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A Comparison on Control Algorithms for a BEV Propulsion Motor with Road load under NEDC

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Abstract—In this paper a Comparative analysis is made between Indirect field oriented control and Space Vector Modulation based Direct torque control (SVM-DTC) methods to regulate the performance of the propulsion motor of a Battery Electric Vehicle(BEV) with road load under NEDC drive cycle. Owing to the splendid characteristics like rapid torque control and higher efficiency, the Induction Motor (IM) is adopted as the preeminent for BEV propulsion motor. The most significant techniques used for propulsion motor torque and speed control are Indirect field oriented control (IFOC) and Space Vector Modulation based direct torque control (SVM-DTC).In IFOC the propulsion motor control is achieved by synthesizing stator currents from two quadrature components, corresponding to flux and torque respectively. In SVM-DTC decoupling and linearization of current vectors through coordinate transformation is eradicated and a reference stator flux vector originated by the adaptive motor model provides d and q axis reference voltages fed to SVM. Simulation results are explored to accentuate the performance of the propulsion motor with road load for both methods under NEDC drive cycle.

Index Terms—Direct torque control, Indirect field oriented control, NEDC drive cycle, Road load, Space Vector Modulation, Three phase Induction Motor.

I. INTRODUCTION

In this contemporary automotive world, in the vision of environmental impacts, the use of zero emission vehicles is most essential in cities and towns and also attaining considerable impact in automotive market. As a result, it is required to supplant the ordinary gasoline Internal Combustion Engine (ICE) with the electric motor drives in vehicle propulsion system. Researchers are endlessly keeping efforts in developing efficient battery charging systems and high energy efficiency drives for an electric vehicle. By this a new range of electric vehicles are evolved which are categorized as Hybrid electric vehicles (HEV), Battery electric vehicle (BEV), Fuel Cell Electric Vehicles (FCEV), Plug-in hybrid electric vehicles (PHEV) and Solar powered electric vehicles. Among these, BEVs are gaining more attention because of their superior performance characteristics such as feasible operation, smooth propulsion, fast control, zero emission, hushed operation and frequent start-stop driving capability.BEV comprises of a stack of lithium ion batteries which power the vehicle, a propulsion motor to provide necessary tractive force, a controller which enables control signals and mechanical transmission system which provides sufficient tractive force at wheels.

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An efficient on-board or off-board charging units offer quick charge from utility grid. In BEVs, only the propulsion motor delivers torque to drive wheels. Thus the vehicle performance is completely determined by selection of specific propulsion motor type, its torque speed or power-speed characteristic and control strategy. The conventional layout of electric motor propulsion system for a BEV is shown in Figure 1.

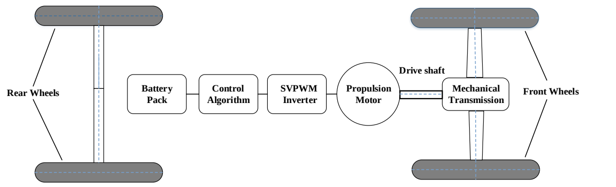

Fig. 1 The layout of Electric propulsion system of a BEV

Propulsion motor for BEVs is chosen based on a several aspects such as the driving profile, acceleration, braking and drive range. The vehicle parameters such as size and mass of the vehicle which depend on class and cargo also play a key role in the choice of the propulsion motor rating. The research for an efficient propulsion motor for BEVs plays a major role in the automotive industry even today. The major requirements of propulsion motor for BEV are confer in the previous literatures [1] - [5].

Majority of electric vehicles adopt induction motors as propulsion motors due to their ruggedness in construction, low weight, compactness, low maintenance, economic, potential to work in destructive environment, high efficiency at rated conditions, higher torque during hill climbing, higher rate of acceleration or deceleration, zero torque at high-speed cruising and also necessitate simple control structure. The added advantages are that it can be operated in constant power/extended speed range operation. Higher output can be achieved from these motors due to the absence of brush friction and also variable frequency operation offers wide range of speed control.

