

DESIGN AND IMPLEMENTATION OF MODIFIED
MULTILEVEL INVERTER FED BLDC MOTOR
FOR ELECTRIC VEHICLE APPLICATION

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Abstract

In this work a modified hybrid multilevel inverter with reduced device is proposed. The system considerably reduces the quantity of power electronic power switches to twenty-one so as to create fifteen level three phase output, whereas conventional structures require higher number of power devices. Higher number of power switches leads to increased distortion, losses and cost. The recommended circuit gives better response, higher efficiency, reduced cost, high reliability and fault tolerance. Decrease in number of power switches, intensely diminishes the convolution of the switching circuitry.

Key words: multilevel inverter, electric vehicle, particle swarm optimization, permanent magnet brushless DC motor, total harmonic distortion, pulse width modulation

Introduction. Multilevel inverters (MLI), because of their benefits like less dv/dt stress, flexibility, and enhanced waveform quality are being widely engaged in FACTS devices, Battery operated EVs and Smart Grid [1,2]. MLIs are traditionally divided into three types: Diode Clamped MLI (DCMLI), Flying Capacitor MLI (FCMLI), and Cascaded H-bridge MLI (CHMLI). DCMLI necessitates a higher quantity of diodes as the levels in the output waveform grow, high numbers of components, making circuit management difficult. The voltage balancing problem produced by the diodes in DCMLI may be handled in FCMLI by exploiting

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redundancy in switching schemes provided by the capacitors; however, a larger count of passive circuit components would compromise circuit dependability [3–6]. If compared to these topologies, CHMLI is enormously modular and easier to regulate. Furthermore, it needs separate DC sources, hence the need for balancing circuits is eliminated. Nonetheless, every additional DC voltage source raises the need of electronic power switches by four in standard CHMLI. The requirements of more power devices in traditional circuits have pushed the door for research into increased level of inverter called reduced element count MLI configurations with fewer power devices [7–9]. Because of the unique qualities, multilevel inverters are gaining popularity in a variety of average to high-voltage, high-power applications [10–12]. The Modified Hybrid Multilevel Inverter combines the concepts of hybrid multi-conversion cell and h-bridge which make both positive and negative polarity. The suggested configuration's key design feature has fewer components.

Modified hybrid multilevel inverter. Figure 1 shows overall construction of a suggested topology for MLI. A multi conversion cell and two serially connected power switches make up this inverter. The cell is made up of three independent voltage sources (V_{m1} , V_{m2} , V_{m3}), each of which is connected to the others via a circuit that includes a diode and an active switching element which can only produce the positive polarity resultant voltage source with many levels. To achieve alternate polarity in nature, four power switches are connected like h-bridge. The first level of resultant voltage $+1 V_{dc}$ is attained by switching on the power switches S_{11} (S_{12} and S_{13} are turned off). Other levels can be achieved in the same way by turning on appropriate power switches at specific intervals, as depicted in Table 1. The following equation may be used to compute the number

