Compensating the Thermally Derated Torque for Six-Phase Induction Machine Based Electric Drive System Using Linear Parameter Varying Control

Athar Hanif
Center for Automotive Research
The Ohio State University
Columbus, OH, USA
hanif.6@osu.edu

Qadeer Ahmed
Center for Automotive Research
The Ohio State University
Columbus, OH, USA
ahmed.358@osu.edu

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***Abstract*—Multiphase induction machine posses the several advantages compared to three-phase induction machine when used in the Electric Drive System (EDS) of Electric Vehicles (EV). The performance of an EDS in extreme working conditions is extremely compromised. An electric drive suffers from torque derating as its parameters change due to the rise in operating and ambient temperatures. The performance of commonly used Field-oriented Control (FOC) in the EDS of EV is deteriorated under the vast variations in the rotor and stator resistances due to the change in the operating conditions. In this work, a robust Linear Parameters Varying (LPV) based FOC technique is proposed to estimate the thermally derated torque and flux to improve the performance of EDS when it operated in harsh environment. The performance of the proposed control technique is verified and investigated for the electric drive of a passenger bus (class-4) used in urban transportation. The Federal Urban Driving Schedule (FUDS) is adopted for the simulation experiment and validation of the proposed approach. The nonlinear simulation results show the capability of the proposed technique to accurately estimate and track the derated torque and flux demands in a six-phase Induction Machine (IM) based EDS.**

Index Terms*—Multiphase induction machine, LPV control, Electric drive system

I. Introduction

In order to meet the energy demands and reduce the emissions to the environment, the automobile industry has decided to escalate the new technologies such as electric ship propulsion, electric aircraft, hybrid and electric on road and off road vehicles. In energy efficient propulsion and traction applications, the Electric Machine (EM) is an integral part of the EDS. Hence, an EM has significant impact on the performance of the EDS for modern ground and aerial vehicles. In order to improve the performance of the EDS, major efforts are in the direction of design and realization of closed loop controllers [1] and reasonable design of an EM [2]. Conventional, three-phase EM based solutions for the electrification of the above-mentioned applications, are not necessarily the optimum choices. Indeed, multiphase electric machines offer several potential benefits over three-phase equivalent. The two most important advanatges are: (i) due to the the split of the power over more phases, power rating requirements of the power semiconductor devices on the converter can be reduced and (ii) regardless of the number of the phases, two independent controllable currents are required for flux and torque control [3]. Among the existing electric machines, Induction Machine (IM) offers the several advantages over the other types of electric machines [4] . Multiphase induction machines has the advantages of low pulsating torque due to the use of multi step inverter, better reliability, ability to operate in case of open phase fault and smaller rated current per phase as compare to $3-\phi$ induction machine with similar nominal power [5], [6].

In traction applications, the main objective for the efficient operation of EDS is to achieve precise and accurate tracking to meet the road load demands. An existing, conventional Field-oriented Control (FOC) technique is used for torque and flux control of induction machine. The performance of the conventional FOC deteriorates due to the parameter variations during the operation. The IM parameters, rotor and stator resistances, vary due to operating conditions such as traffic situations, driving cycles and operating temperatures. Hence, flux and torque of an EDS derates. Therefore, to obtain the improved performance of EDS for above-mentioned systems, effective implementation of FOC for an EDS requires accurate and precise knowledge and control of thermally derated torque and flux.

A conventional indirect field-oriented control (IFOC) scheme has been presented in [7] for the operation and control of multiphase induction machine. The drawbacks of a conventional indirect field-oriented control (IFOC) are discussed in [8] and the authors has proposed model reference adaptive system (MRAS) to estimate the rotor resistance and rotor time constant for accurate realization of sensorless control for six-phase induction machine. In [6], a control system for multiphase induction machine with the utilization of backstepping technique has been proposed to improve the performance of the induction machine drive in the presence of uncertainties in plant model. Sliding mode and fuzzy logic based controls for six-phase induction machine have been presented in [9]. Sliding-Mode Control(SMC) is robust against

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the uncertainties in the model parameters but it suffers from the chattering problem. Hence, it is difficult to ensure the accurate and precise performance of the EDS. To overcome the problem of chattering, LPV control techique has been discussed and presented in [1], [4], [10] but it is for three-phase induction machine. The main objective of an LPV control (gain scheduling) technique is to control the plant over a predefined operating range. However, it allows the controller to schedule itself based on some measurements in addition to robustness.

