International Journal of Electrical and Electronics Engineering (IJEEE)
ISSN 2278-9944
Vol. 2, Issue 2, May 2013, 27-40

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

NEW MULTILEVEL CASCADED PWM INVERTER TOPOLOGY FOR HYBRID ELECTRIC VEHICLE DRIVE

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ABSTRACT

Multilevel inverter technology is an emerging trend for the control of electric drives in hybrid electric vehicles of high power rating. Harmonic distortion in output voltage waveform is reduced by this multilevel inverters as switching frequency used is the power frequency, which also minimizes the switching losses. This paper presents a hybrid cascaded multilevel inverter with PWM technique. Hybrid electric vehicle (HEV) is an emerging technology in recent days because of the fact that it reduces the environment pollution, increases fuel efficiency of the vehicle and enhances the drive performance. Hybrid cascaded inverter with PWM technique which uses 36 switches to get 7 level output voltage which is serving the purpose of operating electric drive in HEV is proposed in this paper and different configurations of HEV are explained. The simulation results of HEV electric drive performance based on new proposed hybrid cascaded multilevel inverter (IGBT based) are compared with the simulation results of conventional multilevel inverter based HEV electric drive. Simulation is done in MATLAB.

KEYWORDS: Hybrid Electric Vehicle, Cascaded Inverter, Multilevel Inverter, Powertrain, PWM Technique

INTRODUCTION

In recent years, Hybrid Electrical Vehicles (HEV) has undergone several developments on various aspects of design such as component architecture, engine efficiency, reduced fuel emissions, material for lighter components, power electronics, efficient motors and High Power Density batteries [4]-[7]. To meet some of the aspects of HEV cascaded multilevel Inverter is used to meet high power demands. The multilevel Voltage Source Inverters with unique structure allow them to reach high voltages with low harmonics without the use of transformers or series connected synchronised Switching devices [10]. Several multicarrier techniques have been developed to reduce harmonics or distortion in multilevel Inverter output. In this paper, classical SPWM i.e., Sinusoidal Pulse Width Modulation with Triangular carriers is used. Based on the classical SPWM with Triangular carriers some methods use carrier disposition and others use phase shifting of multiple carrier signals. A number of N_c –cascaded inverters in one phase with their carriers shifted by an angle, $\theta_c = \frac{360°}{N_c}$ and using the same control voltage it produces an output voltage with the smallest distortion. This property allows a reduction in the switching frequency of each inverter and thus reducing switching losses [2].

This paper describes various configurations of HEV and the Simulation Results showing performance of Electric Drive [20KW, 3-Φ Induction Motor] based on newly proposed Hybrid cascaded multilevel inverter(IGBT based) for HEV is compared with the performance of electric drive for HEV based on conventional multilevel Inverters. Simulation is done in MATLAB and RESULTS are presented in the paper.

HEV CONFIGURATIONS

Although a number of configurations are used for HEV power trains, the main architectures are the series, parallel and series-parallel ones [5-6]. They are analysed in this section i) by disregarding the losses in the electric and mechanical devices, the power consumption of the auxiliary electric loads, and the presence of gearboxes and clutches, and ii)by considering the static converters used for the interface of the electric devices as a whole with the devices themselves. Moreover, the analysis is carried out by assuming that i) the powers are positive quantities when the associated energy flows in the direction of the arrows reported in the schemes of the architectures, and ii) the driving requirements for a vehicle are the speed and the torque at the wheels, where the product of the two variable gives the required propulsion power.

Series Architecture

The powertrain of a series HEV (SHEV) has the architecture of figure 1. It comprises a genset (i.e. a generation set) and a drivetrain of electric type, which are connected through a common power bus (B). To B is also connected an energy storage system(S).

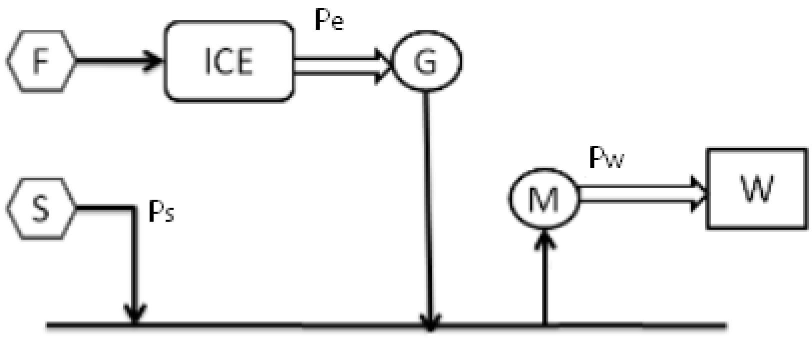


Figure 1: SHEV Powertrain Architecture (Electric and Mechanical Connections Are Traced Respectively with Single & Double Lines, whereas the Fuel Path is Traced with Dashed Line)

In the genset, ICE is fed by the fuel tank (F) and delivers the mechanical power p_e to the electric generator (G). The latter one converts p_e in to electric form and supplies B. The energy associated to p_e can be either stored in S (in this case the power p_s of figure 1 is negative) or drawn by the electric drivetrain or both. During the engine start-up, G behaves as a crank motor energized form S.

