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New Multilevel Inverter Topology with Reduced Switching Devices for Hybrid Electric Vehicles

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Abstract— Multi level inverters are used to control electric drive of hybrid electric vehicle(HEV) of high power and they enhances drives performance, as they can generate sinusoidal voltages with only fundamental switching frequency. Hybrid Electric Vehicle is an emerging technology because of the fact that it avoids environmental pollution and increases vehicles fuel efficiency . This paper describes various topologies of HEV and compares the simulation results of electric drive controlled by the cascaded transformer less multi level inverter with the electric drive controlled by the proposed new topology of the multi level inverter with the reduced number of switching devices.simulation is done in MATLAB.

Index Terms— Hybrid Electric Vehicle, Cascaded Inverter, Multilevel Inverter, Powertrain, Common mode voltage.

1. Introduction

In modern days , research is going on in the development of hybrid electric vehicles (HEV)to improve the various design aspects such as component architecture , engine efficiency , reduced fuel emissions , material for lighter components, efficient motors and high density batteries [2]-[4]. To meet some of the aspects of HEV, multilevel inverter is used so as 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 synchronized switching devices [5]. The general function of the multilevel inverter is to synthesize a desired voltage from several levels of dc voltages. For this reason, multilevel inverters can easily provide the high power required of a large electric drive. As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches a desired waveform. Also, as more steps are added to the waveform, the harmonic distortion of the output wave decreases, approaching zero as the number of levels increases. As the number of levels increases, the voltage that can be spanned by summing multiple voltage levels also increases.The structure of the multilevel inverter is such that no voltage sharing problems are encountered by the active devices. HEV Configurations.This paper describes various configurations of HEV's and compares a simulation results of electric drive [20kw , 3-phase induction motor suit based multilevel inverter with the electric drive controlled by the newly proposed multilevel topology with reducedswitchingdevices.Simulation is done in MATLAB and are presented in the paper.

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2. HEV Configurations

Although a number of configurations are used for HEV powetrains, the main architectures are the series, parallel and series-parallel ones [5-6]. They are analyzed 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 variables gives the required propulsion power.

A.Series Architecture

The Powertrain of a Series HEV (SHEV) has the architecture of Fig.1. It comprises a genset (i.e. a generation set) and a drivetrain of electric type, which are connected together through a common power Bus (B). To B is also

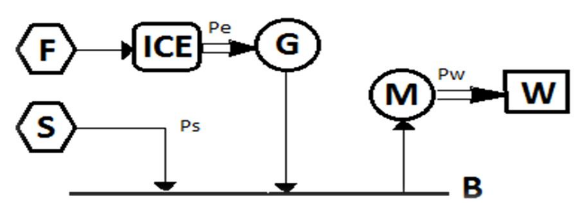

Fig 1:SHEV Powertrain architecture (electric and mechanical connections are traced respectively with single & double lines)

In the genset, ICE is fed by the Fuel tank (F) and delivers the mechanical power pe to the electric Generator (G). The latter one converts pe into electric form and supplies B. The energy associated to pe can be either stored in S (in this case the power ps of Fig.1 is negative) or drawn by the electric drivetrain or both. During the engine start-up, G behaves as a

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crank motor energized from S.The electric drivetrain is constituted by one (or more) electric Motor (M) that draws the propulsion power pw from B and delivers it to the Wheels (W). Note that in this architecture the wide speed-torque regulation allowed by M may 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 vehicle into 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 conveniently 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 reduction 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 more convenient the electric propulsion.

B. Parallel Architecture

The Powertrain of a Parallel HEV (PHEV) has the architecture of Fig.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 Fig.2, the mechanical drivetrain generates the part pe of the propulsion power, whilst the electric drivetrain delivers the remaining part pm. The propulsion power pw is then equal to

$$Pw = Pe + Pm \quad (1)$$

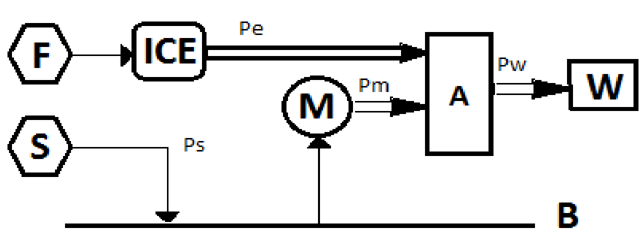

Fig 2:PHEV Powertrain architecture

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

$$\omega_w = c_{\omega e}\omega_e + c_{\omega m}\omega_m \quad (2)$$

Where Cwe and Cwm are coefficients that depend on the gear arrangement Of A. By (1), the relationships between the torques are

