

# SENSORLESS INDUCTION MOTOR DIRECT TORQUE CONTROL BASED ON MODEL REFERENCE ADAPTIVE SYSTEMS

Hamid M.B. Metwally, Sameh I. Selem, and Alhassan H.M.Alattar

*Department of Electrical power and machines, Faculty of Engineering, Zagazig University*

## ABSTRACT

The classical direct torque control (DTC) system of three phase induction motor suffers from many drawbacks such as the need for motor speed sensor, flux and torque ripples, and constancy of the stator resistance in the DTC controller. In this paper a sensorless system based on Model Reference Adaptive System (MRAS) is designed to estimate the rotor speed without using encoder. The classical and MRAS systems are compared. Computer simulation proves the effectiveness and robustness of the proposed MRAS for estimating the motor speed over the classical one.

ان نظام التحكم المباشر في عزم المحركات التآثيرية ثلاثية الأوجه يعاني من العديد من العيوب مثل الحاجة الى حساسات لقياس سرعة المحرك وتشوهات المجال والعزم الكهرومغناطيسى و ثبات مقاومة العضو الثابت. في هذا البحث تم تصميم نظام معتمد على نموذج النظام المرجعي التكييفي وذلك لقياس سرعة المحرك. تم عمل مقارنة بين النظام التقليدي والنظام المقترح. النتائج باستخدام برنامج الماتلاب تثبت فعالية وقوة النظام المقترح الذي تم تصميمه مقارنة بالنظام التقليدي.

*Keywords:* Induction motor, Direct torque control, Model reference adaptive system.

## 1. INTRODUCTION.

The direct torque control is developed by Takashi in 1984. DTC of IM has a simple control structure compared to field oriented control (FOC) technique.

DTC is similar to FOC in the sense that the motor torque and field are controlled independently. The difference is that in FOC the motor torque and stator flux linkage are controlled indirectly by the imaginary and real component of the stator current, respectively. While in DTC these quantities are controlled directly. Therefore, the DTC is faster than the FOC. There is no need for coordinate transformation and pulse width modulation (PWM) regulator as required in FOC. The DTC scheme for the control of AC machines becomes popular since its first industrial sensorless application introduced by ABB in 1995 [1]. According to ABB, the DTC is the ultimate and most advanced AC drive technology. The DTC scheme is almost 10 times faster than any AC or DC drive. The dynamic speed accuracy is 8 times better than any open loop AC drive and comparable to a DC drive that is using feedback. The current industry is looking for a simple, reliable, faster, efficient, low noise and economical motor drive scheme.

The only available variable speed drive, matching most of the desired requirements is an IM with DTC scheme.

Its advantages are summarized in Ref [2] such as no need for PWM, uses torque and flux as control parameters, all parameters are referred to stator frame, so no need for coordinate transformation. DTC however has some problems as direct control in flux and torque leads to high ripples in these components. Open loop integration problem and the problem of sensors required for speed measurement. The estimation of torque and flux involves the stator resistance ( $R_s$ ). This parameter varies during motor operation due to temperature variation, motor case deterioration and operation at low speeds, so it needs on line adaptation. Thus the only requirement is to eliminate or reduce some of the above operational drawbacks. Many papers are introduced. First in the field of torque ripple minimization authors of Refs. [3,4] replace the switching look-up table by space vector modulation (SVM) and use three-level inverter instead of two level one, authors of [5] use a modulated hysteresis comparator by adding reference signal to the reference torque signal this make the switching frequency constant. Another works are developed based on

A.I (Artificial intelligence). In Ref. [6] the authors replace the look-up table and hysteresis comparators by fuzzy logic controllers. Also in [7] the authors use ANFIS (artificial neural fuzzy interference networks).

The second problem is the variation of  $R_s$ . Due to the estimation of the stator flux depends on the stator resistance specially at low speeds as the resistance voltage drop appears dominantly at this region. So its variation affects the estimation of the flux. This estimation not only affects the flux value but also affects the overall system response. Stator resistance variation is due to temperature variation and skin effect. Ref. [8] estimates the stator resistance by deriving a mathematical expression for it from the motor model. Other works [9,10,11,12,13] are based on non-linear observers as MRAS and extended kalman filter (EKF). Also there are methods based on A.I as in Ref. [14] that uses FLC which needs pre-stored data about stator current change and stator resistance.

The third problem is the encoder-based (sensor control). Many papers have dealt with this problem. For examples, Ref. [15] which uses luenberger observer (L.O) instead of the classical encoder. In Refs. [9,10,11] the authors use EKF to estimate the required rotor speed. In Refs. [16,17] the authors use MRAS observer. Also in Ref. [9] the authors compare between EKF and MRAS observers. Author in Ref. [18] uses MRAS with neural integrator.

