FUZZY LOGIC BASED HPWM-MRAS SPEED OBSERVER FOR SENSORLESS CONTROL OF INDUCTION MOTOR DRIVE

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ABSTRACT

The main aim of this paper is to present hybrid space vector pulse width modulation (HPWM) based model reference adaptive system (MRAS) speed observer for sensorless control of induction motor drive. The proposed method is designed by using the notion of stator flux ripple and the switching times are calculated by utilizing the concept of imaginary switching times that uses the instantaneous values of the reference voltage of the three phases. By using this method ripples present in the torque can be minimized and also the speed performance can be improved in the way that the error between the adaptive model speed and the reference model speed is made as low as possible so that the estimated speed is made as nearly equal as the speed of the reference model. Also in this paper the conventionally used PI controller in the adaptation mechanism of the MRAS observer is replaced by a fuzzy logic controller (FLC). In conventionally used PI controller when the reference speed or the load changes the control parameters are to be changed manually but when a FLC is used in place of PI controller this is not necessarily required. The fuzzy logic is also helpful in keeping the speed relatively constant during the load variations which can be seen from the simulation results. The simulations of the proposed method are performed and the results are presented to validate the proposed method.

Keywords: induction motor, sensorless control, MRAS, HPWM, fuzzy logic control.

Nomenclature

v_s^d = d axis stator voltage (V)
v_s^q = q axis stator voltage (V)
v_r^d = d axis rotor voltage (V)
v_r^q = q axis rotor voltage (V)
i_s^d = d axis stator current (A)
i_s^q = q axis stator current (A)
i_r^d = d axis rotor current (A)
i_r^q = q axis rotor current (A)
R_s = Stator resistance (Ω)
R_r = Rotor resistance (Ω)
L_s = Stator inductance (H)
L_r = Rotor inductance (H)
L_m = Mutual inductance (H)
ω_r = Rotor Speed (rad/sec)

INTRODUCTION

In literature there are numerous sensorless control techniques discussed and these are summarized in [1]. Various techniques are suggested such as Luenberger and Kalman filter observers, Model Reference Adaptive System (MRAS), Artificial Intelligence (AI) Technique and so on. Out of the different rotor estimation techniques available in literature the MRAS technique is found to be most common method and finds lot of attention due to its straight forward stability approach, low computational efforts and simplicity [2]. MRAS observers based on rotor flux, back emf, reactive power is some of the MRAS observers that have been introduced in literature [3-6]. Schauder was the first to propose rotor flux MRAS [5], which is the most popularly used MRAS strategy. A lot of effort by the researchers has been focused on this strategy to further improve its performance.

Space vector pulse width modulation (SVPWM) technique is being for a long time now. The main advantage of this technique is that the switching losses are low; the harmonic performance is improved and produces an improved output voltage for the same dc bus voltage [7-10], when compared to a sinusoidal PWM (SPWM). SPWM is a technique in which PWM outputs are produced based on the principle that compares a triangular carrier signal with a sinusoidal reference wave [11]. SVPWM is an advanced PWM method and one of the best methods among all the different types of PWM methods available in literature for variable speed drives and hence becomes the mostly used PWM technique [12-15]. This scheme of SVPWM may look simple theoretically but the implementation of this scheme becomes little difficult with the use of low sampling period or high switching frequency [16]. In [17-20] different types of hybrid PWM algorithms have been developed for reduced current ripple.

In the proposed method a HPWM MRAS speed observer is developed based on notion of stator flux ripple and switching times are calculated using the logic of imaginary switching times which uses the instantaneous values of the reference voltage of the three phases. Also there are significant uncertainties in the industrial applications so that the performance of the drive may deteriorate if PI controllers are used. Due to this it is worth using controllers which have the capability of handling uncertainties caused by parameter variations. A fuzzy logic controller offers a good performance during parameter variations and it can be used in place of conventional PI controller in the adaptation mechanism of MRAS observer [21]. In the proposed method the performance of the drive is also enhanced by replacing PI controller with fuzzy logic controller.

PRINCIPLE OF CONVENTIONAL MRAS

The conventional MRAS model developed by Schauder is shown in Figure-1. The main logic behind MRAS scheme is that there is a reference model and an adaptive model where in the reference model is used to determine the required states and the adaptive model also known as adjustable model provides the estimated values of the states. The error obtained between the reference and adaptive model is given to an adaptation mechanism which adjusts the adaptive model by generating the estimated value of rotor speed. The process of adjusting the adaptive model is made to continue till the error obtained between the two models tends to zero.

