system

Also, a low pass filter is used to filter out the high-order harmonics and the switching harmonics of the output signal. It is observed that the filter size depends on cutoff switching frequency, modulating voltage and current, fundamental frequency and phase angle. The switching loss depends on the filter designed with different values of inductor and capacitor. The state space expressions of full-bridge PSI are presented in equations (1) and (2) [12].

\[
\begin{bmatrix}
i_L(t) \\
v_c(t)
\end{bmatrix} = \begin{bmatrix}
\frac{Z(R_L+R_C)-R_LR_C}{L(Z+R_C)} & -\frac{Z}{L(1+\frac{DC}{2})} \\
\frac{1}{C(1+\frac{DC}{2})} & -\frac{1}{ZC(1+\frac{DC}{2})}
\end{bmatrix} \begin{bmatrix}
i_L(t) \\
v_c(t)
\end{bmatrix} + \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix} V_{AB}(t)
\]

(1)

\[
V_{OUT} = \begin{bmatrix}
\frac{ZR_C}{Z+R_C} & \frac{Z}{Z+R_C}
\end{bmatrix} \begin{bmatrix}
i_L \\
v_c
\end{bmatrix}
\]

(2)

Here, a state variable \(i_L\) denotes the inductor current and another state variable \(v\) denotes the capacitor voltage. The load impedance \(Z\) and full-bridge voltage \(V_{ab}\) are defined by equation (3).

\[
U(t) = \begin{cases}
1 & V_{AB}(t) = +\frac{V_{DC}}{2} \\
0 & V_{AB}(t) = 0 \\
-1 & V_{AB}(t) = +\frac{V_{DC}}{2}
\end{cases}
\]

(3)

3. Pulse width modulation controller

The PWM controller is the most popular method of using carrier-based modulation technique. In PWM technique, the carrier signal with a high frequency and triangular shape are superpositioned on the reference sinusoidal signal. The carrier-based PWM technique is less complex and it provides a dynamic response which is suitable for PS inverter [13]. The switching ratio \((SW_r)\) of the PWM technique has been given in equations (4) and (5).

\[
SW_r = \frac{\text{Carrier Wave Frequency}}{\text{Output Voltage Frequency}}
\]

(4)
SW, is related to harmonic frequency, and the harmonics have standard located at:

\[ f_c = kSWRf_m \]  \hspace{1cm} (5)

In equation (5), the frequency of the modulating signal is termed by \( f_m \) and \( k \) is an integer (1, 2, 3...). Furthermore, modulation index \( (M_i) \) is found by the ratio of the amplitudes of the modulating reference signal \( (A_r) \) and the carrier signal \( (A_c) \). This is expressed by,

\[ M_i = \frac{A_r}{A_c} \]  \hspace{1cm} (6)

The PWM controller modulation signal is applied to control the phase of the inverter. This is illustrated in figure 2.

\[ \text{Switching ref & carrier signal} \]

\[ \text{Line to Line inverter output Voltages} \]

\[ \text{Phase Voltages} \]

\[ \text{Time (S)} \]

\[ \text{Figure 2. The modulation signal of a PWM controller} \]

In figure 2, initial phase angles of the reference and the first carrier are considered as zero. On the basis of the relation expressed by equations (7) and (8), the generated voltage by every half-phase from the middle of the DC link is:

\[
V_A(t) = \frac{V_{DC}}{2} \left[ \frac{M}{2} \cos(\omega_1) + \sum_{m=1}^{+\infty} \frac{2}{m\pi} J_0 \left( \frac{m\pi M}{2} \right) \sin \frac{m\pi}{2} \cos(m\omega_c t) \right. \\
+ \sum_{m=1}^{+\infty} \sum_{n=\pm1}^{+\infty} \frac{2}{m\pi} J_n \left( \frac{m\pi M}{2} \right) \frac{\sin (m + n)\pi}{2} \cos(m\omega_c t + n\omega_1 t) \right]
\]  \hspace{1cm} (7)
\[ V_B(t) = \frac{V_{DC}}{2} \left[ \frac{M}{2} \cos(\omega_2 t) + \sum_{m=1}^{+\infty} \frac{2}{m\pi} J_0 \left( \frac{m\pi M}{2} \right) \sin \left( \frac{m\pi}{2} \cos(m\omega_c t - \pi) \right) \right. \]

\[ + \sum_{m=1}^{+\infty} \sum_{n=\pm 1}^{+\infty} \frac{2}{m\pi} J_n \left( \frac{m\pi M}{2} \right) \sin \left( \frac{(m+n)\pi}{2} \cos(m\omega_c t + n\omega_1 t) \right) \]

