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Design Methodology and Sensorless Control of Electric Propulsion System using DTC-SVM

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***Abstract*—Electric propulsion system (EPS) employing Induction Motors (IM) have gained acceptance due to their robust structure, reliability, technological advancement and low cost. This paper presents the technical considerations and design methodology of EPS for urban cars. Direct torque control (DTC) is a prominent technique in controlling the IM due to its easy configuration and fast performance. Nevertheless, it generates high torque ripple coupled with variable switching frequency. To get sophisticated results like ripple free torque and constant switching frequency, IM can be controlled by DTC scheme using the space-vector modulation (SVM) technique. The speed of the motor is estimated in limp-home mode operation of the vehicle by rotor flux based model reference adaptive system (MRAS). The performance of IM in limp-home mode of electric vehicle using DTC and DTC-SVM techniques considering the drive cycle are presented.**

***Index Terms*—Electric vehicles, sensorless control, torque control, traction motors, vehicle dynamics.**

I. Introduction

In developing countries like India, apprehension about energy efficiency and environmental protection, the spread of EVs has been accelerated [1]. The features of an EV drive system are summarized in [2]. The basic composition of an

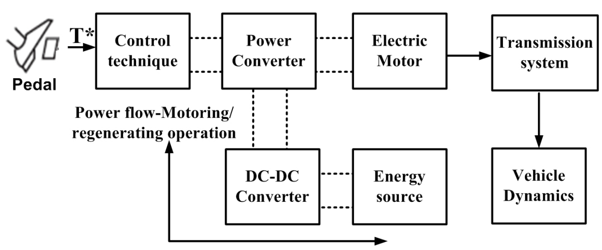

Fig. 1. An electric propulsion system architecture of an urban car

EPS for EVs is shown in Fig. 1. The electric vehicle controller unit (ECU) get inputs from the accelerator and brake pedals to control the energy flow between the traction motor and energy source [3]. The selection of a proper drive, control method and robust energy management are crucial in efficient design of EVs [4]. The comparison of different traction motors such as IM, permanent magnet synchronous motor (PMSM), switched reluctance motor (SRM), synchronous reluctance motor (SynRM) used for EV application is listed in Table I [5], [6]. Each of them is graded from 1-5 points, where 5 denotes the best.

TABLE I
Comparison of electric motors for EVs

Characteristics	IM	PMSM	SRM	SynRM
Torque/power density	3	5	3.5	3
Efficiency	3.5	5	3.5	4
Overload capability	4	4	4	5
Controllability	**5**	4	3	4.5
Reliability	**5**	4	5	5
Thermal limitations	4	3.5	5	5
Torque ripple/noise	**5**	5	2	3
Fault tolerant	**5**	3	5	4
Field weakening	4.5	3	5	4.5
Technological maturity	**5**	4	3	4
Manufacturability	**5**	3.5	4	5
Cost	**5**	3	3.5	5

The study reveals that IM drives are highly recommend for EV propulsion, due to low cost, wide speed range, manufacturing technology, high reliability, established converter, less acoustic noise, low torque ripple, longer field weakening range and free from maintenance [7]. However, IM drives were facing drawbacks of lower efficiency, lower power factor and inverter-usage factor, these aspects have been taken care in designing IMs used for EVs [8]-[11]. The study of IM with different number of poles was carried out in [10] and performance analysis discloses that 4-pole IM is a suitable option for urban cars. The control method plays a vital role for enhancing motor efficiency, lengthening battery life and subsequently improving the driving range [12]. The two accepted torque control techniques of IM are Field Oriented Control (FOC) and Direct Torque Control (DTC). DTC is simple control structure and provides fast instantaneous torque control under dynamic operating conditions which are viable for EV applications [13]-[18]. Sensorless control is required for EVs especially in limp-home mode operation of EVs and also to achieve high performance. It offers the lower component count - no need of speed sensor, signal interface, corresponding cables and connectors. It enhances reliability, robustness, increased noise immunity, and extended motor temperature range [19]. Model-based sensorless methods such as model reference adaptive schemes (MRAS) are very simple