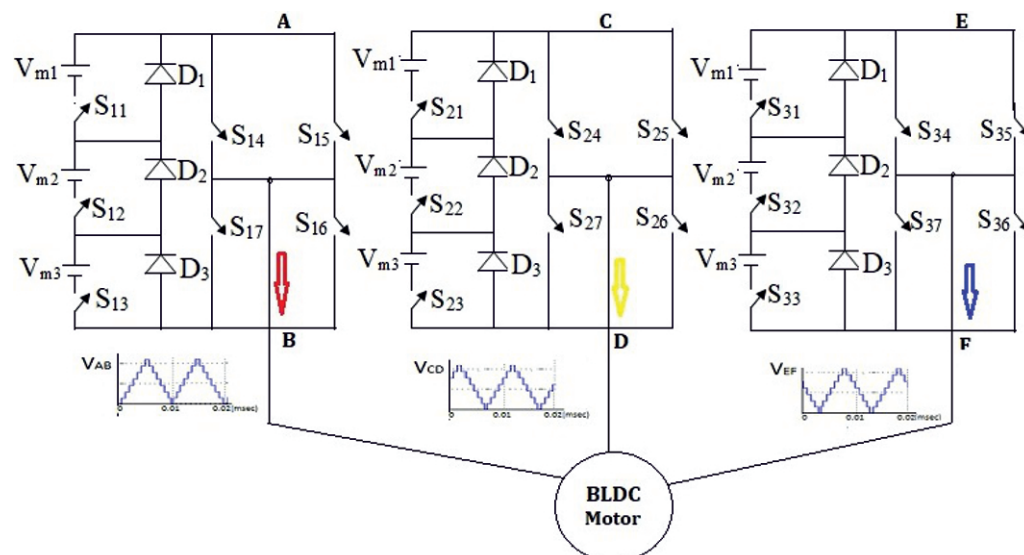


Fig. 1. Configuration of modified hybrid multilevel inverter

L of DC voltage sources and the related quantity of output levels:

$$(1) \quad N_{\text{level}} = 2^{L+1} - 1.$$

As an example, if the value of $L = 3$, the resultant waveform will have fifteen stages ($\pm 7 V_{\text{dc}}$, $\pm 6 V_{\text{dc}}$, $\pm 5 V_{\text{dc}}$, $\pm 4 V_{\text{dc}}$, $\pm 3 V_{\text{dc}}$, $\pm 2 V_{\text{dc}}$, $\pm 1 V_{\text{dc}}$ and $0 V_{\text{dc}}$). Also resultant output on every level can be evaluated by employing the following equation

$$(2) \quad V_{mL} = 2^{L-1} V_{\text{dc}}, \quad L = 1, 2, 3.$$

The quantity of power switches involved in this configuration to generate single phase voltage is given by the following equation

$$(3) \quad N_{\text{switch}} = L + 4, \quad L = 1, 2, 3.$$

Estimation of loss and efficiency. Power switches are employed as a polarity conversion in a unit in the proposed inverter and the load current in a single phase is measured with respect to the neutral. The loss due to conduction period of switches during the quarter of the basic cycle is derived in this situation

$$(4) \quad P_{\text{CON}} = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} I_{\text{RM}}^2(t) R_{\text{ON}} T dt.$$

The on-state resistance and load current of transistor, are designated as R_{ON} , T , and $I_{\text{RM}}(t)$, respectively. The current in the load side can be considered to be sinusoidal. As a result, the load current may be expressed as

$$(5) \quad I_{\text{RM}} I_{\text{PM}} \sin wt.$$

Using (4) and (5), the average loss of the single-phase system during conduction is derived as follows:

$$(6) \quad P_{\text{CON1}} = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} I_{\text{PM}}^2 \sin^2 wt R_{\text{ON}} T dt.$$

For the multi-conversion part, one MOSFET switch is turned on throughout the fundamental period. For the period of π , the loss in multi-conversion is as follows:

$$(7) \quad P_{\text{CON2}} = \frac{1}{\pi} \int_0^{\pi} I_{\text{PM}}^2 \sin^2 wt R_{\text{ON}} T dt.$$

The conduction losses of the diode in multiconversion cell's single leg is given by

