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Hybrid Switching Control-Based DC to AC Inverter for Microgrid Using Renewable Energy Sources

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SPWM; Hybrid DC to AC Inverter; Switching Topology; LCL filter; VSC and Microgrid.

Abstract

Hybrid switching control-based direct current (DC) to alternating current (AC) inverter is a method of controlling the flow of power from DC sources such as solar panels or wind turbines to AC loads in a microgrid. In a microgrid, renewable energy sources are often used to supplement traditional sources of energy and improve overall energy efficiency. To simulate micro-grid systems, an effective three-legged IGBT inverter has been developed using Matlab R2016a/Simulink. The inverter switches are controlled by a pulse controller, which creates the switching gate pulses. This work models the output voltage and current waveforms of the three-phase 180° voltage source inverter that supplies nonlinear loads. To lower the total harmonic distortion (THD) of the current and voltage outputs of the three-phase voltage source converter (VSC), a filter circuit and a two-level pulse width modulation (PWM) generator have been presented. This pulse-width modulation generator compares the modulating signal and a high-frequency triangular carrier wave. Sinusoidal pulse width modulation (SPWM) is used for PWM control. Moreover, the hybrid switching control-based DC-to-AC inverter utilizes a combination of pulse width modulation (PWM) and hysteresis current control techniques to maintain a constant AC output voltage and frequency. PWM control is used to regulate the voltage, while hysteresis current control is used to regulate the current. Additionally, an inductor-capacitor-inductor (LCL) filter is used to improve the stability of the power converter by providing a damping effect on the system. Overall, the LCL filter is a versatile and effective tool for improving the performance of power inverters, especially in applications where high efficiency and low harmonic distortion are important.

1. Introduction

By the year 2041, Bangladesh wants to be a developed country, however, to do so, sustainable site management is required due to rising energy and electricity consumption (Islam *et al.*, 2021). Solutions to this conundrum are available from the general economics department (GED). As just 1.04% of the country's energy is now generated by renewable sources (Tükenmez & Demireli, 2012), Bangladesh needs to increase its use of these energy sources. 15% renewable energy production by 2041 is the goal that the government has set (Bardhan, *et al*., 2019). By making improvements to renewable energy technologies, it may be possible to export power at a profit and improve people's lives. Using a lot of renewable energy is the answer to the problem of satisfying the nation's energy demands. The average annual temperature of Bangladesh is 26°C, with the hottest months occurring during the rainy season (April to September) and the coldest, driest months occurring in the winter (December-February) (Alam *et al*, 2022). MPPT helps in improving the power output of PV modules. Since Bangladesh's average temperature of 26°C, solar energy may be the perfect solution to the country's electricity needs. The annual temperature averages are shown in Fig. 1 (Basak *et al*., 2013).

Power is a feature in our lifestyles that is becoming more significant every day. The electricity system has undergone several transformations as a result of technological advancement, economic advantages, and environmental issues. Centralized generating plants for distributed generation are appearing (Garg and Sharma, 2018). Microgrids are compact, locally managed electrical systems that can run both on and off the main grid and are intended to provide electricity to small towns. They can use multiple energy sources, like as wind turbines and solar power panels, and can function

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independently when the grid is down. Microgrids can improve distribution systems and increase reliability, but they face challenges in integrating energy sources and controlling imbalances (Ahamed *et al.*, 2015). Microgrids can deliver great power quality and increase supply dependability to suit the different electrical needs of consumers. Power electronic devices that can flexibly adjust active power, reactive power output and voltage output of generation are typically used as the interface between distributed power and the power grid. This increases the dependability of the power grid (Zhou *et al.*, 2015). For the delivery and generation of tiny amounts of power, microgrids are growing in popularity. For microgrids, there are two supervisory control methods: centralized and decentralized. The central microgrid controller used in the centralized control approach controls all decisions and information about our anticipated generation and load demand. The distributed energy resource (DER) control approach, in contrast, assigns a local controller to each DER who is in charge of maximizing power production and satisfying load demand. Grid-connected and island modes are the two subcategories of microgrid technology. Particularly during load changes or while connecting to other networks, microgrid control systems aid in maintaining frequency and voltage stability. Frequency and voltage stability are maintained using control techniques including PQ control, droop control, voltage/frequency control, and current control (Ahamed *et al.*, 2015) and (Hartono *et al.*, 2013).

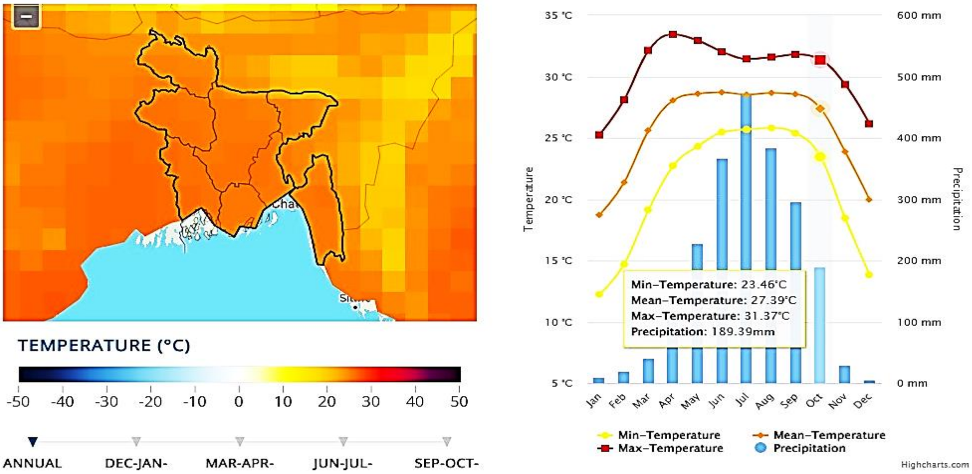


Figure 1: Yearly average temperature of Bangladesh (Basak *et al.*, 2013)

The micro-grid is a viable method for rural electrification and sustainable power supply in areas where main grid expansion may not be financially feasible. For the balance between the power supply and demand to be maintained, distributed load sharing is essential. Micro-sources, distribution lines, loads, and grid-connected or grid-forming inverters are all components of an inverter-based microgrid. It is a standalone unit that can be isolated or linked to the main grid. Because of their grid-connected inverters and grid-forming characteristics, inverter-bamicrogridsrids maintain constant operating points as shown in Fig. 2 (Fani *et al.*, 2022).

The need to find alternate energy sources has increased along with global energy demand. Even while they offer a short-term fix, fossil fuels nonetheless contribute to greenhouse gas (CO_2) emissions. For micro-grid systems, it is necessary to effectively convert renewable energy sources like solar, wind, and tidal wave energy using devices like the Hybrid DC to AC Inverter. The electric switching and inverter system is crucial to the efficiency of the microgrid, which connects various PV systems via common local networks. The development of innovative switching technologies and algorithms is being done by researchers to improve system efficiency. A Hybrid DC to AC Inverter can be powered by the sun either directly or indirectly (Rahman *et al*., 2016) and (Motakabber *et al*., 2018).

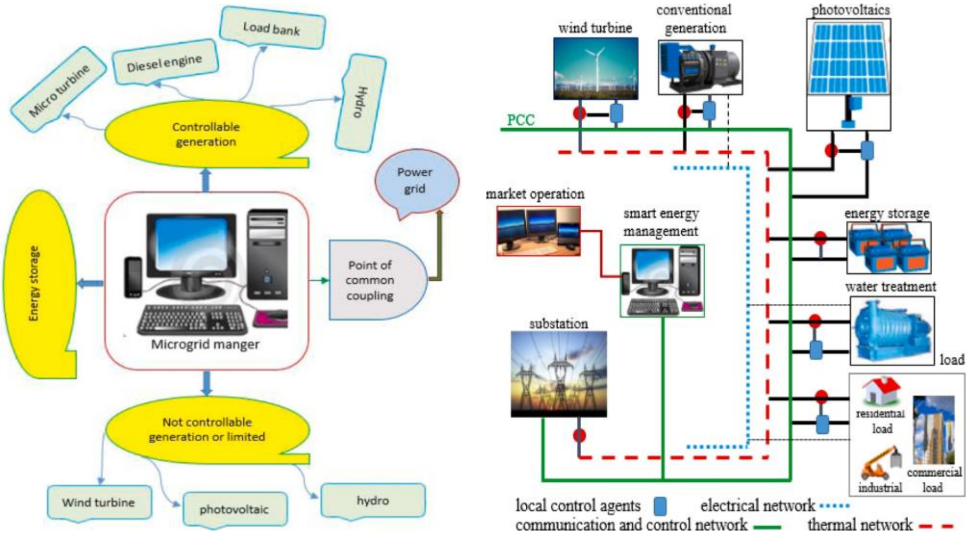


Figure 2: Structure of micro-grid connected with different energy sources and typical scheme of an inverter base micro-grid (Fani *et al*., 2022)