Like the case of full bridge phase synchronous inverters, harmonic cancellation between \(i_{L1}\) and \(i_{L2}\) can be considered the basis of the higher frequency harmonic cancellation voltage between \(v_1\) and \(v_2\). By observing the above comparison between a couple of expressions, it is found that the entire odd harmonics and their side-bands of the carrier are cancelled out through interleaving. Furthermore, it is observed that the amplitudes of each even-order harmonic become zero. Consequently, only the harmonic of \(v_1(t) + v_2(t)\) remains as the sideband component with odd-order regarding the carrier harmonics with even-order. This relationship is presented in equation below,

\[ \frac{4V_{DC}}{2} \sum_{m=2,4,...}^{+\infty} \sum_{n=\pm 1, \pm 3,...}^{+\infty} \frac{1}{m} J_n \left( \frac{m\pi M}{2} \right) \sin \left( \frac{(m+n)\pi}{2} \cos(m\omega_c t + n\omega_1 t) \right) \]

The relationship with the ripple cancelation principle expressed in equation (9) is extendable for parallel or series inverters of any number as \(N\). This can be characterized by using the harmonic scaling factor [14]:

\[ K_m = \frac{1}{N} \sum_{k=1}^{N} e^{im\theta_{ck}} \]  

Here, \(K_m\) is the scaling factor which permits the combined harmonic spectrum of \(N\) parallel or series inverter to select a single inverter through multiplying harmonics by \(N_{km}\). Figure 3 shows the PWM MATLAB circuit diagram of full bridge PSI inverter system.

4. The PSI switching topology
Figure 4 shows that the full bridge PSI, which comprises of two input and output terminals, IGBT switches, lowpass \(LC\) filter and microgrid resistive load. IGBT switches are controlled by the PWM gate pulse signal to reduce switching loss and phase delay. The lowpass \(LC\) filter is used to convert the
sinusoidal wave and to reduce THD and synchronize the phase between the inverter and microgrid. In this system, two half phases are connected in parallel, which operates at 1.65 kHz of the carrier frequency, 95% of the duty cycle and 50 Hz of the fundamental frequency. However, switching performance significantly depends on the intrinsic parameters of the switches. In this IGBT switches, 1.6e5 Ω of the snubber resistance ($R_s$), 0.001 Ω of the internal resistance ($R_{on}$) and 1e-6 µF of the snubber capacitance ($C_s$) are assumed.

![Figure 4. Full bridge PSI circuit](image)

The inverter takes an input DC voltage, then transforms to sinusoidal AC voltage along with same microgrid frequency. There are four switching states $S_1$, $S_2$, $S_3$ and $S_4$ have presented in Table 1. The semiconductor switches in every branch should work on the opposite hand means they are not in the similar mode of operation (ON/OFF) particularly at the same time. Besides that, each switch remains OFF for a little period known as blanking time to avoid short-circuiting.

| Table 1. Switching states of the PSI |
|-------------------------------------|
| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $V_A$ | $V_B$ | $V_{AB}$ |
| ON   | OFF  | OFF  | ON   | $V\over2$ | $V\over2$ | +V       |
| OFF  | ON   | ON   | OFF  | $-V\over2$ | $-V\over2$ | -V       |
| ON   | OFF  | ON   | OFF  | $V\over2$ | $-V\over2$ | 0        |
| OFF  | ON   | OFF  | ON   | $-V\over2$ | $V\over2$  | 0        |
However, $S_1$ and $S_2$ switches should work in a pair to get the inverter output and $S_3$, $S_4$ also made another pair. These legs have switched such an OFF and ON conditions that the output voltage and current have moved from one to another and therefore the shift in polarity follows in voltage waveform. If the movement angle is zero, the voltage output is additionally zero and maximal after change plot is ‘$\pi$’.

5. **Output filter design**

Figure 5 shows an $LC$ type of lowpass filter, a circuit that consists parameters of inductor and capacitor. The proper value of that parameter has needed in creating an $LC$ filter.

![Figure 5. Output LC filter](image)

**Inductor Selection:** The inductor is utilized to cut off current swell. The estimation of inductor depends on the passable swell current of the inductor. Then again, the swell current of the inductor is due to PWM switching (15). Determining the value of the inductor has done by the following equations:

$$L = \frac{V \times dt}{di}$$  \hspace{1cm} (11)

$$L = \frac{2 \times V_{dc} \times D_{max}}{\Delta I_{max} \times f_c}$$  \hspace{1cm} (12)

Where, $L$ is the output filter inductor, $V_{dc}$ is the input DC voltage, $f_c$ is the switching frequency, $\Delta I_{max}$ if the permissible ripple current and $D_{max}$ is the duty cycle maximum.

