Performance comparison of series and parallel damped LCL filters using 5-level voltage source converter

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Abstract

The high harmonic content produced by conventional converters has resulted in the increased system size and cost, due to the need for large-sized low-order harmonic passive filters and cooling system requirement. Given that, multilevel inverters and special modulation techniques were developed to suppress or eliminate the low-frequency harmonics and the left behind high-order ones are eliminated using a high-frequency small-sized filter. Hence, this paper designs and compares the total harmonic distortion (THD) and efficiency values of three set of filters, namely LCL filter, LCL with series and parallel resistance on a novel five-level multilevel voltage source inverter topology. The novelty lies with the proposed inverter, which, apart from using a single direct current source, it can extend its elimination capability beyond the normal five level using the concept of multiple switching per step and an optimised selective harmonic elimination pulse width modulation. The converter can eliminate eleven lower-order odd nontriplen harmonics, hence making the 37th harmonic at 1.85 kHz to be the first dominant harmonic. At 2-kW loading, two of the filters have THD below 5%, therefore satisfying the IEEE 519 standard. The parallel resistance damped filter (LCL-P-R) has less THD value but poor efficiency due to the resistance introduced into the circuit. The study was carried out using PSIM and MATLAB software.

Keywords Multilevel inverters · Total harmonic distortion · LCL filters · Voltage source inverters (VSI)

Abbreviations

THD	Total harmonic distortion
MLI	Multilevel inverters
LCL	Inductor capacitor inductor
SHE-PWM	Selective harmonic elimination pulse width modulation
LCL-P-R	LCL parallel resistance damped filter
LCL-S-R	LCL series resistance damped filter
VSI	Voltage source inverters
DC	Direct current
MVSI	Multilevel voltage source inverters
DiC	Diode clamp
FC	Flying capacitor
NPC	Neutral point capacitor
CHB	Cascaded H-bridge
SMPS	Switch mode power supplies

IGBT	Insulated gate bipolar junction transistors
FFT	Fast Fourier transform

List of symbols

f_{sw}	Switching frequency
M	Modulation index
N	Angles per-quarter waveform
n	Nth harmonics
h_n	Amplitude of coefficient
P_g	Active power
Q_c	Reactive power
$G_{(s)}$	Transfer function

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1 Introduction

Energy conversion has been the centre of discussion in recent times due to the significant advancements achieved in renewable energy technology [1, 2]. An effective energy conversion requires the service of multilevel voltage source inverters (MVSI), which serves as the interface between the renewable source (solar, wind, etc.) and the load [3]. MVSI appears to have overcome the numerous drawbacks posed by the conventional two-level topologies [4, 5]. Its modular nature makes it possible to achieve a high power rating by concatenating smaller power modules [4, 6]. In the event of damage/fault, its modularity warrants the ease of having component replacement and repair. Unlike the conventional topology, MVSI provides better switching freedom with minimum switching losses for the same voltage level [7]. The elimination of lower-order harmonic shrinks the size of the filter passive components since the remaining harmonics are at a high frequency [8].

Several new and hybrid MVSI topologies were proposed, most of which are modified and upgraded version of the conventional diode clamp (DiC), flying capacitor (FC), neutral point capacitor (NPC) and cascaded H-bridge (CHB) [7, 9, 10]. The converter topology and control strategy determine the type of filter needed as an interface to the grid [11].

Figure 1 shows the stages involved in the renewable energy system. It depicts the energy harvesting/harnessing, conversion and the distribution stages [12], and similar set-up applies to standalone configurations. Each sub-block stage is a broad area with enormous potential research output. The primary function of the filtering device is to mitigate the unwanted signals in the inverter output to satisfy the IEEE standard grid requirements [13]. The nonlinearity of power converters results in the harmonic generation at its output, which, if not addressed, will inject the unwanted output components into the entire system. The harmonics are said to be integer multiples of the fundamental frequency (2nd, 3rd, 4th....etc.).

Harmonics results in pulsating torque in motors and system overheating, which leads to insulation damage, efficiency degradation and possible system shutdown [14].

Based on the half-wave symmetry theorem the even harmonics present in any periodic signal cancels out. Therefore, 2nd, 4th, 6th, 8th, etc., harmonics disappear in the phase output [15, 16].

Filters are categorised into active and passive based on the nature/type of the components. The predominant type is the passive filter; this is due to its simplicity, abundance and cheap components [17, 18]. There are quite a few filter design procedures, including ripple calculation, iterative algorithms and power loss optimisation [19–21].