LCL filters are used in inverters to decrease current ripple, however, they require a bigger filter since they require more inductance. LCL filters still have a high cut-off frequency and potent low-frequency noise filtering compared to other filters, which is one of their main benefits. To avoid system instability, it is essential to handle the crucial issues of choosing the filter's settings and controlling resonance. These difficulties call for a thorough comprehension of the application and the noise sources that need to be eliminated. LCL filters are a helpful tool in power electronics overall, but careful planning is required when using them to prevent unintended consequences (Renzhong *et al*., 2013). Electricity generated must fulfill utility standards for things like power quality and inject current, specified by standards like IEEE 1547, IEC 61727, and ENC 61000-3-2, to be connected to the grid (Gundersen, 2010). Due to their tiny size, the injected current is limited by IEEE 1547 and IEC 61727, which can be challenging to monitor (Gundersen, 2010). This can be facilitated by placing a line-frequency transformer between the inverter and the grid. Based on the fundamental elements of in-phase grid voltage and current, instantaneous power (P_{grid}) may be calculated using Equation 1.

$$P_{grid} = 2P_{grid}\ sin^2(\omega_{grid} t) \ldots\ldots\ldots\ (1)$$

P_{grid} is the average power injected into the grid, ω_{grid} is the angular frequency, and *t* is the time (Nandurkar and Rajeev., 2012). Table 1 presents several standards and THD ceilings. The power conversion stages and control system are designed for the micro-grid linked Hybrid DC to AC Inverter. All of the semiconductor switches, Pulse Wide Modulation generator, and filters are part of the power conversion step. The inverter controller includes several inner and outer control loop stages with the standard control bandwidth. To lower switching loss and harmonic distortion in the micro-grid system, a unique Hybrid DC-AC Inverter circuit is required (Rahman *et al*., 2017; Rahman, 2016).

Table 1: Standards of interconnection of PV system to the grid

Issues	**IEC61727**		**IEEE1547**	
Nominal Power	10 kW		30 kW	
Harmonics Current Limits	Harmonics	THE	Harmonics	THE
	3 - 9	4%	3 - 9	4%
	11 -15	2%	11 -15	2%
	17 – 21	1.5%	17 – 21	1.5%
	23 -33	0.6%	23 -33	0.6%
			(>) 33	0.3%
Maximum current THD	5.0%		5.0%	

2. Material and methods

The network must be protected from harmonics, which can shorten the network's lifespan, heat conductors, and transformer windings, and cause fuses and circuit breakers to operate incorrectly. Filter circuits are effective but expensive in reducing lower-order harmonics, but higher-order harmonics filters are more compact and economical. To minimize harmonics, filter circuits are built to reduce higher-order harmonics while SPWM methods are employed to reduce lower-order harmonics (Bhattacharjee et al., 2018).

2.1 Design and Development of the Proposed Hybrid DC to AC Inverter

A hybrid DC to AC inverter is a type of power inverter that is used to convert direct current (DC) power to alternating current (AC) power. The term "hybrid" refers to the fact that this type of inverter uses a combination of different control techniques to achieve its desired output. The hybrid DC to AC inverter is commonly used in renewable energy systems, where it can be used to convert the DC power generated by sources such as solar panels or wind turbines into AC power that can be used to power household or industrial loads. In a hybrid DC to AC inverter, pulse width modulation (PWM) and hysteresis current control techniques are typically used in combination to regulate the output voltage and frequency. PWM is a method of controlling the output voltage by modulating the width of the output pulses, while hysteresis current control is a method of controlling the output current by using a hysteresis band around the reference value. Additionally, an LCL filter is often used in a hybrid DC to AC inverter to improve the stability of the system. The LCL filter consists of an inductor (L), two capacitors (C), and a resistor (R), connected in series. It is used to filter out high-frequency noise and reduce harmonic distortion in the output waveform. The resistor in the LCL filter can be used to control the damping factor of the system, which affects the transient response of the system. Overall, a hybrid DC to AC inverter is an effective and efficient way to convert DC power to AC power, particularly in renewable energy systems. By using a combination of different control techniques and an LCL filter, it can provide a stable and reliable source of AC power for a wide range of applications. Due to their high current, high voltage, and high-efficiency ratings, three phases, multi-level inverters are increasingly popular for systems used in commercial applications. Because the system produces fewer harmonics, switching loss, and cheap costs, this inverter's total performance is extremely effective. The output voltage waveform also grows as the level's quantitative measurement does as shown in Fig. 3.

The SPWM control method is used to synchronize the phase between the inverter and the utility grid and regulate the semiconductor switches (Rahman *et al.*, 2016).

Inverters are the technical term for DC to AC power converters. To put it another way, an inverter is a circuit that transforms DC electricity into AC power at a desired output voltage and frequency. Depending on the application forced commutated thyristors or controlled turn-on and turn-off devices like BJTs, MOSFETs, IGBTs, etc. are used to convert energy (Baroi *et al*., 2017).

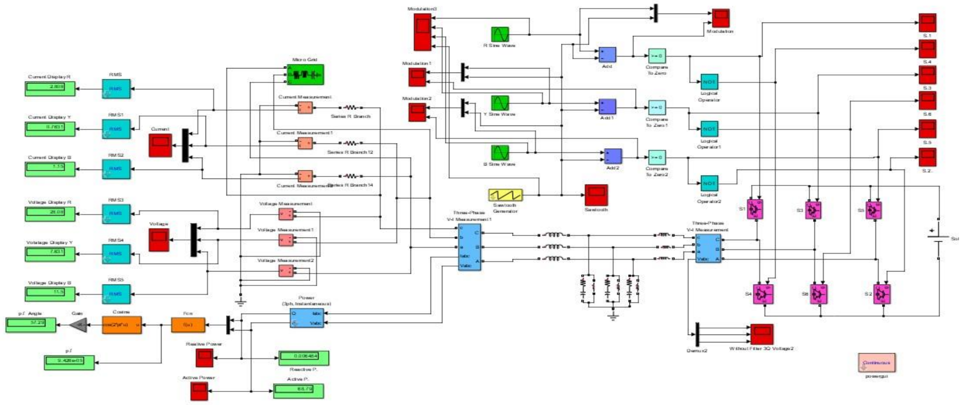


Figure 3: Design of hybrid DC to AC inverter.

Fig. 3 shows the design and proposal of the open loop Hybrid DC to AC Three Phase Inverter. With the help of series and parallel damped resistors, a low-pass LCL filter has been connected to a hybrid DC to AC three-phase inverter. The series-damped resistor enhances the bandwidth by lowering the selectivity of the circuit, but the parallel-damped resistor improves stability and lowers ringing or oscillations in the circuit. For performance improvement, series and parallel damped resistors are used in the low-pass LCL filter design.

2.2 Design of Switching Topology for Hybrid DC to AC Inverter

Fig. 4 depicts the upper and lower switches of the hybrid DC to AC inverter, which are essential components of the inverter circuit. These switches are responsible for converting DC power input into AC power output. The upper switch is connected to the positive DC input terminal and the AC output terminal. When the upper switch is turned on, the load receives a DC voltage, and an AC voltage is produced across the output. Typically, an IGBT that can withstand high voltage and current levels is used as the upper switch. On the other hand, the lower switch is connected to the negative DC input terminal and the AC output terminal. The lower switch is turned on when the upper switch is closed, allowing the DC to pass through the load and complete the circuit. In most cases, the lower switch is an IGBT that can tolerate high current and voltage levels, as reported in the studies by Motakabber *et al.* (2018) and Nandurkar *et al.* (2012).The generation of six PWM signals to operate the three-phase is more favorable. Additionally, fewer switching devices and snubber circuits are required with three phases. In reality, it is simple to supply three-phase using two inputs of DC voltage. The three-phase inverter requires six switching topologies, which are employed in microgrid systems, for power conversion. To operate three-phase inverters, six SPWM signals must be produced (Bhattacharjee *et al.*, 2018). Now the approach of this paper is how to get three phase AC supply from a DC supply of solar panels to utilize solar energy. To obtain three-phase AC output from a DC supply battery the proposed system uses six IGBT as switches for 180^0 conduction of each switch and star connected load with four terminals a, b, c, o is considered as micro-grid. The six switches (IGBT) are triggered ON and OFF at regular intervals of 60^0. This sequence is designed to obtain a three-phase voltage (Zhao *et al*., 2017).

