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Application of Nine-Switch Inverter for Electric Vehicles/ Electric Wheel Chairs

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***Abstract*—This paper is proposed to use nine switch inverter in electric vehicle/ electric wheel chair along with electric differential. The electric differential action is achieved with nine switch inverter as it can deliver two independent outputs. This paper uses indirect vector control method for the closed loop control of induction motors. The simulation results were obtained by considering different cases and the results were similar to that of the differential action in electric vehicles using two separate full bridge inverters. From the results it is ascertained that the nine switch inverter is a good substitute for the full bridge inverters which are currently being used in electric vehicle/electric wheel chair applications.**

***Index Terms* –** Closed loop Vector Control , Electric Differential(ED), Electric Vehicle (EV),Electric Wheel Chair, Nine Switch Inverter, Squirrel Cage Induction Motor.

Nomenclature :

Ψ_r - Flux
I_q - Torque component of current (quadrature axis component)
I_d - Flux component of current (direct axis component)
T_e^* - Reference electromagnetic torque
I_q^* - Reference torque component of current
I_d^* - Reference flux component of current
ω_m - Mechanical speed
L_m - Mutual inductance
L_r - Rotor inductance
I_a, I_b, I_c - Stator currents
I_a^*, I_b^*, I_c^* - Stator reference currents
R_r - Rotor resistance
V_{in} -Input voltage
K_p - Proportional gain constant
K_i - Integral gain constant
θ - Electrical angle

I. INTRODUCTION

Due to pollution and paucity of fossil fuels, the world is moving towards a green technology. Hence the use of electric vehicle proliferates every year [1]. Earlier DC motors were used in electric vehiclesbecause of its battery source which is DC. But there are difficulties with the use of DC motors like sparking at the brushes at high speeds and the brushes need regular maintenance. Hence this can be replaced with the robust three phase squirrel cage induction motor [2]. Moreover, due to the advancements in power electronic converters, electric vehicle with in-wheel ac drive system is widely being manufactured. It also provides stability while climbing hills and in slippery places [3]. Major power loss in EVs occur in the clutches, mechanical differential and the gear box. Hence in electric vehicle with in-wheel drive system, these losses can be minimized as each wheel is fitted with a motor. This even makes the mechanical layout easier [4].In conventional in-wheel drive electric vehicle, separate inverters are used for each motor in order to achieve electricdifferential operation [5].When the vehicle needs to move straight, both the motors can be made to run at the same speed. When the vehicle travels straight, a closed loop control is essential to ensure that both the motors run at equal speed irrespective of the imbalance in load. If the vehicle needs to make left/right turn(i.e. when the steering wheel is rotated), then one motor can be made to run at a higher speed than the other one depending upon the direction of rotation of the steering wheel(equivalent to mechanical differential in cars). Hence this nine switch inverter is an apt inverter for the use in EVs. Eventhough two motor single power electronic converter (chopper) drive system exist, they use only DC motors which has sparking problems and require regular maintenance [6]. The aim of this paper is to use nine switch inverter instead of two full bridge inverters and to use AC motors. This provides equivalent operation of two full bridge inverters with reduced number of switches and saves the size, weight and cost of the inverter employed. This nine switch inverter can be used to independently control the motors [7]-[8].This can be extended for four wheel drive system with just two nine switch inverters. Besides, this concept can even be extended for differentially abled people who use electric wheel chairs where the operations are similar to that of the electric vehicles [9] - [10].