Power electronic converters have a wide range of applications ranging from switch mode power supplies (SMPS), electric drives, renewable energy conversion, etc. [22–25]. The primary issue associated with them is the harmonics found at their output, which has a direct relationship with the modulation strategy involved. The harmonics appear at the switching frequency (f_{sw}) and its multiples [26].

Converters with less harmonic-order elimination capability tend to have larger-sized filter components, hence increasing its physical size, weight and cost [21]. This issue is addressed by employing special modulation technique or new converter topology or both to eliminate the lower harmonics, hence, leaving behind only the higher-order ones that require a smaller-sized filter component [4, 16, 21].

In an effort to improve the filter power density and attenuation capability, several LCL filter topologies were proposed [27–35].

LCL passive filter is a third-order filter that has numerous advantages over the L and LC filters. It has remarkable attenuation ability at high frequency. However, its major downside is the resonance effect. The resonance effect leads to either voltage or current instability as the inverter frequency of operation approaches the system resonance frequency [35]. One suitable solution to reduce or eliminate the resonance effect is to introduce an additional resistor to the filter circuit, which serves as a damper [36, 37]. There are two ways of connecting the damping

Fig. 1 System block

resistance, i.e. the LCL filter with series resistors (LCL-S-R) and also the parallel resistor (LCL-P-R) connections. In some researches, it has been shown that the introduction of parallel damping resistors is better at suppressing the resonance effect and the THD component as compared to the series-configured one [4, 9, 13]. However, the majority of researchers fail to report the efficiency deterioration caused by incorporating the passive component into the system [38–40].

The contribution of this article is that it is the first to apply and assess the harmonic content of the proposed 5-level voltage source inverter presented in Shanono et al. [4] using LCL, LCL-R-S and LCL-R-P passive filters. In addition, most research articles only analyse and report harmonic elimination capabilities of a specific filter at a fix output power, ignoring that the inverter output THD content along with the filter eliminating ability changes with an increase in loading. Therefore, this article addresses the issue by comparing the output THD variation of the three sets of filters with different output powers. Moreover, few research articles analyse the effect of the filtering circuit on the efficiency of the inverter and the efficiency variation with increasing output power. Hence, this article analyses and compares the efficiency of all the three filters against a varying output load.

2 Multilevel converter topologies

This section describes the proposed inverter topology mode of operation, how the switching angles were obtained, and the switching function used to realise the five-level voltage waveform.

2.1 Inverter circuit description

Figure 2 is the inverter circuit configuration used to generate the 5-level voltage waveform. It comprises of two cascaded H-bridge topology modules powered through the same input source. Each module output terminal is connected to a special transformer having two independent primary and series-connected secondary windings with 1:1 and 1:1 turn ratio, respectively. The single DC input source could either be a photovoltaic, lithium-ion batteries or fuel cells. Insulated gate bipolar junction transistors (IGBT) (S_{11a} to S_{24b}) were the power electronic switches, with each of the gating terminal controlled using an offline precalculated switching angle stored in a pulse generator. With an appropriate control signal, each of the H-module is capable of generating three voltage steps ($-V_{DC}$, 0 and

Fig. 2 Converter circuit topology

VDC). Table 1 gives the state of each switch and the corresponding terminal voltages.

Figure 3 shows a sketch of the 5-level voltage waveform to be generated by the converter topology. The first module generates terminal voltage V_{01} using switches S_{11a} to S_{14a} . The voltage is used for step synthesis by adding a series of notches to the output voltage (V_{out}), while the second module generates V_{02} with switches S_{21b} to S_{24b} and is for the bulk power transfers. Note that this research is not intended to address switching and power balancing in both electronic switches and transformers, and it is interested in voltage step level generation and the filters harmonic elimination.

2.2 Switching angles

The multilevel inverter is controlled using selective harmonic elimination (SHE) pulse width modulation (PWM) technique. Therefore, the switching angles are obtained by optimally solving the generated nonlinear transcendental equations using a genetic algorithms optimisation technique. Equation (1) shows the generalised output waveform equation. There are twelve angles with each representing a single notch (N) added per-quarter waveform at predetermined points. Equation (1) with $n = 1$ represents the fundamental component and is equated to a specific value based on the modulation index (M), whereas all other equations with ($n > 1$) representing the harmonic amplitudes are equated to zero. Based on selective harmonic elimination theory, the converter eliminates ($N - 1$) harmonics, meaning all the 11 lower-order odd harmonics. In the prior study presented in [4], only the odd nontripplen harmonics were selected for elimination, i.e. (5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, 29th, 31st, 35th).