From above discussion, it is clear that a observer-controller scheme is needed to address the problem of thermally derated torque in EDS for the efficient and accurate operation of electrified vehicles. Main contributions of this work are:

- Design of a robust observer-controller pair based on LPV gain scheduling technique for the estimation and control of thermal flux and torque derating in EDS.
- Calculate the optimal flux command for the EDS using the knowledge of different losses in the EM to minimize the energy consumption.
- The proposed scheme is evaluated for six-phase induction machine based electrified powertrain under standard driving cycle.

The rest of the paper is organized as: Section II describes the architecture of the six-phase IM drive and modeling of IM. Variations in the operating temperature of high power IM are presented in Section III. Estimation of the thermally derated torque and flux is presented in Section IV. Section V gives the design details of robust LPV based IFOC scheme. The proposed control scheme is validated in Section VI. Concluding comments are presented in last section.

II. MATHEMATICAL MODELING OF ELECTRIC POWERTRAIN

A. ARCHITECTURE OF SIX-PHASE IM DRIVE

Fig. 1 describes the architecture of six-phase traction IM which is fed by the six-phase open-end Voltage Source Inverter (VSI). The asymmetric architecture of six-phase traction IM is achieved by having the spatial displacement of $30^o e$ between the two sets of $3-\phi$ winding. This also gives the two isolated neutral points which ensure optimized utilization of V_{dc} link and eliminate zero sequence currents.

The Clark transformation matrix (Eq. 1) is adopted to construct the decoupled orthogonal subspaces ($\alpha-\beta$, $\mu_1-\mu_2$, and z_1-z_2) from the normal six-phase system ($a-b-c, x-y-z$).

$$T_6 = \frac{1}{3}\begin{bmatrix} 1 & \cos(\phi) & \cos(4\phi) & \cos(5\phi) & \cos(8\phi) & \cos(9\phi) \\ 0 & \sin(\phi) & \sin(4\phi) & \sin(5\phi) & \sin(8\phi) & \sin(9\phi) \\ 1 & \cos(5\phi) & \cos(8\phi) & \cos(\phi) & \cos(4\phi) & \cos(9\phi) \\ 0 & \sin(5\phi) & \sin(8\phi) & \sin(\phi) & \sin(4\phi) & \sin(9\phi) \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \tag{1}$$

Eq. 2 is utilized to convert the electrical quantities from $\alpha-\beta$ axes to $d-q$ axes for the realization of proposed control technique.

$$\begin{bmatrix} f_{\alpha s} \\ f_{\beta s} \end{bmatrix} = \begin{bmatrix} -\sin\theta_e & \cos\theta_e \\ \cos\theta_e & \sin\theta_e \end{bmatrix} \begin{bmatrix} f_{qs} \\ f_{ds} \end{bmatrix} \tag{2}$$

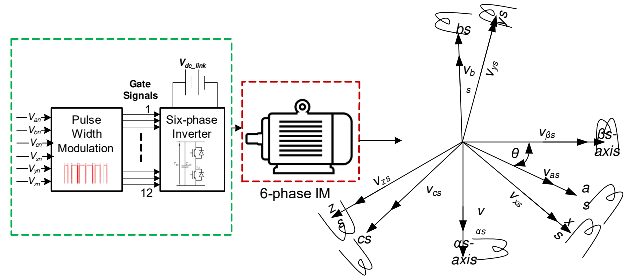

Fig. 1. Architecture of voltage source inverter (VSI) fed six-phase traction induction machine.

Where, $f_{(.)}$ represent the voltage, current and flux.

B. MODELING OF VEHICLE

The vehicle speed (v_w) is proportional to the machine speed (ω_m). It can be defined in term of ratio of gear box (g_i), transmission gain (g_d) and radius of tire (R_t) and given as [11]:

$$v_w = \frac{R_t}{g_d g_i}\omega_m \tag{3}$$

The load torque (T_L) of an EV can be written as:

$$T_L = (F_R + F_d + F_g + F_a)\, R_t \tag{4}$$

where, F_R is rolling resistance force, F_d is the drag force, F_g is grad resistance force and F_a is acceleration resistance force.