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and widely used for the EVs [19]-[22]. The selection and design methodology of electric propulsion systems and applied to a small 4-wheeler EV are illustrated. Simulation was carried out by modelling of components considering inverter, stator flux based IM model and vehicle dynamics. The methodology of detection of speed sensor fault and transition to sensorless control using rotor flux based MRAS are proposed in this paper. The performance analysis of DTC and DTC-SVM with MRAS based sensorless control of IM with the application of EV load in steady state as well as dynamic response are presented in this paper.

II. Vehicle Dynamics and Sizing of an electric Propulsion System

To evaluate the power and energy required to ensure vehicle operation by considering the principles of vehicle mechanics and aerodynamics. The motion of a vehicle can be modeled as [1]:

$$k_m m \frac{dv}{dt} = F_t - \Sigma F_r \tag{1}$$

where, m = mass of the vehicle (kg); k_m = rotational inertia coefficient (1.08-1.1); F_t = vehicle tractive force (N); v = vehicle speed (m/s); F_r = resistive forces as given as:

$$F_r = \mu_r mgcos\theta + \frac{1}{2}C_d\rho Av^2 + mgsin\theta \tag{2}$$

where, μ_r = rolling friction coefficient, g = 9.8 m/s^2 = gravitational acceleration, C_d = drag coefficient, A = aerodynamic reference area (m^2), ρ = air density (1.2 kg/m^3 at 20^oc). The power requirement can be evaluated by considering the driving cycle and vehicle requirements into three modes of operation.

- Power required to achieve max speed V_{max} (km/hr)

$$P_{V_{max}} = (\mu_r mg + \frac{C_d\rho AV_{max}^2}{21.15}) \times \frac{V_{max}}{3600\eta_t} \tag{3}$$

- Power required to achieve maximum climbing gradient with velocity V_{gr}

$$P_{gr_{max}} = (\mu_r mgcos\theta + mgsin\theta) \times \frac{V_{gr}}{3600\eta_t} \tag{4}$$

- Power P_{acc} required corresponding to acceleration time t_a to achieve vehicle speed from 0 to V_{acc} km/hr

$$(\frac{\mu_r mgV_{acc}}{7.2t_a} + \frac{\mu_r mgV_{acc}}{1.5} + \frac{0.4C_d\rho AV_{acc}^2}{21.15}) \times \frac{V_{acc}}{3600\eta_t} \tag{5}$$

The rated power of motor can be evaluated by following equation

$$P_{rated} = Max(P_{V_{max}}, P_{gr_{max}}, P_{acc}) \tag{6}$$

The speed of the motor N_m with suitable gear transmission ratio G_r and vehicle speed V_{max} can be evaluated

$$N_m = \frac{30V_{max}G_r\eta_t}{\pi r} \tag{7}$$

where, r=wheel radius (m), η_t=transmission efficiency. Torque of the motor can be evalauted with vehicle moment of inertia J from the dynamic equation of vehicle motion [1]

$$(m + \frac{J}{r^2})\frac{dv}{dt} = \frac{T_m}{r} - \mu_r mg - \frac{1}{2}C_d\rho Av^2 - mgsin\theta \tag{8}$$

The parameters of a small 4-wheeler EV used for the simulation and analysis are from [23].

A. Driving Cycle

The design and selection of the EPS depends on not only on vehicle constraints (vehicle configuration and weight) but also on driving profile. Some of the standard driving cycles are US drive FTP75, New York City Cycle (NYCC), Unified Cycle Driving Schedule (LA-92), New European Driving Cycle (NEDC), High way Fuel Economy Test (EPA-HWFET), Japan 10.15 Mode, Urban Dynamometer Driving Schedule (UDDS). Driving cycle is essentially represents speed profile with respect to time which includes the acceleration at a given slope, max speed during the short or long time interval, climbing, braking profile and operation range. Fig. 2 shows the Indian driving cycle for urban cars which is essentially follows the European Urban Driving Cycle (EUDC) which contains ECE-15 also.

