Traction System with MRAS Sensorless Vector Control and PSM Technique

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***Abstract*—With the advancement of control philosophies, induction motor emerged as traction motor precluding the DC series motor known for a long time for such an application. Due to stringent harmonic requirements of traction systems, the focus is to reduce the harmonics within a multi converter active front ends. For reliability and maintenance concerns, Sensor less speed control has become popular. The purpose of this article is to study the phase shifted modulation (PSM) technique for reduction of harmonics in multi converter front ends with unity power factor. Sensorless Speed estimation technique using MRAS along with the indirect vector control of traction motor is implemented. Reactive power based MRAS scheme is used for developing speed estimator which can eliminate the physical speed sensor. Performance of the overall system is observed.**

***Index Terms*—active front end rectifier (AFEC), phase shifted modulation (PSM), model reference adaptive system (MRAS), popov's hyper stability**

I. Introduction

In the last one decade the electric traction technology has undergone a major change with 3-phase ac traction motors, gate turn off thyristor, IGBTs & variable voltage variable frequency traction systems. This technology offers many advantages in addition to being highly energy efficient. The main feature of 3-phase electric locomotives is the use of 3-phase asynchronous motor drive, which is powered by variable voltage variable frequency ac power supply from the GTO based power inverter. The 3-phase asynchronous motors are far more reliable, compact & require very little maintenance attention. Besides this main feature, there are several other advanced features in the 3-phase locos namely regenerative braking and unity power factor, which result in reduced energy bills, higher adhesion, fine step less control on tractive effort, facility of pre-set speed, high tractive effort, reduced harmonics, less unsprung mass resulting in less rail wear & tear and less distortions to the track geometry. It is crew friendly & maintenance friendly.

Earlier versions of electric locomotives (WAG4/WAG5) use diode bridges for rectification. These Rectifiers draw pulsed currents from line resulting in many disadvantages and problems: creation of harmonics and RF. high losses, require over dimensioning of parts, reduced max. power that can be drawn from line. Large spectrum of harmonic signals caused by the diode bridge rectifiers interfere with the communication lines running parallel to the track. New laws and restrictions are in effect since 1992, requiring active power factor control on all power supplies above 200VA. Maximum allowable currents at the signalling frequencies with a specified band width caused by converter are limited according to Standards [1]. Recent technology changes in railways such as using active devices viz. GTO, IGBT enables to control the harmonic emissions from the power electronic converter. With interlaced PWM technique, it is possible to cancel out the harmonics between different converters in a multi converter system. In this work two front end converters with shifted interlaced PWM technique have been chosen to study the harmonic cancellation effect in the input current.

The advancements in Field oriented control (FOC) along with the advancements in power electronic device technology have led the induction motor to replace the DC motor even in Traction application. Generally FOC drives are used for better dynamic response. FOC makes the induction motor looks similar to the DC motor. With FOC Input current can be divided into two orthogonal components controlling torque and flux independently. For FOC of Induction machine, knowledge of either the flux or speed is necessary. With an induction motor, the use of flux and speed encoders positioned inside the machine can deteriorate the ruggedness of the machine and increase the associated maintenance costs. A rotational transducer cannot be mounted in some cases such as motor drives in hostile environment. This has led to the active research in sensor less control techniques in recent past.

Various techniques have been proposed earlier for sensorless speed estimation for the control of induction machines [2]. Majority of sensor less speed estimation