C. MODELING OF SIX-PHASE INDUCTION MACHINE

The mathematics of a six-phase IM in stationary reference frame can be expressed as follows, [8]:

The voltage equations for $\alpha-\beta$ reference frame are:

$$\begin{cases} \dot{\psi}_{\alpha s} = v_{\alpha s} - R_s i_{\alpha s} \\ \dot{\psi}_{\beta s} = v_{\beta s} - R_s i_{\beta s} \\ 0 = R_r i_{\alpha r} + \dot{\psi}_{\alpha r} + \omega_r \psi_{\beta r} \\ 0 = R_r i_{\beta r} + \dot{\psi}_{\beta r} - \omega_r \psi_{\alpha r} \end{cases} \tag{5}$$

The voltage equations for $\mu 1 - \mu 2$ reference frame are:

$$\begin{cases} L_{ls}\dot{i}_{\mu 1s} = v_{\mu 1s} - R_s i_{\mu 1s} \\ L_{ls}\dot{i}_{\mu 2s} = v_{\mu 2s} - R_s i_{\mu 2s} \end{cases} \tag{6}$$

The flux linkages equations are:

$$\begin{cases} \psi_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha r} \\ \psi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r} \\ \psi_{\alpha r} = L_m i_{\alpha s} + L_r i_{\alpha r} \\ \psi_{\beta r} = L_m i_{\beta s} + L_r i_{\beta r} \end{cases} \tag{7}$$

The electromagnetic torque equation is:

$$\begin{cases} T_e = (\frac{3}{2})P(\psi_{\alpha s} i_{\beta s} - \psi_{\beta s} i_{\alpha s}) \\ \psi = \sqrt{\psi_{\alpha s}^2 + \psi_{\beta s}^2} \end{cases} \tag{8}$$

and the speed dynamics

$$\dot{\omega_m} = (\frac{P}{2J})(T_e - T_L - b\omega_m) \tag{9}$$

where

$i_{\alpha s}$, $i_{\beta s}$, $v_{\alpha s}$, $v_{\beta s}$ and $\psi_{\alpha s}$, $\psi_{\beta s}$ are the α-axis and β-axis stator currents, voltages and fluxes respectively. ω_m is the electrical rotor speed. L_s, L_r and L_m are the stator, rotor and mutual inductance respectively. R_s and R_r are the stator and rotor resistances, T_e is the electromagnetic generated torque, T_L is the load torque, P is the number of pole, J is the rotor inertia, b is the viscous friction coefficient, respectively.

D. LPV MODELING OF SIX-PHASE INDUCTION MACHINE

Since the flux and torque producing component in a six-phase induction machine are only the $\alpha - \beta$ components ($d - q$ components in case of rotating reference frame). The description of the rotor flux and electromagnetic generated torque of an IM presented in Eqs. (5) and (8) are same as for $3 - \phi$ IM. Hence, the FOC scheme for any number of phases on IM is similar to the conventional $3 - \psi$ IM. The only difference is the coordinate transformation calculation.

The LPV model of IM, needed to design the observer and controller to compensate the thermally derated of an EDS, has been presented in [1], [4] and described below.

$$\begin{cases} \dot{x} = (\underbrace{A_c + A_\nu \nu_1 + A_\nu \nu_2 + A_\nu \nu_3}_{A(\rho)})x + B_c u \\ y = C_c x \end{cases} \tag{10}$$

where A_c, B_c, C_c are the actual state-space matrices and $A_\nu \nu_1$, $A_\nu \nu_2$, $A_\nu \nu_3$ are the varying parameter depended matrices. The definition of these matrices are given as

$$A(\rho) = \begin{bmatrix} A_{11}(\rho) & 0 & A_{13}(\rho) & A_{14}(\rho) \\ 0 & A_{22}(\rho) & A_{23}(\rho) & A_{24}(\rho) \\ A_{31}(\rho) & 0 & A_{33}(\rho) & A_{34}(\rho) \\ 0 & A_{42}(\rho) & A_{43}(\rho) & A_{44}(\rho) \end{bmatrix} \tag{11}$$