The electric drivetrain is constituted by one (or more) electric motor (M) that draws propulsion power from Pw and delivers it to the wheels (W). Note that in this architecture the wide speed-torque regulation allowed by M my make superfluous the insertion of a variable-ratio gearbox between M and W. During the regenerative braking, M operates as a generator to recover the kinetic energy of the vehicles in to S.

The mechanical separation between genset and electric drivetrain, and the energy buffering action of S give the series architecture the maximum flexibility in terms of power management. As a matter of fact, SHEV may be considered as a purely electric vehicle equipped with a genset that recharges S autonomously instead of at a recharge station. Sometimes, the genset is undersized with respect to the average propulsion power absorbed during a typical travel mission. In this case, the genset is used to extend the operating range allowed by S, and SHEV is referred to as “range extender”.

Pros and cons of the series architecture may be summarized as follows. Pros: i) ICE and G are conventionally sized for the average propulsion power or even less; ii) genset and electrical drivetrain are mechanically separated thus permitting to maximize the ICE efficiency with a consequential substantial reductions of emissions. Cons: i) two electric machines (i.e. G and M) are required; ii) M must be sized to provide the peak propulsion power; iii) the power generated by ICE is transferred to W by means of at least two energy conversions (from mechanical to electrical to possibly chemical inside S, and vice versa), with a lower efficiency than a direct mechanical connection.

The series architecture is reputed to be more suited for vehicles mainly used in urban area, with rapidly varying requirements of speed (and power); it is also used in large vehicles, where the lower efficiency of both ICE and the mechanical transmission make convenient the electric propulsion.

Parallel Architecture

The powertrain of a parallel HEV (PHEV) has the architecture of figure 2. It comprises two independent drivetrains, namely one of mechanical type and the other one of electric type, whose powers are "added" by a 3-way mechanical devices the adder (A)-to provide the propulsion power as shown in figure 2, the mechanical drivetrain generates the part p_e of the propulsion power, whilst the electric drivetrain delivers the remaining part pm. The propulsion power pw is then equal to

$$P_w = P_e + P_m \tag{1}$$

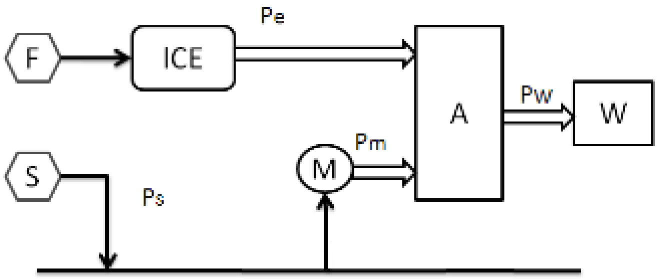


Figure 2: PHEV Powertrain Architecture

The power sum may be done by adding either the speeds or the torques of ICE and M. In the first case it is

$$\omega_w = c_{\omega e}\,\omega_e + c_{\omega m}\,\omega_m \tag{2}$$

Where c_{we} and c_{wm} are coefficients that depend on the gear arrangement of A. By (1), the relationships between the torques are

$$\tau_e = c_{\omega e}\,\tau_w \ \ , \ \ \tau_m = c_{\omega m}\,\tau_w \tag{3}$$

In the second case it is

$$\tau_w = c_{\tau e}\,\tau_e + c_{\tau m}\,\tau_m \tag{4}$$

Where c_{we} and c_{wm} are coefficients that depends again on the gear arrangement of A. By (1), the relationships between the speeds are

$$\omega_e = c_{\tau e}\,\omega_w \ \ , \ \ \omega_m = c_{\tau m}\,\omega_w \tag{5}$$

The simplest implementation for A is a torque adder with a mechanical shaft that couples ICE and M to W. With this implementation it is

$$c_{\tau e} = c_{\tau m} = 1 \tag{6}$$

Differently from SHEV, M acts here as generator not only during the regenerative braking but also during the normal driving, whenever S must be recharged; in the latter circumstance, M draws energy from ICE through A.

As a matter of fact, PHEV may be considered as a conventional vehicle supplemented with an additional drivetrain of electric type that overtakes the role of the traditional generator-battery set by contributing to the propulsion. Sometimes, S is chosen to have small storable energy but high power capability, and M is sized with a wide overload margin. In this case the electric drivetrain is used as a power boost to supplement ICE during fast changes of the driving conditions. The resultant PHEV is often referred to as “power-assist”; a commercial example of it is the Honda Insight Car [7].

The modifications to convert a conventional vehicle into PHEV may be somewhat moderate, and this makes easier the manufacturing of PHEVs using the existing production process. A vehicle built up accordingly is termed “minimal” or “mild” HEV depending on the extent of the modifications introduced in the original powertrain.

Pros and cons of the parallel architecture may be summarized as follows. Pros: i) only one electric machine is needed; ii) the peak power requirement for M is lower than in SHEV since both M and ICE is transferred to W directly, which is more efficient than through a double energy conversion. Cons: i) an additional 3-way mechanical device is required to couple together ICE, M and W; ii) such coupling imposes a tighter constraint on the power flow compared to SHEV, possibly turning in to worse operation of ICE.

