Model Reference Adaptive System Sensorless Vector Control of an Induction Motor Using a Novel Fractional Order PI Controller Adaptation Mechanism

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ABSTRACT

Recently, speed sensorless control of Induction Motor (IM) drives received great attention to avoid the different problems associated with direct speed sensors. Among different rotor speed estimation techniques, Model Reference Adaptive System (MRAS) schemes are the most common strategies employed due to their relative simplicity and low computational effort. In this paper a novel adaptation mechanism is proposed which replaces normally used conventional Proportional-Integral (PI) controller in MRAS adaptation mechanism by a Fractional Order PI (FOPI) controller. The performance of two adaptation mechanism controllers has been verified through simulation results using MATLAB/SIMULINK software. It is seen that the performance of the induction motor has improved when FOPI controller is used in place of classical PI controller.

Keywords: Induction Motor, Speed Sensorless, Model Reference Adaptive System, Proportional-Integral Controller, Fractional Order PI controller

I. INTRODUCTION

Electric motors for variable speed drives have been widely used in many industrial applications. High performance electric motor drives require decoupled torque and flux control. In the past, Direct Current (DC) motors were commonly preferred. Because torque and speed controls of DC motors are easier than Alternating Current (AC) motors. In DC motor drives torque is proportional to armature current, so DC motor drive may directly control the torque by using a current control loop. Also flux control is easy in DC drives. The torque and flux controls are independent from each other. However, DC motors have the disadvantage of brush erosion, maintenance requirements, environmental effects, complex structures and power limits. On the other hand, the three phase induction motors have been the most widely used and are often viewed as the workhorse of modern industry in fixed speed applications for reasons of cost, size, weight, reliability,

ruggedness, simplicity, efficiency and ease of manufacture. In contrast to the commutation DC motor, it can be used in aggressive or volatile environments since there are no risks of corrosion or sparks. However, because of the involved model high nonlinearities, multivariable, highly coupled, the electrical rotor variables are rarely measurable and its parameters vary with operating conditions; these require much more complex methods of control, more expensive and higher rated power converters than DC motors [1].

The development of enabling technologies was slow until the introduction of semiconductor power switches in the 1950's, allowing the development of commercial variable frequency inverters in the 1960's. It then became viable to use variable speed induction motors in some low performance variable speed applications. The search for simple control schemes similar to those used for DC drives, has led to the so-called Vector Control (VC) or Field Oriented Control (FOC) schemes, in

which by means of a variable transformation to a rotational frame, it is possible to obtain two current components to produce the torque and the flux respectively. Furthermore, these current components can be independently controlled so as to achieve a decoupled control. By using these techniques, vector controlled induction motors have proved to outperform the DC ones. Since then, the induction motor has replaced the DC motor in many demanding high performance motion control applications, offering many advantages when compared with DC motor. There are essentially two general methods of VC. One called the direct or feedback method, and the other, the indirect or feedforward method. Indirect vector-controlled (IVC) induction motor drives are increasingly used in high performance systems due to their relative simple configuration compared to Direct Vector Control (DVC) scheme which requires flux and torque estimators. Implementation of the vector controlled induction motor drive techniques requires the motor speed information. Tachogenerators, resolvers, incremental or optic encoders are usually used to detect the rotor speed. Unfortunately the need of speed sensors in order to apply effective vector control algorithms is one of their main constraints. Indeed, there are several disadvantages of those sensors such as higher number of connection between motor and its driver, additional cost, susceptibility to noise and vibrations, extra space, volume and weight on the overall actuator [2-7].

Therefore, vector controlled induction motor methods in the absence of any speed sensor have been investigated by many researchers. The advantages of speed sensorless induction motor drives are reduced hardware complexity and lower cost, reduces size of the drive machine, elimination of the sensor cable, better noise immunity, increased reliability and less maintenance requirements. Recently, several methods have been proposed for speed estimation of sensorless induction motor drives based on the motor model. A comprehensive study of the different speed estimation techniques and their specific merits and demerits as well as their feasibility for estimating the rotor speed are presented and compared in. These strategies make use of the instantaneous values of stator voltages and currents to estimate the motor speed. Model reference adaptive systems offer simpler implementation and require less computational effort compared to other methods and are therefore the most popular strategies used for sensorless