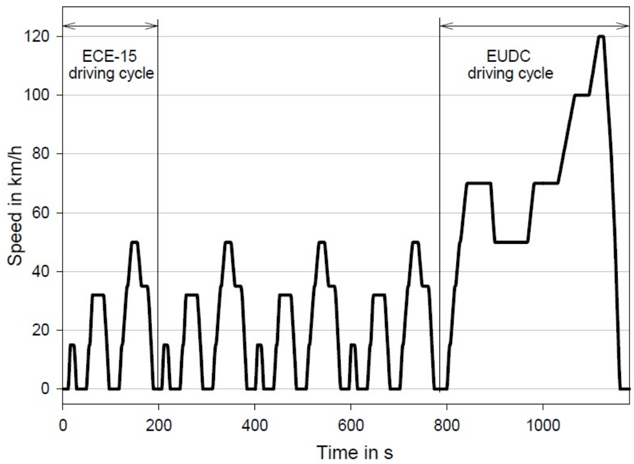

Fig. 2. Typical Indian Driving Cycles for Urban Electric Cars

B. Selection and parameters determination of Electric Motor

The factors to be considered when selecting and designing an appropritе EV motor are:

- Good efficiency map and high power density over a wide torque and speed range
- Able to withstand for frequent start/stop, high acceleration and declaration rates
- The design trade-offs between driving cycle, acceleration and gradability requirements
- Thermal constraints, overload capability, mechnical dimensions, weight and material
- The control technique should posess high steady state accuracy and good dynamic performance

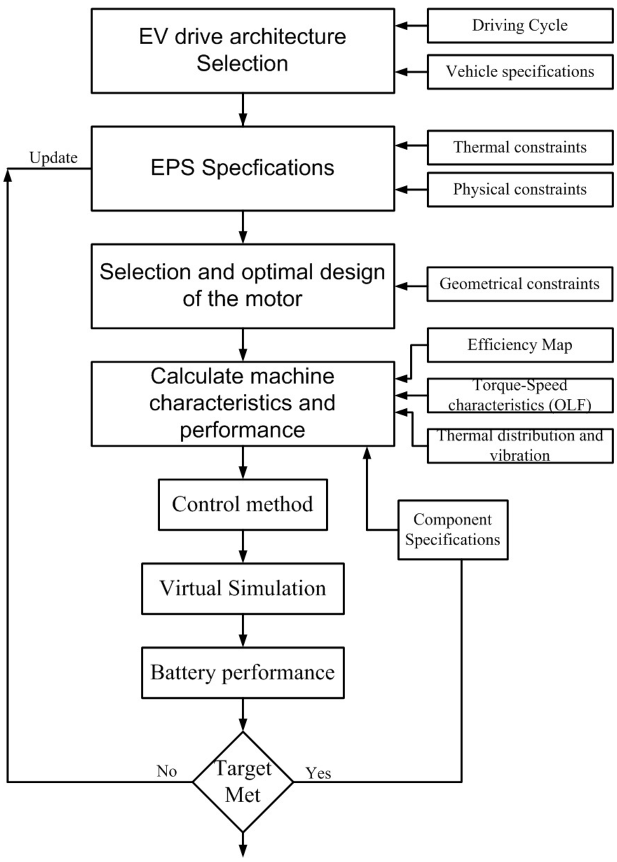

Fig. 3. Proposed design methodology of the EPS

- It should capture energy through regenerative braking
- System voltage and insulation level
- The optimum speed ratio for IM is 3 with appropriate selection of the stator winding cross-sectional area which criteria factor for transmission design [24].

The motor behaviour over a operating region and over loading factor (OLF) are the vital considerations for the design of an EPS for given driving cycle. The considerations of above characteristics allow effective battery utilization and the improve the power density of the drive. Therefore, selection of an appropriate control technique should maximize the induction motor efficiency. The design methodology of EPS system in form of flowchart is shown in Fig. 3.