where

$A_{11}(\rho) = A_{22}(\rho) = -\frac{L_m^2 \rho_1 + L_r^2 \rho_2}{\sigma L_s L_r^2}$, $A_{13}(\rho) = \frac{L_m \rho_1}{\sigma L_s L_r^2}$,
$A_{14}(\rho) = \frac{P L_m \rho_3}{2\sigma L_s L_r^2}$ $A_{23}(\rho) = -\frac{P L_m \rho_3}{2\sigma L_s L_r^2}$ $A_{31}(\rho) = \frac{L_m \rho_1}{L_r}$,
$A_{24}(\rho) = \frac{L_m \rho_1}{\sigma L_s L_r^2}$, $A_{42}(\rho) = \frac{L_m \rho_1}{L_r}$, $A_{33}(\rho) = -\frac{\rho_1}{L_r}$
$A_{34}(\rho) = -\frac{P}{2}\rho_3$, $A_{43}(\rho) = \frac{P}{2}\rho_3$, $A_{44}(\rho) = -\frac{\rho_1}{L_r}$
$\sigma = 1 - \frac{L_m^2}{L_r L_s}$

$$B_c = \frac{1}{\sigma L_s}\begin{bmatrix} I & O \end{bmatrix}^T, C_c = \begin{bmatrix} I & O \end{bmatrix} \tag{12}$$

The state, time varying signal, input and output vectors of the achieved LPV model are

$$\begin{cases} x(t) = \begin{bmatrix} i_{\alpha s} & i_{\beta s} & \psi_{\alpha s} & \psi_{\beta s} \end{bmatrix}^T, y(t) = \begin{bmatrix} i_{\alpha s} & i_{\beta s} \end{bmatrix}^T \\ u(t) = \begin{bmatrix} v_{\alpha s} & v_{\beta s} \end{bmatrix}^T, \rho(t) = \begin{bmatrix} R_r & R_s & \omega_m \end{bmatrix}^T \end{cases} \tag{13}$$

This LPV model is validated on experimental setup in closed-loop against the actual model and described in [4].

III. TEMPERATURE PROFILE OF HIGH POWER ELECTRIC MACHINE

Fig.2 shows the change in operating temperature of a high power traction electric machine deployed in EDS of an EV. This change can be more for different road loads, traffic conditions, driving schedule, ambient temperature and loading.This change in the operating temperature affects the model parameters. In this work, only the rotor and stator resistance variation are considered. Due to these variations in model parameters, the torque and flux of an EDS is degraded. Hence, the performance of the conventional IFOC scheme is deteriorated. This work proposes the LPV based IFOC scheme to cater for the above mentioned issues in the EDS. Following sections outline the proposed scheme.

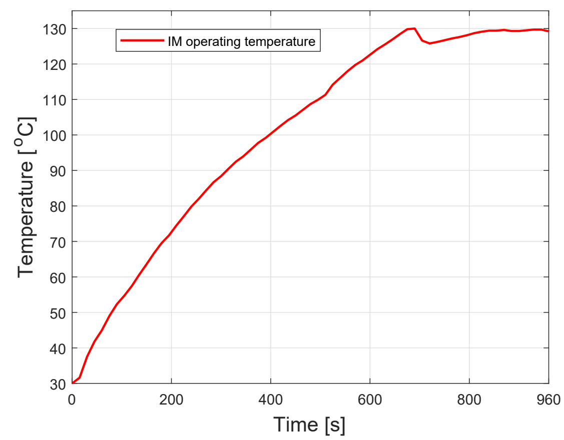

Fig. 2. Operating temperature profile of high power IM.

IV. ESTIMATION OF THERMALLY DERATED TORQUE AND FLUX

For the efficient operation of six-phase traction IM drive, the estimation of the thermally derated torque and flux is most crucial component in the EDS. A LPV control technique based estimation of thermally derated torque and flux is proposed and validated in [4], [10] for three-phase traction IM drive. Hence, in this article, LPV based torque and flux estimator is adopted. For this purpose, induction machine model (Eqs. (5)-(9)) is changed into an LPV model as presented in (Eqs. (10)-(13)) taking R_r, R_s and ω_m as time varying parameters.