$$\tau_e = c_{\omega e}\tau_w, \tau_m = c_{\omega m}\tau_w \quad (3)$$

In the second case it is

$$\tau_w = c_{\tau e}\tau_e + c_{\tau m}\tau_m \quad (4)$$

Where Cwe and Cwm are coefficients that depend again on the gear arrangement of A. By (1), the relationships between the speeds are

$$\omega_e = c_{\tau e}\omega_w \;,\; \omega_m = c_{\tau m}\omega_w \quad (5)$$

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

$$C_{\tau e} = C_{\tau m} = 1 \quad (6)$$

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 propulsion power, thus permitting ICE to adapt slowly to 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 required to convert a conventional vehicle into PHEV may be somewhat moderate, and this makes easier the manufacturing of PHEVs using the existing production processes. 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 provide the propulsion power; iii) the power generated by 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 into worse operation of ICE.The parallel architecture is reputed to be more suited for small- and mid-size vehicles mainly traveling along extra urban routes, where the range for the required propulsion power is not too wide.

C. 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 SEHV 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 pb, 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 decoupled 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

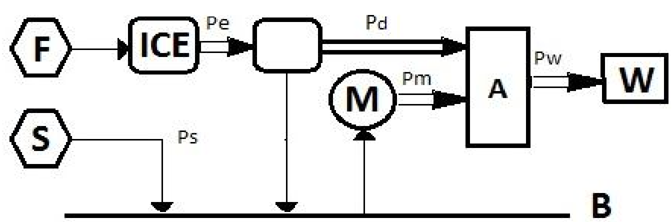

Fig 3:SPHEV Powertrain architecture

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

i. an apparatus based on a mechanical devices.
ii. an apparatus based on electrical device.

3. 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 as shown in fig. 4(a). So a three phase unit will have 15 H-bridge with 60 IGBTs cascaded as shown in fig. 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 fig. 4(b) shows the switching pattern of four switches in a single H-bridge.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 cascade inverter is defined by V_{an}, V_{bn}, V_{cn} given as

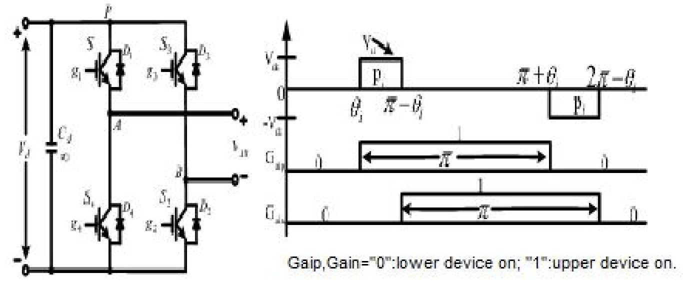

Fig. 4: (a) One H-bridge with 4 IGBTs (b) Switching sequence of one H-bridges inverter .

$$V_{an}=V_{a1}+V_{a2}+V_{a3}+\ldots\ldots+V_{am-1} \qquad (7)$$

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 represented in Fourier series as follows

$$B_n = \frac{4Vdc}{\pi}\left[\int_{\alpha_1}^{\frac{\pi}{2}}\sin(n\omega t)\,d\omega t+\cdots+\int_{\alpha_{m-1}}^{\pi/2}\sin(n\omega t)d\omega t\right]$$
$$= \frac{4Vdc}{n\pi}\sum_{j=1}^{(m-1)/2}\cos(n\alpha_j) \qquad (8)$$

$$Van(\omega t)=\frac{4Vdc}{\pi}\left[\sum_{j=1}^{\frac{m-1}{2}}\cos(n\alpha_j)\right]\sin(n\omega t) \qquad (9)$$