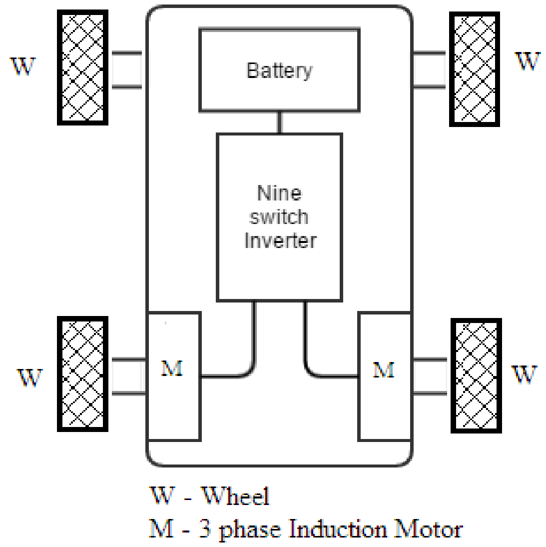

Fig. 1. Block diagram of the electric vehicle

II. Electrical Differential System

In IC engine drive system, mechanical differential is being used. But the mechanical differential system has losses due to gear mechanism. Hence this system can be replaced by electric differential system in the case of electric vehicles. Mostly electric vehicles use motors as their drives and hence electric differential system has to be used. When a vehicle is moving forward both the rear wheel motors should run with equal speed. When the vehicle turns, the inner wheel has to run at a lower speed as they have to cover only a smaller distance whereas the outer wheel has to run faster than the inner wheel as they need to cover a longer distance. This action is done with the help of an electric differential unit.This differential action is required only for the rear wheels and not for the front wheels in the case of rear wheel drive system. This method of electric differential is usually done with the help of two separate full bridge inverters as the rear wheel motors must be individually controlled. In this paper, electric differential is achieved with the help of nine switch inverter which is equivalent in operation to two full bridge inverters. The operation of nine switch inverter will be explained later. The electric differential system has to control the speeds desired for the motors simultaneously to maintain stability of the vehicle or else the vehicle may topple. When the steering turns to a certain angle on either direction, an error factor either positive or negative depending on the direction of turn is added or subtracted to the reference speed and the motors are being run at the reference speed with the help of a closed loop control. The block diagram shown in Fig.2 explains this mechanism.A fast and closed loop torque control for the electric machine is a major requirement for high dynamics.

III. Nine-Switch Inverter

A nine switch inverter, a three legged structure with three switches in each leg is shown in Fig. 3. It is comparable to two three phase full bridge inverters as a single nine switch inverter unit can supply two three phase A.C loads at same time. It has the advantage that the number of switches is less as compared to two three phase inverters. Two individual inverters are essential as there is a need to use two independent loads where they cannot be paralled. With this advantage of independent control of two loads at the same time this inverter can be utilized in an electric vehicle in which two motors require an independent control.Fig. 4 shows the voltage waveform of one of the output of the nine switch inverter along with the fundamental component of the waveform.