$$(8) \quad P_{\text{CD}}(t) = [V_{\text{DM}} + R_{\text{DM}} i(t)] i(t).$$

Table 1
Switching configuration of multilevel inverter

S.No	Intervals	S ₁₁	S ₁₂	S ₁₃	S ₂₁	S ₂₂	S ₂₃	S ₃₁	S ₃₂	S ₃₃	S ₁₄	S ₁₅	S ₁₆	S ₁₇	S ₂₄	S ₂₅	S ₂₆	S ₂₇	S ₃₄	S ₃₅	S ₃₆	S ₃₇
1	I	0	0	0	1	0	1	0	0	1	1	0	1	0	0	1	0	1	1	0	1	0
2	II	1	0	0	0	1	0	1	0	1	1	0	1	0	0	1	0	1	1	0	1	0
3	III	0	1	0	1	0	0	0	1	1	1	0	1	0	0	1	0	1	1	0	1	0
4	IV	1	1	0	0	0	0	1	1	1	1	0	1	0	0	1	0	1	1	0	1	0
5	V	0	0	1	1	0	0	0	0	0	1	0	1	0	0	1	0	1	1	0	1	0
6	VI	1	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0	1	0	1	0	1
7	VII	0	1	1	1	1	0	0	1	0	1	0	1	0	0	1	0	1	0	1	0	1
8	VIII	1	1	1	0	0	1	1	1	0	1	0	1	0	0	1	0	1	0	1	0	1
9	IX	0	1	1	1	0	1	0	0	1	1	0	1	0	0	1	0	1	0	1	0	1
10	X	1	0	1	0	1	1	1	0	1	1	0	1	0	0	1	0	1	0	1	0	1
11	XI	0	0	1	1	1	1	0	1	1	1	0	1	0	0	1	0	1	0	1	0	1
12	XII	1	1	0	0	1	1	1	1	1	1	0	1	0	1	0	1	0	0	1	0	1
13	XIII	0	1	0	1	0	1	0	1	1	1	0	1	0	1	0	1	0	0	1	0	1
14	XIV	1	0	0	0	0	1	1	0	1	1	0	1	0	1	0	1	0	0	1	0	1
15	XV	0	0	0	1	1	0	0	0	1	1	0	1	0	1	0	1	0	0	1	0	1
16	XVI	1	0	0	0	0	1	1	1	0	1	0	1	0	1	0	1	0	0	1	0	1
17	I	0	0	0	1	0	1	0	0	1	0	1	0	1	1	0	1	0	0	1	0	1
18	II	1	0	0	0	1	0	1	0	1	0	1	0	1	1	0	1	0	0	1	0	1
19	III	0	1	0	1	0	0	0	1	1	0	1	0	1	1	0	1	0	0	1	0	1
20	IV	1	1	0	0	0	0	1	1	1	0	1	0	1	1	0	1	0	0	1	0	1
21	V	0	0	1	1	0	0	0	0	0	0	1	0	1	1	0	1	0	0	1	0	1
22	VI	1	0	1	0	1	0	1	0	0	0	1	0	1	1	0	1	0	1	0	1	0
23	VII	0	1	1	1	1	0	0	1	0	0	1	0	1	1	0	1	0	1	0	1	0
24	VIII	1	1	1	0	0	1	1	1	0	0	1	0	1	1	0	1	0	1	0	1	0
25	IX	0	1	1	1	0	1	0	0	1	0	1	0	1	1	0	1	0	1	0	1	0
26	X	1	0	1	0	1	1	1	0	1	0	1	0	1	1	0	1	0	1	0	1	0
27	XI	0	0	1	1	1	1	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0
28	XII	1	1	0	0	1	1	1	1	1	0	1	0	1	0	1	0	1	1	0	1	0
29	XIII	0	1	0	1	0	1	0	1	1	0	1	0	1	0	1	0	1	1	0	1	0
30	XIV	1	0	0	0	0	1	1	0	1	0	1	0	1	0	1	0	1	1	0	1	0
31	XV	0	0	0	1	1	0	0	0	1	0	1	0	1	0	1	0	1	1	0	1	0
32	XVI	1	0	0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	1	0	1	0

R_{DM} is the diode equivalent resistance and V_{DM} is the diode voltage drop in the forward path.

The power losses of the diode in multiconversion cell's single leg is given by

$$(9) \quad P_{CON3} = \frac{1}{2\pi} \int_0^{2\pi} N_{DM}(t) P_C D(t) dt.$$

There are three numbers of multi-conversion unit in the proposed multilevel inverter, the loss during conduction is obtained as follows:

$$(10) \quad P_{CON,TOTAL} = 3 \times P_{CON1} + 3 \times P_{CON2} + 3 \times P_{CON3}.$$

The switch losses occur due to overlying of voltage and current in MOSFET during the changeover from turn on to off condition or vice versa. The energy loss of MOSFET power switches throughout their on and off periods is calculated as follows:

$$(11) \quad E_{ON} = \frac{V_{ON} \times I}{6} T_{ON},$$

where V_{ON} , I , T_{ON} are the MOSFET voltages during ON state, the MOSFET current after ON and OFF period, respectively.