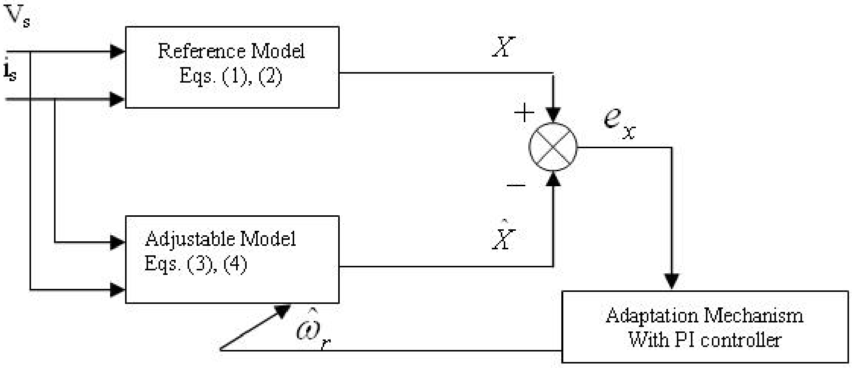

Figure-1. Conventional rotor flux MRAS speed observer.

The reference rotor flux components that are obtained from the reference model are given as [5, 6, 22]

$$p\psi_r^{\ d} = -\frac{L_r}{L_m}\left(R_s i_s^{\ d} + \sigma L_s p i_s^{\ d} - v_s^{\ d}\right) \tag{1}$$

$$p\psi_r^{\ q} = -\frac{L_r}{L_m}\left(R_s i_s^{\ q} + \sigma L_s p i_s^{\ q} - v_s^{\ q}\right) \tag{2}$$

The rotor flux components that are obtained from the adaptive model are given as [5, 6, 22]

$$p\hat{\psi}_r^{\ d} = -\hat{\omega}_r \hat{\psi}_r^{\ q} + \frac{1}{T_r}\left(L_m i_s^{\ d} - \hat{\psi}_r^{\ d}\right) \tag{3}$$

$$p\hat{\psi}_r^{\ q} = \hat{\omega}_r \hat{\psi}_r^{\ d} + \frac{1}{T_r}\left(L_m i_s^{\ q} - \hat{\psi}_r^{\ q}\right) \tag{4}$$

Where σ is leakage coefficient and is given as

$$\sigma = 1 - \frac{L_m^{\ 2}}{L_s L_r} \tag{5}$$

From the above (1) and (2) the reference model is developed and the adaptive model is developed by using (3) and (4). After developing adaptive and reference models the adaptation mechanism is to be designed which forms the very important part of the MRAS scheme. The adaptation mechanism is designed in a way to generate the value of estimated speed used so as to minimize the error between the estimated and reference fluxes. In the commonly used adaptive mechanism this is done by more generally used PI controller. The speed tuning signal e_x is minimized by PI controller which generates the estimated speed and is fed back to the adaptive model as shown in Figure-1.

The speed tuning signal e_x is given as

$$e_x = \psi_r^{\ q}\hat{\psi}_r^{\ d} - \psi_r^{\ d}\hat{\psi}_r^{\ q} \tag{6}$$

and the estimated speed is given as

$$\hat{\omega}_r = \left(k_p + \frac{k_i}{p}\right)e_x \tag{7}$$

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The electromagnetic torque equation of induction motor in stationary frame is given as

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\left(i_s^{\ q}\psi_r^{\ d} - i_s^{\ d}\psi_r^{\ q}\right) \tag{8}$$

HYBRID PWM METHODOLOGY

The voltage vectors, produced by a 3-phase, two-level inverter, divide the space vector plane into six sectors as shown in Figure-2. As the sectors are symmetric, the discussion in this paper is limited to first sector only. In the space vector approach, the desired reference vector is generated by time averaging the suitable discrete voltage vectors in sampling period Ts. For a given reference voltage V_{ref} and angle in sector I, the volt-time balance is maintained by applying the active vectors 1, 2 and zero states together for durations T_1, T_2 and T_Z respectively, as given in (9) to (11)