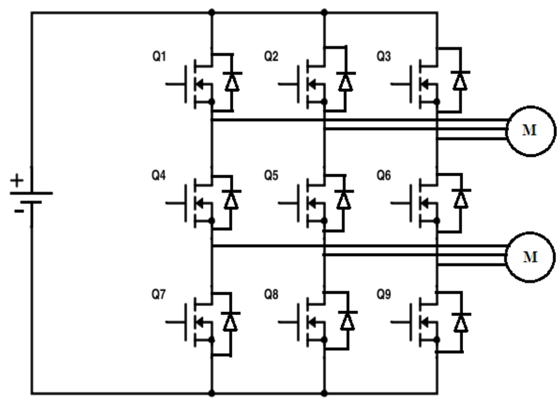

Fig. 3. Structure of Nine Switch Inverter

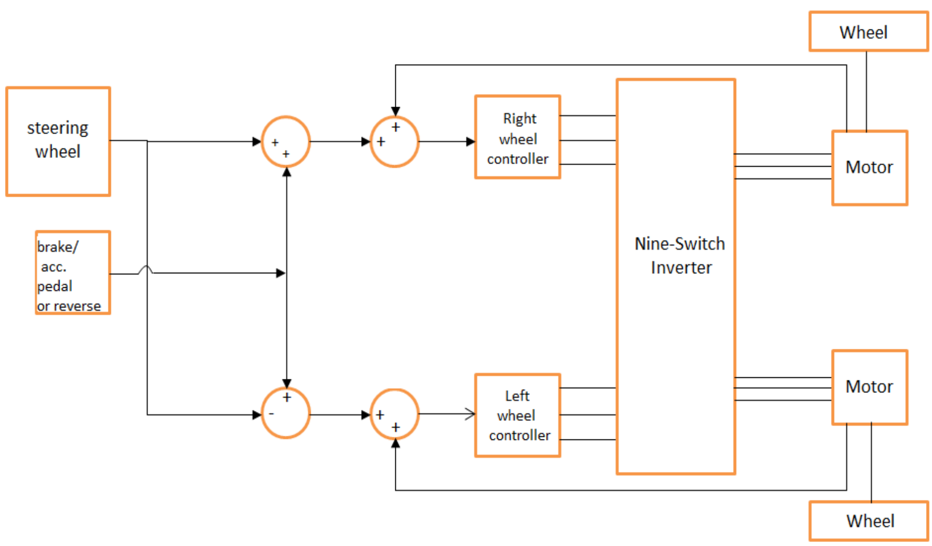

Fig. 2. Layout of electric vehicle system

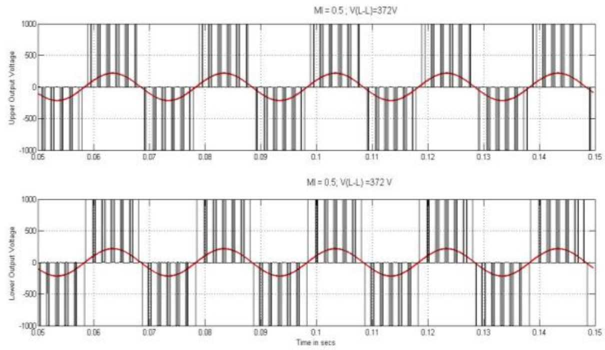

Fig. 4. Upper and lower output voltage of the nine switch inverter

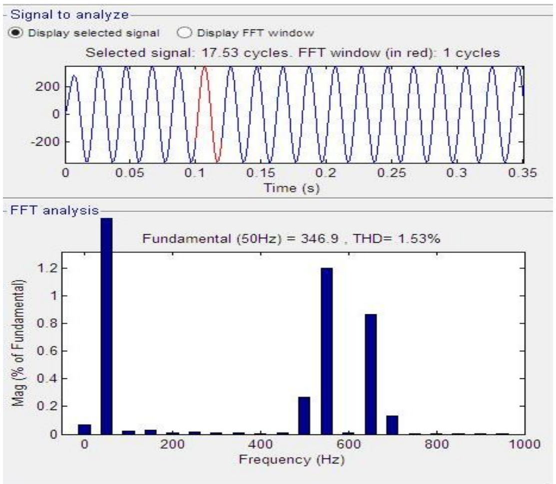

Fig. 5. THD analysis and Filtered voltage of nine switch inverter

In general for the inverter switches, a modulation technique is used. This proposed paper is utilizing PWM method. The upper set Q_1, Q_2, Q_3 and lower set Q_7, Q_8, Q_9 switches get their independent signals from their respective vector control method but the middle set Q_4, Q_5, Q_6 get the EXOR of the two levels (upper and lower level switches). Fig. 5 shows the filtered waveform and the THD analysis of the nine switch inverter output voltage after passing through a low pass filter with cut off frequency of 100Hz.

IV. CLOSED LOOP CONTROL OF INDUCTION MOTOR:

Indirect vector method of closed loop control of induction motor is shown in Fig. 6. This method makes the control of torque and speed of the induction motor flexible as that of a dc shunt motor. It helps to decouple the current as torque current or armature current (I_q) and the flux or the field current(I_d). Hence by decoupling the currents, the control becomes easier.