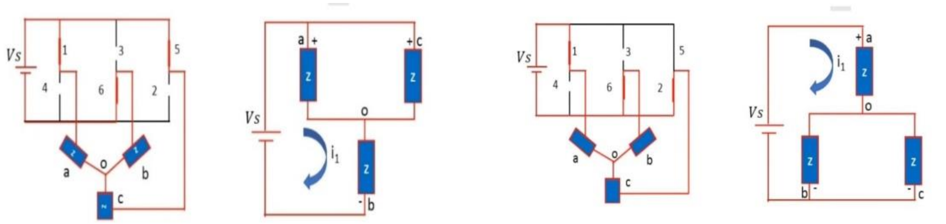


Fig. 4: Upper and lower switches of the hybrid DC to AC inverter

The upper and lower switches are two critical components of the hybrid DC to AC inverter used for converting DC power input into AC power output. The upper switch is typically connected to the positive DC input terminal and the AC output terminal. When the upper switch is turned on, it allows the DC voltage to flow through the load and generates an AC voltage across the output. The upper switch is often implemented using insulated gate bipolar transistor (IGBT) due to its ability to withstand high voltage and current levels. On the other hand, the lower switch is typically connected to the negative DC input terminal and the AC output terminal. The lower switch is turned on when the upper switch is closed, allowing the DC to pass through the load and complete the circuit. Like the upper switch, the lower switch is also usually implemented using IGBT due to its ability to tolerate high current and voltage levels. The operation of these switches is controlled by a pulse width modulation (PWM) technique, which controls the duration of the on and off states of the switches. By modulating the duty cycle of the PWM signal, the output voltage and frequency of the inverter can be adjusted to meet the desired specifications. Overall, the upper and lower switches play a crucial role in converting the DC input into AC output in the hybrid DC to AC inverter.In step one switching topology for three phase inverter. The circuit operates in six-step, each step is 60^0 and each switch (IGBT) is triggered after an interval of 60^0 and remains at 180^0. Starting with switch 1 (IGBT) which fires from 0^0 and conducts still 180^0. When switch 1 is conducting switch 2 fires when $\omega t = 60^0$ and remains still at 240^0. The pattern continues for a switch (1, 2, 3, 4, 5, and 6). This sequence continues for another cycle of 360^0. In step one that is 0^0 to 60^0 are on condition simultaneously. Now the calculation is how the circuit is cuctedGBT based swing the 5, 6 & 1 have to close because of conducting. For an equivalent circuit, DC voltage has a positive terminal and a negative terminal. Terminal "a" and "c" is connected with a positive bus and "b" is connected with a negative bus and there is a common terminal "o", this pole polarity shows in Table 3. Fig.5 shows every load has impedance "z". "ao" and "co" is parallel and "bo" is connected with the series.

The design of the switching topology of a three-phase inverter involves selecting the appropriate circuit topology and selecting the components that meet the design requirements. The switching topology determines how the DC input voltage is converted into a three-phase AC output voltage. One commonly used topology for three-phase inverters is the Voltage Source Inverter (VSI) topology. In this topology, the DC input is converted into an AC output by connecting six switches in an H-bridge configuration. Each switch can be turned on or off independently using a pulse width modulation (PWM) technique to control the output waveform.

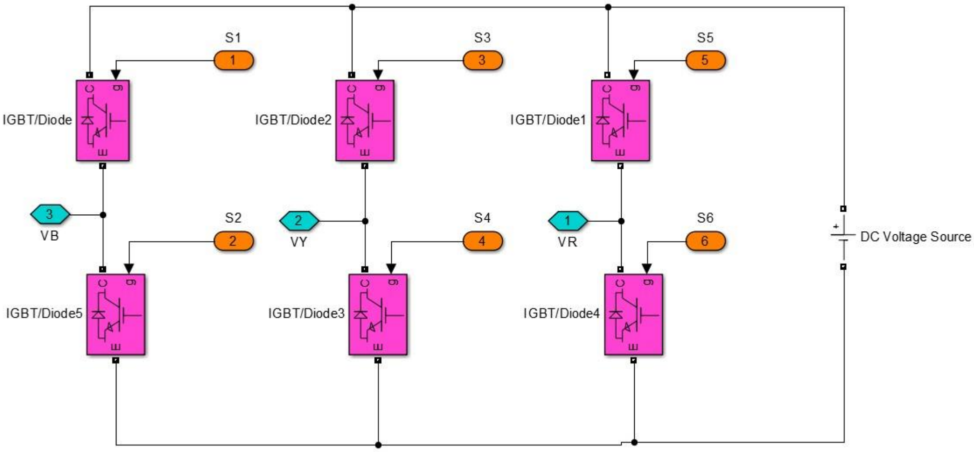


Figure 5: Design of switching topology

The CSI topology is generally less common than the VSI topology due to its complexity and higher cost. In addition to selecting the appropriate topology, the selection of components, such as the switches, diodes, and capacitors, is crucial for the design of the switching topology of a three-phase inverter. The components should be able to handle the high voltage and current levels that are present in the circuit. The size and rating of the components should be selected based on the maximum power rating and voltage of the inverter. Once the topology and components have been selected, the PWM technique can be used to generate the switching signals for the six switches in the H-bridge configuration. The PWM technique adjusts the duty cycle of the switching signals to control the output waveform and maintain a constant AC output voltage and frequency. Overall, the design of the switching topology of a three-phase inverter involves selecting the appropriate topology, selecting components that meet the design requirements, and using PWM technique to control the output waveform.

Table 3: Pole polarities of hybrid DC to AC synchronous inverter

Step	IGBT Conducts	V_a	V_b	V_c
1	156	+	-	+
2	612	+	-	-
3	123	+	+	-
4	234	-	+	-
5	345	-	+	+
6	456	-	-	+

In step two IGBT base switches no 6, 1 & 2 are conducted. The equivalent circuit in this case on the positive bus “b” and “c” on the negative bus and “a” on the positive bus this pole polarities are shown in Table 3. The current will have the same magnitude, however, the voltage drop across the load will vary as the parallel combination of “ob” and “OC” this time and “ao” is series with that parallel combination. The voltage value are changing as per the impedance value. In step three IGBT base switches no 1, 2 & 3 are conducted. The equivalent circuit in this case on the positive bus “a” and “b” on the positive bus and “c” on the negative bus this pole polarity is shown in Table 3. The current will have the same magnitude, however, the voltage drop across the load will vary as the parallel combination of “ob” and “OC” this time and “co” is series with that parallel combination. The voltage value are changing as per the impedance value. Step three is identified with step one. In step four IGBT base switches no 2, 3 & 4 are conduction. The equivalent circuit in this case on the negative bus “a” and “c” on the negative bus and “b” on the positive bus this pole polarity is shown in Table 3. The current will have the same magnitude, however, the voltage drop across the load will vary as the parallel combination of “ao” and “co” this time, and “bo” is series with that parallel combination. The voltage value are changing as per the impedance value. Step four is identified as step two. In step five IGBT base switches no 3, 4 & 5 are conduction. The equivalent circuit in this case on the negative bus “b” and “c” on the positive bus and “a” on the negative bus this pole polarities are shown in Table 3. The current will have the same magnitude, however, the voltage drop across the load will vary as the parallel combination of “bo” and “co” this time and “ao” is series with that parallel combination. The voltage value are changing as per the impedance value. Step five is identified as steps one and three. In step six IGBT base switches no 4, 5 & 6 are conduction. The equivalent circuit in this case on the positive bus “a” and “b” on the negative bus and “c” on the positive bus this pole polarity is shown in Table 3. The current will have the same magnitude, however, the voltage drop across the load will vary as the parallel combination of “ao” and “bo” this time and “co” is series with that parallel combination. The voltage value are changing as per the impedance value. Step six is identified with steps two and step four.