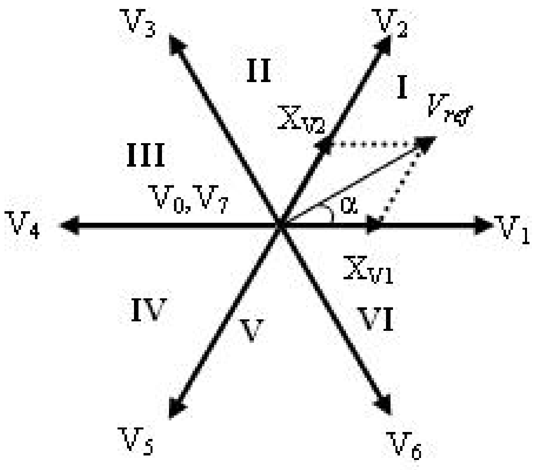

Figure-2. Switching states and corresponding voltage vectors.

$$T_1 = \frac{2\sqrt{3}}{\pi}\left(\sin\left(60^o - \alpha\right)\right)M_i T_s \tag{9}$$

$$T_2 = \frac{2\sqrt{3}}{\pi}\left(\sin\alpha\right)M_i T_s \tag{10}$$

$$T_z = -\left(T_1 + T_2 - T_s\right) \tag{11}$$

In the proposed algorithm, the switching times can be calculated by using the concept of imaginary switching times which uses instantaneous values of the reference voltages of a, b and c phases. This method does not depend on the magnitude of the reference voltage space vector and its relative angle with respect to the reference axis. The imaginary switching time periods proportional to the instantaneous values of the reference phase voltages are defined as

$$T_{an} = T_s\left(\frac{V_{an}}{V_{dc}}\right) \; T_{bn} = T_s\left(\frac{V_{bn}}{V_{dc}}\right) \; T_{cn} = T_s\left(\frac{V_{cn}}{V_{dc}}\right) \tag{12}$$

Fuzzy logic controller

Fuzzy logic is especially advantageous for problems that cannot be easily represented by mathematical modeling because data is either unavailable, incomplete or the process is too complex. Such systems can be easily upgraded by adding new rules to improve performance or add new features.

In many cases, fuzzy control can be used to improve existing traditional controller systems by adding an extra layer of intelligence to the current control method. The different types of fuzzy controllers that are discussed in literature are basically multi input single output (MISO) type controllers [21, 23-25]. The main preference of the fuzzy logic is that is easy to implement control and it has the ability of generalization. In the conventional methods of MRAS speed observer PI controller was commonly used in the adaptation mechanism which is generating estimated speed which in turn is reducing the speed tuning signal e_x or error between the adaptive and reference models. In the proposed method the PI controller that is used in the adaptation mechanism is replaced by a fuzzy logic controller. The general block diagram of fuzzy controller is represented as shown in Figure-3.

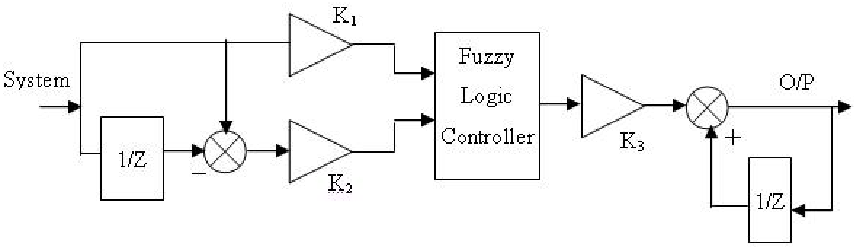

Figure-3. Block diagram of fuzzy logic controller.

Speed tuning signal e_x and its rate of change are the inputs to the proposed FLC which are multiplied by two scaling factors K_1 and K_2 respectively. Then the output of the controller is multiplied by a third scaling factor K_3 and estimated speed is obtained. The trial and error technique is used to find the values of scaling factors for the best performance [21, 26]. The values hence obtained for K_1, K_2 and K_3 are 0.05, 2 and 3 respectively.

The first step in designing the fuzzy controller is to generate the fuzzy rules based on the knowledge of the expert. According to the expert, three situations can be distinguished for the motor speed, namely, above, around and below the desired reference speed. By defining the system error between the measured speed and the desired speed, the propositions, higher, around and beneath the desired reference speeds are otherwise expressed as Positive, Zero and Negative errors.