Furthermore, the constant-power operation is restricted due to the occurrence of a breakdown torque at critical speed which is about twice the synchronous speed. And the motor will get stall beyond this operating point.

However, the induction motor enters the natural mode at which point it digresses from the constant power operating region. In this mode maximum torque available is inversely proportional to speed square [6]. Therefore these Torque-speed characteristics are most suitable for BEV as represented in Figure 2.

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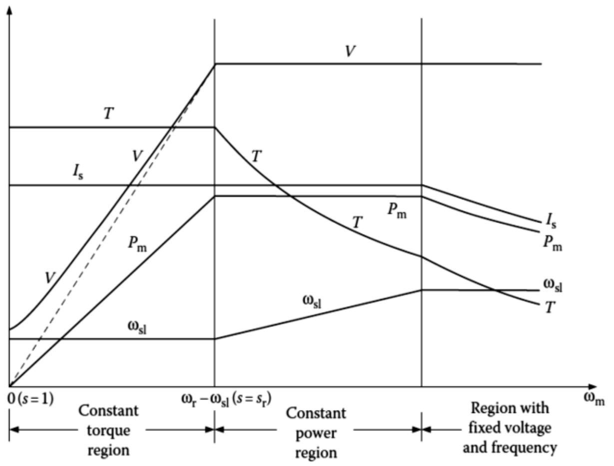


Fig.2 Torque-speed characteristics of an induction motor

BEV propulsion majorly needs to operate in the constant power region to meet higher acceleration with rated power [2].

However, it is not possible for any practical BEV motor to operate entirely in constant power region. The ideal characteristics of a BEVs propulsion motor are shown in Figure 3.

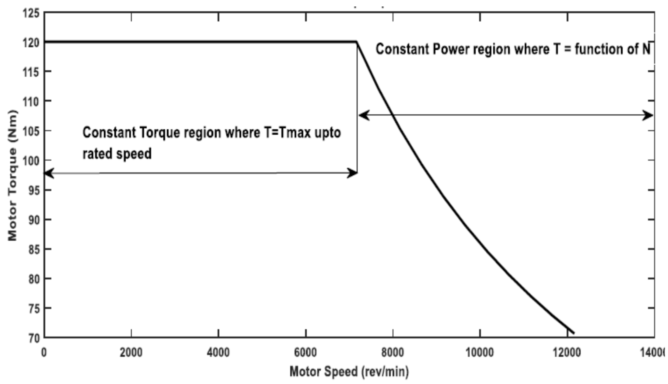


Fig.3 Torque-speed characteristic of a propulsion motor

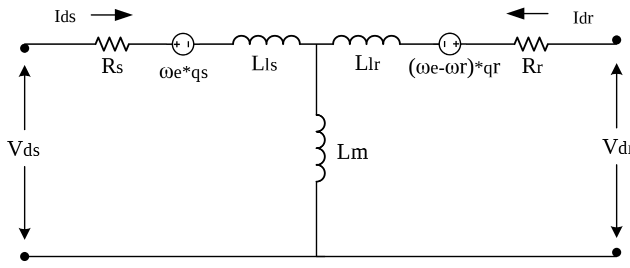
From above characteristics it is perceived that the adopted induction motor can meet desired characteristics of BEV propulsion system.

The motor drive control systems play a key role in controlling the propulsion motor speed and torque during acceleration and deceleration. As driver impulse the accelerator the commanded torque signal is processed through the controller and the motor input is varied to meet the commanded torque.

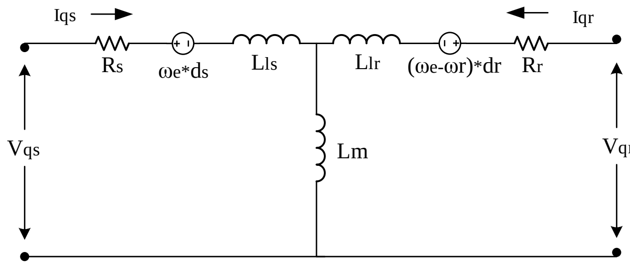
This control action can be achieved with the help of IFOC and Space Vector Modulation based Direct Torque Control (SVM-DTC) techniques.