The parallel is reputed to be more suited for small and mid-size vehicles mainly travelling along extra-urban routes, where the range for the required propulsion power is not too wide.

Series-Parallel Architecture

The powertrain of a series-parallel HEV (SPHEV) has the architecture of fig.3. It may be viewed as a mix of the SHEV and PHEV architectures, obtained by employing a power split apparatus (P) with 2 mechanical ports and 1 electric port. The 3 ports are connected to ICE, A and B, respectively. P divides the power generated by ICE into two parts, i.e. the part pd, which is delivered directly in mechanical form to W via A, similarly to PHEV, and the part p_b,which is delivered in electric form to B, similarly to SHEV. The task of the power split apparatus is then twofold; besides dividing the power generated by ICE, it must convert mechanical energy into an electric form.

The series-parallel architecture has two main features: the propulsion requirements are developed from the ICE operation and the overall losses are lower since a fraction of the power generated by ICE is delivered to W without any intermediate energy conversion. The former feature makes the management of the power flow very flexible, enabling in principle to optimize the ICE operation in a wide range of driving conditions.

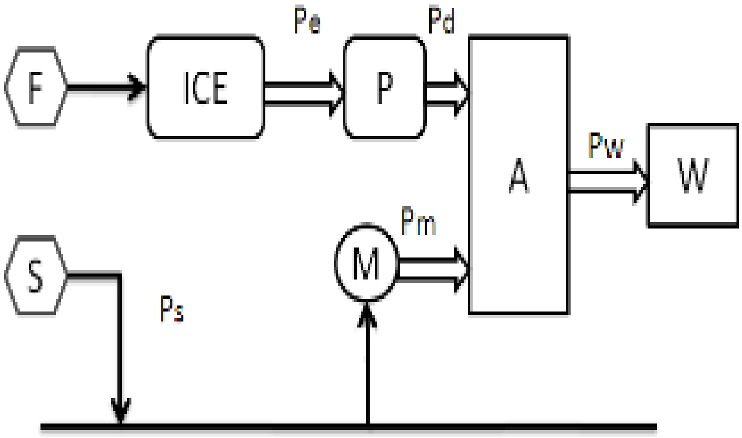


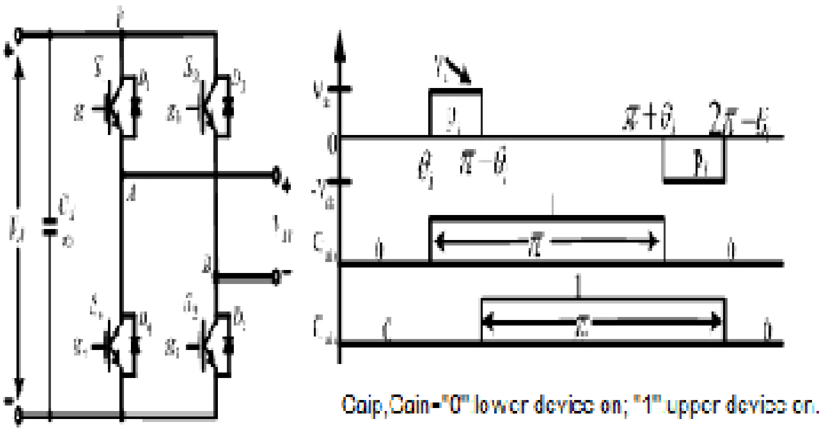
Figure 3: SPHEV Powertrain Architecture

So splitting of the ICE powers is obtained by two ways:

- An apparatus based on a mechanical device.
- An apparatus based on electrical devices

CASCADED MULTILEVEL INVERTER

Among various configurations of multilevel inverters, cascaded multilevel inverter is important. An eleven level multilevel inverter consists of five H-bridge cascaded in single phase. One H-bridge consisting of 4 IGBTs is as shown in figure 4(a). So a three phase unit will have 15 H-bridge with 60 IGBTs cascaded as shown in figure 5. A multilevel inverter synthesize a desired voltage from several separate dc sources (SDCS's),which may be obtained from batteries, fuel cells, or solar cells [8]. Each SDCS is connected to a single-phase full-bridge inverter. Each H-bridge can generate three different voltage outputs (+Vdc, 0 and –Vdc) by the different combinations of the four switches (S1, S2, S3 and S4). The figure 4(b) shows the switching pattern of four switches in a single H-bridge.