For 2 inputs and N number of linguistic variables the numbers of rules are given as N^2. In this proposed method linguistic value of 5 is chosen which gives 25 rules. For fuzzyfication triangular fuzzyfication is used and for deffuzzyfication the centroid deffuzzyfication method is used in the proposed method. The fuzzy sets used in the proposed method are NB: Negative Big, NS: Negative Small, ZE: Zero Equal, PS: Positive Small, PB: Positive Big.

The look-up table for the proposed method is shown in Table-1 and FLC implementation using this is shown in Figure-3.

Table-1. Fuzzy rules for proposed system.

e_x Δe_x	PB	PS	ZE	NS	NB
PB	PB	PB	PB	PS	ZE
PS	PB	PB	PB	ZE	NS
ZE	PB	PS	ZE	NS	NB
NS	PS	ZE	NS	NB	NB
NB	ZE	NS	NB	NB	NB

Fuzzy logic based MRAS speed observer is shown in Figure-4. Conventionally PI controllers were used in adaptation mechanism which is replaced by a fuzzy logic controller so that the performance of the drive can be enhanced and also during load variations the speed can be kept constant.

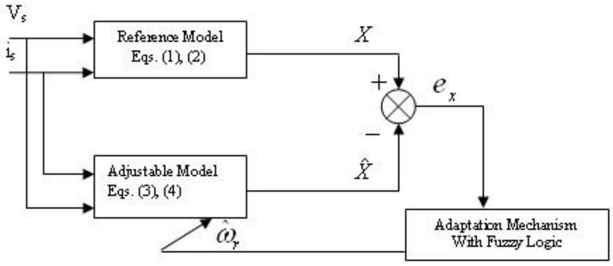

Figure-4. FLC based MRAS speed observer.

PROPOSED FUZZY LOGIC BASED HPWM MRAS SPEED OBSERVER

The proposed fuzzy logic based HPWM MRAS speed observer for sensorless control of induction motor drive is shown in Figure-5.

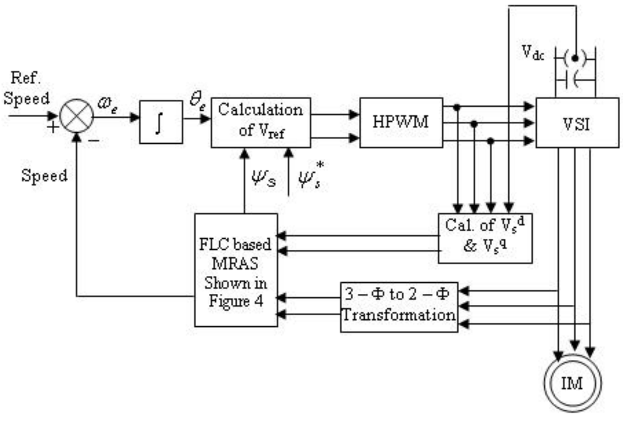

Figure-5. Block diagram of proposed FLC based HPWM MRAS speed observer.

In the proposed method, the position of the reference stator flux vector ($\overline{\psi_S}^{*}$) is derived by the adding slip speed and actual rotor speed. After each and every sampling duration actual stator flux vector ($\overline{\psi_S}$) is adjusted by the error and it tries to attain the reference flux space vector. Thus the flux error is minimized in each sampling interval. Reference values of the d and q axes stator fluxes and actual values of the d and q axes stator fluxes are compared in the V_{ref} calculator block. The errors in the d and q axes stator flux vectors are obtained as

$$\Delta\psi_s^{\ d} = \psi_s^{\ d*} - \psi_s^{\ d},\ \Delta\psi_s^{\ q} = \psi_s^{\ q*} - \psi_s^{\ d} \qquad (13)$$

We can determine the appropriate V_{ref} space vector by using flux error and stator ohmic drop and it is given as

$$V_s^{\ d*} = R_s i_s^{\ d} + \frac{\Delta\psi_s^{\ d}}{T_s},\ V_s^{\ q*} = R_s i_s^{\ q} + \frac{\Delta\psi_s^{\ q}}{T_s} \qquad (14)$$