II. DYNAMIC MODEL OF INDUCTION MOTOR

The d-axis and q-axis circuit models in synchronously rotating reference frame are epitomized in the Figure 4 (a) and 4 (b) respectively.



(a)



(b)

Fig.4. Dynamic model of three phase induction motor (a) d-axis circuit model (b) q-axis circuit model

From the circuit model shown in Figure 4, the expressions for the induction motor voltages, flux and torque in d-q coordinates are obtained as follows:

$$V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \qquad (1)$$

$$V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \qquad (2)$$

$$\psi_{dr} = L_{lr} I_{dr} + L_m(i_{ds} + i_{dr}) \qquad (3)$$

$$\psi_{qr} = L_{lr} I_{qr} + L_m(i_{qs} + i_{qr}) \qquad (4)$$

$$T_e = \frac{3}{2} * \frac{P}{2} * \frac{L_m}{L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \qquad (5)$$

Where V_{dr} is direct axis motor voltage, V_{qr} is quadrature axis motor voltage, ψ_{dr} direct axis rotor flux, ψ_{qr} quadrature axis rotor flux, I_{dr} direct axis motor current, I_{qr} quadrature axis motor current, ω_r is motor angular speed in electrical degrees and T_e is the electromagnetic torque developed by the motor. P is number of poles, R_r, L_r is resistance and inductance of rotor circuit and L_m is coupled inductance. By discarding, the saturation effect of the core, skin effect in rotor circuit and the stator resistance thermal effect, the dynamic model of an IM is defined by the Equations (1) – (5). Also modeled as follows:

$$V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} \qquad (6)$$

$$V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} \qquad (7)$$

Where V_{ds} is direct axis stator voltage, V_{qs} is quadrature axis stator voltage, ψ_{ds} direct axis stator flux, ψ_{qs} quadrature axis stator flux, I_{ds} direct axis stator current, I_{qs} quadrature

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axis stator current.Equations (6) – (7) defines the dynamic model in stationary reference frame.

III. INDIRECT FIELD ORIENTED CONTROL

Torque control of an induction motor can be decoupled from field control using Field Orientation Control (FOC). This enables the induction motor to behave as a separately excited dc motor without speed limitations of a dc motor and operation ahead of base speed can accomplish by flux weakening with range of up to 3-5 times. Field-oriented control also referred to Vector control as it involves the control of magnitude and phase of the AC quantities in together [9]-[10]. In FOC control scheme the rotor stance is sensed through speed sensor or speed encoder and the two-phase currents are measured through current sensors to produce instantaneous the torque and flux control components. Based on the procedure with which the unit vector is determined in FOC, it is classified into two types: Direct or Feed forward control and Indirect or Feed backward control. FOC has improved dynamic response, also able to offer a higher output torque at zero speed [5]-[6].

The basic Indirect field oriented vector control scheme with road load through mechanical gear transmission is represented in Figure 5. The induction motor as a propulsion motor of BEV is fed by a current regulator in inner current loop and the reference quadrature axis currentI_{qs}^*which is accountable for torque control is attained through Proportional controller (PI) of the outer speed loop. Whereas the flux control is achieved by the reference direct-axis currentI_{ds}^* which is assumed to be constant up to base speed beyond that it is decreased as a function of speed in field weakening mode. The Inverse transformation block transfers the reference currents I_{ds}^* & I_{qs}^* into voltage references V_{ds}^*&$V_{qs}^*$for the Space Vector Pulse Width Modulation (SVPWM).In this method, decoupled control of torque and stator flux is achieved so that theI_{ds}^*regulates the rotor flux and I_{qs}^*regulates the torque developed by propulsion motor. The reference stator d-axis component $I_{ds}^*$is determined by the expression (8).