The total circuit impedance is, $z + \frac{z}{2}$

So, the total circuit impedance is:

$$i_1 = \frac{V_s}{z + \frac{z}{2}} = \frac{2}{3} * \frac{V_s}{z} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(1)}$$

The voltage drop across parallel impedance for upper switches:

$$V_{ao} = V_{co} = i_1 * \frac{z}{2} = \left[\frac{2}{3} * \frac{V_s}{z}\right] * z = \frac{2V_s}{3} \dots\dots\dots\dots\dots \text{(2)}$$

The voltage drop across parallel impedance for lower switches:

$$V_{bo} = V_{co} = i_1 * \frac{z}{2} = \left[\frac{2}{3} * \frac{V_s}{z}\right] * z = \frac{2V_s}{3} \dots\dots\dots\dots\dots\dots\text{(3)}$$

The voltage drop across series impedance for upper switches:

$$V_{bo} = i_1 * z = \left[\frac{2}{3} * \frac{V_s}{z}\right] * z = \frac{V_s}{3} \dots\dots\dots\dots\dots\dots\dots\dots\dots\text{(4)}$$

The voltage drop across series impedance for lower switches:

$$V_{ao} = i_1 * z = \left[\frac{2}{3} * \frac{V_s}{z}\right] * z = \frac{V_s}{3} \dots\dots\dots\dots\dots\dots\dots\dots\dots\text{(5)}$$

It is seen that the series load has a bigger voltage drop than the parallel load. In every switching stage, the circuit impedance is the same that is shown in Equations 2, 3, 4 & 5. The voltage drop across parallel impedance is the same for each switching stage as shown in Equations 2 and 3. The voltage drop across series impedance is the same for each switching stage as shown in Equations 4 and 5. After finishing one cycle, it repeats for another cycle of 0^0 to 360^0. IGBT-based six switches (S1, S2, S3, S4, S5 & S6) are shown in Fig. 6 and Table 3 shows the pole polarities of each switch (IGBT) for a different step discussed above.

2.3 Design of SPWM-based Control System for Hybrid DC to AC Inverter

The SPWM signals are produced by comparing a single triangular carrier signal with three low-frequency sinusoidal modulation signals. This SPWM technique is based on the individual switching of an IGBT's inverter. The phase of these modulation signals is 180 degrees out of phase. With the help of SPWM-generating signals (which may be produced either physically by three comparators or digitally by microcontrollers), upper switches (S1, S3, and S5) can cooperate with lower switches (S2, S4, and S6) (Eslami *et al.*, 2022).

The inverter output voltage may be controlled and THD can be reduced by changing the pulse width. In Fig. 6 by comparing the triangular carrier signal of cut-off frequency fc with the sinusoidal reference signal, the pulse signal is generated using the SPWM method. When the reference sinusoidal signals exceed the carrier triangular wave, the switching devices will turn ON. Line side by altering the modulation signal's frequency and amplitude, fundamental component frequencies and magnitudes can be changed. In this case, Hybrid DC to AC Inverter requires three sine waves as reference signals. In Fig. 6 these sine waves are phase-shifted by 180° and then taken at the necessary output voltage frequency. The signals are compared to a carrier signal with a very high frequency.

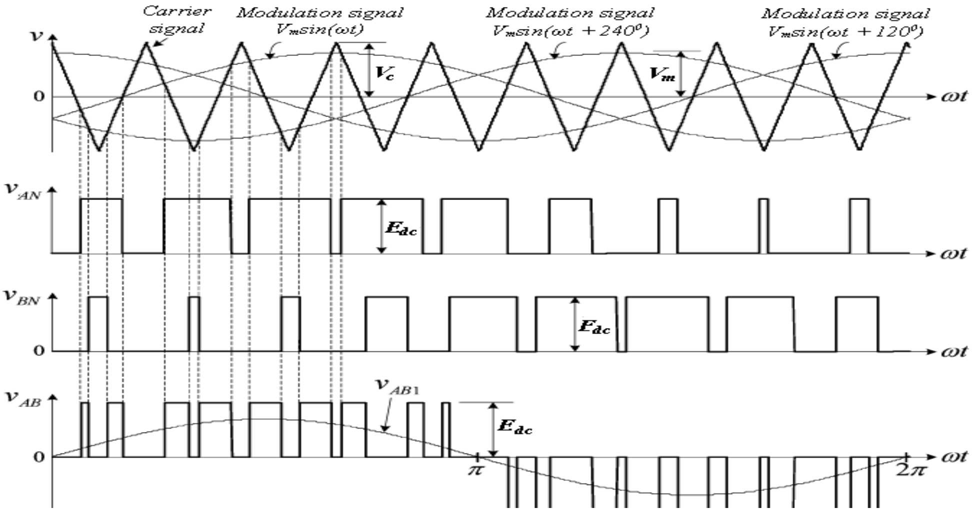


Figure 6: Hybrid DC to AC inverter conventional SPWM generating method (Rahman *et al*., 2019)

In Fig. 6 and 8, when $V_m$sin (ωt) >vctriang S1 is switched on, followed by S2, and then V_{AN} = E_{DC} . When V_m sin (ωt) > victorian S1 is off and S2 is on, resulting in $V_{AN} = 0$. Three IGBTs can be switched on simultaneously in three distinct inverter legs, depending on the symmetry of the switching patterns (gate driving PWM signals), but they can never be turned on simultaneously in the same inverter leg's upper and lower IGBTs to prevent a DC bus short circuit (E_{dc}). The magnitude of the carrier signal is higher than or equal to the amplitude of the modulation signals, as illustrated in Fig. 6, As a result, the amplitude modulation index cannot be lower than one ($0<m_a<1$). In this instance, the input and SPWM output voltage is maintained in a linear connection. The ratio of the peak value of the sinusoidal modulated signal to the carrier triangle signal is known as the amplitude modulation index (m_a) that shown in Fig. 7 and Equation (6).

Given that the modulating signals are $V_m$sin (ωt), $V_m$sin (ωt + 120^0), and $V_m$sin (ωt + 240˚), and that the amplitude of the triangle carrier signal varies between the peak values of $+V_c$ and $-V_c$ then:

$$m_a = \frac{Vm}{Vc} \text{ ....(6)}$$

Over modulation occurs when the amplitude of the modulating signal is greater than the amplitude of the carrier signal ($m_a > 1$) by Equation 8. However, the linear relationship between the input and PWM is no longer maintained because lower frequency harmonics are introduced into the output waveform, which leads to distortion of the load current as shown in Fig. 8.

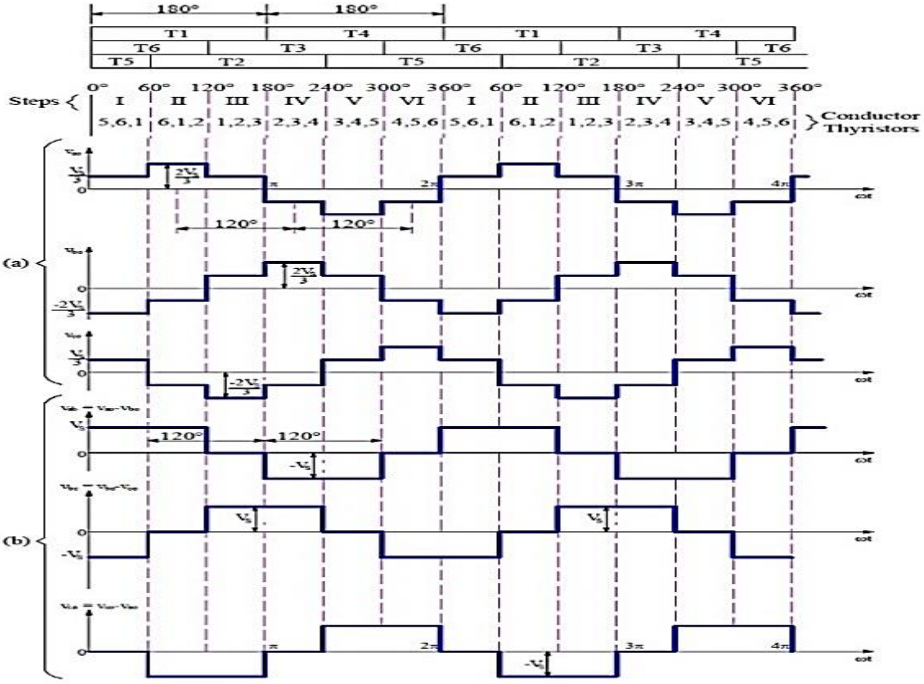


Figure 7: Waveform of line to neutral (V_{ao}, V_{bo} & V_{co}) and line to line (V_{ab}, V_{bc} & V_{ca}) voltage (Rahman *et al.*, 2018).

The frequency modulation ratio (m_a), which is used in SPWM inverters, is also significant. The frequency of the modulation sinusoidal signal (V_m) divided by the frequency of the triangular carrier signal (f_c) is what determines this ratio (V_c). In the output voltage, it regulates harmonics (Rahman *et al.*, 2022). By solving $f_{sw} = V_c = V_m * m_A$, the switching frequency of the active switches in the two-level Hybrid DC to AC Synchronous Inverter may be determined. The modulation signals and the current signal's frequencies are:Frequency of $V_{\text{triangle signal}} = f_{sw}$

Frequency of $V_{\text{modulation signal}} = f_1$

Where f_1 is the fundamental frequency and f_s is the PWM frequency (switching frequency). While f_{sw} remains constant, the effective value of the output voltage in all PWM inverters relies on the amplitude of the modulation index.