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techniques can be grouped into two categories: Fundamental wave model based, magnetic saliency based. Saliency based observers utilizes machine anisotropies like rotor slotting, inductance saliency to estimate the speed and rotor position. They require high precision measurement and increase the overall complexity of the system [3]. Early fundamental wave based estimators processed the open loop machine voltage and currents to estimate the speed. These techniques were sensitive to variations in the machine parameters. Recent techniques employ closed flux estimates for the better dynamic response and noise immunity. State observers such as Luenberger observer and Kalman Filter assume a Linear Time Invariant machine model to estimate the speed. Huge Real time computations involved in those techniques makes them difficult to implement in Industry. Further an accurate knowledge of machine parameters is required. Model Reference Adaptive systems (MRAS) method is one of the most popular adaptive control methods for tracking and observing the system parameters and states. A Simple and accurate estimates can be obtained by using MRAS technique. There exist a number of different MRAS techniques such as parallel model, series model, direct model etc. [3]. In this work, a parallel MRAS technique has been used. For every MRAS techniques an adaptive law has to be defined such that the system becomes stable and estimate converges to the actual value. Popov's hyper stability theory has been used for adaption law which will be explained later.

A general model of MRAS scheme is shown in Fig. 1. It consists of two different models viz. Reference model and Adaptive model. Main principle of MRAS is observing and adjusting the state variable of a system using two different models in order to estimate a quantity. In Fig. 1, X represents the state variable of system. Reference model is based on a set of equations which does not include the parameters to be estimated. Adaptive model is used to observe the same state variable with different set of equations employing different inputs which include the parameter to be estimated. A set of adaptive laws are devised to minimize the error between two models and ensures the stability of the system.

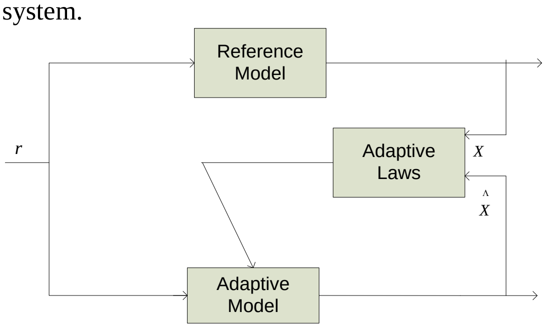


Figure 1. General model of MRAS scheme

In application of MRAS to Induction machine, the state variable can be rotor flux, instantaneous reactive power or back emf. Accordingly three techniques were reported [3]. Studies conducted earlier [4], [5] revealed that instantaneous reactive power based MRAS scheme is the reliable method to implement an estimator. Reactive power based estimator is free from pure integrator and not dependent on stator resistance. Therefore reactive power based estimator is implemented in this work.

II. Instantaneous Reactive Power Based MRAS Observer

In Rotor flux based MRAS observer, open loop integration is needed for flux calculation in Voltage Model. This Pure integration is difficult to implement because of DC drift and initial condition problems. Replacement of a pure integration by a Low Pass filter may help. However flux estimation deteriorates below the filter cut off frequency. Parameter sensitivity is another problem associated with the Rotor flux based MRAS scheme. Since the Reference model is derived based on machine parameters, Rotor flux Based estimator is highly sensitive to parameter variations. Stator Resistance variation with temperature is most serious problem at low speeds. At low speeds, since the stator voltage is low, the resistance drop becomes comparable to the applied voltage and it is difficult to maintain stable operation at low speeds. To avoid these difficulties, instantaneous reactive power is chosen as a state variable for Reference and Adaptive models.

A. Reference Model

Reference model is based on the voltage model of the machine. Back emf of the machine can be expressed as

$$\overline{e_m} = \overline{v_s} - R_s\overline{i_s} - \sigma L_{ss} p\overline{i_s} \tag{1.1}$$

Reactive power is the cross product between the stator current vector and back emf vector.

$$q = \overline{i_s} \otimes \overline{e_m} \tag{1.2}$$

From equations (1.13) and (1.14), Reference model can be deduced as expressed in equation (1.15).

$$q = \overline{i_s} \otimes \overline{v_s} - \sigma L_{ss}(\overline{i_s} \otimes p\overline{i_s}) \tag{1.3}$$

It is evident that no pure integration is involved in the reference model and model is robust for the stator resistance variations. In practical applications, the stator applied voltage is to be deduced from PWM signals applied using a low pass filter or a FIR filter.