$$I_{ds}^* = \frac{|\psi_r|}{L_m} \quad (8)$$

The reference q-axis component I_{qs}^*,for a given torque demand T_e^*, can be obtained as (9).

$$I_{qs}^* = \frac{2}{3} * \frac{2}{P} * \frac{L_r}{L_m} \frac{T_e^*}{|\psi_r|_{est}} \quad (9)$$

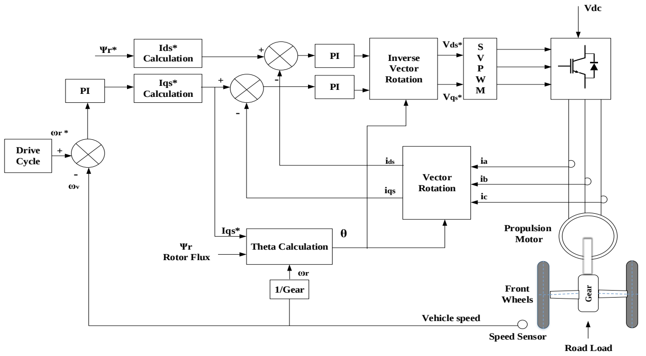

Fig 5. Block diagram of Indirect Field Oriented Control of Propulsion Motor of a BEV

IV. DIRECT TORQUE CONTROL

In DTC scheme both torque and flux of the motor can be controlled autonomously by the direct-axis voltage and quadrature- axis voltage of the stator. The DTC method was developed by Takahashi; it is universally approved control scheme and an alternative for IFOC scheme. This method is adopted in most of the industries for motor drive control, and also most suited for BEV propulsion motor control. However, the Classical DTC (CDTC) has some drawbacks such as

needs higher sampling frequencies for the hysteresis comparator, it produces high ripples in torque, overshoot at starting and speed variations and not suited for low speed operation. Subsequently, the new method characterized as SVM based DTC provides high performance as it offers torque, flux and speed control without the requisite of position and speed encoder, no coordinate transformation is required and also offers constant switching frequency, also overcome the complexities involved in IFOC [7]- [10].

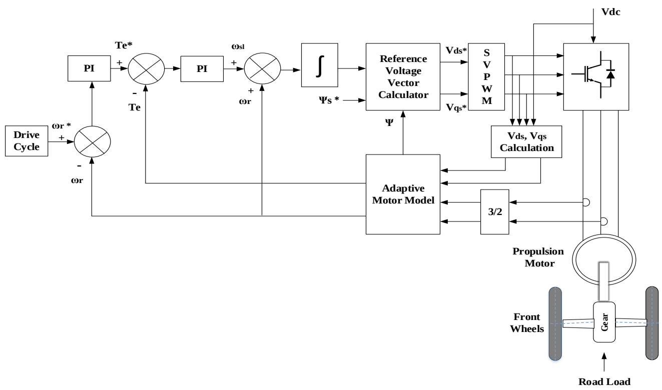

Fig 6. Block diagram of SVM based DTC of propulsion motor of a BEV

V. ROAD LOAD AND VEHICLE DYNAMICS

Consider a vehicle as in Figure 7 with allied forces on the vehicle, ‘M’ represents vehicle mass in Kg, ‘v’ linear velocity in forward motion in m/sec, the gravitational acceleration g in Kg/m^3 and ‘α’ defines degree of gradient in degrees.

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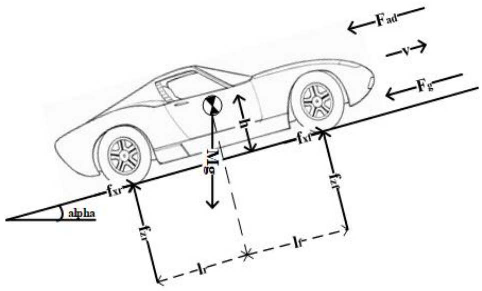