III. Torque Control Techniques

Usually FOC is used to control IMs for electric vehicle propulsion [25]. FOC uses quite complicated coordinate transformations in order to decouple the interaction between torque control and flux control, thus the algorithm takes more execution time. This results in demand of a fast microprocessor with higher million instructions per second. It is also sensitive to the external disturbances, system variations and load changes.

A. DTC controller

The stator voltage vectors (switching states) are selected based on the deviations between the reference and the actual values of torque and stator flux linkage [16]. The stator flux linkage in d-q axes is estimated by:

$$\overrightarrow{\lambda_s} = \int (\overrightarrow{v_s} - R_s \overrightarrow{i_s}) dt \tag{9}$$

The magnitude of flux linkage phasor λ_s is expressed as

$$\lambda_s = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} \tag{10}$$

$$\theta = tan^{-1}(\frac{\lambda_{qs}}{\lambda_{ds}}) \tag{11}$$

The electromagnetic torque can be estimated as

$$T_{est} = \frac{3}{2} P(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{12}$$

where P = number of pole pairs, λ_{xs} and i_{xs}, $x \epsilon \{d, q\}$ are d-q axis components of flux-linkage and current repectively. The scheme is based on 2-level flux and 3-level torque hysteresis controllers, where the resultant status along with the sector determination, are used to select the optimized look-up table. Detailed description of DTC controller and the complete analysis of the induction motor using DTC scheme was explained in [17].

The main problems with basic DTC are variable switching frequency, torque and current distortion, the violence of polarity consistency rules are highly influenced by motor speed. Futhermore, high sampling rate is essential for digital implementation of hysteresis comparators [26]- [28]. The possible solutions can be either variable hysteresis bands or selection of an appropriate voltage vector at regular intervals i.e switching period is divided into more switching states in minimum torque ripple. This can be done either by duty cycle method or SVM [26], [27]. Above all constraints can be eradicated if a high-speed processor is exploited. The best way to perform the DTC algorithm at the highest sampling rate with a low-cost and fast speed processor is the use of Field Programmable Gate Array (FPGA)/ Digital Signal Processor (DSP). This can be achieved either by using variable hysteresis bands or by performing the switching at regular intervals. Later will be better due to less complexity which is basically represent the selection of an appropriate voltage vector at regular intervals. The minimum torque ripple can be achieved either by duty cycle control or SVM. For appreciably small torque ripple demands a smaller sampling time and also the voltage vectors or duty cycles need to be calculated for every sampling period. This results in neccessity of fast processor for fixed switching frequency methods.

B. DTC-SVM controller

In order to reduce the torque and flux ripple a switching strategy utilizing SVM with symmetrical switching is used because of its coherence and accurate location of the voltage space vector at every instant of time explicitly. The manner in which stator voltage is generated defines these techniques.

SVM has advantages of lower torque ripple, better DC bus utilization, lower current THD, lower switching losses and easy implementation in DSP/FPGA [26], [27]. The time intervals can be calculated based on volt-sec concept can be expressed as

$$T_1 = T_z a \frac{sin(\frac{\Pi}{3} - \theta)}{sin\frac{\Pi}{3}} \tag{13}$$

$$T_2 = T_z a \frac{sin(\theta)}{sin\frac{\Pi}{3}} \tag{14}$$

$$T_0 = T_z - (T_1 + T_2) \tag{15}$$

where as T_z is the sampling time, T_1, T_2, T_0 are time intervals for which V_1, V_2 and V_7 or V_8 is applied and V_{sx} represents $x \ \epsilon \ \{d, q\}$ are d-q axis components of voltage repectively. The magnitude $|V_s|$ and phase angle θ are given as

$$|V_s| = \sqrt{V_{sd}^2 + V_{sq}^2} \tag{16}$$

$$\theta = tan^{-1}(\frac{V_{sq}}{V_{sd}}) \tag{17}$$

DTC-SVM can overcome defects such as torque ripple, current harmonics and electromagnetic noise with retaining the eminence of FOC technique. The stator voltages and currents for DTC as well as DTC-SVM is shown in Fig. 4. The comparsion of torque control techniques are shown in Table II.

