Theoretical Analysis of LC Filter to Three Level Diode Clamped Inverters in Low/Medium Voltage Applications

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Abstract. The employing of power electronic devices for converters plays a vital role in the conversion of AC to DC vice versa. Applications of these converters more demand in renewable energy, hybrid vehicles, Drives, HVDC, etc. In renewable energy, especially a solar-based power generation stations require inverter stations. These inverters stations have the multilevel inverters. Multilevel inverters are emerging day by day in the sector of the renewable energy sector. The increasing level of multilevel inverters can be effectively utilized in low and medium voltage applications to get the desired voltage and frequency. But output voltage is not in sinusoidal. However, most of the loads require a pure sinusoidal form of voltage. To get sinusoidal voltage across loads a high switching frequency is required to switch the MOSFETs or IGBTs. Along with a suitable value of LC, filters make the sinusoidal nature of waveform with less total harmonic distortion (THD) levels. To get a sinusoidal wave, a proper theoretical analysis of filters is required. In this paper theoretical analysis has been done for LC filters and checked with simulation results for various loads. The performance of theoretical LC filters values checked using diode clamped multi-level inverters have been examined through MATLAB/SIMULINK by POD PWM by POD PWM.

1. Introduction
Remarkable advancement in semiconductor technology leads to the using of applications of power electronics technology is widely in the areas of smart grid, solar, wind energy conversions, marine engineering, biomedical applications, etc. In the converter technology power electronics plays a vital role during conversions of dc to ac and vice versa. Also, the applications of power electronics are finding in shaping, conditioning and transforming frequency, voltage, power factor, etc. The major advantages of these devices are is possible to get a quick response using digital controllers in a closed-loop system for the dispensation of power from renewable energy sources is remarkable.

Naik Raghuram, et.al.[2] has discussed a review of grid-connected WECS for the three-level diode clamped voltage source inverter with different modulation techniques. The paper covered, SPWM, Multicarrier method, SPWM using multiple references frame, carrier Phase Variation method, SVPWM, Hysteresis control, soft-switching algorithm has been discussed concerning its advantages and disadvantages of these techniques. With the use of SPWM the use of DC bus utilization is less, in Multicarrier method suffers in shortcoming such as narrow pulse width, capacitor voltage imbalance, in SPWM using multiple reference frame suffers in the switching the frequency will be doubled and losses hence it is preferable and recommended. For higher voltage levels circuit complexity is more in hysteresis control complexity of the circuit, in the soft-switching algorithm, requires supplementary components. But the utilization of DC bus is high in the SVPWM algorithm and said problems are less among compared to said techniques and are also suitable for three-level neutral point clamped inverter in wind energy conversation systems (WECS).
Bharti Katre, et.al. [5] presented the better utilization of renewable resources such as solar, wind, etc. has led to the establishment of the MLI. An inverter is the power device that converts DC to AC direct as per application requirements. The multilevel inverter is the power electronic devices that are capable of achieving alternating current at the desirable stage at the output by using multiple dc sources at the input. In diode clamp multilevel inverter topology for three levels, there are four switches and two clamped diodes are required. The clamped diodes help in reducing the stress of dc sources from the switching devices. As the levels of inverter increases, the output voltage becomes smoother but with many levels, the inverter becomes complex with the increase in switching devices as well as complexity in controllers function. The pulse width modulation techniques are created, by comparing the combinations of the fundamental frequency and the triangular carrier wave where the intersection point determines the switching points of devices hence establishes a switching frequency. Azah Mohamed et.al [6] implemented the dSPACE DS1104 is one of the controllers by using which multilevel inverter is implemented. The simulation is carried out through MATLAB/Simulink with the help of controllers which gives real-time operation. The three-phase inverter gives stable and near to the sinusoidal voltage of 415Vrms with a low THD of 2.26%.

Gautam ghosh, et.al [7], an inverter is used in various applications in as example adjustable speed drive, UPS and ac operation appliances with a low THD in output voltage, high efficiency and good power factor from batteries or solar-based PV system. The main disadvantages are that the dc-bus capacitors suffer from voltage balancing across the series-connected. This tends to either overcharge of the DC capacitors or entirely discharges. In such conditions, balancing of capacitor charge by reverts passion to a three-level inverter unless an explicit control technique is devised. Lakshman Rao S.P, et.al. [8] presented to meet the load requirement the output voltage of inverter can be fed to the filter to get sinusoidal waveforms which can be again fed to the transformer for theoretical output. S. M. Cheratiet. et.al, [9] developed the close-loop current mode PI controller has been implemented in MATLAB/SIMULINK using Sisotool. A Continuous second-order state-space model for resistive load has done. Then a multiple feedback control loop tested with PWM gain is considered the inner loop parameter as an inductor current of the filter and the outer loop parameter as output voltage. K. Deepa et.al, [10] comparative analysis has been done for different PWM techniques 7 level inverter. In this paper concerted on analysis of the substance of effect of LC filters to get output sinusoidal waveforms for Neutral Point Clamped inverter. The main motto of this paper studies the design of LC filters for multilevel inverters for low voltage applications with less no of switching devices with minimum THD levels.