B. Adaptive Model

Adaptive model can be derived from the back emf equation from rotor side.

$$\hat{e}_m = \frac{M}{L_{rr}} p\hat{\lambda}_r \tag{1.4}$$

From Γ equivalent circuit of induction machine, Rotor flux can be expressed as

$$p\hat{\lambda}_r = \frac{M}{\tau_r}\overline{i_s} + \hat{\lambda}_r[-\frac{1}{\tau_r} + j\hat{\omega}] \tag{1.5}$$

Instantaneous Reactive power as expressed in equation (1.2), with the help of equations (1.4) and (1.5) yields

$$\hat{q} = \frac{M}{L_{rr}}\left[\frac{1}{\tau_r}(\hat{\lambda}_r \otimes \bar{i}_s) + \hat{\omega}(\bar{i}_s \otimes \hat{\lambda}_r)\right] \quad (1.6)$$

Equations (1.3) and (1.6) formulates the instantaneous reactive power based MRAS.

III. Phase Shifted Modulation (PSM)

The traction motors in an AC locomotive system uses power electronic converters for variable voltage and variable frequency (VVVF). Associated DC link circuits are powered from multiple single phase rectifier systems which operate in PWM mode. These line side converters generate harmonics which will be injected into the line spreading as travelling waves in either direction from the feeding point. These travelling waves create resonances in the power system which acts as a wave guide since it consists of sub-stations and other traction loads. The resonating currents can be substantially higher than the original harmonic currents. The effect of these resonating currents creates a radiated interference where overhead line acts as an antenna. This interference can create severe problems to track side running communication lines in view of safety and protection systems. PWM techniques for line side converters can be interlinked through supervisory control to reduce harmonic pollution created by the locomotive.

In Phase Shifted Modulation PWM technique, switching function of each converter is optimized so as to cancel out the maximum harmonic frequencies inside the line converters [6]. The harmonic components of Indidual converter currents cancels out and the current drawn from the primary can be made free from those components. By this method, there is an effective reduction in total harmonic distortion without increasing the switching frequency.

IV. Indirect Vector Control of Induction Machine

Vector control or field oriented control implicates processing the stator currents in a specified coordinate system. Stator currents are time varying when processed in stator coordinates. The control system then produces an undesirable velocity error. Therefore it is preferable to implement the current control in synchronous coordinates. Traditional methods such as Volts-Hertz control method, controls the amplitude and frequency of the applied voltage. Field oriented control method controls the frequency, voltage and phase as well. Position of rotor flux can be estimated directly or indirectly. Indirect vector control can be considered as a special means of controlling the stator currents and slip frequency [7]. Through indirect vector control it is possible to control the instantaneous torque in all speed range. The toque is controlled with the help of q-axis stator current and slip frequency. The rotor flux is controlled by means of d-axis stator current.

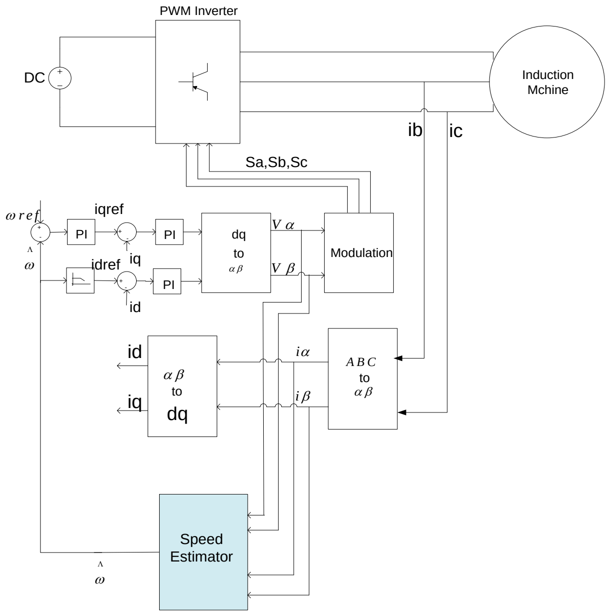


Figure 2. Indirect sensorless vector control of induction machine

To implement an Indirect Vector control Scheme shown in Fig. 2, the following dynamic model of Induction machine should be considered [7].