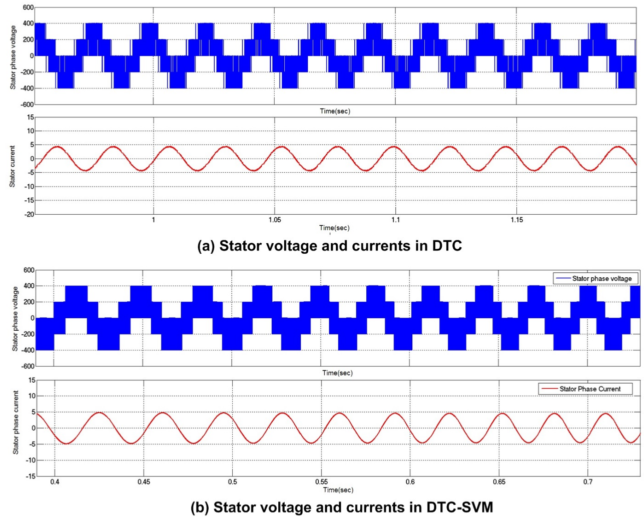

Fig. 4. Stator voltages and currents (a) DTC (b) DTC-SVM

TABLE II
COMPARISON OF FOC, DTC AND DTC-SVM

Parameter	FOC	DTC	DTC-SVM
Co-ordinate transformation	Yes	No	No
Current loop	Multi	No	No
Type of controller	PI	Hysteresis	PI
Parameter sensitivity	High	Low	Low
Torque ripple	Low	High	Low
Switching frequency	Constant	Variable	Constant
Inverter output voltage	Unipolar	Bipolar	Unipolar
Efficiency	Low	Low	High
PWM modulator	Yes	No	Yes
Sampling frequency	Low	High	Low
Computation time	High	Low	Medium
Torque and flux estimation	Better	Good	Improved
Regulators	Three	Two	Two

IV. SENSOR-LESS OPERATION: MODEL REFERENCE ADAPTIVE SYSTEM (MRAS)

Irrespective of the control strategies, the motor speed can be measured using tachometer or optical encoder. As per the vehicles functional safety standards (ISO26262), EPS should be fault-tolerant in case of the speed/position failure. This demands the passengers should reach their destinations safely even in case of failure or faults, which is known as limp-home mode. The concept of limp-home mode is smooth transistion from sensored to sensorless control. This demands a robust and accurate speed estimators with enhanced availability and reliability [29]. The speed estimation techniques can be broadly classified as high frequency signal injection and machine model based. MRAS based schemes offer simpler implementation, good high performance ability and straightforward stability approach and thus considered as most attractive technique among all sensor-less control strategies [19]-[21]. The rotor flux MRAS observer composed of a reference model (voltage model), an adaptive model (current model) and an adaptation mechanism which generates the estimated speed is shown in Fig. 5. The reference model represents describes the stator equation is given as

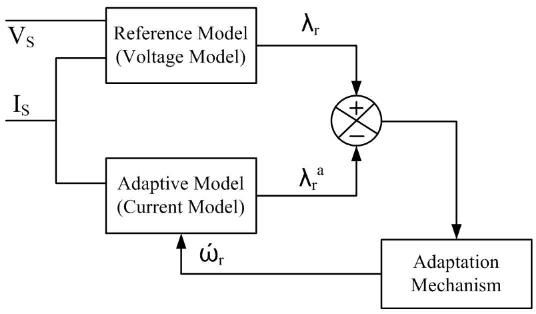

Fig. 5. Rotor-flux-MRAS speed observer

$$\bar{\lambda_r} = \frac{L_m}{L_r}\bar{\lambda_s} - L_s\bar{I_s} \tag{18}$$

The adaptive model describes the rotor equation is given as

$$\bar{\lambda_r}^a = \frac{1}{T_r}\left[\int(L_m\bar{I_s} - \bar{\lambda_r}^a + j\omega\bar{\lambda_r}^a)dt\right] \tag{19}$$