The construction, stability analysis and error dynamics of the LPV estimator are presented in the author's previous work [10].

$$\begin{cases} \begin{bmatrix} \dot{\hat{i}}_s \\ \dot{\hat{\psi}} \end{bmatrix} = A(\rho)\begin{bmatrix} \hat{i}_s \\ \hat{\psi} \end{bmatrix} + B_c v_s + L(\rho)(i_s - \hat{i}_s) \\ i_s = C_c \begin{bmatrix} i_s \\ \psi \end{bmatrix}, \hat{i}_s = C_c \begin{bmatrix} \hat{i}_s \\ \hat{\psi} \end{bmatrix} \end{cases} \tag{14}$$

Where, $L(\rho)$ is the LPV oberver's gain.

The gain of the robust LPV estimator is obtained by solving Linear Matrix Inequalities (LMIs) formulated as follows:

$$\begin{cases} A_i^T P - C_i^T Q_i^T + P A_i - Q_i C_i \prec 0, i = 1, ..., 2^\rho \\ P = P^T \succ 0 \end{cases} \tag{15}$$

Where, A_i is the system matrix at each vertex.

The solution of the LMIs (Eq. (15)) is used to find the gain at each polytope (Eq. (16)).

$$L_i = P^{-1}Q_i \tag{16}$$

The gain of the LPV estimator for the six-phase IM is computed as:

$$\begin{cases} L = \sum_{i=1}^{i=2^{\rho}} a_i L_i \\ \sum_{i=1}^{i=2^{\rho}} a_i = 1 \end{cases} \tag{17}$$

where, $a_i(t) \geq 0$,

The estimation of observed torque is done as

$$\hat{T}_e = (\frac{3}{2})P(\hat{\psi}_{\alpha s} i_{\beta s} - \hat{\psi}_{\beta s} i_{\alpha s}) \tag{18}$$

V. LPV based Field-oriented Control Design for Six-phase IM

Fig. 3 presents the details of the proposed control strategy of a six-phase IM based EDS employed in the HEVs and EVs. The proposed framework is developed based on the concept of FOC. An LPV based control strategy is developed to control and track the synchronously reference frame $(d-q)$ currents in the inner loop based on the reference currents generated by the flux and speed controllers existing in the outer loop. In this strategy, the thermally derated torque and flux is estimated by the LPV technique which is discussed in Section IV. The optimal flux command is generated by considering the IM losses and estimated torque. This will help to minimize the energy consumption and hence increase the EDS's efficiency and performance. The gains for the speed and flux regulators are obtained by formulating an LMI based on the theory of input-output feedback linearization.

A. Design of Inner Loop LPV current controller

A practically valid, robust LPV current control ($d-q$ currents) technique is synthesized for the LPV model of six-phase IM (presented in Section II). Actuator constraints, disturbance rejection and reference tracking are the design specifications. In LPV control theory, these design specifications can be obtained by the definition of control sensitivity function (to ensure the efficient operation of EDS), complementary sensitivity function and sensitivity function (to achieve the road loads demands).

The reference $d-q$ currents are obtained by differentiating the Eqs. (7) and (8) and it yields the following equation after simplification:

$$\begin{bmatrix} i_{ds}^* \\ i_{qs}^* \end{bmatrix} = \frac{1}{|E|\psi^2}[E]^{-1}[F] \tag{19}$$

where

$$E = \begin{bmatrix} \frac{L_m R_r}{L_R}\psi_{dr} & \frac{L_m R_r}{L_r}\psi_{qr} \\ -n_p \frac{L_m}{L_r J}\psi_{qr} & n_p \frac{L_m}{L_r J}\psi_{dr} \end{bmatrix}, F = \begin{bmatrix} \psi(v_2 + \frac{R_r}{L_r}\psi) \\ v_1 + \frac{b}{J}\omega_m + \frac{1}{J}T_L \end{bmatrix}$$

In LPV control, the gains of the weighting filters are tuned until (i) stability of the plant, (ii) disturbance and noise rejection with fast tracking, and (iii) constraints on the control actuator, are achieved. The objective is to compute the output feedback LPV control which maximizes the performance of EDS in the presence of vast variations in operating temperature. The dynamic LPV controller can be represented as

$$\begin{cases} \dot{x}_K = A_K(\rho)x_K + B_K(\rho)y \\ u = C_K(\rho)x_K + D_K(\rho)y \end{cases} \tag{20}$$

which ensures the L_2 gain bound and internal stability of the closed-loop system. The design methodology and steps for the LPV current controller's computation are outlined in [4].