(a) (b)

Figure 4: (a) One H-Bridge with 4 IGBTs (b) Switching Sequence of One H-Bridge Inverter

Cascaded waveform can be obtained which is almost similar to a sinusoidal waveform and in this way we get an ac output voltage. The ac outputs of each of the different level full-bridge inverters are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels in a cascaded inverter is defined by v_{an}, v_{bn}, v_{cn} given as

$$V_{an} = V_{a1} + V_{a2} + V_{a3} + \cdots + V_{am-1} \tag{7}$$

Where the number of output phase voltage level is given by m=2s+1. Where's' is the number of H-bridges in a leg. Phase voltage of a 5-level cascaded inverter can represent in Fourier series as follows [9]:

$$B_n = \frac{4V_{dc}}{\pi}[\int_{\alpha_1}^{\pi/2} \sin(n\omega t)d\omega t + \ldots + \int_{\alpha_{m-1}}^{\pi/2} \sin(n\omega t)d\omega t]$$

$$B_n = \frac{4V_{dc}}{\pi}\sum_{j=1}^{(m-1)/2} \cos(n\alpha_j) \tag{8}$$

$$V_{an}(\omega t) = \frac{4V_{dc}}{n\pi}[\sum_{j=1}^{(m-1)/2} \cos(n\alpha_j)] \sin(n\omega t) \tag{9}$$

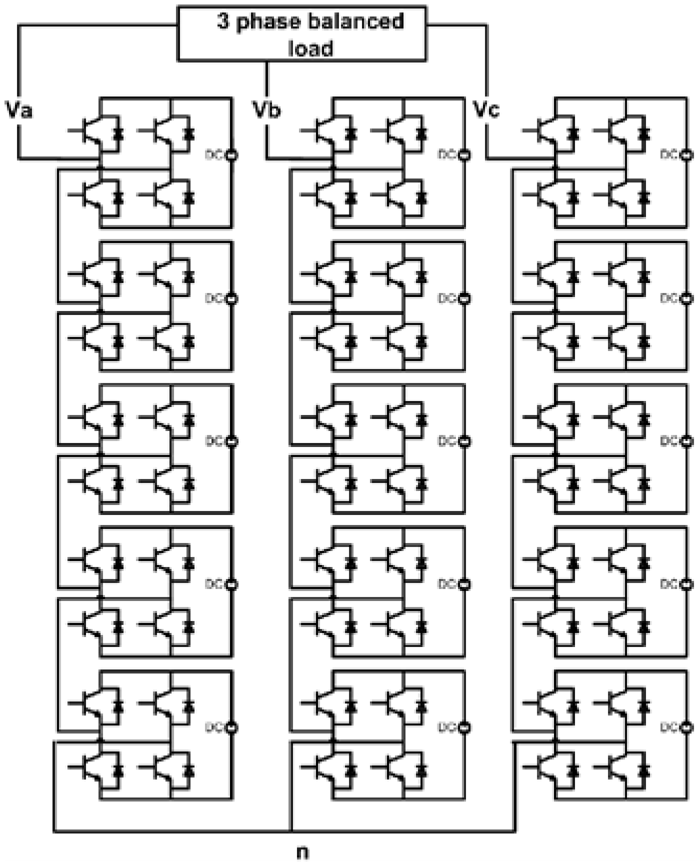


Figure 5: Power Circuit of three Phase Cascaded H-Bridges Multi-Level Inverter Using IGBT

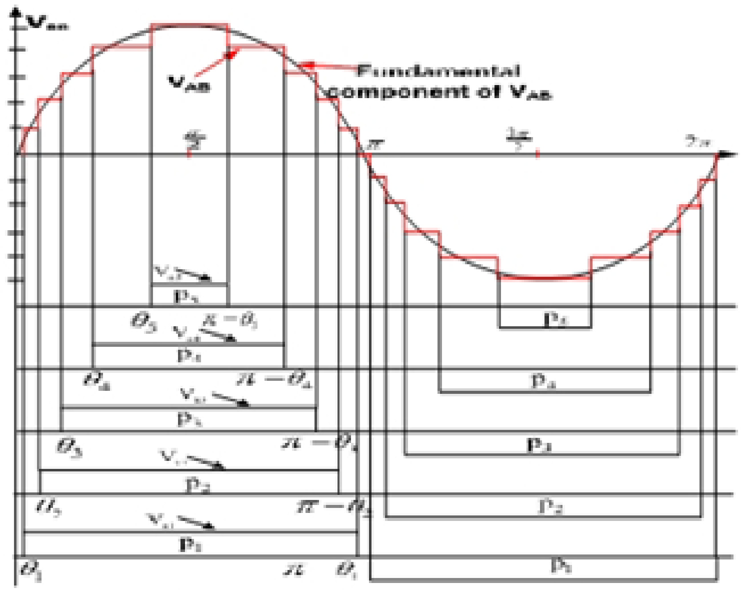


Figure 6: Output Voltages and Switching Patterns for One Leg of the 3-Phase Cascaded Multilevel Inverter