The speed of the motor is compared with the reference speed(ω_r^*)and it produces the reference torque (T_e^*). Currents I_q^* and I_d^* are obtained using equations (1) and (2). The angle θ is obtained using currents I_a, I_b, I_c and I_q , $I_d$currents as in equations (3)-(5). The three phase reference currents I_a^*, I_b^*, I_c^* are obtained using the equations (6)-(8). The current regulator produces the firing pulses for the nine switch inverter in accordance with the reference currents $I_a^*, I_b^*, I_c^*$and the stator currents I_a, I_b, I_c . The gates pulses are produced by current controller using PWM technique depending on the references I_a^*, I_b^* and I_c^*[12]. Gate pulses given to the switches of the leg A is depicted in the Fig. 7. The gate signal for the middle switch in each leg is obtained by the EXOR of the two switches (top and bottom switches) in that leg.

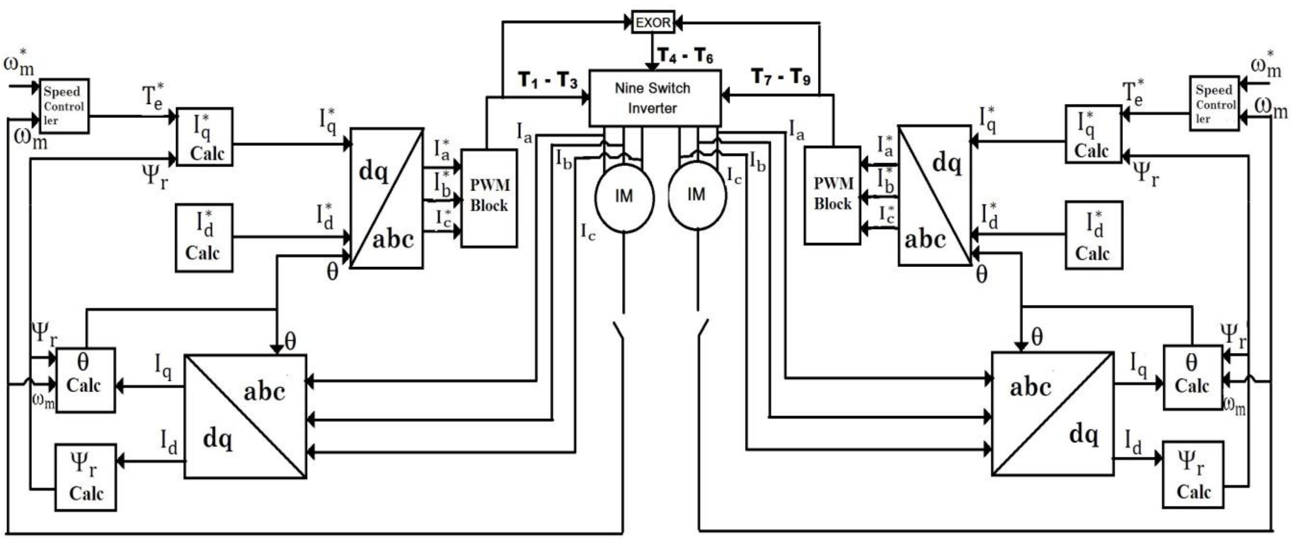

Fig. 6. Vector control closed loop control of Induction motor

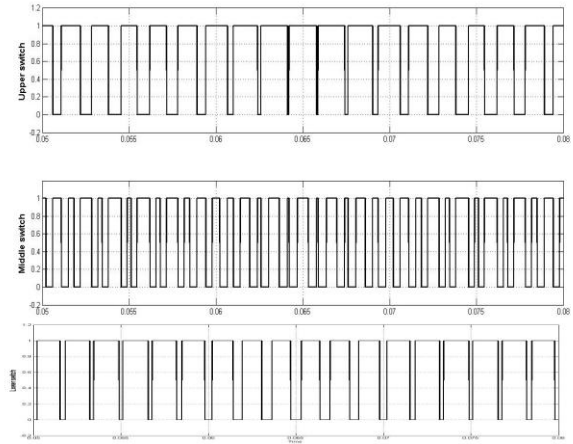

Fig. 7. Gate pulses of the switches of a leg

I_d^* Calculation:

$$I_d^* = \frac{\Psi_r^*}{L_m} \quad \text{--------(1)}$$

I_q^* Calculation:

$$I_q^* = \frac{4 L_r T_e}{3P\, L_m \Psi_r} \text{--------(2)}$$

θ Calculation:

$$\theta = \int \left[\frac{L_r I_q}{\Psi_r T_r + 1\, e^{-3}} + 2\omega_m\right] \text{--------(3)}$$

abc to dq Transformation:

$$I_d = \frac{2}{3}\left[(\cos\theta)I_a + 0.5\left(\sqrt{3}\sin\theta - \cos\theta\right)I_b + 0.5\left(-\cos\theta - \sqrt{3}\sin\theta\right)I_c\right] \text{-------- (4)}$$

$$I_q = \frac{2}{3}\left[(-\sin\theta)I_a + 0.5\left(\sin\theta + \sqrt{3}\cos\theta\right)I_b + 0.5\left(\sin\theta - \sqrt{3}\cos\theta\right)I_c\right] \text{--------(5)}$$

dq to abc transformation:

$$I_a^* = I_d^*\cos\theta - I_q^*\sin\theta \quad \text{-------(6)}$$

$$I_b^* = 0.5\left(-\cos\theta + \sqrt{3}\sin\theta\right)I_d^* + 0.5\left(\sin\theta + \sqrt{3}\cos\theta\right)I_q^* \quad \text{-------(7)}$$

$$I_c^* = -(I_a^* + I_b^*) \text{-------(8)}$$

V. SIMULATION RESULTS AND DISCUSSION

The prototype model of the electric vehicle circuit is developed and simulated using Matlab/Simulink.Here different cases of operation of the electric vehicle are considered for simulation.

Table I : Simulation Parameters

Parameter	Values
V_{in}	800V
3 phase Squirrel Cage Induction Motor	
Capacity	50HP
Voltage rating	460 V
L_m	34.7mH
L_r	35.5mH
R_r	0.228Ω
Speed controller	
K_p	13
K_i	26

Case study for the following vehicle operations are done by simulation, varying the reference speed.

(1)When the vehicle moves straight
(2)When the vehicle turns left
(3)When the vehicle turns right.
(4)When the vehicle accelerates in the forward direction
(5) When the vehicle halts
(6)When the vehicles moves in the reverse direction

Case 1: When the vehicle moves straight

As the vehicle moves straight(i.e. under normal operation), both the motors run at the same speed. The controller reference speed is set at 100rpm. Hence the rms output voltage of both the inverters are same as shown in Fig.8 which resultsthe motor to run at the same speed (each at 100 rpm) which is shown in Fig. 9.

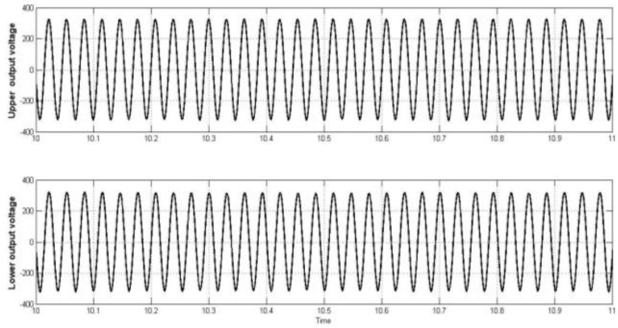

Fig. 8. Output voltage of the nine switch inverter when the vehicle moves straight