B. Design of Outer Loop flux and speed regulators

The outer loop flux and speed regulators are designed for the proposed LPV based FOC strategy using the concept of Robust Input-Output Linearization (RIOL). The model parameters uncertainties are taken into account in the process of computing the robust gains for the outer loop regulators. The closed-loop error dynamics for the model described in Section II are constructed using the stator currents (i_{ds}, i_{qs}), the rotor flux and the speed (ψ, ω_m) are considered as input and output vectors respectively. The definition of bounded real lemma [12] is deployed to achieve the LMI from the developed error dynamics as given in Eq. (21).

$$\begin{bmatrix} H^T + H & PB_e & I_2 \\ B_e^T P & -\gamma I_2 & 0 \\ I_2 & 0 & -\gamma I_2 \end{bmatrix} \prec 0 \tag{21}$$

where, $P = P^T \succ 0$ and $\gamma \succ 0$.

The solution of Eq. (21) gives the H and P. From these, the gains of the speed and flux regulators can be obtained as:

$$G_e = P^{-1}H \tag{22}$$

Where, G_e is the diagonal gain matrix.

C. Optimal Flux Calculation

The six-phase IM for an EDS operates at different speed and torque over the entire driving cycle. In order to minimize the energy consumption during the operation, it is not a good practice to operate the EDS at rated flux. Hence, electric machine's losses are considered to compute the optimal flux command to obtain the high efficiency of EDS. The three main losses in IM can be described as:

The stator losses:

$$P_s = \frac{3}{2}R_s(i_{ds}^2 + i_{qs}^2) \tag{23}$$

The rotor losses:

$$P_r = \frac{3}{2}R_r(\frac{L_m}{L_r})^2 i_{qs}^2 \tag{24}$$

The stator iron losses:

$$P_i = \frac{1}{R_c\omega_c^2}(L_m^2 i_{ds}^2 + (L_m^2 - \frac{L_m L_r}{L_s})^2 i_{qs}^2) \tag{25}$$

The total steady state losses are given as:

$$P_{loss} = P_s + P_r + P_i \tag{26}$$

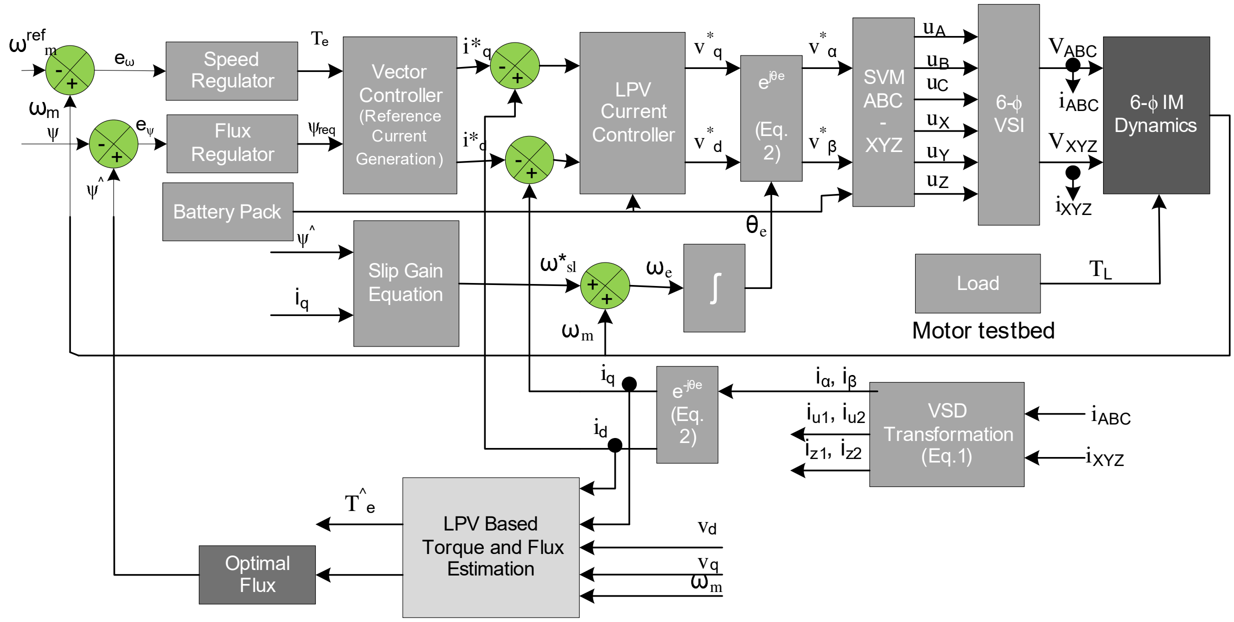

Fig. 3. Detailed diagram of the induction machine feedback control system.

TABLE I
SPECIFICATIONS OF PASSENGER BUS (CLASS-4) VEHICLE

Parameter	Value	Parameter	Value
m	1419 Kg	R_t	0.205 m
a_f	2.1 m^2	c_r	0.0.013
c_d	0.42	g_d	8.32

TABLE II
PARAMETERS OF SIX-PHASE INDUCTION MACHINE

Parameter	Value	Parameter	Value
P	4	R_s	11.6Ω
R_r	10.4Ω	L_s	0.597H
L_r	0.597H	L_m	0.557H
J	0.004Kg.m^2	b	0.0028N.m.s.rad^{-1}

Putting the steady state values of the i_{ds}, i_{qs} and ω_e and minimizing the Eq. (26), optimal flux trajectory can be computed as:

$$\begin{cases} \psi_{ref} = \psi_{opt}\sqrt{|T_{e_{ref}}|} \\ \psi = k\left(\frac{\left(R_s+\omega_e^2 L_m^2\right)}{\left(R_s+\left(\frac{R_r L_m^2}{L_r^2}\right)+\left(\frac{\left(\omega_e^2 (L_m^2 - L_s L_r^2)^2\right)}{(R_c L_r^2)}\right)\right)}\right)^{1/2} \end{cases} \tag{27}$$

where $k = \frac{4}{3}\frac{L_m}{P}$

VI. SIMULATION EXPERIMENTS

In order to validate the efficacy and performance of the proposed LPV based IFOC scheme, simulation experiments are performed on the high fidelity EV simulator developed in MATLAB/SIMULINK as commonly exercised by automotive community to evaluate their control frameworks. Tables I and II present the parameters values for the passenger bus (class-4) vehicle and six-phase IM which are adopted in this study. The evaluation is performed under the variation of different operating conditions such as variations in operating and ambient temperatures, change in stator and rotor resistances and change in the load.

Federal Urban Driving Schedule (FUDS) is adopted to show the efficacy of the proposed control scheme. To obtain the best possible performance, the observer-controller pair is designed as outlined in Sections IV and V.

Fig. 4 depicts the tracking performance of vehicle speed. It is vivid that the proposed LPV based IFOC scheme shows the better performance in the presence of vast variations in operating and ambient temperature (in result, variations in rotor and stator resistances of IM). The performance of conventional IFOC is also presented under the same operating conditions in Fig. 4. It is signified from the Fig. 4 that LPV based IFOC scheme achieved the better tracking performance of vehicle speed as compared to conventional IFOC. The performance of conventional IFOC at higher operating temperature (higher change in rotor and stator resistance) is degraded more as compare to proposed scheme. In this context, the tracking performance for the demanded torque and flux can be determined and analyzed further.