$$(12) \quad E_{OFF} = \frac{V_{OFF} \times I}{6} T_{OFF}.$$

V_{OFF} , I_{OFF} , and T_{OFF} are the MOSFET voltages during OFF state, current passing through the MOSFET before ON and OFF period, respectively. The average loss in the projected configuration is estimated using equations (11) and (12) and is determined independently for power switches in each unit. The switching loss in polarity conversion unit is calculated as follows:

$$(13) \quad P_{SW1} = 2 \times f \times (E_{ON} + E_{OFF}) = \frac{1}{3} \times f \times I \times (V_{ON} T_{ON} + V_{OFF} T_{OFF}).$$

The fundamental switching frequency is f . Similarly, during the half period, the switching loss of multi-conversion unit is given as

$$(14) \quad P_{SW2} = 2 \times f \times (E_{ON} + E_{OFF}) f \times I (V_{ON} T_{ON} V_{OFF} T_{OFF}).$$

The switching losses of the diode in the multiconversion unit are given as

$$(15) \quad P_{SW3} = \frac{1}{2} C_R \times V_R^2 \times f_{sw} + \frac{1}{6} I_{RR} * V_R \times t_b \times f_{sw}.$$

For a full cycle, the overall switching loss can be deduced as

$$(16) \quad P_{SW,TOTAL} = f \times (P_{SW1} + P_{SW2} + P_{SW3}).$$

The total loss and the efficiency of the projected inverter are determined by using (17) and (18)

$$(17) \quad P_{\text{LOSS,TOTAL}} = P_{\text{CON,T}} + P_{\text{SW,T}}.$$

The efficiency of the suggested configuration has been calculated using the following formula:

$$(18) \quad \text{Efficiency} = \frac{P_{\text{OUT}}}{P_{\text{OUT}} + P_{\text{LOSS,T}}} \times 100\%.$$

Particle swarm optimization for modified hybrid multilevel inverter.

In this part, efficiency and reliability of suggested multilevel inverter topology by decreasing the harmonics using PSO optimization algorithm are detailed. Particle swarm optimization method is an appropriate algorithm for diminishing the harmonics in MLI. By re-iterating the triggering angles, the harmonics can be compressed in the presence of non-linear loads. The performance and accuracy of the inverter can be increased through triggering angles. Its calculation time hangs on the iterations count and initial stage search space in the algorithm primes its acceleration variables B_1 , B_2 and M_{max} and M_{min} . The formula for movement of a particle is specified by (19).

$$(19) \quad V_i^{i+1} = V_{ij}^t w^{t+1} B_1 x r_{1j}^t x (P_{\text{best}t x i j}^t - x_{ij}^t) + \{B_2 x r_{2j}^t x (G_{\text{best}}^t - x_{ij}^t)\},$$

$$(20) \quad x_{ij}^{t+1} = x_{ij}^t B_1 x v_{1j}^{t+1},$$

where w^{t+1} is the inertia weight and it is given by

$$(21) \quad M^{t+1} = M_{\text{max}} - \left\{ \frac{M_{\text{max}} - M_{\text{min}}}{TNI} \right\} Cl.$$

The optimized point is discovered for the particle based on updated velocity and position at P_{Best} . The alteration will continue until the particles reach the repetition end point. Newton–Raphson (NR) method was used to solve the non-linear transcendental equations through first particles. The PSO method is used to enhance the triggering angles by the following equation

$$(22) \quad F(\theta_1, \theta_2, \theta_3) = \left[\sum_{n=1}^s V_1 \cos(\theta_n - m) \right]^2 + \left[\sum_{n=1}^s V_2 \cos(3\theta_n - m) \right]^2 + \left[\sum_{n=1}^s V_s \cos(2s - 1) \right]^2.$$

Total harmonic distortion (THD) is the substantial apprehension for the system, hence the formula of THD for the proposed multilevel inverter and frequency

of switching can be calculated by the following equations

$$(23) \quad THD = \left[\frac{1}{a_1^2} \sum (an) \right]^{\frac{1}{2}} \times 100,$$

$$(24) \quad f = \{3.28M - V_1\}^2 + \{V_2\}^2 + \{V_7\}^2.$$

An amalgamation of PSO with hybrid search technique has been carried out in the research work to improve the convergence rate of the algorithm. In this work three phase fifteen level modified hybrid multilevel inverter is executed in Simulink tool and experimental verification is done for single phase.