2. Inverter Topologies

The highly developed multilevel inverter topologies are

- Diode Clamped or Neutral Point Clamped Technique (DC-MLI or NC-MLI)
- Flying Capacitor (FC-MLI)
- Cascaded Full Bridge (CMLI)

In 1981, Nabae, Takahashi, and Akagi proposed first the neutral point three-level diode clamped inverter. The most important idea of this inverter is to reduce the voltage stress of the power devices with the help of diodes. The voltage over each capacitor and each switch is \( V_{dc} \). In this topology, it consists of four switches and two diodes have consisted of a three-level diode clamped inverter. Here the pair of switches work in complimentary mode and access of mid-point voltage balanced by the diodes. By connecting the two DC capacitors (C1 and C2) in series the bus voltage is dividing into three voltage levels. The two diodes \( D_1 \) and \( D_2 \) are used as clamping diodes to diminish the voltage stress across each switching device is partial to \( V_{dc} \). It is supposed to maintain the total dc-link voltage is \( V_{dc} \) and mid-point is synchronized at half of the dc-link voltage, the voltage across each capacitor is \( V_{dc}/2 \) (\( V_{C1}=V_{C2}=V_{dc}/2 \)). In a three-level diode clamped inverter there are three different feasible switching states which apply the staircase voltage on output voltage relating to DC link capacitor voltage rate. To get three-level output voltage simultaneously two switches should be on and so on.
Figure 1. Circuit diagram of one leg diode clamped inverter

Table 1. Switching state of diode clamped three level inverter

| Switching Status | State | Voltage |
|------------------|-------|---------|
| S1=High, S2=High | +ve Voltage | \( V_{out} = \frac{V_{dc}}{2} \) |
| S2=High, S3=High | 0 | \( V_{out} = 0 \) |
| S3=High, S4=High | -ve Voltage | \( V_{out} = -\frac{V_{dc}}{2} \) |

The classification of Modulation strategies based on fundamental frequency switching,
- Pulse Width Modulation (PWM)
- Sinusoidal Pulse Width Modulation (SPWM)
- Space Vector Pulse Width Modulation (SVPWM)
- Carrier-Based Space Vector Pulse Width Modulation (CB-SVPWM)

3. Theoretical calculations of the LC filter
All loads with a pure sinusoidal waveform from the inverter, which can be done by using a properly designed LC filter. During designing filters the criterion of cost, size, losses, etc are to be considered. Along with an additional criterion is required i.e. minimum reactive power, which helps indirectly, reducing the cost, size, and losses. The harmonics of the LC filter are given in the Fourier series form the closed-form expressions of the inductance and capacitances of the LC filter were not obtained. The reactive power of the LC filter can be calculated as [4].

\[
Pr = \frac{W}{r} \int (i^2 + j^2) + \frac{W}{r} \int (VVo + VVo) 
\]

(1)

Where, \( Is \) and \( Vo \) is the fundamental component of the RMS value of inductor current and load voltage, respectively.

The RMS value of the inductor current can be calculated as

\[
Is = \left[ (io)^2 + (io - WVCFVo)^2 \right]^{\frac{1}{2}}
\]

(2)

Where, \( Io \) and \( Io \) are the RMS values of the real and imaginary components of the load current.

Where, \( CF \) is the filter capacitance of

\[
CF = K \frac{Rd}{Ld^2 Vo \omega}
\]

(3)

and

\[
K = \left[ \frac{k^2 - 15}{4} \frac{k^2 + 64}{4} \frac{k^2 + 2}{4} \frac{k^2 + 5}{4} \frac{k^2 + 8}{4} \right]^{\frac{1}{4}}
\]

(4)
Where,

\[ f = \sqrt{2} \times \frac{V_o}{E_d} \]  

(5)

\[ V_o = \text{RMS value of Output voltage} \]

\[ E_d = \text{DC Voltage} \]

From equation 3 in 1, the optimum value of the inductance of the filter can be calculated by using equation;

\[ L_f = \frac{V_o}{E_d} \frac{K}{\pi \omega_m} \left\{ 1 + 4\pi^2 \left( \frac{f_o}{f} \right)^2 K \frac{E_d}{V_o \omega_m} \right\}^{1/2} \]  