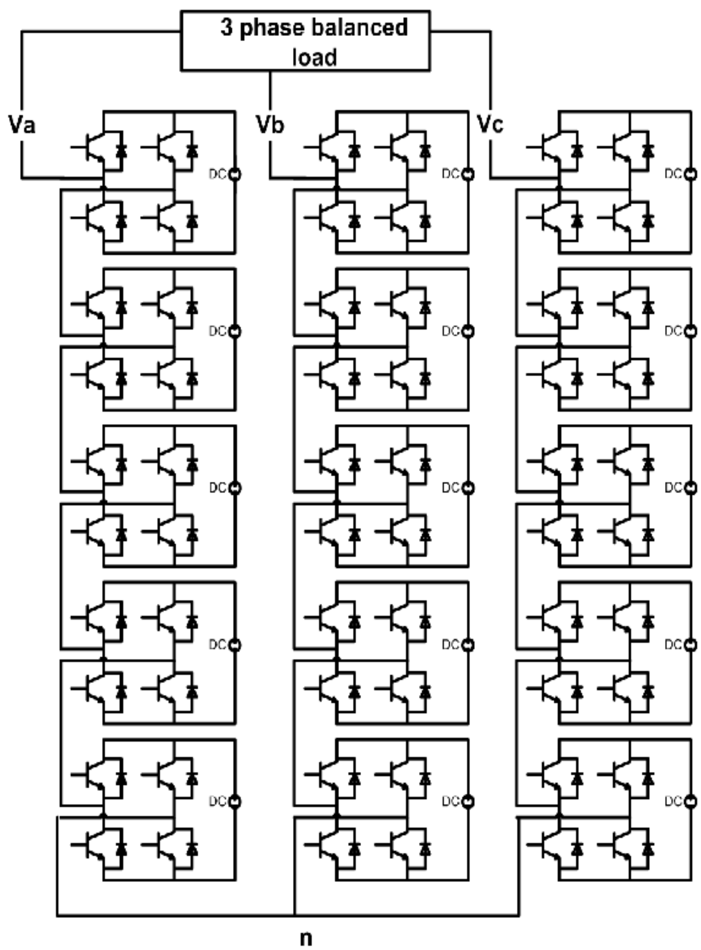

Fig 5 :Power circuit of three phase cascaded H-bridges multi –level inverter using IGBT

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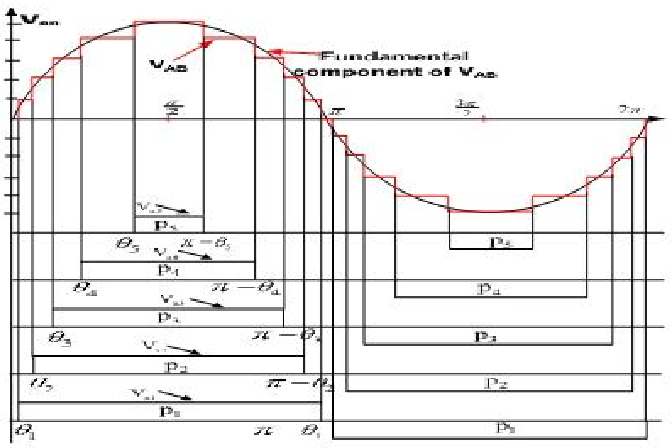


Fig 6 :Output voltages and switching pattern for one leg of the 3-phase cascaded multilevel inverter

Fig. 6 shows the switching timings to generate a quasi-square waveform. Note that each switching device always conducts for 180 (or ½ 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 Fig. 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 lower frequency harmonics [10]. For the 5-level case in fig. 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:

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

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

$$Van(peak) = (m-1)Vdc = Vcr\,(peak) \quad (11)$$

For the harmonics (n=1, 3, 5, 7, 11, 13 …) the set of nonlinear transcendental equation (from eq. 9) can be represente as follows

$$\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)+\cos(5\theta_4)+\cos(5\theta_1)= 0$$
$$\cos(7\theta_1)+\cos(7\theta_2)+\cos(7\theta_3)+\cos(7\theta_4)+\cos(7\theta_5)=0$$
$$\cos(11\theta_1)+\cos(11\theta_2)+\cos(11\theta_3)+\cos(11\theta_4)+\cos(11\theta_5)=0$$
$$\cos(13\theta_1)+\cos(13\theta_2)+\cos(13\theta_3)+\cos(13\theta_4)+\cos(13\theta_5)=0$$
$$\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)+\cos(\theta_4)+\cos(\theta_5)= (\frac{m-1}{2})M \quad (12)$$

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.