Where, T_s is sampling period also known as the duration of sub-cycle

SIMULATION RESULTS AND DISCUSSIONS

To validate the proposed method simulations of conventional MRAS scheme and proposed scheme are performed for 3- phase 2 pole induction motor with parameters as R_r = 3.55 Ω, R_s= 4.15 Ω, L_r = L_s = 0.76 mH, L_m= 0.646 mH and moment of inertia of 0.33 kg/m^2. Figure-6 and 7 show the speed response and torque developed for the conventional MRAS drive for a speed of 100 rpm and in Figure-8 and 9 the speed response and torque developed are shown for the proposed drive. As can be seen from simulation results the ripples present in the torque are reduced and the steady state of the drive is reached faster than the conventional drive. Figure-10, 11 shows the speed response and torque developed at 1300 rpm with load applied at 1 sec for conventional MRAS. Figure-12, 13 shows the response of the proposed drive with a load of 10 N-m applied at 1 sec. In Figure-14, 15 and Figure-16, 17 the speed response and torque developed when the for both conventional and proposed drive when a load of 10 N-m applied at 0.8 sec and removed at 1.5 sec at 1300 rpm. From the waveforms it can be observed that when the load is applied the speed is remaining more stable for the proposed drive when compared to the conventional MRAS drive and the ripples present in the torque are also reduced.

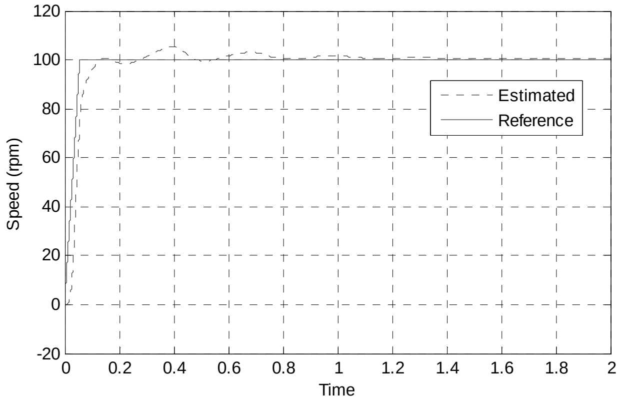

Figure-6. Speed response of conventional MRAS without load.

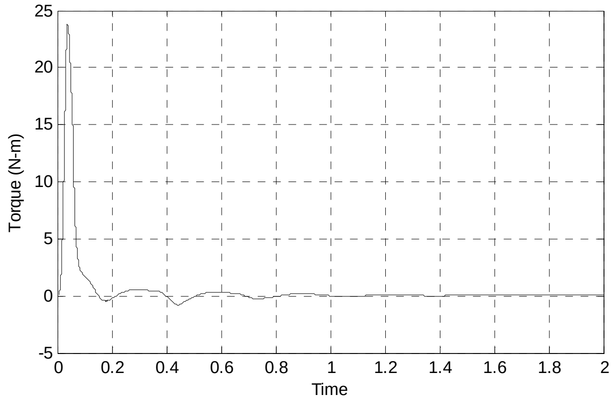

Figure-7. Torque developed for conventional MRAS.

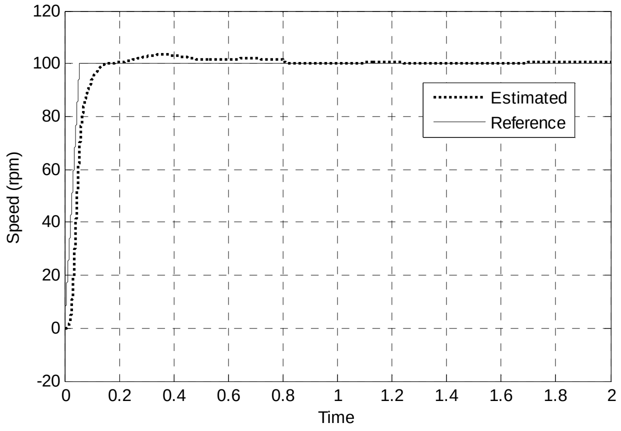

Figure-8. Speed response of proposed drive without load.

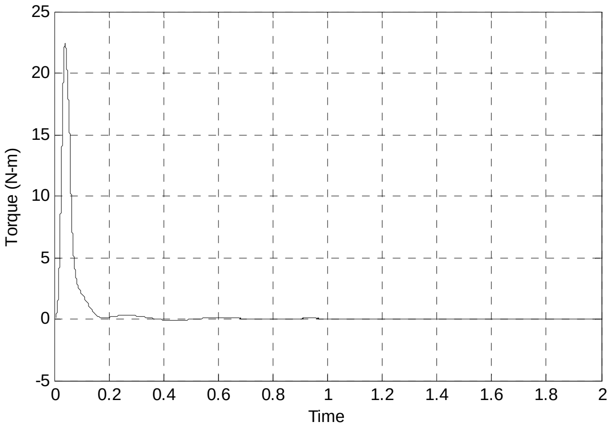

Figure-9. Torque developed for proposed drive.