$$\theta_e = \int \omega_e dt = \int (\omega + \omega_{sl}) dt$$

The rotor side equation

$$\left.\begin{aligned} \frac{d}{dt}\lambda_{dr} + \frac{R_r}{L_{rr}}\lambda_{dr} - \frac{M}{L_{rr}}R_r i_{ds} - \omega_{sl}\lambda_{qr} = 0 \\ \frac{d}{dt}\lambda_{qr} + \frac{R_r}{L_{rr}}\lambda_{qr} - \frac{M}{L_{rr}}R_r i_{qs} + \omega_{sl}\lambda_{dr} = 0 \end{aligned}\right\} \quad (1.7)$$

For de coupling control, entire rotor flux directs along the d-axis and therefore

$$\lambda_{qr} = 0$$

$$\lambda_{dr} = \lambda_r$$

Considering all these, the equation (1.26) can be modified as

$$\frac{L_{rr}}{R_r}\frac{d}{dt}\bar{\lambda}_r + \bar{\lambda}_r = M i_{ds}$$

Slip frequency can be calculated as

$$\omega_{sl} = \frac{M R_r}{L_{rr}\bar{\lambda}_r} i_{qs}$$

$$\bar{\lambda r} = M i_{ds}$$

The torque expression can be written as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{M}{Lrr}\lambda_{dr} i_{qs}$$

V. Results and Discussions

Fig. 3 depicts the system studied to observe the performance of speed estimator and Phase shifted modulation. Induction Motor with the parameters given in Table I has been simulated using Matlab/Simulink tool. Rotor flux oriented Vector control has been implemented with a voltage source inverter using Hysteresis modulation Technique. Estimated speed through MRAS schemes has been used for speed control and the rotor flux angle calculation. Actual measured speed is only used for the validation of the MRAS estimators (to observe the speed error). Phase Shifted Modulation technique has been used on input rectifier side to maintain unity power factor, and mitigate harmonics.

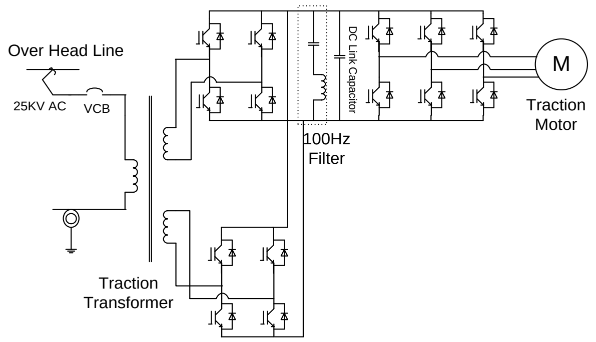


Figure 3. Schematic diagram of system used for simulation

TABLE I. MACHINE SPECIFICATIONS

Power	1000Hp
Rated Voltage	2180 V
Rated Frequency	65 Hz
Stator Resistance/phase, R_s	0.087 ohm
Stator Leakage Inductance. L_{ls}	0.8e-3 H
Rotor Resistance ref to stator /phase, R_r	0.228 ohm
Rotor Leakage Inductance ref to Stator, L_{lr}	0.8e-3 H
Mutual Inductance, M	34.7e-3 H
Moment of Inertia, J	1.662 $Kg - m^2$
Friction Factor, B	0.1 N-ms
Pole pairs, P	3

In this section, the results obtained are presented for both steady state and transient state. Fig. 4 shows the performance of the reactive power based estimator along with AFEC functionality at light load (200Nm) and 100Rad/sec. Regulation of DC link voltage and Unity power factor feature at transformer primary have been shown in Fig. 5. As it is evident that there is no 100Hz component in DC link. The accuracy of the estimator is found to be 99.57%. (Estimator accuracy is obtained by finding the percentage error between estimated speed and actual speed). Input current at transformer primary which is the sum of the two secondary currents is shown to be sinusoidal and in phase with the catenary voltage making power factor in close vicinity to 1. The regulation of DC link voltage is well below 1%.