Fig. 8 shows the pulse wide modulation generator for a hybrid DC to AC inverter that gives gate pulse to the IGBT switch for on and off conditions to get non-sinusoidal voltage from the output of the hybrid DC to AC inverter and this non-sinusoidal voltage has distortion that is shown in Fig. 8. With a reduced THD and less electromagnetic interference, Sinusoidal Pulse Width Modulation (SPWM) produces sine waves of excellent quality. It provides better output voltage and frequency control. An essential modulation approach is the modification of the carrier waveform frequency and modulation index, which controls output amplitude and frequency.

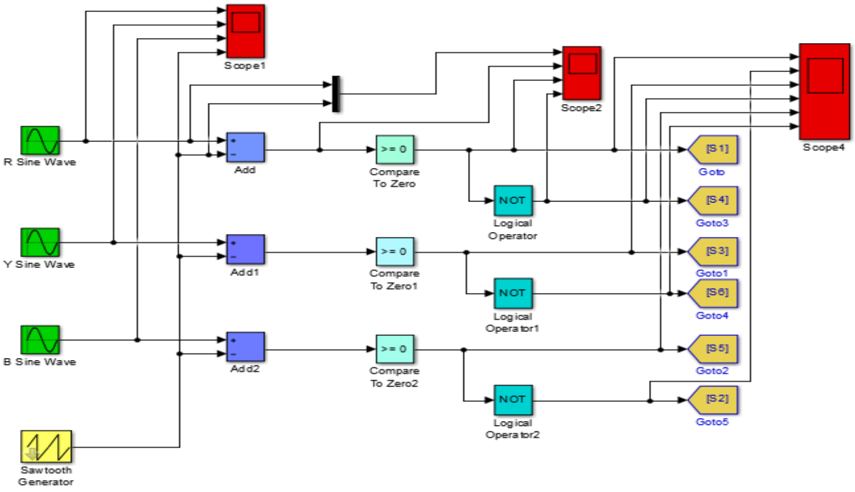


Fig. 8: Pulse wide modulation (PWM) generator for hybrid DC to AC inverter

Pulse Width Modulation (PWM) is a commonly used technique to control the output voltage of a DC to AC inverter. The PWM technique involves generating a series of pulses with variable widths, which are used to control the switching of the inverter's output voltage. In a hybrid DC to AC inverter, a PWM generator is used to generate the gate pulses for the inverter's upper and lower switches. The PWM generator consists of a modulating signal and a high-frequency triangular carrier wave. The modulating signal is a low-frequency sinusoidal wave that represents the desired output waveform. The carrier wave is a high-frequency triangular wave that is used to switch the upper and lower switches of the inverter at a high frequency. The modulating signal is compared to the carrier wave in the PWM generator, and the result is a series of pulses with variable widths. The width of each pulse is proportional to the amplitude of the modulating signal at that point in time. The width of the pulses determines the amount of time that the upper and lower switches of the inverter are turned on and off, which controls the output voltage of the inverter. The resulting PWM signal is then used to control the upper and lower switches of the inverter. By adjusting the width of the pulses in the PWM signal, the output voltage of the inverter can be controlled to match the desired output waveform. Overall, the PWM generator for a hybrid DC to AC inverter is a crucial component that allows for the control of the output voltage and frequency of the inverter, making it suitable for use in a microgrid or other renewable energy systems.

2.4 Design of output LCL Filter with series and parallel damped resistor for Hybrid DC to AC Inverter

The quality of energy produced by a power converter is crucial as non-sinusoidal currents can cause voltage drops and distortions. The LCL filter can attenuate the harmonics above resonant frequency by 60 dB/decade (M Hojabri and Hojabri, 2015), as shown in Fig. 9, which allows for lower converter switching frequency and greater decoupling. Although the filter can potentially result in resonances and unstable states, it is still effective in decreasing current ripple and suitable for the intended purpose. The cutoff frequency is an important parameter and should be at least half the converter's switching frequency.

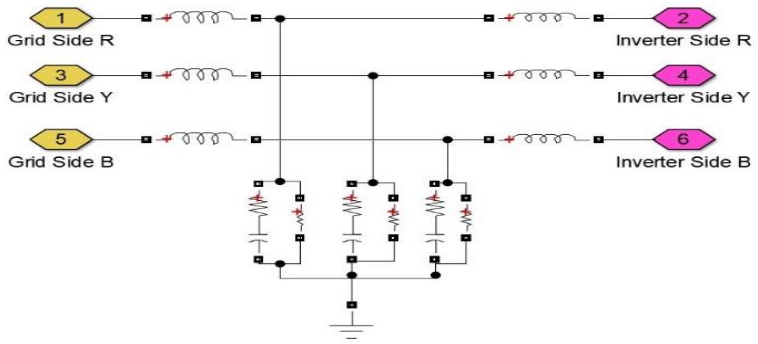


Figure 9: LCL filter with series and parallel resistor for Hybrid DC to AC Inverter

The filter needs to be damped as it is susceptible to oscillations. Adding a damping resistor to the inductor or filter capacitor on the inverter side can reduce the voltage without any losses. This actively damps the filter, ensuring smooth energy transmission and effective operation. Damping resistors can be incorporated into the LCL circuit to address this issue. The objective of the damper is to lower the Q-factor (attenuation and damping) at the typical resonance frequency (Lettl *et al*., 2011; M Hojabri and Hojabri, 2015).

LCL filters are commonly used in power electronics to filter the output voltage of an inverter system. They consist of three components: an inductor, a capacitor, and another inductor in series. The LCL filter is used because it provides better filtering performance compared to other filter types like simple LC or RC filters. The inverter system inverts a DC voltage into an AC voltage, and this conversion generates harmonic distortion in the output voltage. These harmonic frequencies can cause problems like electromagnetic interference (EMI) and may also reduce the efficiency of the system. The LCL filter is designed to attenuate these harmonic frequencies, thus improving the quality of the output voltage. The inductors in the filter help to attenuate high-frequency harmonics, while the capacitor is used to attenuate low-frequency harmonics. By using an LCL filter, the inverter system can meet the required output voltage quality standards and operate more efficiently. Overall, the LCL filter is an important component in an inverter system as it helps to reduce harmonic distortion and improve the performance of the system.

2.4.1 Filter Inductor:

To design the inductance settings for the optimum effect, one must balance the trade-offs between ripple reduction and tracking speed of current, weight, volume, and cost. Underrated conditions, the voltage drop across the filter inductor must be less than 5% of the network voltage, and the peak-to-peak amplitude of the harmonic current should be kept between 10% to 20% of the inverter's rated value. The inrush current should also be decreased. A smooth current at low frequencies and a rapid attenuation rate at high frequencies are necessary for an LCL filter to operate at its best. Low-order harmonics should go through inductance, whereas high-order harmonics should do so (Renzhong *et al*., 2013 ; M Hojabri and Hojabri., 2015).

$$X_c = \frac{1}{cs}, \; X_L = sX_2$$

Therefore, f is either bigger and Xc is smaller, or f and X_{L2} are both smaller and better. P is referred to as the three-phase grid-connected inverter's rated output power where cos is the power factor, B is the rated network voltage, and f is the driving frequency.

Inductance and capacitance have very low internal resistances. The I_2 to U_{pwm} transfer function is given as:

$$G(s) = \frac{I_2}{U_{pwm}} = \frac{1}{s^3 * L_1 * L_2 * s + (L_1 + L_2) * s} \ldots\ldots\ldots\ldots\ldots (7)$$

$$G(s) = \frac{I_2}{U_{pwm}} = \frac{1}{Ls} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

From constraint (7) and reference (Renzhong *et al.*, 2013), we may get (9):

$$\frac{4\pi fPL}{3B^2 \cos\varphi} \leq 5\% \ldots \ldots \ldots \ldots \ldots (9)$$

From constraint (8) and reference (Renzhong *et al.*, 2013), we may get (10) and (11):

$$\Delta i_{max} = \frac{2B_{dc}/_3 + B}{2Lf} \ldots \ldots \ldots \ldots \ldots (10)$$

$$\Delta i_{max} \leq \frac{2P}{3B \cos\varphi} * (0.1 \sim 0.2) \ldots \ldots \ldots \ldots \ldots (11)$$

Restrictions 8)–11) demonstrate that L and C values are both larger and better. The value 196uH<L<187uH might be calculated while taking into account the aforementioned restrictions. The reaction rate is taken into account, and L is determined to be 191uH. The suggested range for L1 and L2 is according to the reference (Renzhong *et al.*, 2013),. L1 is 196mH and L2 is 187mH as a result.