T_r = rotor time constant, L_m = mutual inductance λ_{rx} and $\bar{\lambda_{rx}}^a$, L_r = rotor inductance, $x \ \epsilon \ \{d, q\}$ are d-q axis components of reference and adaptive model flux repectively.

To minimize error (ε), the adaptation mechanism can be implemented by a PI controller (K_p and K_i) based on Popov's hyper-stability criteria as follows:

$$\varepsilon = \lambda_{rq}\lambda_{rd}^{a} - \lambda_{rd}\lambda_{rq}^{a} \quad (20)$$

$$\acute{\omega_{rest}} = (K_p + K_i\frac{1}{s})\varepsilon \quad (21)$$

In case of sensor fault, system adapts rotor flux-based MRAS

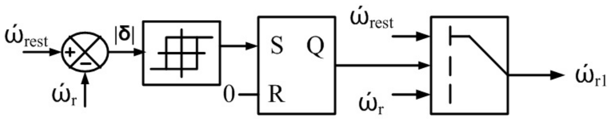

Fig. 6. Fault-tolerant sensorless controller in limp-home mode

sensorless control. The speed sensor fault detection can be performed by satisfying condition (22) and fault tolerant control block is shown in Fig. 6.

$$|\acute{\omega_r} - \acute{\omega_{rest}}| = |\delta| \geq \theta_{th} \quad (22)$$

If the condition in (22) satsisfies then it is recognised as a speed sensor fault. An adaptive threshold value θ_{th} is around 2-3% of the rated speed. This algorithm guarntees the stable operation of the drive in limp-home mode and the speed is estimated using adaptive model [30].

V. Simulation Results

To evaluate the performance of induction motor using DTC and DTC-SVM, simulation studies have been carried out in Matlab/Simuink. The motor parameters used for the simulation are given in [17]. Fig. 7 compares the stator flux vector trajectory in a d-q plane in both schemes. Fig. 8 and 9 shows

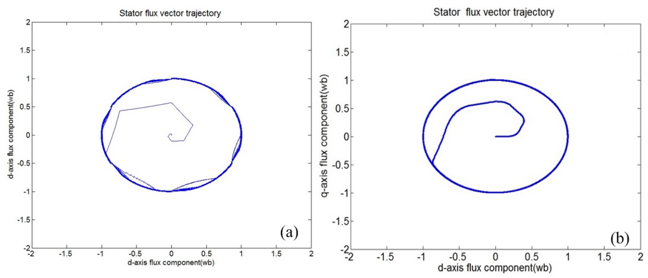

Fig. 7. Stator flux vector trajectory in d-q plane (a) DTC (b) DTC-SVM

the dynamic response of induction motor with vehicle load using DTC and DTC-SVM respectively. The torque is able to follow the vehicle load torque very efficiently. We can monitor that torque response is very rapid notably during the startup stage and the stator flux is controlled very effectively. During decelertion mode at t = 2 s i.e IM moves from 600 rpm to zero speed, a negative torque is developed due to generator action which can power supply back to batteries. The IM currents are closer to sinusoidal and are maximum during during acceleration and deceleration. DTC-SVM technique offers less torque ripple, quick response and flexible in control as evident from the results. Fig. 10 shows the estimated speed using MRAS controller in case of speed sensor fault.