Table 1 Switching combinations

Voltage	Switching states							
	S_{11a}	S_{12a}	S_{13a}	S_{14a}	S_{21b}	S_{22b}	S_{23b}	S_{24b}
0	1	0	1	0	1	0	1	0
+E	1	0	0	1	1	0	1	0
+E	1	0	1	0	1	0	0	1
0	0	1	0	1	0	1	0	1
-E	0	1	1	0	1	0	1	0
-E	1	0	1	0	0	1	1	0
+2E	1	0	0	1	1	0	0	1
-2E	0	1	1	0	0	1	1	0

Fig. 3 Five-level waveform with 3/9 distribution ratio

$$h_1 = \frac{4 * E}{\pi} \left\{ \begin{array}{l} \cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3 + \cos \alpha_4 - \cos \alpha_5 + \cos \alpha_6 - \cos \alpha_7 + \cos \alpha_8 \\ - \cos \alpha_9 + \cos \alpha_{10} - \cos \alpha_{11} + \cos \alpha_{12} \end{array} \right\} \quad (1)$$

$$h_n = \frac{4 * E}{n\pi} \left\{ \begin{array}{l} \cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_3 + \cos n\alpha_4 - \cos n\alpha_5 + \cos n\alpha_6 \\ - \cos n\alpha_7 + \cos n\alpha_8 - \cos n\alpha_9 + \cos n\alpha_{10} - \cos n\alpha_{11} + \cos n\alpha_{12} \end{array} \right\} \quad (2)$$

The amplitude of the fundamental component is controlled by the modulation index (M) and is given by the expression.

$$\text{Modulation Index } (M) = \frac{h_1}{E} \quad (3)$$

For all $n=1$.

While $M=0$ for all $n+1$.

Hence, using Eqs. (1), (2) and (3) are used to generate the nonlinear transcendental equations that can be expressed as:

Table 2 Calculated switching angles

(sn/α_n)	0–90	90–180	180–270	270–360
1	13.40246	103.40246	193.4025	283.4025
2	15.67567	105.67567	195.6757	285.6757
3	19.61681	109.61681	199.6168	289.6168
4	35.50001	125.50001	215.5000	305.5000
5	37.80673	127.80673	217.8067	307.8067
6	46.26136	136.26136	226.2614	316.2614
7	48.24797	138.24797	228.248	318.248
8	54.85481	144.85481	234.8548	324.8548
9	58.37752	148.37752	238.3775	328.3775
10	61.01313	151.01313	241.0131	331.0131
11	83.87128	173.87128	263.8713	353.8713
12	86.01930	176.0193	266.0193	356.0193

$$\left[\begin{array}{c} \cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3 + \cos \alpha_4 - \cos \alpha_5 + \cos \alpha_6 - \cos \alpha_7 + \cos \alpha_8 \\ - \cos \alpha_9 + \cos \alpha_{10} - \cos \alpha_{11} + \cos \alpha_{12} \end{array} \right] = \frac{M\pi}{4} \quad (4)$$

$$\left[\begin{array}{c} \cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3 + \cos 5\alpha_4 - \cos 5\alpha_5 + \cos 5\alpha_6 - \cos 5\alpha_7 + \cos 5\alpha_8 \\ - \cos 5\alpha_9 + \cos 5\alpha_{10} - \cos 5\alpha_{11} + \cos 5\alpha_{12} \end{array} \right] = 0 \quad (5)$$

⋮

$$\left[\begin{array}{c} \cos 35\alpha_1 - \cos 35\alpha_2 + \cos 35\alpha_3 + \cos 35\alpha_4 - \cos 35\alpha_5 + \cos 35\alpha_6 - \cos 35\alpha_7 \\ + \cos 35\alpha_8 - \cos 35\alpha_9 + \cos 35\alpha_{10} - \cos 35\alpha_{11} + \cos 35\alpha_{12} \end{array} \right] = 0 \quad (14)$$

Equations (4)–(14) are the nonlinear transcendental equations that are solved using the optimisers to obtain the optimum switching angles (Table 2).

3 Filter design

This section discusses the three types of filters used in this research, their circuits configuration, transfer function and the design steps.

3.1 LCL filter

Due to the large inductor size, time delay and resonance issues associated with the LC filter, the LCL filter was introduced to address the said problems [13]. It is a third-order filter because it has three energy storage components with an attenuation factor of 60 db per decades. Its circuit is distinct from the LC filter in that it has an additional series-connected inductance between the capacitor and the grid. This filter effectively addresses the problem of size and time delay, but still has resonance issues, which, if not addressed, can cause instability in the voltage and current at the resonance frequency. Figure 4 shows the LCL filter circuit arrangement.