2.4.2 Filter Capacitance:

To prevent an excessive amount of high-frequency harmonics from entering through the shunt capacitor branch, capacitance specifications must be carefully selected. Insufficient shunt capacitance (X_c) can result in large high-frequency harmonic current flows in the grid, while too much X_c can lead to an increase in inverter output current and system losses due to reactive current flow. Therefore, finding the right balance is crucial. The resonant frequency of the LCL filter should be between 1/4 and 1/5 of the carrier frequency to provide optimal filtering effectiveness (Rahman *et al.*, 2023). The LCL filter's resonant frequency can be calculated using the following formula:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \ldots \ldots \ldots \ldots . (12)$$

Where L_1 and L_2 are the inductance values of the filter, C is the capacitance values, and f_{res} is the resonant frequency. Properly designing the LCL filter is important to ensure that the inverter system operates efficiently and meets the required output voltage quality standards. Resonant frequencies are typically greater than 10 times the power frequency and less than 1/2 times the switching frequency.

$$C = \frac{1}{4\pi^2 {f_{res}}^2 L} \ldots \ldots \ldots \ldots \ldots (13)$$

The reactive power absorbed by filter capacitance should not be more than 5% of the rated active power to prevent the grid-connected inverter's power factor from being too low. Where,

$$C \leq \frac{\gamma P}{6\pi f_{res} E_m^2} \ldots \ldots \ldots \ldots \ldots (14)$$

When taking into account the (13) and (14) according to the reference (Rahman *et al.*, 2023), C in this study is 350uF.

2.4.3 Damping Resistance:

LCL-Filter with Series Damping Resistor: The LCL filter's transfer function makes it evident that it has Lara ge gain (infinite "Q"), at the frequency of operation. As the capacitor current is mostly to blame for resonance in LCL filters, the easiest remedy could be to increase the series resistance to the capacitor to lower the "Q." Series damping topology is seen in Fig. 10.

The frequency response of the current in the capacitor also makes it evident. It mostly contains resonant components, with very few fundamental as well as switching components. It is displayed that this filter's transfer function is Equation (15).

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1+SRC}{(L_1*L_2*C)S^3+RC(L_1+L_2)S^2+(L_1+L_2)S}\ldots\ldots(15)$$

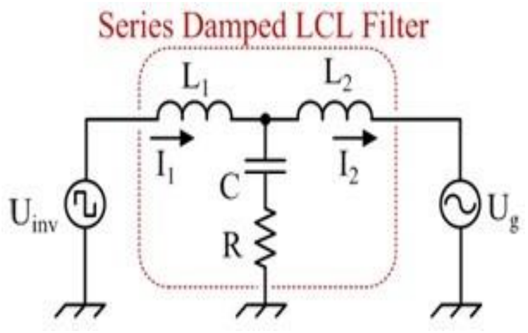


Fig. 10: Micro-grid connected series damped LCL-filter (Renzhong *et al.*, 2013)

By raising the value of the series resistor in equation no 15, as illustrated in Fig. 11, damping effects to suppress the peak resonance become effective. However, as seen in Fig. 11, the filter responds better at high frequencies.

2.5 Total Harmonic Distortion (THD) of Hybrid DC to AC Inverter

Harmonic distortion is caused by the presence of nonlinear devices in the power system network. Nonlinear elements in this context are those whose current is not proportional to the applied voltage. In the IEEE 519- 1992 standard, the necessity for controlling harmonics is stated. Total harmonic distortion, or THD, is the measurement of an effective value of a harmonic component inside a distorted waveform. To evaluate the output voltage and current quality of the inverter, THD analysis is crucial. The output waves may become non-sinusoidal due to the presence of harmonics (Bhattacharjee *et al*., 2018).

$$THD_V=\frac{\sqrt{\sum_{h>1}^{h_{max}}V_h^2}}{V_1}\ldots\ldots\ldots\ldots\ldots(17)$$

Where,

Harmonics order is the "h"
Harmonics voltage is the "V_h"
Fundamental voltage is the "V_1"

The output voltage of the inverter's THD is calculated by Equation 17.

$$THD_I = \frac{\sqrt{\sum_{h>1}^{h_{max}} I_h^2}}{I_1} \ldots\ldots\ldots\ldots\ldots (18)$$

Where,

Harmonics order is the “h”
Harmonics current is the “I_h”
The fundamental current is the “I_1”

The output current of the inverter’s THD is calculated by Equation 18. The created Three Phase Synchronous Inverter VSI Simulink model's THD of output voltage and current has been calculated by MatLab R2016a simulation using the FFT toolkit.

3. Results and Discussion

3.1 Hybrid DC to AC Inverter Control Switching Waveform

A hybrid DC to AC inverter must rapidly turn the DC input on and off to complete the conversion of direct current to alternating current. In Fig. 11 the gate pulses that are applied to the hybrid DC to AC inverter’s switches (IGBT) regulate this switching which influences the output waveform, frequency, and control of the voltage or current. Even when the load varies, the inverter can maintain a consistent output voltage or current by altering the timing and length of the gate pulses. Using SPWM with other control methods including space vector modulation (SVM), selective harmonic elimination (SHE), and phase-shifted carrier modulation creates the hybrid DC to AC inverter control switching waveform (PSCM). Digital logic is used in the design of the control circuitry, which makes the hybrid waveform by using these techniques. The switches of the inverter circuitry then are triggered by the waveform. By adjusting the pulse width, a sine wave is produced using the commonly used SPWM method. .however, there are some efficiencies and harmonic distortion restrictions with SPWM. This restriction is intended to be overcome by a new technology called the hybrid DC to AC inverter control switching waveform.

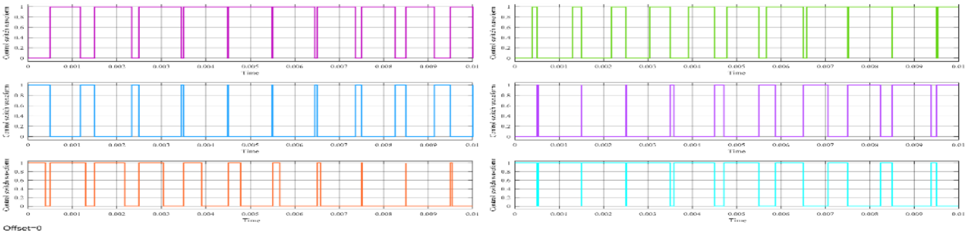


Figure 11: Control signals switching waveform of PWM generator for S1, S2, S3, S4, S5 & S6 (IGBT)

Implementing an SPWM generator is the SPWM Generator block. The pulse width modulation technology manages power transmission by swiftly switching between full power transfer and no power transfer between electrical components. Fig. 12 shows that the control switch of each switch gate pulse through IGBT for getting the ON/OFF condition to get the sine wave. Six gate pulse signals are generated using three reference signals in a three-phase SPWM system. These internal-generated reference signals are dependent on the frequency, phase, and modulation index of the output voltage as defined. For the formation of each reference signal, which is accomplished by a couple of pulse signals, the control circuits take into consideration several characteristics. Fig. 13, depicted that the waveform mixing of carrier frequency and carrier frequency consider as 1 kHz. However, they compare R, Y, and B phase sin wave with the sawtooth waveform (carrier frequency).

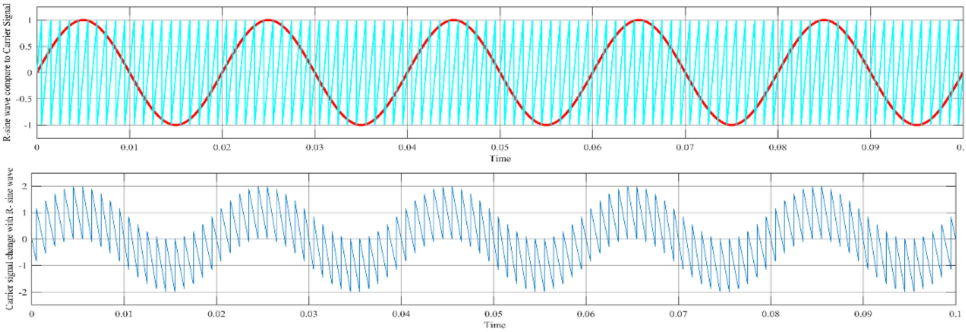


Figure 12: Carrier frequency mixing with R-sine wave

The Sawtooth generator creates waveform according to the Sin wave R, Y, and B phases. When the carrier signal is less than with compared to a Sinusoidal wave that time the pulse will be high and the carrier signal is greater than with compared to a Sinusoidal wave that time the pulse will be low. When the carrier signal is less than the reference signal then the gate pulse of the switch (IGBT) will be high. When the carrier signal is greater than the reference signal then the gate pulse of the switch (IGBT) will be low that as shown in Fig. 13.