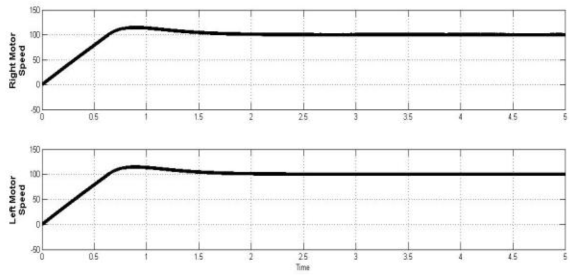

Fig. 9. Speed curves when the vehicle moves straight

Case 2: When the vehicle turns left

When the vehicle turns towards left, the inner wheel (left wheel connected to lower inverter output) should run at a lower speed and the outer wheel(right wheel connected to upper inverter output) should run at a higher speed. The reference speed of the outer wheel is increased because of the steering wheel factor and the reference speed of the inner wheel is decreased proportional to the steering wheel factor from t = 4.3 to 7 secs. This results in increase of rms output voltage/frequency of the inner/upper wheel inverter whereas the rms voltage/frequency of the outer/lower wheel inverter is decreased as depicted in Fig. 10 which makes the inner wheel to run at a lower speed (80rpm) and the outer wheel at a higher speed (120rpm) achieving the electric differential action as shown in Fig. 11.

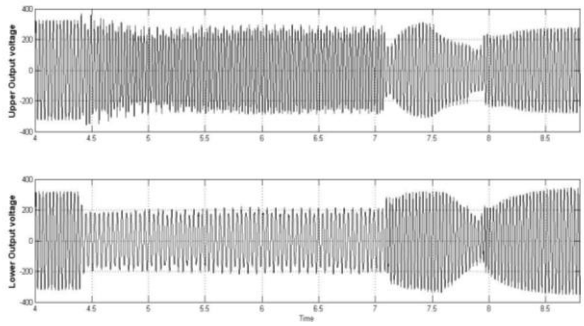

Fig. 10.Output voltages of the inverter when the vehicle turns left

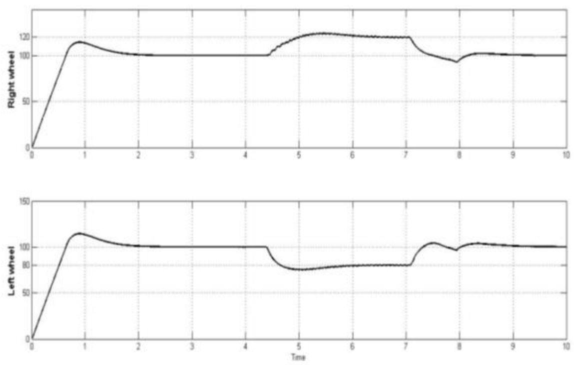

Fig. 11. Speed curves when the vehicle turns left

Case 3: When the vehicle turns right

When the vehicle turns towards right, the outer wheel (right wheel connected to upper inverter output) should run at a lower speed and the inner wheel (left wheel connected to lower inverter output) should run at a higher speed. The reference speed of the outer wheel is increased because of the steering wheel factor and the reference speed of the inner wheel is decreased proportional to the steering wheel factor from t = 4.3 to 7 secs. This results in decrease of rms output voltage/frequency of the inner/upper wheel inverter whereas the rms voltage/frequency of the outer/lower wheel inverter is increased as depicted in Fig. 12 which makes the inner wheel to run at a lower speed (80rpm) and the outer wheel at a higher speed (120rpm) achieving the electric differential action as shown in Fig. 13.