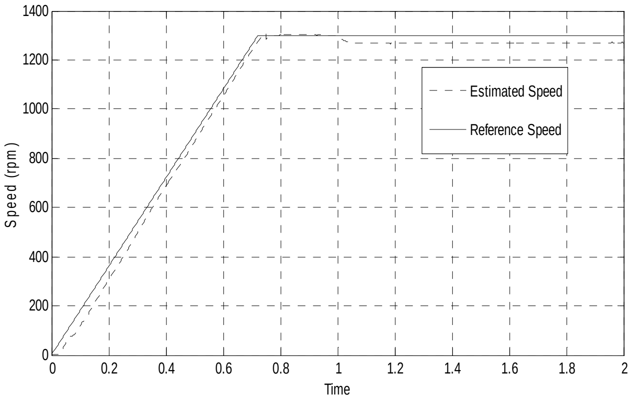

Figure-10. Speed response for conventional MRAS, load of 10 N-m applied at 1 sec.

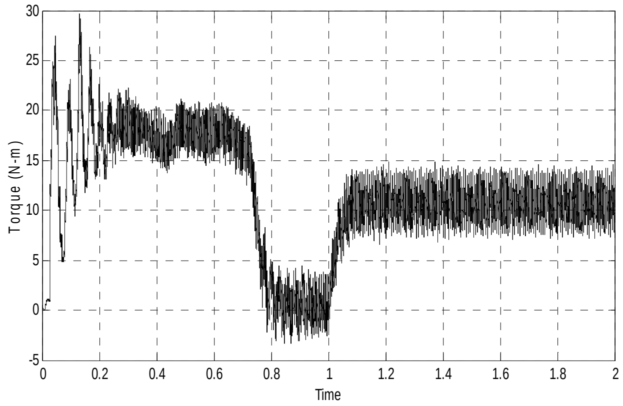

Figure-11. Torque developed for the above case.

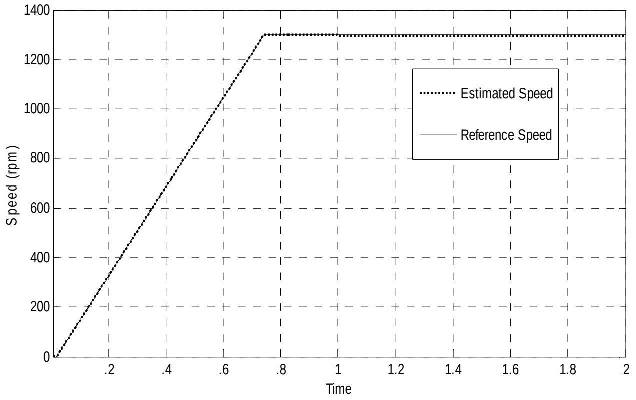

Figure-12. Speed response for proposed MRAS, load of 10 N-m applied at 1 sec.

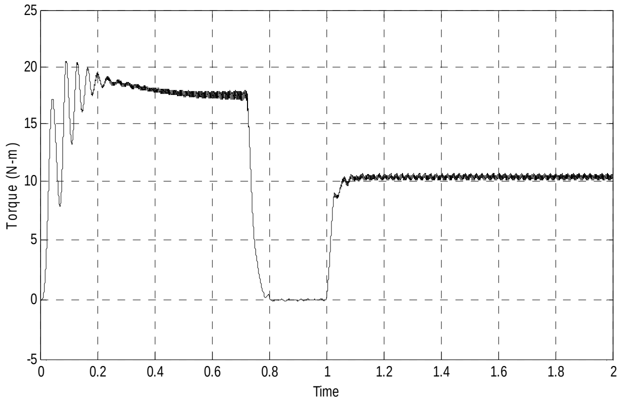

Figure-13. Torque developed for the above case.