control. Rotor flux, back EMF and reactive power techniques are popular MRAS strategies which have received a lot of attention. However, Rotor Flux based Model Reference Adaptive System (RF-MRAS), first proposed by Schauder, is the most popular MRAS strategy and a lot of effort has been focused on improving the performance of this scheme. Conventional RF-MRAS schemes use PI controller as the adaptive mechanism for speed estimation. The reason is that the conventional PI controller is easy to implement either by hardware or by software, inexpensive cost, and no deep mathematical theory is necessary to understand how the conventional PI controller works. In spite of the major features of the conventional PI controller, it has some disadvantages such as the high peak overshoot and response will be sluggish when there is sudden load disturbance [8-13].

This paper proposes a novel adaptation mechanism to replace the classical PI controller used in MRAS speed estimation schemes which are based on rotor flux to reduce these problems. The proposed novel adaptation mechanism is based on FOPI controller strategy. The performance of both controllers is simulated and compared using MATLAB/SIMULINK software package. It will be seen that the novel adaptation mechanism scheme has better performance when compared to conventional PI controller.

II. DYNAMIC MODELS OF INDUCTION MOTOR

In this paper, the dynamic model of a three phase induction motor can be expressed as a set of differential equations as follows [14]:

$$\frac{di_{ds}}{dt} = -\alpha i_{ds} + \beta \psi_{dr} + \delta \psi_{qr} + \frac{v_{ds}}{L_a}$$

$$\frac{di_{qs}}{dt} = -\alpha i_{qs} - \delta \psi_{dr} + \beta \psi_{qr} + \frac{v_{qs}}{L_a}$$

$$\frac{d\psi_{dr}}{dt} = \varepsilon i_{ds} - \frac{R_r}{L_r}\psi_{dr} - \omega_r \psi_{qr} \qquad (1)$$

$$\frac{d\psi_{qr}}{dt} = \varepsilon i_{qs} + \omega_r \psi_{dr} - \frac{R_r}{L_r}\psi_{qr}$$

$$\frac{d\omega_r}{dt} = \frac{P}{2}\left(\frac{\chi}{4L_r J} - \frac{T_L}{J}\right)$$

Where:

$$\alpha = \frac{R_s}{L_a} + \frac{R_r L_m^2}{L_r^2 L_a}$$

$$\beta = \frac{R_r L_m}{L_r^2 L_a}$$

$$\delta = \frac{\omega_r L_m}{L_r L_a} \tag{2}$$

$$\varepsilon = \frac{R_r L_m}{L_r}; \quad L_a = L_s - \frac{L_m^2}{L_r}$$

$$\chi = 3PL_m \left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds} \right)$$

Where i_{ds}, i_{qs}, ψ_{dr} and ψ_{qr} are respectively the stator currents and the rotor fluxes expressed by their d-q orthogonal components; ω_r is the rotor angular speed; v_{ds} and v_{qs} are the d-q stator voltages; L_s and L_r are the stator and rotor inductances; L_m is the mutual inductance; L_a is the redefined leakage inductance. R_s and R_r are the stator and rotor resistances, respectively; J is the moment of inertia of the motor; T_L is the torque of external load disturbance; P is the number of pole; and T_r is the time constant of the rotor dynamics. An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

III. CLASSICAL RF-MRAS SPEED OBSERVER

The basic scheme of the classical rotor flux based model reference adaptive system configuration is given in Figure 1. The scheme consists of two models; reference and adjustable ones and an adaptation mechanism. The reference model or the voltage model generates the reference value of the rotor flux components in the stationary reference frame from the monitored stator voltage and current components and these are obtained from the reference model as follows [15-18]:

$$\frac{\psi_{rd}}{dt} = \frac{L_r}{L_m} (v_{ds} - R_s i_{ds} - \sigma L_s \frac{di_{ds}}{dt})$$

$$\frac{\psi_{rq}}{dt} = \frac{L_r}{L_m} (v_{qs} - R_s i_{qs} - \sigma L_s \frac{di_{qs}}{dt}) \tag{3}$$

Where σ is leakage coefficient which is given as:

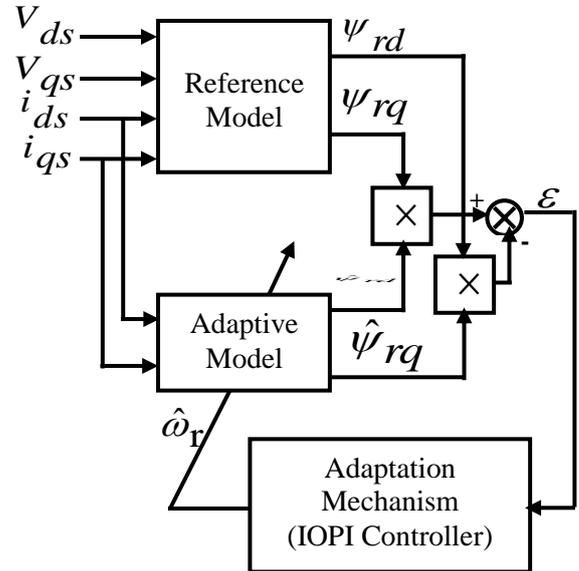$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{4}$$

Figure 1: Classical RF-MRAS speed observer

The Adjustable or adaptive or current model describes the rotor equation and the rotor flux components are expressed in terms of stator current components and the rotor speed. The adaptive model can be expressed in terms of the following equations [15-18]:

$$\frac{\hat{\psi}_{rd}}{dt} = \frac{L_m}{T_r} i_{ds} - \frac{1}{T_r} \hat{\psi}_{rd} - \hat{\omega}_r \hat{\psi}_{rq}$$

$$\frac{\hat{\psi}_{rq}}{dt} = \frac{L_m}{T_r} i_{qs} - \frac{1}{T_r} \hat{\psi}_{rq} - \hat{\omega}_r \hat{\psi}_{rd} \tag{5}$$

After developing reference and adjustable models, the adaptation mechanism is to be designed which forms the very important part of the RF-MRAS Observer. The adaptation mechanism is designed in a way to generate the value of the estimated speed used so as to minimize the error between the reference and estimated fluxes. In the conventional RF-MRAS scheme, this is performed by defining a speed tuning signal ε to be minimized by a PI controller (adaptation mechanism) which generates the estimated speed which is fed back to the adaptive model. This process continues till the error between two models tends to zero. The expressions for the speed

tuning signal and the estimated speed can be given as follows [15-18]:

$$\varepsilon = \psi_{rq}\hat{\psi}_{rd} - \psi_{rd}\hat{\psi}_{rq} \qquad (6)$$

$$\hat{\omega}_r = (K_P + \frac{K_I}{p})\varepsilon \qquad (7)$$

Where K_P and K_I are the proportional and integral constants respectively and "^" signifies the estimated value.

IV. FC AND FOPI CONTROLLER

Integer Order PI (IOPI) controller belongs to the dominating form of feedback industrial controllers and there is a continuous effort to improve their quality and robustness. Design and tuning IOPI controller have been a large research horizon ever since Ziegler and Nichols presented their methods in 1942. Specification, stability, design, applications and performance of the IOPI controller have been widely treated since then. In recent years, there are increasing interests to enhance the performance of IOPI controller by using the concept of Fractional Calculus (FC). The history of the FC covers over three hundred years, similar to that of classical differential calculus. In last two decades, the FC has become much popular among the researchers of different streams. FC is a generalization of integration and differentiation to non-integer (fractional) order fundamental operators represented by $_aD_t^{\lambda}$; where a and t are respectively the lower and upper limits; and λ is the order of fractional differentiation or integration. For positive λ it denotes derivative and for negative λ it denotes integral actions. The continuous integro-differential operator (D) is defined as follows [19]:

$$_aD_t^{\lambda} = \begin{cases} \dfrac{d^{\lambda}}{dt^{\lambda}}; & \lambda>0 \\ 1; & \lambda=0 \\ \displaystyle\int_a^t (d\tau)^{-\lambda}; & \lambda<0 \end{cases} \qquad (8)$$

There are several definitions of fractional order integration and differentiation. Some of the definitions extend directly from integer order calculus. The most

often used are Riemann Liouville and Grunwald-Letnikov definitions. Recently the concept of FC is widely introduced in many areas in science and engineering [10]. FOPI controller can be written as PI^{λ}. The transfer function of the FOPI controller is obtained as [20-23]:

$$G_{FOPI}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s^{\lambda}} = K_P + K_I s^{-\lambda} \qquad (9)$$