(6)

The RMS value of output voltage harmonic over one period of the fundamental output voltage can be obtained as

\[ V_{o,av} = \left[ \frac{1}{2\pi} \int_0^{2\pi} V_o^2 d(2\pi f_o) dt \right]^{1/2} \]  

(7)

Where,

\[ V_o = 2 \times \frac{E_d}{\sqrt{2} \times \pi} \]  

(8)

The practical value of load resistance and inductance is considered for calculation of output voltage, current, and THD level for single-phase inverter for R and RL load. The load impedance is taken as, \( Z = R + jXL = 403.3 + j1043.3 \Omega \).

### Table 2. Calculated Inductance and Capacitance values

| \( E_d (V) \) | \( f_c (Hz) \) | \( f_c (Hz) \) | \( L_f (mH) \) | \( C_f (\mu F) \) | \( R_e (ohm) \) | \( L_s (H) \) |
|--------------|--------------|--------------|--------------|----------------|---------------|--------------|
| 48           | 3000         | 50           | 4.707        | 283.3          | 403.33        | 3.320        |

### 4. Simulation results and discussions

The simulation has been carried out in MATLAB/SIMULINK R2016a by using phase opposition pulse width modulation techniques. In POD-PWM techniques two carrier signals (one is for positive half cycle and other is for negative half cycle) have been used and compared with one reference signal which is a sinusoidal wave. Here, the modulation index has been taken 0.9 to get the required RMS voltage. The theoretical and simulated values are compared with filter and without the filter. The required load voltage 220V gets it by the step-up transformer, which is required for R and RL load in low voltage applications. Fig.2. Shows the Simulink model of the three-level neutral clamped inverter. Table 2 shows the calculated and simulated output voltages and current for a real load impedance of \( R_i = 403.33 \Omega \) and \( X_L = 3.320 \Omega \). Table.3. indicates that THD level and output RMS voltage for different modulation index.
Figure 2. 3 level diode clamped simulink model with transformer

Figure 3. Without filters output voltage and current waveform of inverter
Figure 4. THD level of three level diode clamped inverter without filters

Figure 5. With filters Voltage and current output waveform of inverter (primary side of transformer)

Figure 6. THD level of three level diode clamped inverter with filter
Figure 7. With filters Voltage and current waveform of inverter at load side (secondary side of transformer)

Figure 8. THD level in RL Load with filter

Table 3. A Comparison of theoretical and simulated values for R=403.33Ω and L=3.323H.

| Type of Load                  | Output Voltage (V) | Output Current (A) | THD          |
|-------------------------------|--------------------|--------------------|--------------|
| For R Load Without Filter     | Theoretical Values | 21.70              | 0.0545       | 48.35%       |
|                               | Simulated Values   | 16.90              | 0.059        | 55.16%       |
| For R Load With Filter        | Theoretical Values | 21.61              | 0.054        | 48.35%       |
|                               | Simulated Values   | 19.90              | 0.065        | 44.56%       |
| For RL Load Without Filter    | Theoretical Values | 21.607             | 0.054        | 48.53%       |
|                               | Simulated Values   | 17.01              | 0.600        | 51.6%        |
| For RL Load With Filter       | Theoretical Values | 21.607             | 0.055        | 48.35%       |
|                               | Simulated Values   | 20.97              | 0.053        | 3.51%        |
Table 4. THD level for RL load at different modulation index

| Output Voltage (A) | Output Current (A) | THD |
|-------------------|-------------------|-----|
| 0.5               | 11.93             | 1.20% |
| 0.6               | 13.96             | 3.74% |
| 0.7               | 15.48             | 3.32% |
| 0.8               | 17.84             | 2.04% |
| 0.85              | 19.10             | 1.68% |
| 0.9               | **20.97**         | 3.51% |

5. Conclusion
The theoretically calculated values of LC filters are tested on three-level diode clamped inverter by considering R and RL loads. Simulation has been carried out with and without filters for R and RL load using POD-PWM techniques and secondly checked for RL load with different modulation index. The output results show that simulated values are closer to the calculated values. From the theoretical calculated LC, filters are able to bring the THD level within 5% proven. In the second case, the load fixed and varied the modulation index from 0.5 to 0.9, at 0.85 gives very less THD level and output RMS voltage near to the calculated value. At 0.9 THD level is slightly increased and output RMS voltage closest to the calculated value. With proper analysis of LC values, we can get a voltage in the sinusoidal form for the loads. For low voltage applications using less, no switches can accomplish the THD level within the limits instead of high large no of switches.

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