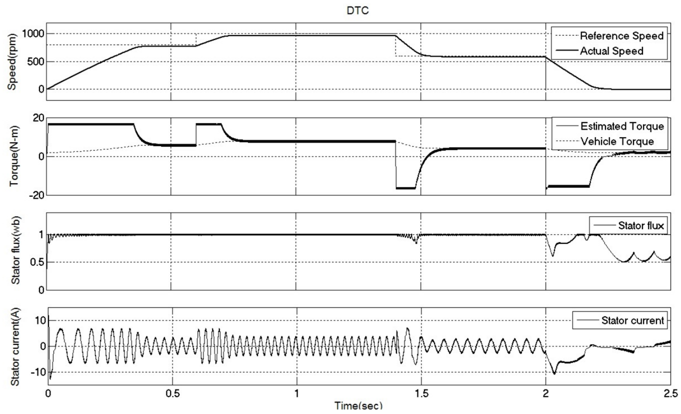

Fig. 8. Dynamic response of inductor motor using DTC scheme on application of vehicle load

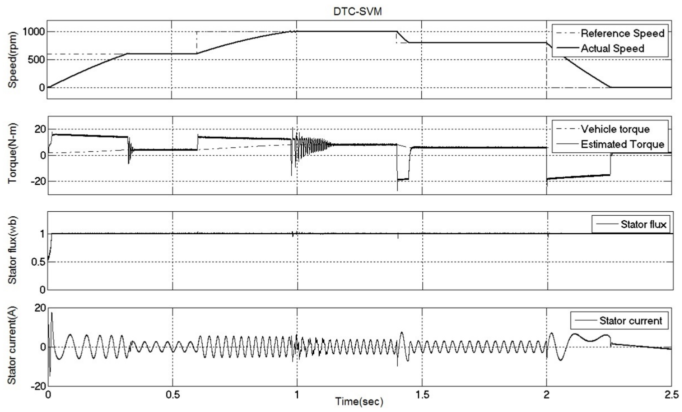

Fig. 9. Dynamic response of inductor motor using DTC-SVM scheme on application of vehicle load

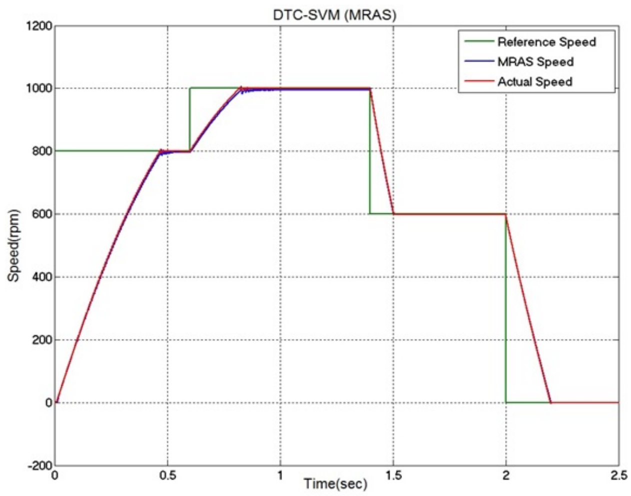

Fig. 10. Estimation of rotor speed using rotor flux-based MRAS

VI. Conclusions

In this paper, the design methodology and technical considerations of electric propulsion system including motor selection are discussed. The fault detection algorithm with smooth transition to sensorless control in case of speed-sensor fault was proposed. The rotor flux-based MRAS sensor less control and adds to the robustness and the reliability for EV as it eliminates the extra speed encoder and in turn reduces the maintenance requirements of the system. The simulation with sensor-less DTC and DTC-SVM is carried out with vehicle load considering the acceleration mode, constant speed and deceleration mode. The results of MRAS based DTC-SVM controlled IM promises for EV propulsion because of following advantages

- Simple, robustness, quick response and ripple free operation
- Capable of operating in both directions which offer optimal energy management
- Excellent performance in motoring and regenerative braking with the recovery of some energy back to the source
- More running distance per battery charge
- Sensor-less operation offers reduce hardware, less size, low cost and enhances reliability, maintenance-free as well as improved noise invulnerability.

Finally, this system improve the overall performance and relaibility which will be a viable solution for EVs.

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