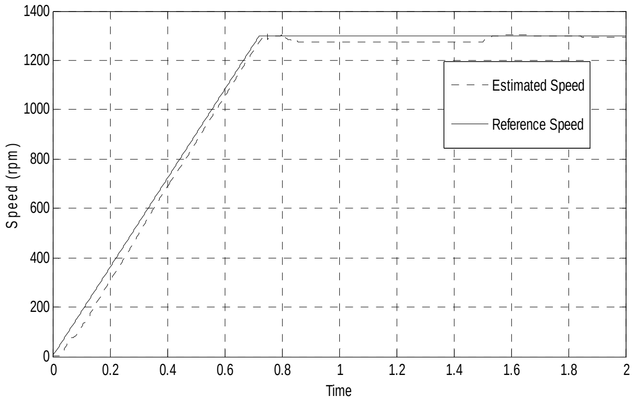

Figure-14. Speed response of conventional MRAS at 1300 rpm with step change in load, Load of 10 N-m applied at 0.8 sec and removed at 1.5 sec.

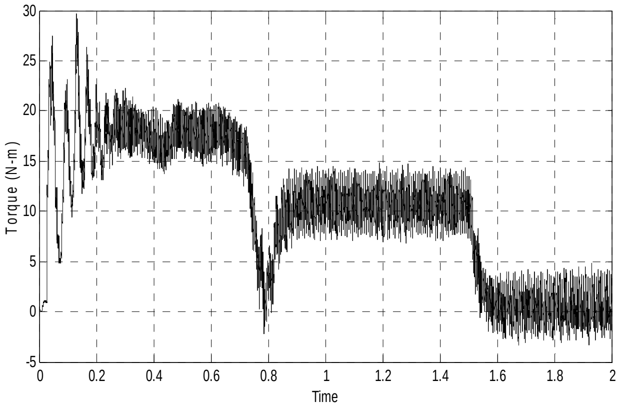

Figure-15. Torque developed for the above case.

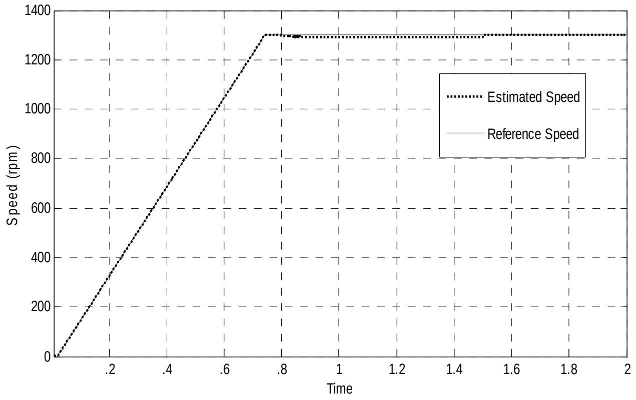

Figure-16. Speed response of Proposed MRAS at 1300 rpm with step change in load, Load of 10 N-m applied at 0.8 sec and removed at 1.5 sec.

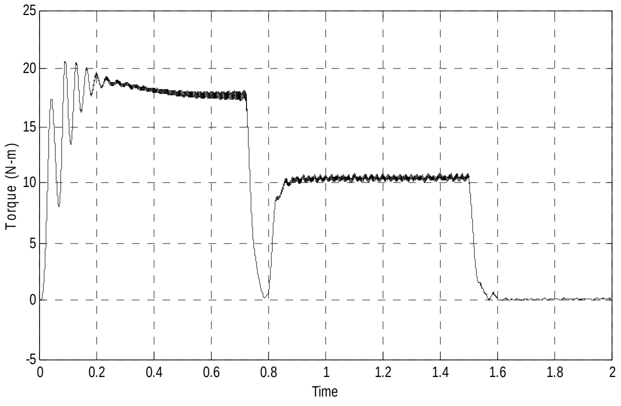

Figure-17. Torque developed for the above case.

CONCLUSIONS

Usually the control of induction motor drive during low speed range is very difficult and the speed performance during low speed region deteriorates. Also in the conventional MRAS control ripples are present in the torque and the speed gets affected with change in loads.

In this paper a novel fuzzy logic controller based HPWM- MRAS method for sensorless control of induction motor drive is proposed. The conventionally used PI controller in the adaptation mechanism of the MRAS observer is replaced by a fuzzy logic controller. As can be seen from the simulation results the performance of the drive during low speed region is improved and also when the load is applied the speed performance is better when the proposed drive is used. The fuzzy logic controller is mainly helpful when the load is varied the speed is less effected by the load variations.

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