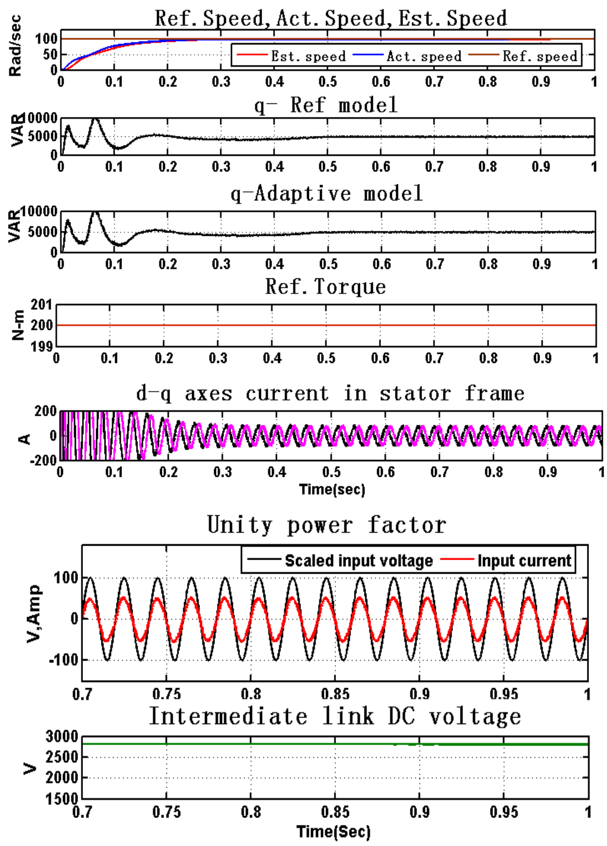


Figure 4. Performance of speed estimator & rectifier at light load (200Nm) at 100Rad/sec

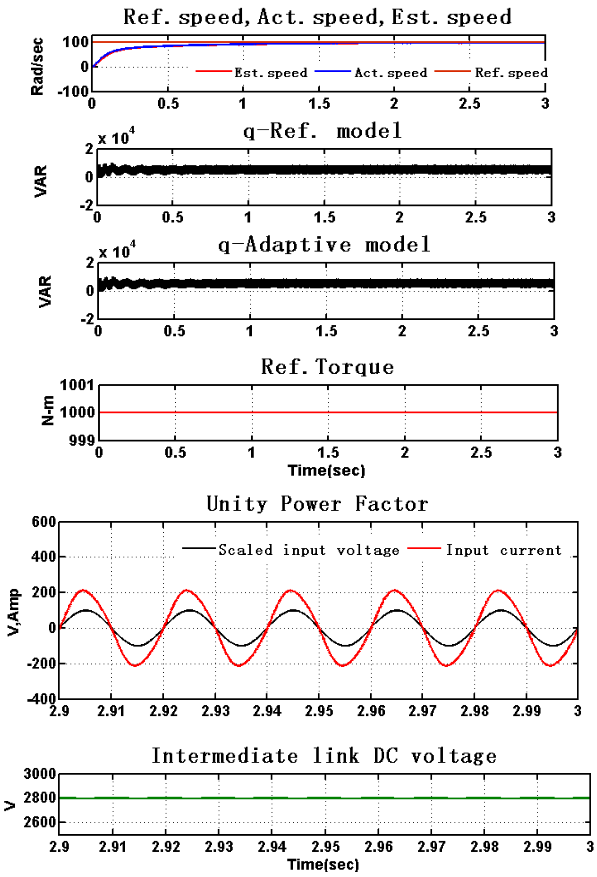
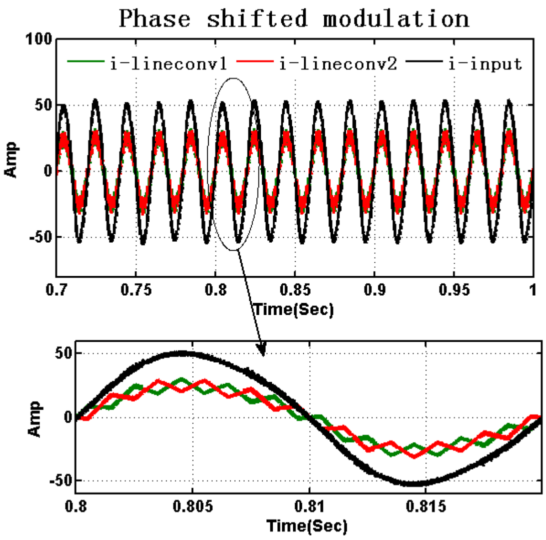
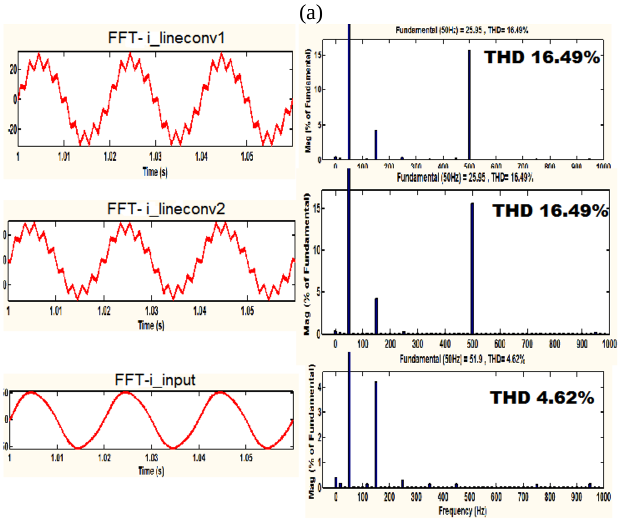