Fig. 5 shows the torque tracking of both control schemes for the comparison over the entire driving cycle. The LPV based IFOC sheme is showing the better torque tracking performance in the presence of variations in model parameters. In result, the proposed control scheme encompasses the rapid changes (due

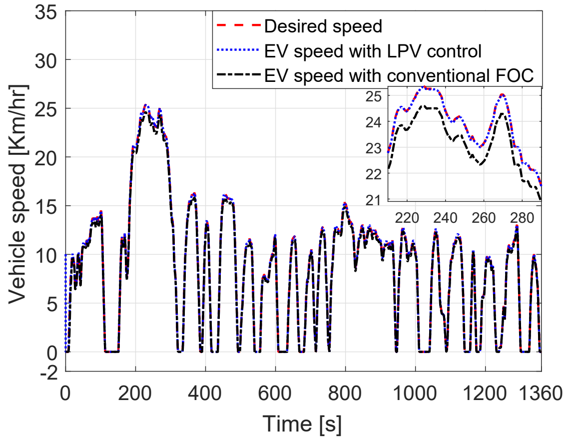

Fig. 4. Vehicle speed tracking: Performance comparison of conventional IFOC and proposed LPV based IFOC schemes.

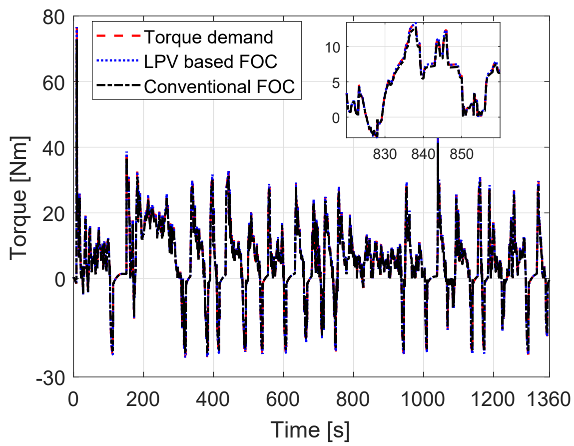

Fig. 5. Vehicle torque tracking: Performance comparison of conventional IFOC and proposed LPV based IFOC schemes

to traffic conditions for a particular route) in the demanded torque well as compared to convention control scheme. Hence, smooth operation of the vehicle is guaranteed.

In order to achieve the higher efficiency of the EDS, IM is required to follow the commanded flux over the entire operation. Fig. 6 presents the flux tracking of the six-phase IM for the conventional IFOC and proposed LPV based IFOC schemes.

The Root Mean Square Error (RMSE) value in EV speed, IM flux and torque is used as a performance metric.. Table III presents the RMSE tracking errors. Hence, it can be seen that the proposed control scheme outperforms the conventional control scheme.

VII. Conclusion

An innovative robust LPV based IFOC technique has been synthesized in this work to achieve the optimal performance of multiphase induction machine's electric drive system. Its efficacy is tested for an EV's powertrain operated in FUDS driving

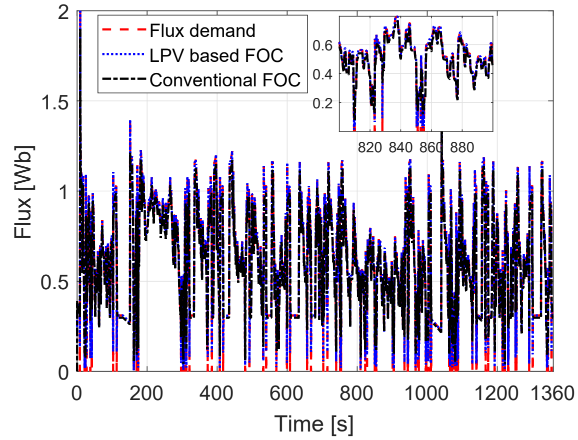

Fig. 6. Six-phase IM flux tracking: Performance comparison of conventional IFOC and proposed LPV based IFOC schemes.

TABLE III
Root Mean Square Error (RMSE) performance index for the comparison of both control techniques for the variations in operating conditions.

EV Speed		IM Torque		IM Flux	
Conv.-FOC	LPV-FOC	Conv.-FOC	LPV-FOC	Conv.-FOC	LPV-FOC
0.236	0.114	0.461	0.183	0.148	0.021

cycle with a dynamic temperature profile. The comparison of the proposed technique is carried out with conventional IFOC. This can be concluded that the proposed LPV based IFOC scheme is more robust to change in operating and ambient temperatures and in turns to R_s and R_r variations as well.

The future work includes: (i) measure the efficacy of the proposed observer controller pair on Hardware-in-Loop (HIL) test setup, and (ii) quantify the the effect of proposed control scheme with respect to efficiency and aging of the EDS.

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