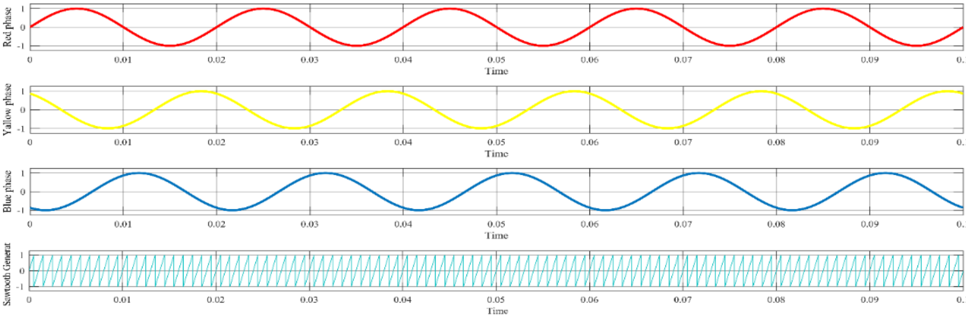


Figure 13: Reference signal red, yellow, blue, sin wave, and sawtooth signal generator waveform

Fig. 13 shows Sine wave R phase is a “0” degree phase shift, the Y phase is a “120” phase shift & B phase is a “240” degree phase shift. The high-frequency carrier signal that is the Sawtooth waveform is 1 KHz. Sawtooth waveform is compared with Red, Yellow & Blue sin waves. Red, Yallow & Blue phase waveform when the carrier signal is high with compared to Red, Yallow & Blue phase sin waves the pulse output will be zero. When the carrier signal is low with compare to the Red, Yellow & Blue phase waveform, the pulse output will be High.

3.2 Hybrid DC to AC Inverter VI Curve

Fig. 14 shows the result of the voltage waveform without filtering. From the result, of the simulation by MatLab R2016a we find that it has distortion that is a non-sinusoidal waveform.

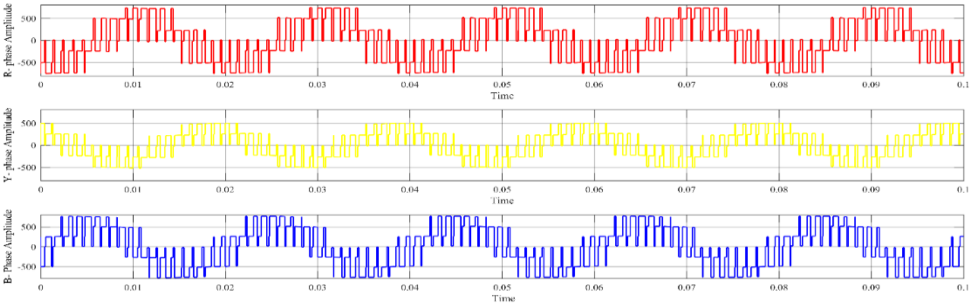


Figure 14: Hybrid DC to AC inverter voltage waveform without filtering

The hybrid DC to AC inverter output waveform appears as a sequence of rectangular pulses that alternate between the positive and negative voltage levels when there is no filtering applied. The hybrid DC to AC inverter control strategy used determines the pulse's form and duration. The output waveform of a basic hybrid DC to AC inverter has a high harmonic content due to the rectangular pulses' sharp edges, which can cause to electromagnetic interference (EMI) and harm connected loads.

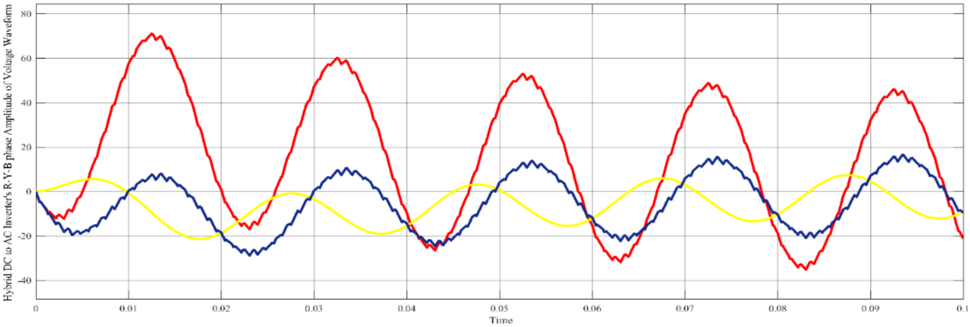


Figure 15: Hybrid DC to AC inverter output voltage waveform with filtering or micro-grid input voltage waveform

However, because of its high harmonic content and potential for electromagnetic interference, this system is not appropriate. For improving the system a low pass LCL filter with series and parallel damped resistor is designed to remove the high-frequency harmonics present in the output waveform of the hybrid DC to AC inverter, resulting in a smoother waveform with lower distortion, shown in Fig. 15 and 16.

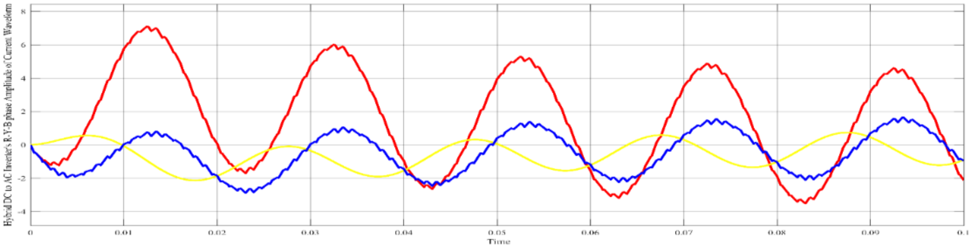


Fig. 16: Hybrid DC to AC inverter current waveform with filtering or micro-grid input current waveform

The output waveform of the hybrid DC to AC inverter is improved by the usage of filtering techniques including low-pass LCL filters with series and parallel damped resistors and carrier-based sinusoidal pulse wide modulation (SPWM).

3.3 Hybrid DC to AC Inverter THD

Fig. 18 shows the Total Harmonics Distortion (THD) of a Hybrid DC to AC Inverter without filtering. The value of Hybrid DC to AC Inverter's THD is 100.21% without filtering and it is not preferable. Now, for getting a preferable THD value we are using an LCL filter with series and parallel damped resistor to reduce the harmonics. Total harmonic distortion (THD), a measurement of the harmonic content contained in the waveform, is frequently used to assess the quality of the output waveform. The output waveform is more similar to a pure sinusoidal waveform as the lower the THD.

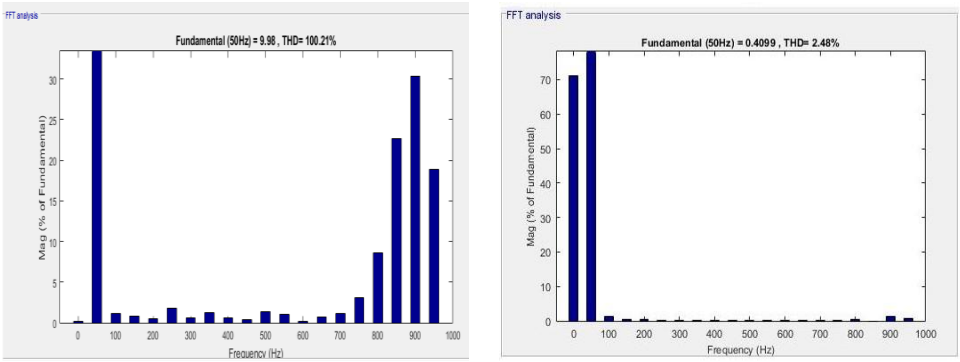
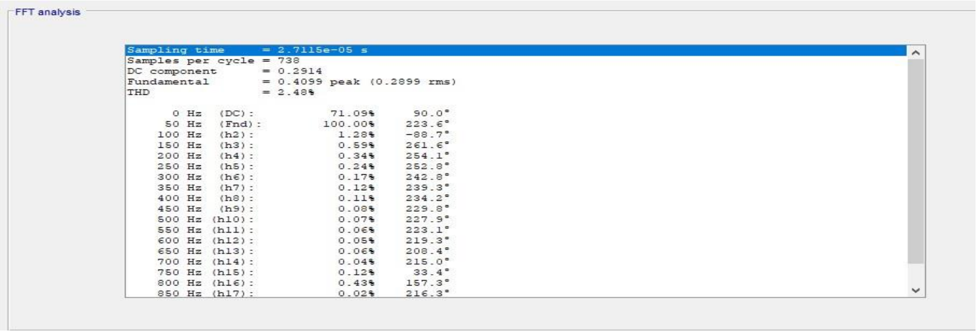