Some rules and approximations need to be followed when designing an LCL filter. One of which is that the inductor voltage drop should not exceed 5–10% of the network root-mean-square of the rated voltage [14],

Fig. 4 LCL filter

whereas the current ripples should not be more than 25% of the rated current. In most cases, it lies within the range of 15–25% [1, 4]. Lastly, the reactive power absorbed by the capacitor (Qc) should be less than the generated active power (Pg). With the help of the above assumptions, the below expressions are derived.

$$I_{Lmax} * X_L = I_{Lmax} * (2\pi Lf) < 0.05 * V_{in} \quad (15)$$

$$Q_c = \frac{V_g^2}{X_c} = V_{in} * (2\pi Cf) = 0.01 * P_g \quad (16)$$

$$L_1 = 4L_2 \quad (17)$$

$$W_{res} = \sqrt{\frac{(L_1 + L_2)}{L_1 * L_2 * C}} \quad (18)$$

$$R = \frac{1}{3W_{res}C} \quad (19)$$

The passive components of all the three set of filters are calculated using Eqs. (15)–(19), as shown below:

The parameters obtained are presented in Table 3 below.

The below expression gives the above circuit transfer function. It is used to analyse the filter stability margin using a bode plot.

$$G_{(s)} = \frac{I_2}{V_{in}} = \frac{1}{(L_1 + L_2)s + L_1L_2Cs^3} = \frac{1}{3.047e - 11s^3 + 0.00089335s} \quad (20)$$

Table 3 List of filter components

Filter type	L_1 (mH)	L_2 (mH)	C (μF)	R (Ω)
LCL	0.715	0.179	239	
LCL series damped	0.715	0.179	239	0.39
LCL parallel damped	0.715	0.179	239	3.90

Fig. 5 **a** Series damped filter. **b** Parallel damped filter

The resonance issue is addressed by damping the system. The damping is achieved by connecting a resistor either in series or in parallel to the filter capacitor. Figure 5a, b represents the two filter circuit arrangements, respectively. The circuits transfer function for both the two circuits is given in Eqs. (21) and (22). The resistance value needs to be carefully selected to minimise losses due to I^2R .

The transfer function for the series damping configuration.

$$G(s) = \frac{I_2}{V_{in}} = \frac{1 + RCS}{(L_1 + L_2)S + (L_1 + L_2)RCS^2 + L_1L_2CS^3}$$

$$= \frac{9.309e - 05S + 1}{3.047e - 11S^3 + 8.316e - 08S^2 + 0.0008933S} \quad (21)$$

While the parallel connection transfer function is given by:

Fig. 6 **a** Unfiltered inverter output voltage and current waveform. **b** Unfiltered voltage and current FFT

$$G_{(s)} = \frac{I_2}{V_{in}} = \frac{R}{(L_1 + L_2)RS + (L_1 L_2)S^2 + L_1 L_2 RCS^3}$$

$$= \frac{3.9}{1.188e - 10S^3 + 1.276e - 07S^2 + 0.003484S} \quad (22)$$

4 Simulation results and discussion

This section presents the inverter output current and voltage waveforms along with their FFT. Based on the inverter output requirements, three sets of filters were designed and analysed. The stability margin for all the filters is ascertained using bode plot. The filters THD and efficiency variation with respect to output power are presented.

4.1 Inverter output without a filter

The proposed inverter topology is simulated in PSIM software controlled using the obtained switching angles to generate the five-level output voltage. Figure 6a shows the current and voltage waveforms across a resistive load. The benefit of SHE-PWM technique is it reduces the inverter output harmonic contents by eliminating lower-order harmonics. Figure 6b shows the fast Fourier transform (FFT) for the output voltage and current. As seen, all the selected lower harmonics are eliminated in both voltage and current waveforms. The only visible harmonics at lower frequency are the triplens which are expected to be eliminated in a 3-phase system. The odd nontriplen dominant harmonic becomes visible at the 37th order, which is not within the SHE-PWM elimination range. Hence, this results in the needs for a smaller size filter with cutoff frequency at 1850 Hz. The un-filtered inverter total harmonic distortion (THD) is 27.46% at 2 kW, which is quite higher than the acceptable 5%.

4.2 Inverter output with LCL filter

To address the time delay, large inductor size and resonance issues associated with passive filters, an LCL filter was introduced. Figure 7a shows the LCL filter output current and voltage waveforms at light load. LCL is capable of addressing the inductor size problem and as well reduces the total harmonic distortion (THD) down to 5.15% at 2 kW. Though it did not satisfy the 5% standard requirement, all the higher-order harmonics have been suppressed. Figure 7b, c represents the output FFT and the filter bode plot, respectively. As seen in the frequency

response, there is a peak amplitude overshoot occurring at a resonance frequency which needs to be addressed. The circuit needs a damper, to suppress the overshoot. This brought about the concept of the LCL series and parallel filter into the picture [15].