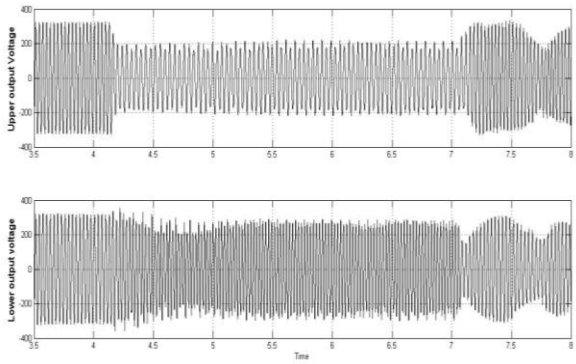

Fig. 12. Output voltages of the inverter when the vehicle turns right

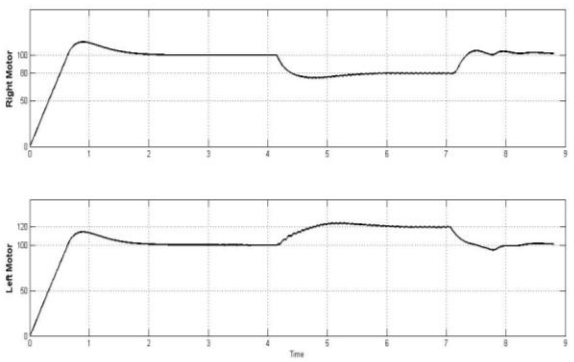

Fig. 13. Speed curves when the vehicle turns left

Case 4: When the vehicle accelerates from 100 rpm to 200 rpm

The acceleration of the vehicle is discussed in this case. Till t = 4, the vehicle runs at a reference speed of 100 rpm. After t = 4, it runs at 200 rpm. As the reference speed is changed at t = 4, the increase in voltage and frequency in both the inverter is depicted in Fig. 14. The corresponding increase in speed from 100 to 200 rpm is also portrayed in Fig. 15.

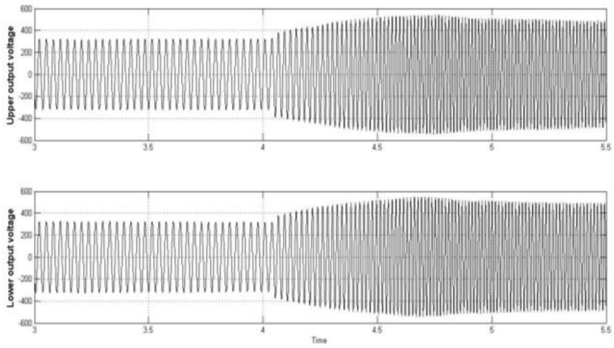

Fig. 14. Output voltages of the inverter when the vehicle accelerates

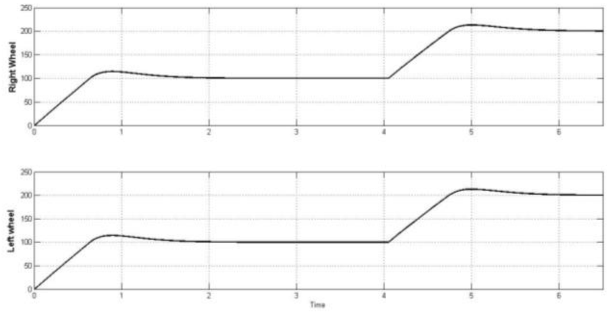

Fig. 15. Speed curves when the vehicle accelerates

Case 5: When the brakes are applied

When the brakes are applied while the vehicle is running at any speed, it comes to halt by reducing the voltages of both the outputs of the inverter. Here, the brakes are applied at t=1.7 secs which makes both the voltages to reach zero after t=1.7secs as shown in Fig. 16 and it results the motor to halt as shown in Fig. 17.