**Capacitor selection:** The capacitor value depends on the peak values of the inverter; focuses the measurement of the ripple voltage of the output [7]. Essentially, the capacitor output retains the greater part of the ripple in the inductor current. The ripple voltage can be found out by

$$\Delta V_{out} = \Delta V_c$$  \hspace{1cm} (13)

$$\Delta V_{out} \approx \frac{\Delta I_L}{C \times f_s} + r_{ESR} \times \Delta I_L$$  \hspace{1cm} (14)

Where, $\Delta V_{out}$ is the output voltage ripple, $\Delta I_L$ is the ripple current of the inductor and $r_{ESR}$ is the capacitor equivalent series resistance. Figure 6 shows the LC lowpass filter phase response waveform.
6. Simulated result and discussion
To solve this problem, of four IGBT/Diodes has used (Figure 4) that relates to output filter and microgrid. Besides that, proposed design can work as a single phase VSI design and make parallel and series resonant, based on the inverter. In this system have been used two level IGBT/Diode, carrier frequency 1.6625 kHz, micro-grid frequency 50 Hz, input voltage ± 35 V<sub>DC</sub>, simulation time = 0.1s and modulation index 0.95, etc.

Simulated results of the proposed PSI circuit (without filtering condition). It is seen that the output voltage <i>V<sub>ab</sub></i> is achieved about 138.94V (peak to peak), the output current <i>I<sub>ab</sub></i> is around 6A (peak to peak). The fundamental frequency is 50Hz square wave output voltage waveform and distorted current waveform, presenting in figure 7 and figure 8.
Figure 8. Inverter output current waveform

For filtering state, the output voltage of the microgrid has been attained almost $120 \ V_{pp}$ of the microgrid voltage, approximately $6 \ A_{pp}$ of the microgrid current and $50\ Hz$ of the microgrid frequency, showing in Figure 9 and Figure 10.

Figure 9. Inverter output voltages after filtering
Figure 10. Output current waveform

Also, FFT analysis has done on the output waveform of the voltage and current, without filtering effect that is illustrated in Figure 11 and Figure 12. This review makes certain that the inverter output voltage has harmonics without filter cases through significant, but with the filtered condition, the output voltage is as like as the micro-grid voltage which has only fundamental harmonics where 50Hz has deceived, and rest of harmonics are insignificant.

Figure 11. The FFT of the inverter output voltage without filtering
Figure 11 demonstrates that the output voltage of the inverter $V_{ab}$ that attained about 138.94 V (peak to peak), corresponding THD is roughly 49.56%. Figure 12 indicates that the inverter output current $I_{ab}$ is around 6A (peak to peak), similar THD is almost 48.95%, whereas, the fundamental frequency is 50Hz square wave output voltage waveform and distorted current waveform (without filtering condition).

![Figure 12. The FFT of the inverter output current without filtering](image)

Figure 12. The FFT of the inverter output current without filtering

Figure 13 and Figure 14 have represented the output voltage and current along with FFT analysis. In the case of with filtering effect, the output voltage and current of the inverter has a low level of THD, which is 0.43% because this system is transformerless.

![Figure 13. The FFT of the output voltage after filtering](image)

Figure 13. The FFT of the output voltage after filtering
It is found from the FFT analysis that THD of the output voltage is approximately 0.43%, THD of the output current is 0.46% while the fundamental frequency is 50 Hz.

**Figure 14.** The FFT of the output current after filtering

7. Conclusions
The major concern of a microgrid power system is to deliver a maximum power from the inverter to the load. Simulated results of the proposed PSI indicate that the value of ripple current is at an acceptable limit due to phase synchronization of the micro-grid system. THD ratio is found as 0.44%, which is much less than the maximum permissible distortion limit of IEEE standard (THD <5%). It has concluded that proposed system needed fewer filter parameters. Therefore, more power can have transferred power from the inverter to the micro-grid load is gained. At that time, the inverter efficiency was about 98%, while the output voltage is 120V AC and load impedance is 20.5Ω, the inverter power is around 100w. Therefore, it is justified that the proposed technique is efficient and operative rather than the traditional reference signal generation by the switching logic controller and identical with the micro-grid voltage at a future stage.

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