Inverter with five SDCS's and five full bridges is shown in figure 5. The output voltage of the inverter is almost sinusoidal, and it has less than 5% THD with each of the H-bridges switching only at fundamental frequency. Each H-bridge unit generates a quasi-square waveform by phase shifting its positive and negative phase legs switching times. Figure 6 shows the switching timings to generate a quasi-square waveform. Note that each switching device always conducts for 180 (0r half cycle), regardless of the pulse width of the quasi-square wave. This switching method makes all of the active devices current stress equal. For a stepped waveform such as the one depicted in figure 6 with steps, the Fourier transform for this waveform is shown in eq. 8. From the magnitudes of the Fourier coefficients when normalized as in eq. (9) gives the conducting angles which can be chosen such that the voltage total harmonic distortion is minimum. Normally, these angles are chosen so as to cancel the predominant low frequency harmonics [10]. For the five level case in figure 10 the 5th, 7th, 11th and 13th harmonics can be eliminated with the appropriate choice of the conducting angles. One degree of freedom is used so that the magnitude of the output waveform corresponds to the reference amplitude modulation index M, which is defined as:

$$M = \frac{V_{an\,(peak\,)}}{V_{cr\,(peak\,)}} = \frac{(\frac{m-1}{2})V_{dc}}{V_{cr\,(peak\,)}} = 0.8 \tag{10}$$

Here Vcr (peak) is the peak value of the carrier wave and Van (peak) is the command voltage. Van (peak) is defined as

$$V_{an\,(peak\,)} = (m-1)V_{dc} = V_{cr\,(peak\,)} \tag{11}$$

For the harmonics (n=1, 3, 5, 7, 11, 13 ...) the set of non-linear transcendental equation (from eq. 9) can be represented as follows

$$\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_{5)} = 0$$

$$\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) + \cos(7\theta_5) = 0$$

$$\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) + \cos(11\theta_5) = 0$$

$$\cos(13\theta_1) + \cos(13\theta_2) + \cos(13\theta_3) + \cos(13\theta_4) + \cos(13\theta_5) = 0$$

$$\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) = (\frac{m-1}{2})M \tag{12}$$

If the number of levels, m=11 (including the zero level) and modulating index "M" is 0.8 then [((m-1)/2)*M]=5*0.8=4

Thus, the values of the firing angles can be obtained by putting the above value in eq. 12 and then solving it by Newton-Raphson iterative method.

NEW PROPOSED MULTILEVEL INVERTER

The newly proposed multilevel inverter with 36 switching devices, which gives a phase to neutral output voltage of 7-level, in which the number of switching devices are reduced to a large extent when compared to cascaded H-bridge multilevel inverter with 60 switches.

The proposed multilevel inverter can produce required voltage from separate DC sources. Each SDC is connected to a single phase full bridge inverter. Each H-bridge can generate three output voltages (+V_{dc}, 0, -V_{dc}) by the different combinations of switches (S1, S2, S3 and S4). To generate a phase-neutral voltage 3 H-bridges are connected in series and voltages are defined by v_{an} , v_{bn} , v_{cn} . Where the output voltage levels in phase are determined by using the formula m=2s+1, here m is the number of levels and s is the number of H-bridges in the leg. Total harmonic distortion is 13.53%for newly proposed method and it is slightly more compared to conventional method with 60 switches. As the numbers of switching devices are reduced, the switching losses are less in this newly proposed topology. The power circuit of proposed 3-phase multilevel inverter using IGBT's operating at fundamental switching frequency is shown in figure (7). Switching pattern of 12 switches in one leg is shown in table (1)

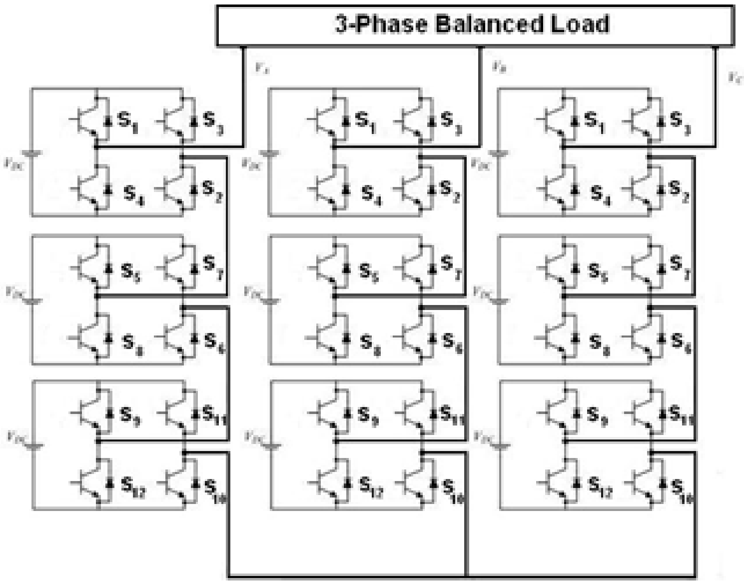


Figure 7: Power Circuit of 3-Phase Newly Proposed Multilevel Inverter Using IGBT's

SWITCHING PATTERN

Table 1: Switching Pattern of One Leg

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	V_0
1	0	1	0	1	0	1	0	1	0	1	0	0
1	1	0	0	1	0	1	0	1	0	1	0	$+V_{dc}$
1	1	0	0	1	1	0	0	1	0	1	0	$+2V_{dc}$
1	1	0	0	1	1	0	0	1	1	0	0	$+3V_{dc}$
0	0	1	1	1	0	1	0	1	0	1	0	$-V_{dc}$
0	0	1	1	0	0	1	1	1	0	1	0	$-2V_{dc}$
0	0	1	1	0	0	1	1	0	0	1	1	$-3V_{dc}$

RESULTS AND DISCUSSIONS

The newly proposed 3-phase multilevel inverter has been developed by using IGBT's. This inverter is loaded with a 3-phase 20KW induction motor to drive HEV power drives. The simulation is done in MATLAB and the simulation circuit of conventional cascaded multilevel inverter based HEV is shown in figure (8).