Where E(s) is an error and U(s) is controller's output. K_P and K_I are the proportional and integral gain values of the FOPI controller and λ is the noninteger order of the fractional integrator. It is obvious that the FOPI controller not only needs design two parameters K_P and K_I, but also design one order λ of integral controller. By taking the value of λ as 1, the FOPI controller is converted to the ordinary IOPI controller. The FOPI controller in time domain is represented by [20-23]:

$$u(t) = K_P e(t) + K_I D_t^{-\lambda} e(t) \qquad (10)$$

The block diagram of the novel RF-MRAS speed observer employing FOPI controller adaptation mechanism is shown in Figure 2.
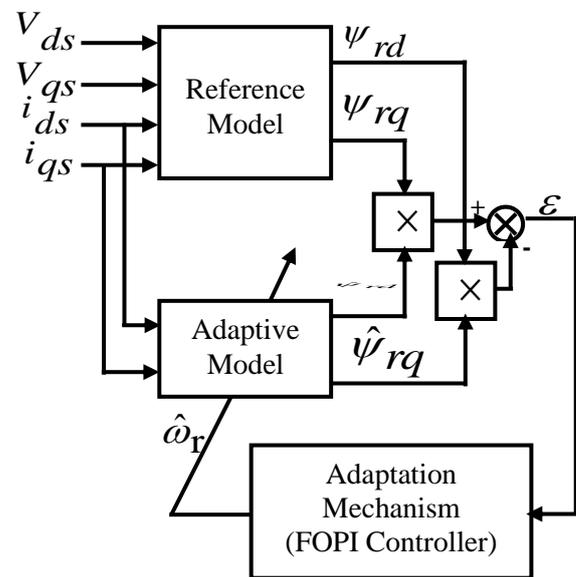

Figure 2: Novel RF-MRAS speed observer

In Equation (9), $s^{-\lambda}$ has fractional order which is not directly compatible with MATLAB software and it becomes difficult to realize hardware of the FOPI controller. Therefore, there are several integer order

approximation methods available for fractional order elements. In MATLAB FOPI controller is implemented using FOMCOM toolbox where Oustaloup's approximation is realized [24].

V. RESULTS AND DISCUSSION

In order to verify the effectiveness and feasibility of estimating rotor speed using novel and conventional adaptation mechanism techniques, a simulation model has been developed in MATLAB/SIMULINK platform. The parameters of the induction motor used in simulations are given in Table I.

TABLE I
PARAMETERS OF THE INDUCTION MOTOR

Parameters	Values
Rotor resistance, R_r	0.72 Ω
Stator resistance, R_s	0.55 Ω
Rotor inductance, L_r	0.068 H
Stator inductance, L_s	0.068 H
Magnetizing inductance, L_m	0.063 H
Moment of inertia, J	0.05 kg.m^2
Viscous friction coefficient, B	0.002 Nms^{-1}

Extensive simulation tests were carried out to compare between the two adaptation mechanisms schemes under different operating conditions such as constant speed command; variable speed command; inversion of the speed command; moment of inertia mismatch; and rotor resistance mismatch. The results are presented in the following sections.

A. Constant Speed Command

Figure 4 shows the behavior of induction motor speed estimation where the induction motor rotates at a constant speed (70rad/sec) without load torque. The simulation is performed for eight seconds. In terms of the estimated speed control trajectories shown in Figure 3, two adaptation mechanisms have a similar performance in term of fast tracking of the desired speed without steady state error. Also, in Figure 3 it can be easily observed that the speed response of the IM drive with new adaptation mechanism shows no sign of overshoot as observed with conventional PI controller thus reducing the settling time. Furthermore, as can be seen from the waveforms the speed error between the actual speed and estimated speed is less with FOPI controller when compared to the control of the IM drive with the conventional PI controller. However, the rise