Fig.7BEV model and its allied forces

It is seen that the diving or tractive force 'F_t' to propel the vehicle has to surmount the rolling resistance force 'F_r', aerodynamic drag 'F_{ad}', gradient force 'F_g' and acceleration force 'F_{ac}'. The first three forces are summarized as road load 'F_{rl}', i.e.,

$$F_{rl} = F_r + F_{ad} + F_g (10)$$

Rolling resistance force F_r is owing to friction at the road surface, at start the initial tractive force essential to propel vehicle is F_r whereas aerodynamic drag and gradient forces tends to zero. Therefore, rolling resistance be determined by the coefficient of rolling friction between the tire and the road C_r which varies with type and size of tire, the normal force F_n due to the vehicle's weight, and the gravitational acceleration g [1]. The expression for rolling resistance is

$$F_r < C_r Mg \ if \ v = 0, \qquad (11)$$

$$F_r = -C_r Mg \ otherwise \qquad (12)$$

The aerodynamic drag is a function of speed and can be determined by the density of air D (kg/m^3), air drag coefficient C_d, vehicle frontal area A_f, and speed v. The expression for the aerodynamic drag is

$$F_{ad} = \frac{1}{2} D C_d A_f v^2 \qquad (13)$$

The gradient force depends on vehicle mass M, degree of gradient α, and the gravitational acceleration g. The expression for this force is

$$F_g = Mg\sin(\alpha) \qquad (14)$$

The acceleration force is to accelerate linearly when vehicle speed changes and, is governed by Newton's second law,

$$F_{ac} = Ma = M\frac{dv}{dt} \qquad (15)$$

And consequently, the total tractive effort is the summation of all forces.

$$F_t = F_r + F_{ad} + F_g + F_{ac} = F_{rl} + F_{ac} \qquad (16)$$

This force propels the vehicle forward and is transmitted through the drive wheels to the ground. The velocity of the vehicle is calculated by integrating the acceleration 'a' and is given by

$$acceleration = a = \frac{F_{ac}}{M} = \frac{dv}{dt} \qquad (17)$$

$$V = \frac{1}{M}\int_{t=0}^{t} (F_t - F_{rl})\, dt \qquad (18)$$

The time required to reach maximum speed and power rating of the motor are determined as follows:

$$t_f = M\int_0^v \frac{dV}{F_{ac}} = M\int_0^v \frac{dV}{\frac{P_{motor}}{v}} \ and \qquad (19)$$

$$P_{motor} = \frac{M}{t_f}\int_0^v v\ dv = \frac{M}{2t_f} v^2 \qquad (20)$$

VI. COMPARATIVE ANALYSIS & RESULTS

A comparative Analysis of most significant vector control schemes IFOC and SVM-DTC is made with help of simulation results obtained for the Induction machine parameters mentioned in Appendix I. Matlab/Simulink model is developed for both control schemes for the propulsion motor of a BEV with road load. Drive cycles are standard vehicle speed versus time profile used for testing vehicle performance and are proposed by the US Environmental Protection Agency (EPA). Different standard drive cycles suggested by EPA are New European Driving Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) driving cycles [3]. The performance of the propulsion motor for both control algorithms is validated through NEDC drive cycle test and is shown in subsequent Figures 8-17. Figures8-12 represents the simulation results of BEV propulsion motor with IFOC control scheme. And Figures 13-17, represents the simulation results of BEV propulsion motor with SVM based DTC control scheme. Figures 8 & 13 depict the actual vehicle speed and reference NEDC drive cycle waveforms. It is observed that in IFOC controller fails to attain reference speed during high accelerations whereas in SVM-DTC smooth speed control is achieved. From Figures 9 & 14, it is observed that the torque waveform has high ripples during acceleration and deceleration periods compared to SVM-DTC. In Figures 10 & 15, it is seen that the current waveform has higher harmonics in IFOC than SVM-DTC. Figures 11 & 16 represents the voltage profile of the three level inverter and observed constant switching frequency operation in SVM-DTC. Figures 12 & 17 represents trajectory of rotor flux and its variations.