Results and discussion. Figure 2(a) shows proposed 15-level modified hybrid MLI 3-phase line voltage waveform. This waveform is almost sinusoidal and the speed and torque response produced by BLDC motor are also precise and also from Fast Fourier Transform analysis window is realized with increased levels and reduced THD. The FFT analysis of the suggested inverter is shown in Fig. 2(b), and it clearly shows that THD is 8.34%. Simulation result is validated with the hardware prototype. MOSFETs are used as switching devices of line to neutral voltage of 84 V, three phase, 15-level suggested architecture. The inverter is made up of 21 MOSFET switches. IRF840 MOSFETs are employed in the hardware setup. The gate signal for inverter switches is generated by Arduino microcontroller. In the input side of proposed 15-level inverter, three asymmetric DC sources, 30 V, 60 V and 120 V are deployed. The suggested inverter output powers a BLDC motor of 3 kW. The voltage and current waveforms of the hardware results are also sinusoidal and speed and torque response is precise. THD of the hardware set up is 8.57%. Figure 3 illustrates the different multilevel circuits. The comparison is made for three phase 15 level depends on usage of power elements, THD and efficiency. The performance of the proposed multilevel is 98.6% efficiency when compared to other conventional inverters. The cost function per level is 3.975 for single leg with weight factor of 1. The modified hybrid multilevel inverter has benefits of 15 levels with only 21 numbers of power switches when the

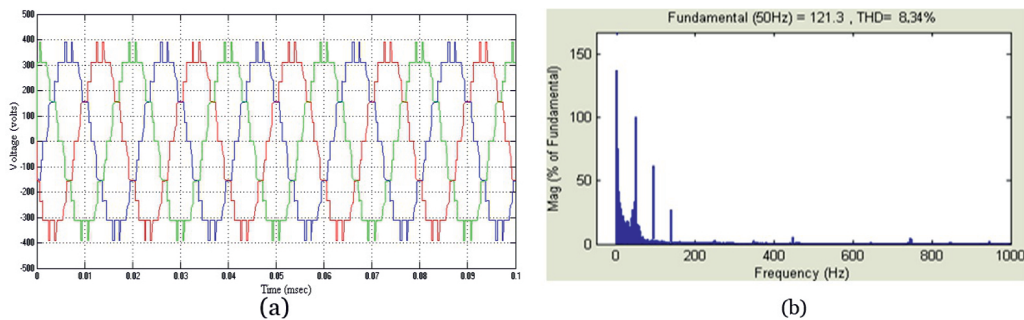


Fig. 2. (a) 15 level three phase line to line output voltage waveform for RL load; (b) FFT analysis