4. PROPOSED MULTILEVEL INVERTER

Proposed new multilevel inverter topology consists of 24 switching devices, which are very less in number compared with cascaded multi level inverter In which there are 60 switching devices. The proposed multi level inverter gives a 3-phase output voltage of 9 level. This multi level inverter synthesizes desired voltage from several separate DC sources . each SDC is connected to a single phase full bridge inverter .each H bridge can generate three different output voltage outputs (+Vdc , 0,-Vdc) by the different combinations of four switches (S1,S2,S3,S4) for generation of one phase voltage 2 Hbriges are cascaded in series which generates phase- neutral voltages defined by Van, Vbn, Vcn . where the number of output phase voltages are given by m=2s+1. Where s is the number of H bridges in the leg . This configuration gives a five level phase- neutral voltage and gives a nine level line-line voltage the power circuit of proposed 3-phase multi level inverter using IGBT's operating at fundamental switching frequency is shown in figure fig(7). Switching pattern of 8 switches in one leg is given in the table(1)

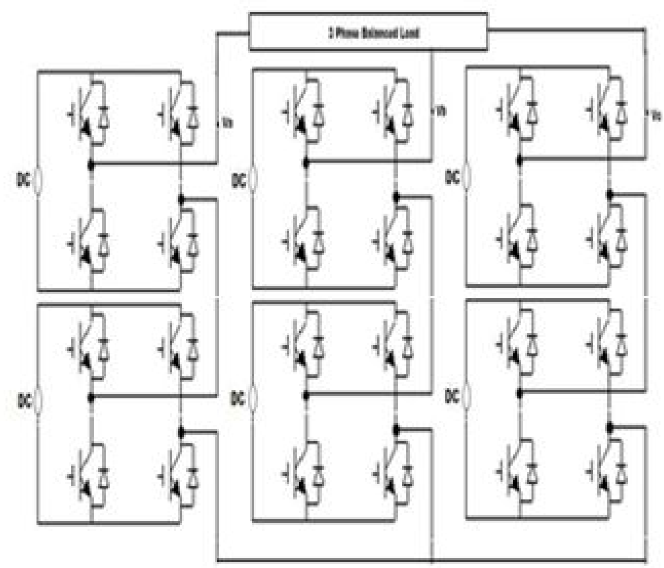


Fig (7):Power circuit of three phase new proposed multi-level inverter using IGBT

SWITCHING PATTERN

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	V_o
1	0	1	0	1	0	1	0	0
1	1	0	0	1	0	1	0	V_{dc}
1	1	0	0	1	1	0	0	$2V_{dc}$
0	0	1	1	0	1	0	1	$-V_{dc}$
0	0	1	1	0	0	1	1	$-2V_{dc}$

Table (1) switching patterns of single leg

5. Results & Discussions

The new proposed 3-phase multi level inverter has been developed using IGBT's .this inverter is loaded with 3-phase 20 KW induction motor to drive HEV power drives.The simulation has done in MAT LAB. The simulation circuit is shown in fig(8). The inverter consists of six bridges and produces nine level line-line voltage the responses of the induction motor controlled by the proposed multi level inverter is compared with the responses of the induction motor controlled by conventional cascaded multi level inverter the simulation results are shown in figures .

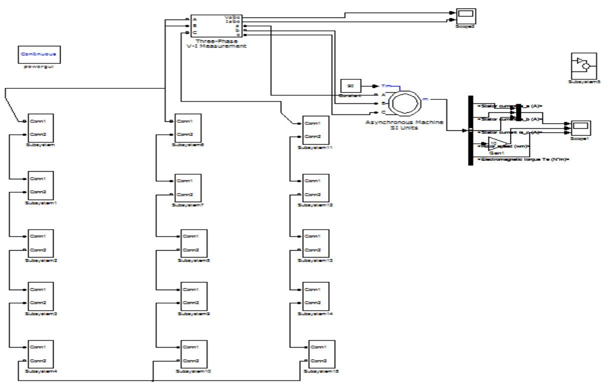
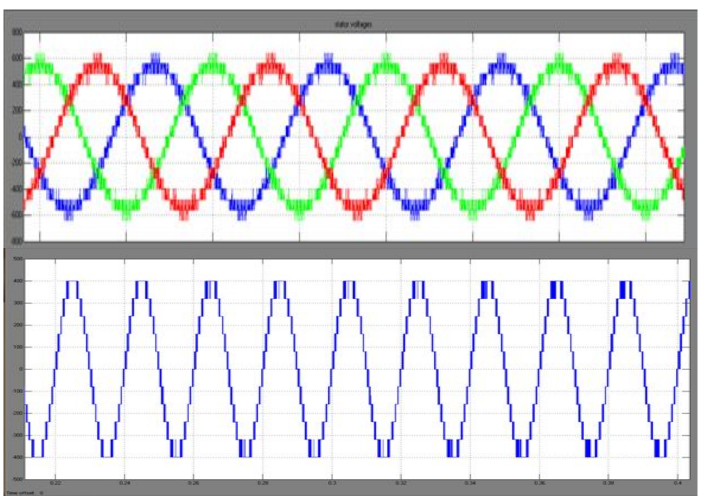
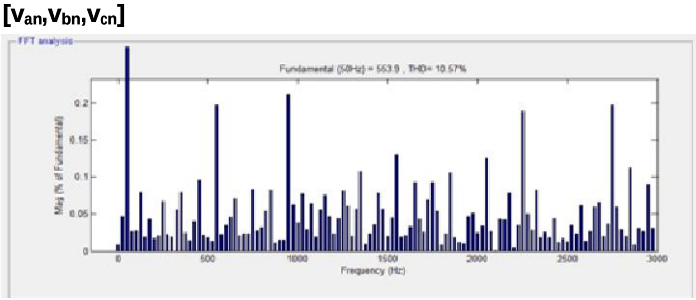