The circuit diagram (subsystem) of newly proposed 3-phase inverter with 9-bridges is shown in figure (12) and a 7-level line to neutral output voltage is shown in figure (13). The results of this new proposed inverter is compared with the responses of the induction motor controlled conventional cascaded multilevel inverter, simulation results of conventional cascaded multilevel inverter based HEV are shown in below figure (9).

The response (stator currents, torque produced by motor, speed of motor) of cascaded multilevel inverter connected to an induction motor is shown in figure (11) and for the newly proposed multilevel inverter is shown in figure (15). Total Harmonic Distortion for cascaded multilevel inverter is show in figure (10) and for proposed multilevel inverter is shown in figure (14).

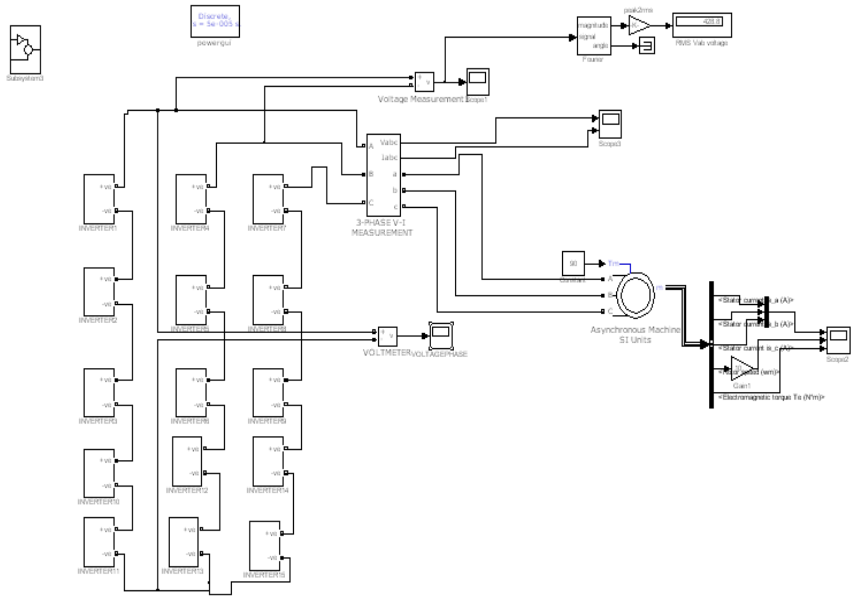


Figure 8: Circuit Diagram of a Cascaded Multilevel Inverter on MATLAB Connected to an Induction Motor

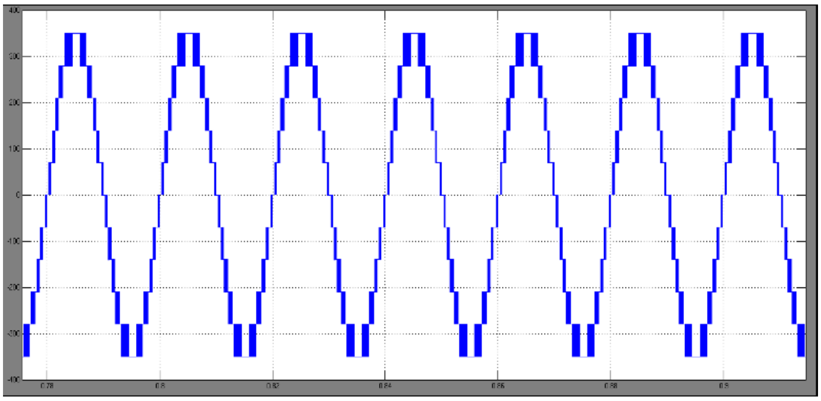


Figure 9: Line to Neutral Output Voltage Level of Cascaded Multilevel Inverter

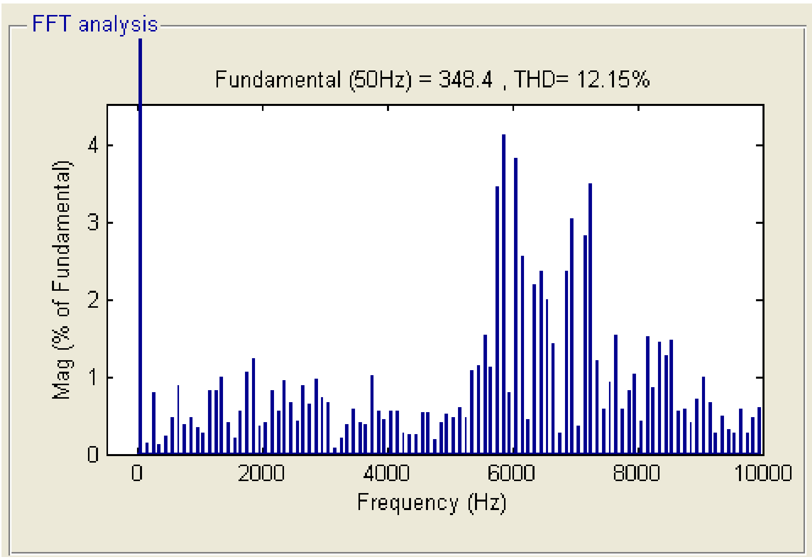


Figure 10: Total Harmonic Distortion of Line to Neutral Voltage in Cascaded Multilevel Inverter Based Induction Motor