4.3 LCL filter with series resistance (LCL-S-R)

To solve the resonance problem associated with the LCL filter, a damping resistor is connected in series with the filter capacitor. Figure 8a shows the filtered output waveform at 2-kW loading. It has fewer ripples as compared with the former indicating reduction in the inverter output THD, which stood at 4.47%. Figure 8b shows its FFT plot, with no lower and higher harmonics visible. It can be seen from Fig. 8c that the introduction of resistance into the circuit has addressed the overshoot problem at resonance. This results in a better stable frequency response and smooth phase transition at the resonance frequency. The drawback of this filter arrangement is a drop in efficiency due to $I_c^2 R$ heat dissipation.

4.4 LCL filter with parallel resistance (LCL-P-R)

The filter-damping factor and output THD can as well be improved by connecting a resistor in parallel with the capacitor. This arrangement has the least THD value of 4.17% at 2 kW. Figure 9a, b shows a smooth inverter output waveforms and harmonic-free FFT plot at the same 2-kW loading. The filter frequency response in Fig. 9c is similar to the previous Fig. 8c with damped overshoot at the resonance frequency.

4.5 Efficiency and THD variation with output power

The literature suggests that the harmonic content of an inverter has an inverse relationship with its output power, as the output power increases, so the THD decreases. To ascertain this theorem with our converter topology and filters, the output harmonics of the topology with and without the filters are measured and plotted as shown in Fig. 10. The plot verifies the THD and output power relationship. The without filter curve obeys the theorem, but as seen, it has a minimal variation with increased loading, whereas the ones with filter experience significant variations as the output power increases. The LCL-P-R has the least THD value within the entire range and then followed by LCL-S-R and lastly LCL filter.

The efficiency of the inverter with various filters is assessed as the output power is varied. From Fig. 11,

Fig. 7 **a** LCL filtered inverter output voltage and current waveform. **b** LCL filtered voltage and current FFT. **c** LCL filter bode plot

it can be seen that all the curves obey the efficiency vs output power exponential relationship. As expected, the damped filters have the least efficiency values due to the

heat-dissipating component (resistor) introduced. The LCL-S-R has a better efficiency between 1 and the 2 kW range, and the efficiency begins to deteriorate as the inverter is

Fig. 8 **a** LCL series resistance filtered inverter output voltage and current waveform. **b** LCL series resistance filtered voltage and current FFT. **c** LCL series resistance filter bode plot

overloaded. The same deterioration is observed in the LCL as well.

5 Conclusion

The paper analyses the THD and efficiency values of a 5-level cascaded H-bridge inverter that is controlled using selective harmonic elimination method (SHE-PWM). The

proposed inverter successfully eliminates the 11 lower-order harmonics. Even with the elimination, the THD is still higher than the IEEE. 519 requirements. To satisfy the requirement, a filter is needed to mitigate the remaining higher-order harmonics. The filter's harmonic elimination capability was evaluated by measuring the THD values obtained in both the voltage and current output waveforms across a resistive load. Figure 12 presents the THD comparison chart of the inverter output with and without

Fig. 9 **a** LCL parallel resistance filtered inverter output voltage and current waveform. **b** LCL parallel resistance filtered voltage and current FFT. **c** LCL parallel resistance filter bode plot

the filters. As seen both the damped LCL filters satisfy the IEEE requirement at 2 kW except for the un-damped LCL filter.

With respect to efficiency value at 2 kW, it can be deduced from Fig. 13 that LCL has the highest efficiency value followed by LCL-S-R, then without a filter and then the least LCL-P-R with approximately 64.75%. The reduced

Fig. 10 THD versus output power relationship

Fig. 11 Efficiency versus output power relationship

Fig. 12 THD comparison histogram at 2 kw

efficiency value in the later has to do with the resistance added in the circuit, which happens to be a lossy component. Therefore, a careful choice of resistance should be made to minimise efficiency deterioration. Lastly, the inverter control strategy and the filters employed had succeeded in minimising the output THD. Hence, making the

Fig. 13 Efficiency histogram comparison at 2 kw

inverter topology suitable in automotive and renewable energy applications. For future recommendations, the converter topology THD and efficiency characteristics can be investigated using different types of filter and modulation techniques.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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