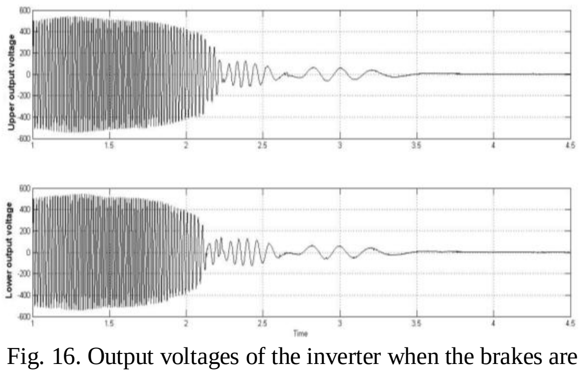

Fig. 16. Output voltages of the inverter when the brakes are applied

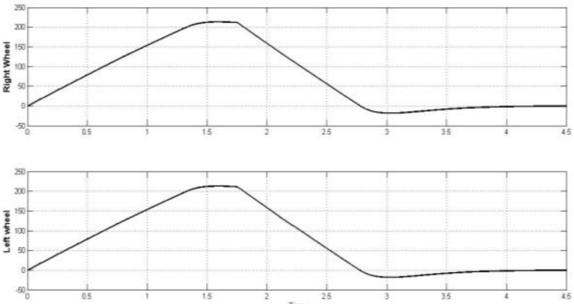

Fig. 17. Speed curves when the vehicle halts

Case 6: When the vehicle moves in the reverse direction

When the vehicle has to move in the reverse direction, the voltages of the inverter are produced in such a way that the speed reverses. Two of the phases are exchanged and this reverses the magnetic field and hence the direction of rotation. Fig 18 shows the three phase output voltage of one of the inverter having two phases exchanged which will produce magnetic field in the reverse direction. The reference speed is set at -40 rpm which is illustrated in the Fig. 19.

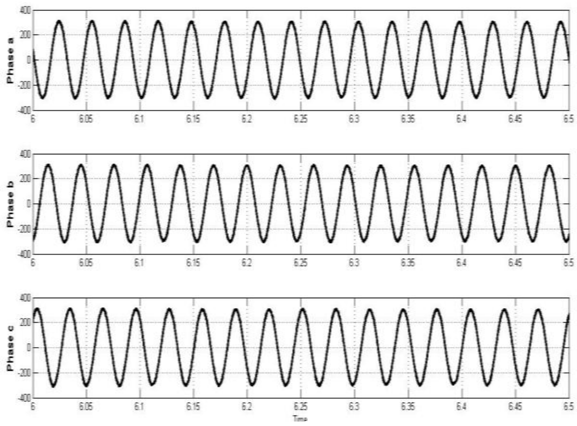

Fig. 18.Three phase output voltages of the upper inverter when the vehicle moves in the reverse direction

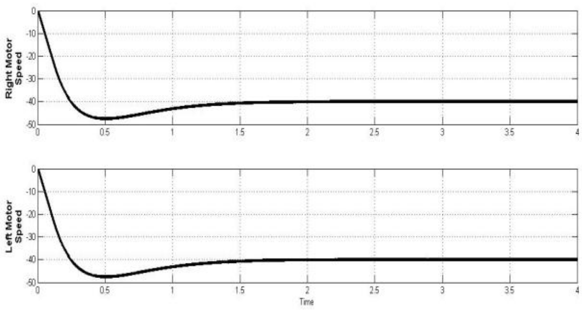

Fig. 19. Speed curves when the vehicle moves in the reverse direction

VI. Conclusion

Reducing the size and cost of the electric vehicle/ electric wheel chair has been a major issue in the past years. From the electrical side of view, the inverter used can be modified to achieve it. This paper makes use of nine switch inverter in electric vehicleand electric wheel chairalong with electric differentialsystem. The simulation results of the protoype model shows that the vehicle can be operated in all the modes discussed, with the help of nine switch inverter. It can be inferred that the full bridge inverters presently used in electric vehicles/electric wheel chairs can be replaced with the nine switch inverter and this will reduces the cost, weight and size of the electric vehicle/ electric wheel chair. Especially in electric wheel chairs, it reduces its size and makes it more compactand less cumbersome to handle. It will be much economical for all wheel drive system where just two nine switch inverters are sufficient unlike four full bridge inverters currently being used.The Matlab simulation explains the feasibility of the proposed system.

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