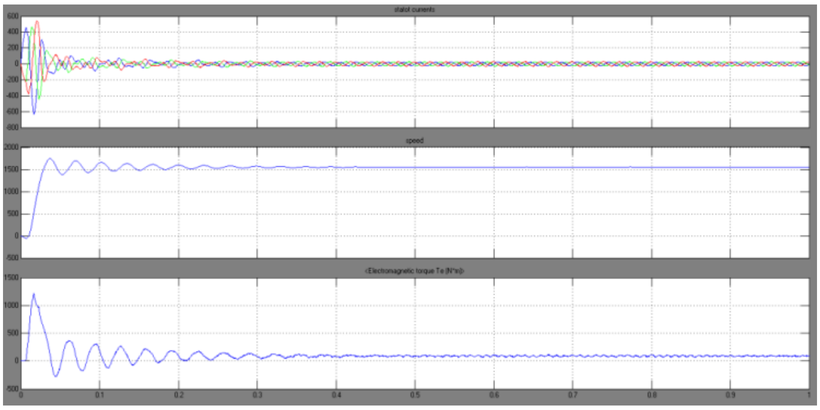


Figure 11: Response of Cascaded Multilevel Inverter Based Induction Motor (a) Three Phase Stator Current (b) Torque Produced by the Motor (c) Speed of Motor

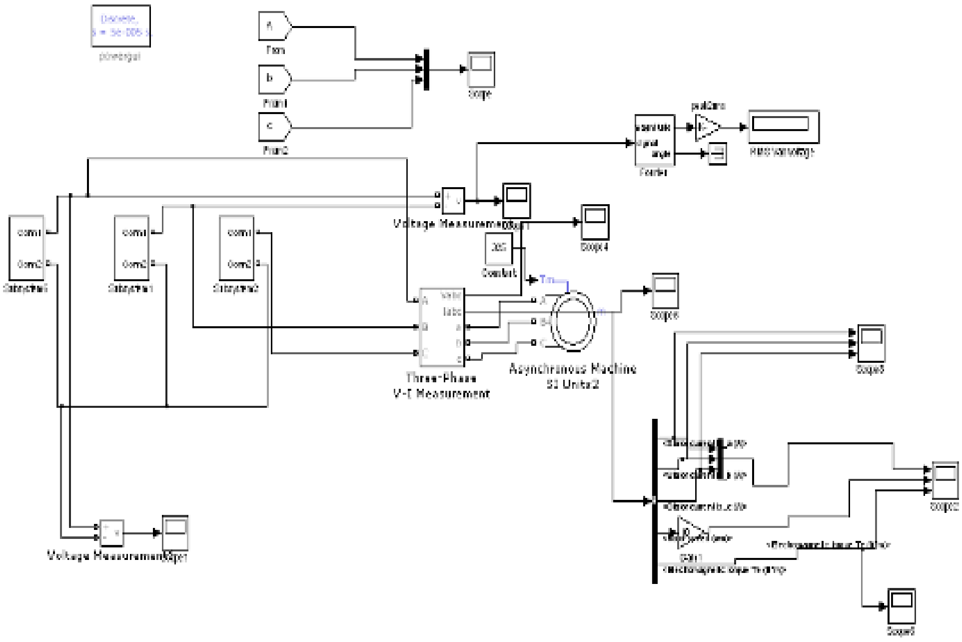


Figure 12: Circuit Diagram of New Proposed Multilevel Inverter on MATLAB Attached to an Induction Motor