Fig. 17: Hybrid DC to AC Inverter's THD value without & with Filtering for current and voltage

Fig. 18 shows the THD value of the Hybrid DC to AC Inverter using the filter. For current and voltage THD value of the Hybrid DC to AC Inverter is the same at 2.48% and the fundamental frequency is 50 Hz.



```
Sampling time      = 2.7115e-05 s
Samples per cycle = 738
DC component       = 0.2914
Fundamental        = 0.4099 peak (0.2899 rms)
THD                = 2.48%

     0 Hz   (DC):              71.09%      90.0°
    50 Hz  (Fnd):             100.00%     223.6°
   100 Hz   (h2):               1.28%     -88.7°
   150 Hz   (h3):               0.59%     261.6°
   200 Hz   (h4):               0.34%     254.1°
   250 Hz   (h5):               0.24%     252.8°
   300 Hz   (h6):               0.17%     242.8°
   350 Hz   (h7):               0.12%     239.3°
   400 Hz   (h8):               0.11%     234.2°
   450 Hz   (h9):               0.08%     229.8°
   500 Hz  (h10):               0.07%     227.9°
   550 Hz  (h11):               0.06%     223.1°
   600 Hz  (h12):               0.05%     219.3°
   650 Hz  (h13):               0.06%     208.4°
   700 Hz  (h14):               0.04%     215.0°
   750 Hz  (h15):               0.12%      33.4°
   800 Hz  (h16):               0.43%     157.3°
   850 Hz  (h17):               0.02%     216.3°
```

Fig. 18: Hybrid DC to AC Inverter's list of THD value with Filtering for current and voltage

Fig. 18 shows the list of THD values of the Hybrid DC to AC Inverter using the filter. For 0 Hz THD value is 71.09%, for 50Hz THD value is 100%, for 100 Hz THD value is 1.33%, for 150Hz THD value is 0.62%, for 200 Hz THD value is 0.36%, for 250 Hz THD value is 0.25%, for 300 Hz THD value is 0.18% and for 850 Hz THD value is 0.04% after that frequency increase and THD value is decreased. The THD value of Current and Voltage is the same as that observed by FET analysis in simulation. In the simulation, the proposed system's frequency is inversely proportional to the THD value that means the value of the THD value is decrease with the value frequency increase.

3.4 Hybrid DC to AC Inverter Power and Efficiency

The power inverting system is simulated using the MatLab/Simulink R2016a power system toolbox software. This study designs the simulation model for the Hybrid DC to AC Inverter Power and Efficiency connected inverter with series and parallel damped LCL filter. Where The series damping resistor R_1 is 22 ohm and the parallel damping resistor R_2 is 20 ohm, inverter side L_1 is 196mH, micro-grid side L_2 is 187mH, C is 350uF. The Hybrid DC to AC Inverter's output voltage and current waveforms with harmonic analysis using the FFT toolbox, gate pulse triggering, and SPWM triggering are displayed using MATLAB Simulink. The following data are taken into account by this model such as 50 Hz is the fundamental frequency, the index of modulation is 1, DC input power is 1000 V, and 1 kHz is the carrier frequency. Whereas the cutoff frequency for the LCL filter is 10 kHz.The output current and voltage waveforms of the Hybrid DC to AC Inverter, which was triggered using gate pulses and phase delay estimated for 180^0 conduction mode, are illustrated in Fig. 17 and 18. The existence of harmonics causes the waveforms to be distorted, and the amount of overall harmonic distortion has been determined and is displayed in Fig. 19. The Active power and Reactive power of the Hybrid DC to AC Synchronous Inverter is 68.91 Watt and 0.006399 VAR. The waveform of the Active power and Reactive power for the Hybrid DC to AC Inverter is shown in Fig. 19 and 20. The power factor of the Hybrid DC to AC Inverter is 56% and the angle between voltage and current is 57.29^0. The maximum voltage of the Red, Yellow, and Blue phase values are 39.69V, 10.78V, and 16.25V respectively. The maximum current of the Red, Yellow, and Blue phase values are 3.97A, 1.08A, and 1.625A respectively.

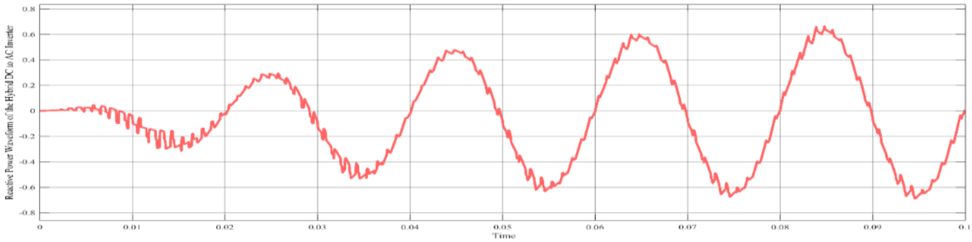


Figure 19: Reactive power for Hybrid DC to AC Inverter

Fig. 19 and 20 show the active and reactive power of a hybrid DC to AC inverter. A hybrid DC to AC inverter's active and reactive power waveform is influenced by the load impedance, the phase angle between the voltage and current, and the modulation method the inverter employs. The load current's amplitude and phase angle determine the active power, whereas the load current's amplitude determines the reactive power. The active and reactive power provided to the load may be managed by adjusting the pulse width of the inverter's output waveform.

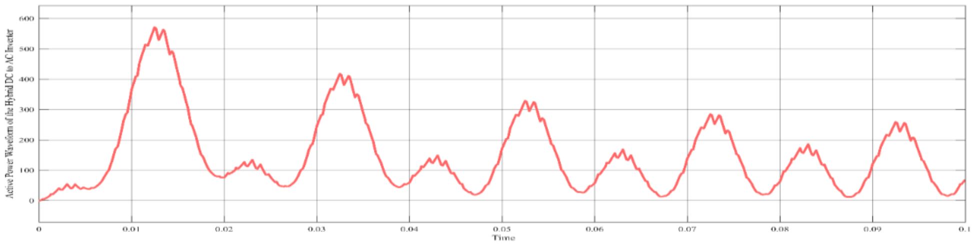


Fig. 20: Active power for Hybrid DC to AC Inverter

3.5 Comparison and Discussion

The hybrid DC to AC inverter with SPWM generator and LCL filter with series and parallel damped resistor connection exhibits a total harmonic distortion is 2.48% and 97.52% efficiency as compared to other papers (Bhattacharjee *et al.*, (2018), as illustrated in Fig. 22 and 23. Thus, it is evident that the total harmonic distortion has been significantly decreased with the usage of the SPWM generator and LCL filter with series and parallel damped resistors.

Table 4: Comparison with other Researcher's work

Reference	Input Voltage	Output Voltage	THD value of Inverter	Efficiency
Proposed Model	1000	240	2.48%	97.73%
Bhattacharjee et al., (2018)	N/A	440	3.98%	96.02%

4. Conclusion

The study talks about the difficulties in designing interface circuits for microgrid systems that use inverters. The switching SPWM controller and output filter are specifically mentioned as significant problem areas since they might result in power loss and lower system efficiency. The SPWM technic reduces the switching loss of the hybrid DC to AC inverter and low order LCL filter with series and parallel damped resistor reduces the harmonic distortion. A series and parallel damped resistor with LCL output filter-based inverter design are developed to overcome these difficulties, raising system efficiency to 97.73%. According to the simulation findings, this design successfully lowers higher harmonic distortion to an acceptable level (2.48%), which satisfies the IEEE criterion of less than 5%. The issue also illustrates the applicability of hybrid DC to AC inverters for situations that economically make sense and require greater AC voltage output than DC input. In simulation 1000V DC supply is considered a solar PV system and Three phase RLC load is considered a micro-grid. The total loss of the Hybrid DC to AC Synchronous Inverter is 68.91 watts and the power factor of the Hybrid DC to AC Synchronous Inverter is 56%. In the simulation, the proposed system is not used a capacitor bank for power factor improvement, if a capacitor bank is used for improving the power factor before sending power to the Microgrid then the power factor will be improved and total loss will be also decreased. We are trying to improve the THD value of the Hybrid DC to AC Inverter which comes to 2.48% which is less than according to the IEEE standards of Hybrid DC to AC Inverter and The efficiency of three-phase inverter is 97.73%.

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