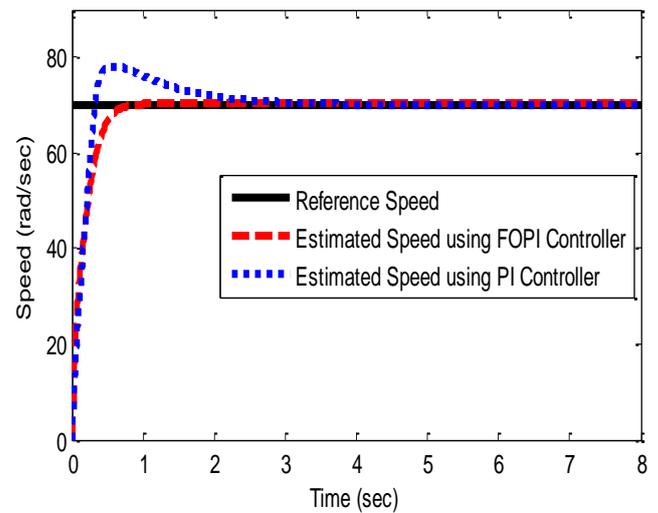time for the conventional PI controller is faster than for the FOPI controller.

Figure 3: Estimated constant speed using two adaptation mechanism controllers

B. Variable Speed Command

In this case, the induction motor drive is tested under variable speed command with no load torque. The speed command is 30rad/sec for the first two seconds, followed by 50rad/sec for the next two seconds, then 80rad/sec for the next two seconds followed by 100rad/sec for the last two seconds. Figure 4 shows the speed response of sensorless controlled induction motor drive with FR-MRAS using two adaptation mechanisms. From Figure 4 it is clear that FOPI controller provided optimum performance in terms of overshoot and settling time. Only rise time remained to be good for conventional PI controller.
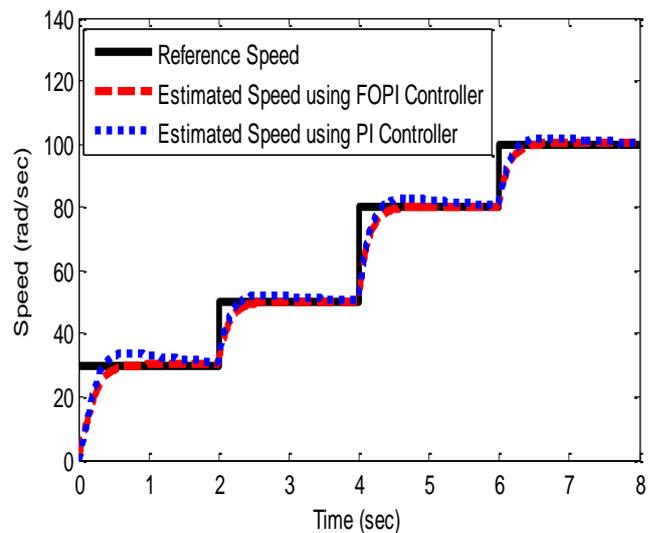

Figure 4: Estimated variable speed using two adaptation mechanism controllers

C. Inversion of Speed Command

Figure 5 shows the simulation result obtained for speed inverting from 80rad/s to -80rad/s without load torque.
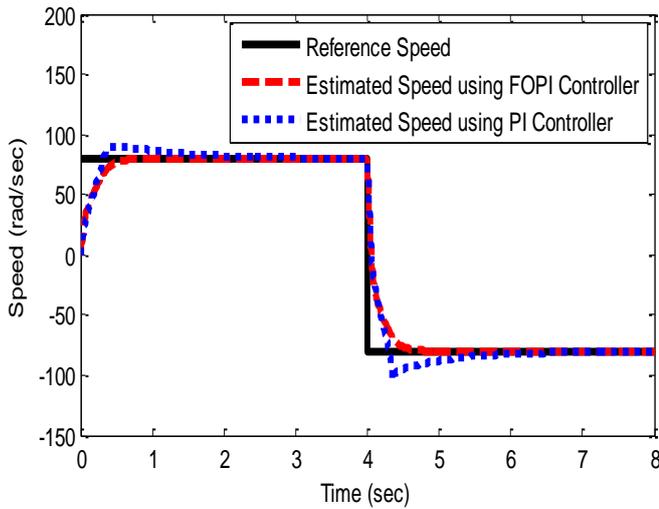

Figure 5: Estimated speeds using two adaptation mechanism controllers with reversing speed reference

When the speed is changed, the response of the induction motor drive shows overshoot and undershoot in case of conventional PI controller whereas in FOPI controller estimated speed settles smoothly without any remarkable overshoot and undershoot. In addition, the settling time for FOPI controller is shorter than for conventional PI controller. Based on rise time characteristic, it can be said that the conventional PI controller is able to response quickly compared to FOPI controller. The last characteristic is the steady state error where the two adaptation mechanisms have almost zero steady state error.