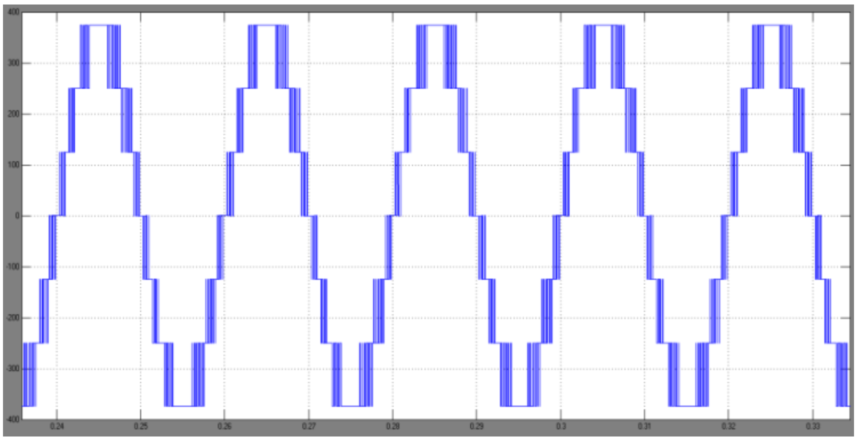


Figure 13: Single Phase Line to Neutral Output Voltage

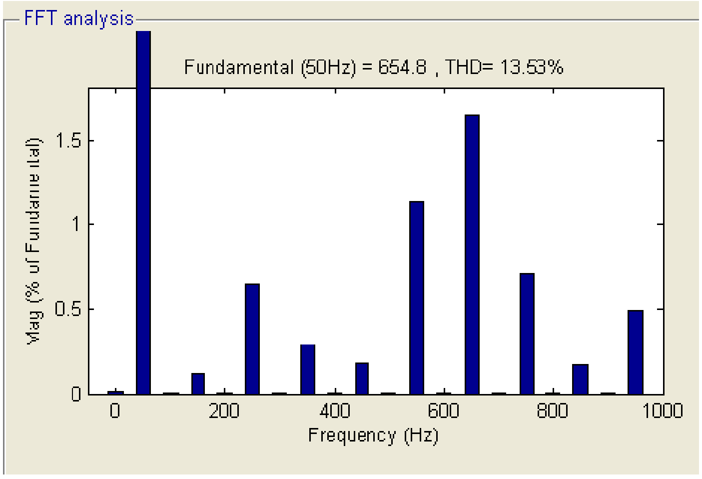


Figure 14: Total Harmonic Distortion of Line to Neutral in a New Proposed Multilevel Inverter Based Induction Motor

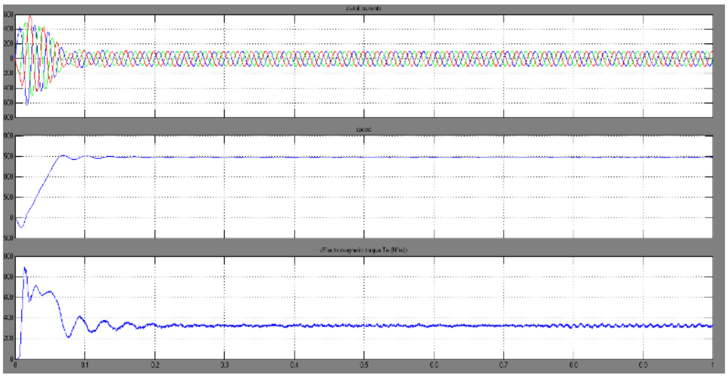


Figure 15: Response of New Proposed Multilevel Inverter Based Induction Motor (a) Three Phase Stator Currents (b) Torque Produced by the Motor (c) Speed of Motor

APPENDIX

Three phase squirrel cage induction motor,

Power = 20KW, Line-Neutral = 375 V, Frequency = 50Hz, Stator Resistance (R_s) = 0.2147Ω, Rotor Resistance (R_r) = 0.22555Ω, Stator Leakage Inductance (L_s) = 991µH, Rotor Leakage Inductance (L_r) = 991µH, Mutual Inductance (M) = 74.19mH, Moment of Inertia = 0.102 JKg.m^2, Friction Factor = 0.00875 FN-m.

COMPARISIONS

The simulation results of conventional cascaded multilevel inverter and the newly proposed multilevel inverter are compared as below:

- In cascaded multilevel inverter 60 switches are used and only 36 switches are used in newly proposed multilevel inverter.
- 11-level line to neutral output voltage is obtained in cascaded multilevel inverter and for proposed multilevel inverter 7-level line to neutral output voltage is obtained.
- The Electric drive performance based on newly proposed multilevel inverter is similar to that of the cascaded multilevel inverter.

- Total Harmonic distortion for newly proposed multilevel inverter is 13.53% and for cascaded multilevel inverter is 12.15%.
- The size of cascaded multilevel inverter is big and requires more space but the newly proposed multilevel inverter size is small compared to conventional inverter and less space is required.

CONCLUSIONS

Hybrid Electric Vehicle (HEV's) is a combination of both electrical and mechanical equipments which provides to power trains to wheels of the vehicles. IGBT based new multilevel inverter is proposed and connected to a 3-phase induction motor. It is simulated in MATLAB. Current, voltage, speed, torque responses are plotted. The induction motor driven by new proposed multilevel inverter has given desired response which is same as obtained by the induction motor fed with cascaded multilevel inverter. In this paper the response of electric drive of HEV interfaced with new proposed multilevel inverter topology is compared with the electric drive of HEV interfaced with cascaded multilevel inverter. From the comparison of results

- The number of switching devices has been reduced to a greater extent in new proposed multilevel inverter compared to cascaded multilevel inverter i.e., number of switches has been reduced to 36 from 60.
- The responses obtained by the drive in both the inverter circuits are almost same.
- The obtained output voltage level is less in the new multilevel inverter compared to cascaded multilevel inverter. But the desired response can be obtained by the drive.
- As the number of switches are reduced in number, switching losses, circuit complexity, cost, size of the circuit are reduced.

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