Figure 5. Performance of speed estimator & rectifier at 1000Nm and 100Rad/sec



(a)



(b)

Figure 6. Phase shifted modulation & THD comaprison at light load (200Nm) at 100 Rad/sec

Fig. 6 depicts the phase shifted modulation technique and THD comparisons of transformer secondary and primary currents. It is evident from Fig. 6(b) that the harmonic components present in the secondary currets are abscent in the primary current. Therefore it is possible to reduce the harmonic content with out increasing the swithcing frequency. THD comparison shows that because of phase shift modulation, harmonic content at switching freuqncies have been cancelled out in primary. Therefore the electo magnetic compatibility of the converter with the track side communication and safety equipment is assured.

Fig. 5 shows the performance of the reactive power based estimator along with the AFEC functionality at light load (1000Nm) and 100Rad/sec. Regulation of DC link voltage and Unity power factor feature at transformer primary have been shown in Fig. 5. Both actual speed and the estimated speed reached to steady state value in 0.85 sec (with error <0.05% with ref. speed). The Max error between the estimator speed and actual speed is 0.02%. Current drawn from catenary is found to be sinusoidal and in phase with the input voltage. Regulation of DC link voltage is good and found to be below 1%. From Fig. 7, the advantage of PSM technique is evident.

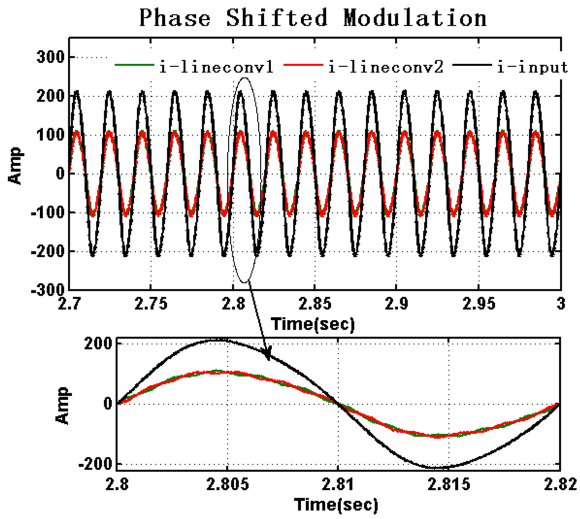


Figure 7. Phase shifted modulation at 1000Nm and 100Rad/sec

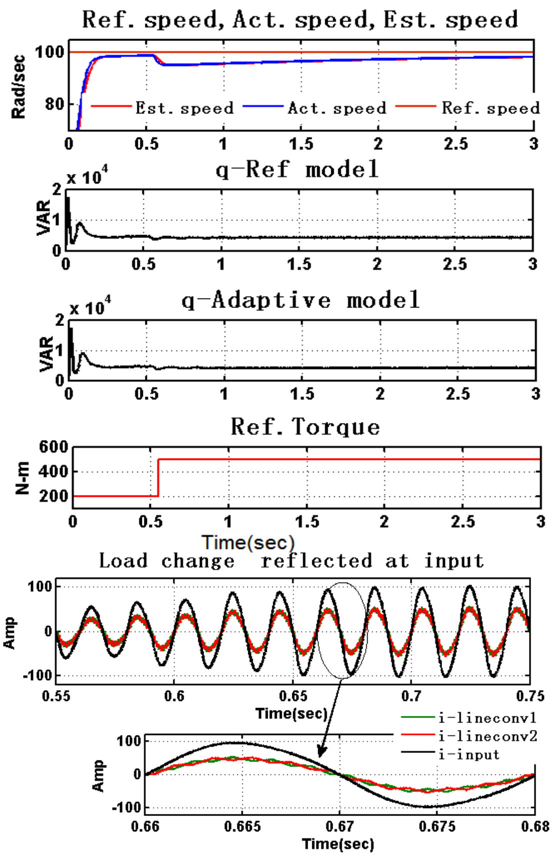


Figure 8. Transient perfromance: Step change in torque at 0.55sec