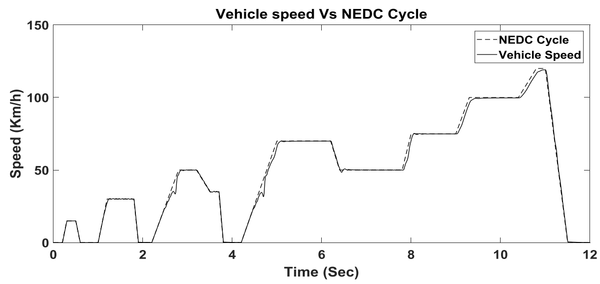

Fig.8 Vehicle Speed vs NEDC drive cycle with IFOC

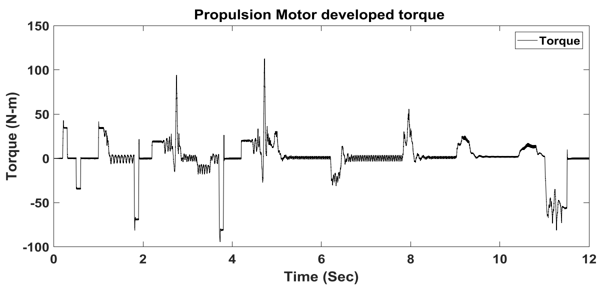

Fig.9 Torque developed by propulsion motor with IFOC

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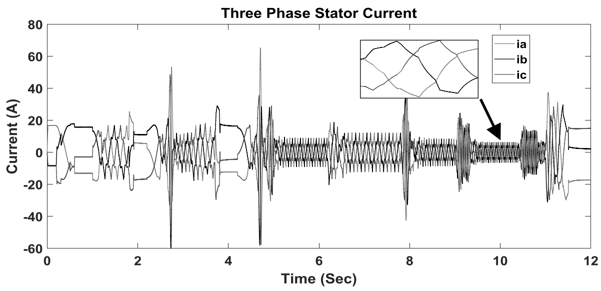