D. Parameters Variation

For high performance applications the new adaptation mechanism controller should be robust to parameters variation. Changes in the moment of inertia (J) and the rotor resistance (R_r) are investigated through simulation tests. The simulation tests are undertaken by changing one parameter at a time while keeping other parameters unchanged. The induction motor is commanded to accelerate from rest to reference speed of 70rad/sec under no torque load. Figure 6 shows the induction motor responses of FOPI and conventional PI controllers when the moment of inertia is increased by 100% of its original value, whilst Figure 7 depicts the estimated speed responses when the rotor resistance increased by 140% of its original value. It is very much clear from Figures 6 and 7 that the new adaptation mechanism controller is less sensitive to parametric variations and a

robust tracking performance is achieved in presence of the uncertain parameters. Furthermore, when carefully study Figure 6 and 7 according to the settling time, overshoot and speed error, the best performance belongs to new adaptation mechanism controller. Although, the rise time for the conventional PI controller is still faster than for FOPI controller.
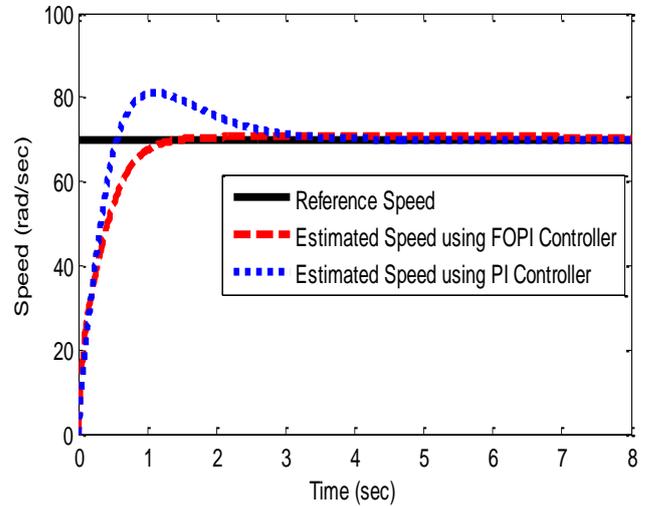

Figure 6: Response of the IM using two adaptation mechanism controllers with variation in the moment of inertia
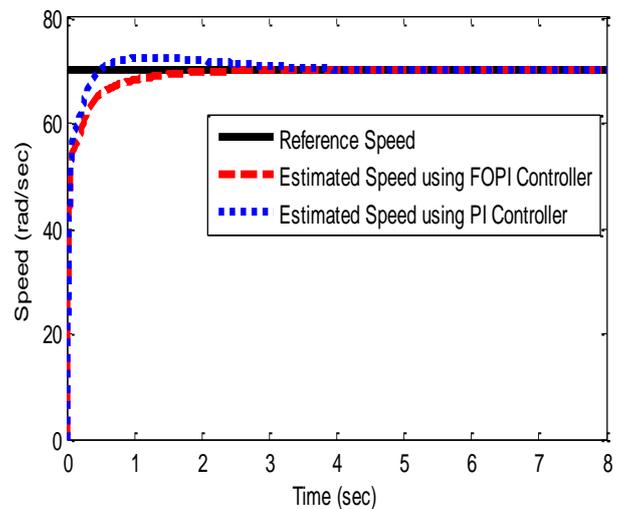

Figure 7: Response of the IM using two adaptation mechanism controllers with variation in the rotor resistance

VI. CONCLUSION

In this paper a novel adaptation mechanism using FOPI controller, which replaces conventionally used PI controller in the adaptation mechanism of the RF-MRAS based speed observer for the sensorless control of induction motor is proposed. Simulation results have been presented to compare both the FOPI

and conventional PI controllers and it was found that FOPI controller shows better transient performance when compared to conventional PI controller. Also as can be seen from the different speed waveforms the speed error between the reference speed and estimated speed is low when FOPI controller is used in place of conventional PI controller. Robustness of the two controllers against system parameters variation is also verified. Simulation results show that the FOPI controller shows better performance than the classical PI controller in the face of system parameters variation. However, the application of the new adaptation mechanism controller does not considerably improve the rise time performance.

VII.   REFERENCES

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