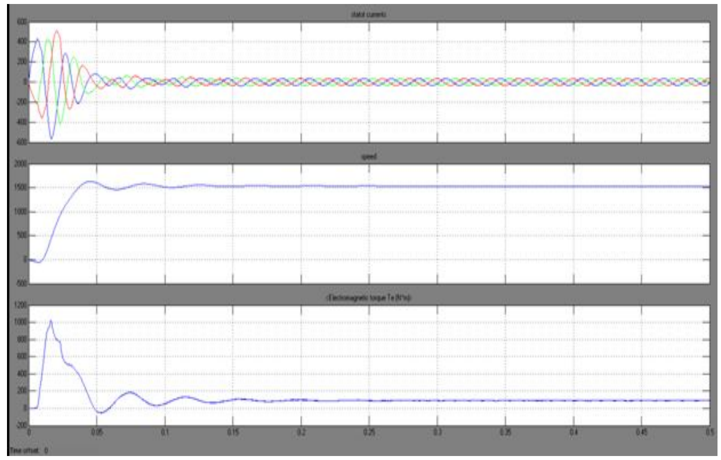
Fig (8):Circuit diagram of cascaded multilevel inverter on MATLAB attached to an induction motor



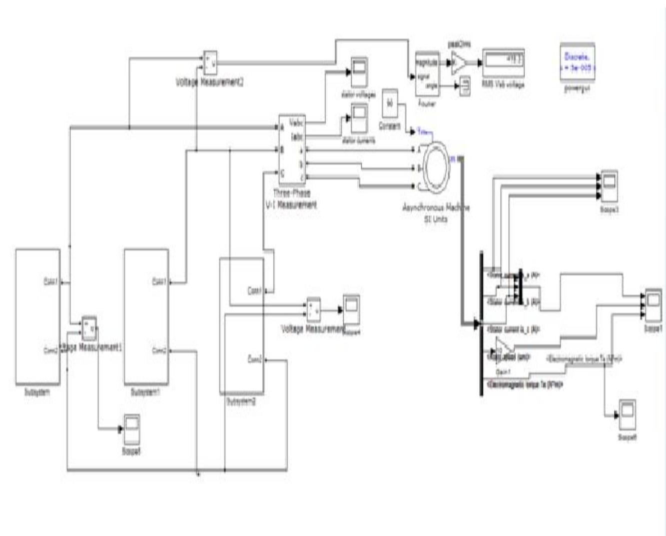
Fig(9): 3-phase load voltage of cascaded multilevel inverter (a)Three line-line voltages[vab,vbc,vca],(b)Three phase voltages [v_{an},v_{bn},v_{cn}]



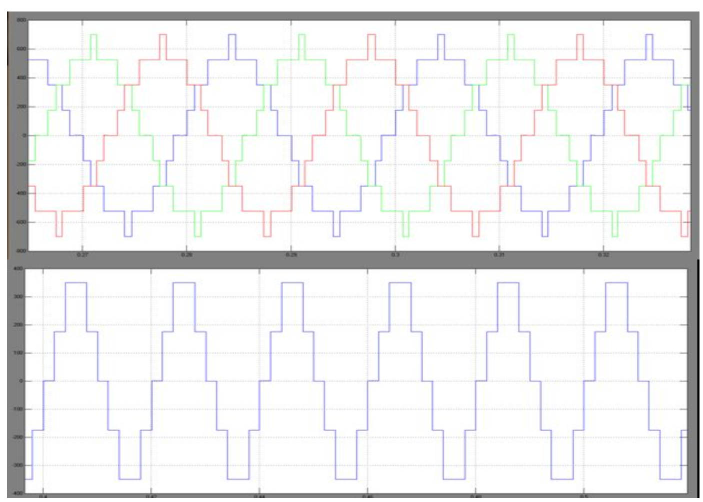
Fig(10): Total harmonic distortion of line-line voltage icascaded multilevel inverter based induction motor.