Fig.10 Motor stator current with IFOC

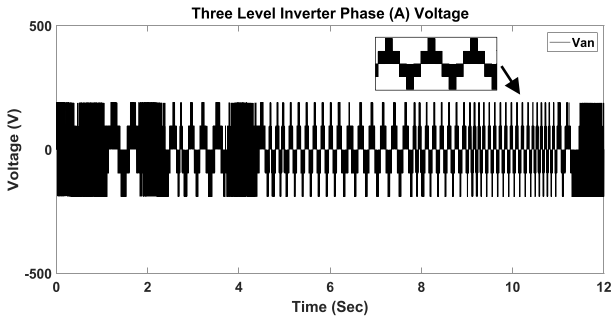

Fig.11 Inverter phase voltage with IFOC

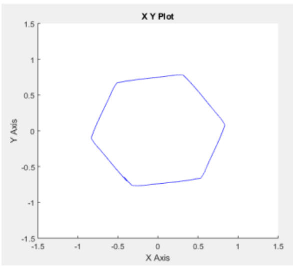

Fig.12 Rotor flux trajectory with IFOC

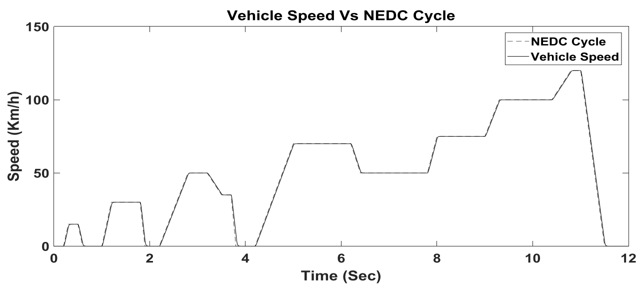

Fig.13 Vehicle Speed vs NEDC drive cycle with SVM-DTC

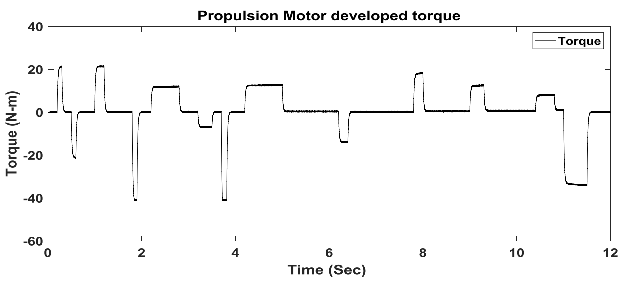

Fig.14 Torque developed by propulsion motor with SVM-DTC

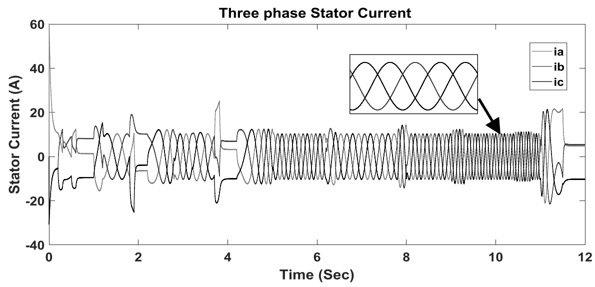

Fig.15 Motor stator current with SVM-DTC

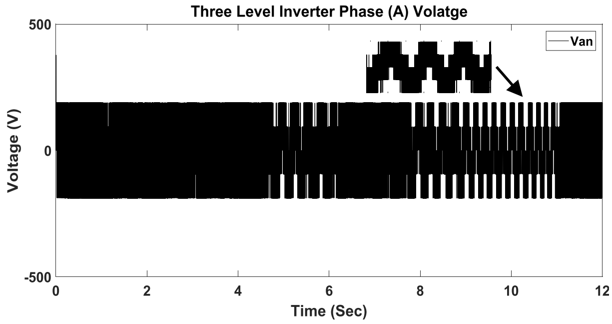

Fig.16 Inverter phase voltage with SVM-DTC

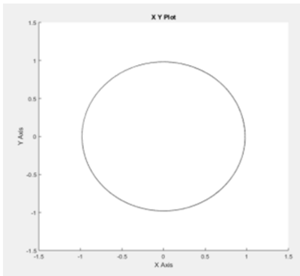

Fig.17 Rotor flux trajectory with SVM-DTC

VII. CONCLUSION

The performance of the BEV propulsion motor with road load under NEDC drive cycle for both IFOC and SVM-DTC control algorithms is observed using simulation results. The simulation result shows that the SVM-DTC control eradicates the inappropriate ripple in BEV propulsion system. Reduction in high torque ripples and overshoot are minimized by more than 50% and the performance is accomplished during acceleration and braking. Consequently, SVM based DTC control intensely fulfills the requirements for the BEV propulsion system.

VIII. APPENDIX I

TABLE I. VEHICLE DATA

VEHICLE SPECIFICATIONS	
Mass of the vehicle, M	1200 Kg
Frontal Area of the vehicle, A_f	0.2 sq.mt
Radius of the Wheel, R_w	0.2794 m
Coefficient of Rolling resistance, C_r	0.0015
Density of the Air, D	1.225 Kg/m^3
Drag coefficient of Air, C_d	0.3
Gravitational constant, g	9.81 Kg/m^2

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Transmission gear ratio, G	6.842
Slope or gradient angle, α	5^{o}

TABLE II. MOTOR MANUFACTURER SPECIFICATIONS

Three Phase induction motor Parameters	
Motor Power rating, P_{motor}	15 Kw
Nominal Voltage, V_n	380 V, RMS
Current rating, I_n	28.9 A
Frequency, f_s	50 Hz
Torque, Te	98 Nm
Motor inertia, J_{motor}	0.0875
Pole pairs, p	4
Nominal stator flux, ψ_s	0.98 Wb
Stator resistance, R_{stator}	0.28 ohm
Stator Inductance, L_{stator}	0.0635 H
Rotor resistance, R_{rotor}	0.26 ohm
Rotor inductance, L_{rotor}	0.635 H
Mutual inductance, L_{mutual}	0.0581 H

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