From Fig. 8, the transient performance of the above system is observed by changing torque from 200Nm to 500Nm at 0.55 sec. Max error between Actual speed and estimated speed is found to be 0.035%. The estimated speed and the actual speed are found to be converging in 0.1% error band with ref speed in 2.4 sec. The reflection of load change at input has also has been depicted. It is further observed that the time lag between the load change and the increase in input current is around 0.15 sec. This will not dip the DC link too much as the capacitance used in traction systems is quite high. However in practical system this index may vary depending on various factors such as computational delay by the processors, ADCs, etc. Normally a feed forward loop is employed to encounter such problems in practical traction systems.

VI. Conclusion

In this paper, Traction system with speed sensor less rotor flux oriented control and phase shifted modulation technique has been studied. Reactive power based MRAS estimator has been used to obtain the speed loop. Phase shifted modulation technique has been employed on multi rectifier input system similar to traction system to make the traction system electro magnetically compatible with other communication and safety equipment in the vicinity of the locomotive. Performance under both the steady state and dynamic state has been studied. The advantage of PSM technique has been clearly brought out. Future scope of this work will be the realization in a locomotive.

Appendix A Nomenclature

$\overline{v_s}$ $[v_{ds}, v_{qs}]^T$, Stator Voltages in Stator Frame

$\overline{i_s}$ $[i_{ds}, i_{qs}]^T$, Stator Currents in Stator Frame

$\overline{e_m}$ $[e_{mds}, e_{mqs}]^T$, Back emf vector in Stator Frame

$\overline{\lambda_r}$ $[\lambda_{dr}, \lambda_{qr}]^T$, Rotor Flux Linkages

L_{ss} Stator Self Inductance

L_{rr} Rotor Self Inductance

M Mutual Inductance

R_s Stator Resistance

R_r Rotor Resistance

τ_r $\frac{L_{rr}}{R_r}$, Rotor Time Constant

σ Leakage Factor

ω Angular speed of the Machine

ε Speed Adaptation Signal

Refernces

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