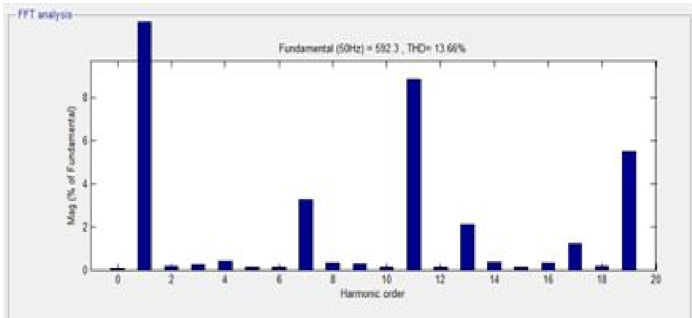
Fig(11):Response of cascaded multilevel inverter based induction motor (a),three phase stator current (b)torque produced by motor (c)speed of motor



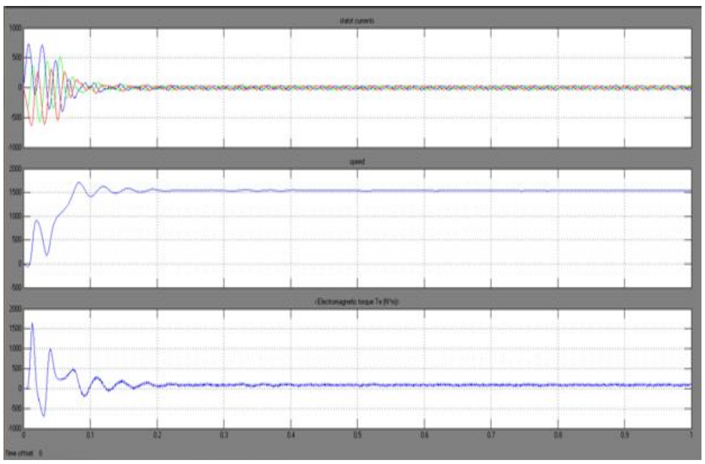
Fig(12): Circuit diagram of new multilevel inverter topology (subsystem) on MATLAB attached to an induction motor.



Fig(13): 3-phase load voltage of new multilevel inverter (a)Three line-line voltages[vab,vbc,vca],(b)Three phase Voltages [v_{an},v_{bn},v_{cn}]



Fig(14):Total harmonic distortion of line-line voltage in a new multilevel inverter based induction motor.



Fig(15):Response of new multilevel invertert based induction motor (a),three phase stator current (b)torque produced by motor (c)speed of motor

6. CONCLUSION

Hybrid Electric Vehicle(HEV) is a combination of electrical and mechanical engineering which provides to power trains to wheels of the vehicle.IGBT Based a new multilevel topology is proposed and connected to **s**tar connected 3-phase motor.It is simulated using MATLAB.Current,voltage,speed,torque waveforms are plotted. The induction motor driven by new multi level inverter has given the desired response which is same obtained by the induction motor fed with cascaded multilevel inverter .

In this paper the response of electric drive of HEV interfaced with new multilevel inverter topology is compared with electric drive of HEV interfaced with cascaded multilevel inverter. From the comparison of results

- The response obtained by the drive is almost same in the two cases
- The number of switching devices has been reduced to a greater extent in the proposed inverter compared with cascaded multilevel inverter i.e number of switches has been reduced to 24 from 60.
- The obtained output voltage level is less in the proposed multilevel inverter compared to cascaded multilevel inverter. But the desired response is obtained by the electrical drive
- As the number of switches are reduced in number, switching losses ,circuit complexity,cost,size of the circuit is / are reduced.

APPENDIX

Three phase Squirrel Cage Induction Motor, Power = 20 kW, Line-Line Voltage = 420 V, Frequency =50Hz,Stator Resistance (Rs) = 0.2147Ω,Rotor Resistance(Rr)= 0.2205Ω,Stator Leakage Inductance(Ls)=991µH,Rotor Leakage Inductance (Lr)=991µH, MutualInductance(M) =64.19 mH, Moment of Inertia = 0.102 JKg.m2, Friction Factor= 0.00575 FNms.

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