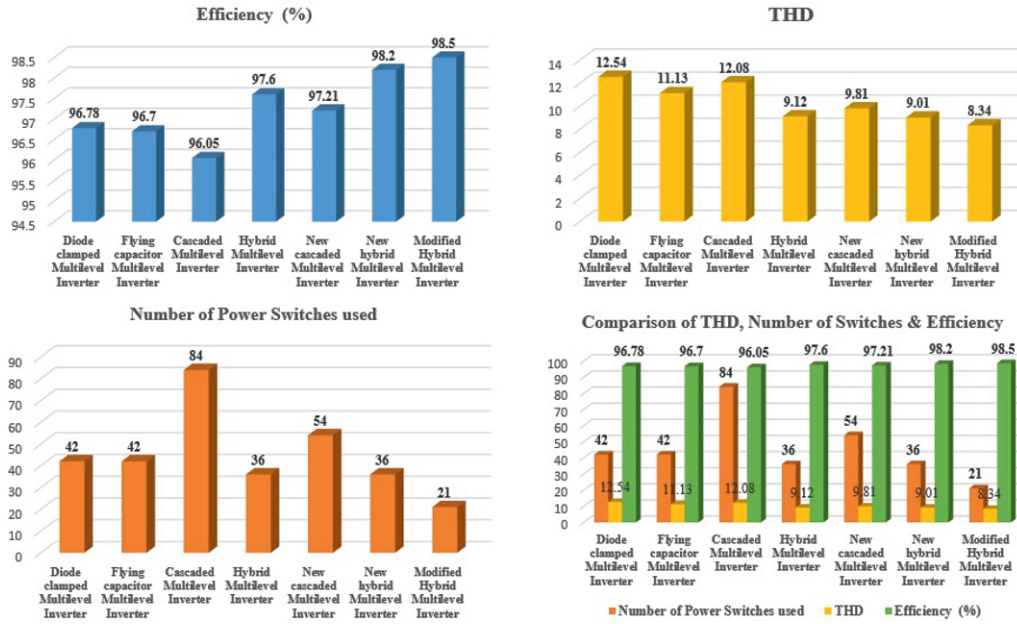


Fig. 3. Comparison of performance parameters of modified hybrid multilevel inverter

multisource is utilized. The comparison results show that the proposed modified hybrid multilevel inverter is best suited for electric vehicle with less number of power switches, reduced in THD and higher efficiency.

Calculation of cost function. The Total Standing Voltage (TSV) of projected multilevel inverter is calculated as follows:

$$(25) \quad \text{Total Standing Voltage} = \sum_{i=1}^n \text{MBV}_{S_i},$$

$$\begin{aligned} \text{TSV} &= \text{MBV}_{S_{11}} + \text{MBV}_{S_{12}} + \text{MBV}_{S_{13}} + \text{MBV}_{S_{14}} + \text{MBV}_{S_{15}} + \text{MBV}_{S_{16}} + \text{MBV}_{S_{17}} \\ &= 5 V_{dc} + 2 V_{dc} + 0 V_{dc} + 8 V_{dc} + 8 V_{dc} + 8 V_{dc} + 8 V_{dc} = 39 V_{dc}, \\ \text{TSV}_{PU} &= \text{TSV}/\text{MBV} = 39 V_{dc}/8 V_{dc} = 4.875. \end{aligned}$$

The Cost function of the proposed MLI is calculated by equation

$$(26) \quad \text{Cost Function} = (N_S + N_{gd} + N_D + N_C + \alpha \text{TSV}_{PU}) \times N_{DC}.$$

When $N_S = 7$, $N_{gd} = 5$, $N_D = 3$, $N_C = 0$, $\alpha = 0.5$, and $N_{DC} = 3$, Cost function is

$$\text{Cost Function} = (7 + 5 + 3 + 0 + 0.5 \times 4.875) \times 3 = 52.3125.$$

Cost function per level is calculated as

$$\text{CF/Level} = \frac{\text{CF}}{\text{Number of Levels}} = \frac{52.3125}{15} = 3.4875.$$

When $N_S = 7$, $N_{gd} = 5$, $N_D = 3$, $N_C = 0$, $\alpha = 1$, and $N_{DC} = 3$, the calculations give the following results

$$\begin{aligned}\text{Cost Function} &= (7 + 5 + 3 + 0 + 1 \times 4.875) \times 3 = 59.625, \\ \text{CF/Level} &= \frac{\text{CF}}{\text{Number of Levels}} = \frac{59.625}{15} = 3.975.\end{aligned}$$

Conclusion. The proposed work has validated the structural set up of modified hybrid multilevel inverter. In the conservative approaches, the number of power switches increased based on the number of levels. Due to the engrossment of large count of power switches, total harmonics distortion, switching losses, and the implementation cost are also increased. The suggested technique histrionically diminishes the power switches to 21 for three phase 15 level which will lessen the losses due to switching, lower order harmonics, cost, and leads to reduction in THD. The cost function of the proposed MLI is 3.4875. Hence, the introduced modified hybrid MLI is suitable for electric vehicle applications.

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