In this paper a sensorless system is proposed based on MRAS observer to solve the encoder problem. A comparison between the classical and MRAS systems is carried out using matlab program to prove the effectiveness and robustness of the proposed system.

## 2. DIRECT TORQUE CONTROL.

### 2.1 INDUCTION MOTOR MODEL.

The induction motor model can be expressed in space vector notation as [9].

Voltage equations:

$$v_s = i_s R_s + \frac{d\psi_s}{dt} \quad (1)$$

$$v_r = 0 = i_r R_r + \frac{d\psi_r}{dt} - (j w_r \psi_r) \quad (2)$$

Stator and rotor flux equations:

$$\psi_s = L_s i_s + L_m i_r \quad (3)$$

$$\psi_r = L_r i_r + L_m i_s \quad (4)$$

Mechanical equation:

$$\frac{dw_r}{dt} = \frac{1}{J} (T_e - T_m) \quad (5)$$

$$T_e = \frac{3P_p}{2} (i_s^* \times \psi_s) \quad (6)$$

Where  $v_s$  and  $i_s$  are stator voltage and current,  $\psi_s$  and  $\psi_r$  are stator and rotor flux,  $R_s$  and  $R_r$  are stator and rotor resistance,

$v_r$  and  $i_r$  are rotor voltage and current,  $w_r$  is the motor speed.

$L_s$ ,  $L_r$  are stator and rotor self inductance,  $L_m$  is the mutual inductance,  $T_e$  and  $T_m$  are electromagnetic and load torque,  $J$  is the moment of inertia and  $P_p$  is the pole pairs.

The motor final equations referred to the stationary reference frame in the state space representation are as follow:

$$\frac{d}{dt} \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{s\alpha} \\ \psi_{s\beta} \\ w_r \end{pmatrix} = \begin{pmatrix} -\gamma_2 R_s - \gamma_1 & -P_p w_r & k_1 & P_p w_r \gamma_2 & 0 \\ -P_p w_r & -\gamma_2 R_s - \gamma_1 & P_p w_r \gamma_2 & k_1 & 0 \\ -R_s & 0 & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 & 0 \\ 3P_p/2J & -3P_p/2J & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{s\alpha} \\ \psi_{s\beta} \\ w_r \end{pmatrix} + \begin{pmatrix} \gamma_2 & 0 & 0 \\ 0 & \gamma_2 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1/J \end{pmatrix} \begin{pmatrix} v_{s\alpha} \\ v_{s\beta} \\ T_m \end{pmatrix} \quad (7)$$

$$T_e = \frac{3P_p}{2} (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \quad (8)$$

Where  $i_{s\alpha}$ ,  $i_{s\beta}$  are stator alpha and beta current components respectively,  $v_{s\alpha}$ ,  $v_{s\beta}$  are stator alpha and beta voltage components respectively  $\psi_{s\alpha}$ ,  $\psi_{s\beta}$  are stator alpha and beta flux components respectively.

$$\sigma = (L_s L_r - L_m^2) / (L_s L_r), \gamma_1 = R_r / (\sigma L_r),$$

$$\gamma_2 = 1 / (\sigma L_s) \quad \text{and} \quad k_1 = R_r / (\sigma L_s L_r)$$

## 2.2 FLUX AND TORQUE ESTIMATION.

For the conventional DTC as shown in Fig. (1) the estimation of stator flux is obtained based on equation (1) using only measured stator voltage and current.

$$\psi_{s\alpha} = \int_0^t (v_{s\alpha} - i_{s\alpha} R_s) dt \quad (9)$$

$$\psi_{s\beta} = \int_0^t (v_{s\beta} - i_{s\beta} R_s) dt \quad (10)$$

It shows that the accuracy of flux Linkage measurements depend on how accurate the sensors used for measuring stator voltages, currents and integration technique. The modulus of stator flux linkage is given by:

$$\psi_s = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad (11)$$

And electromagnetic torque can be calculated also from the equation (6) which leads to equation (8).

## 2.3 CONTROL STRATEGY.

The estimated values ( $\psi_s$  and  $T_e$ ) are compared with their reference/command values and the error signals ( $e_\psi$  and  $e_T$ ) proceed to the corresponding hysteresis comparators. The flux linkage hysteresis comparator is of two, while torque hysteresis comparator is of three levels. The position of stator flux linkage ( $S_n$ ) is determined as

$$\theta = \tan^{-1} \left( \frac{\psi_{s\beta}}{\psi_{s\alpha}} \right) \quad (12)$$

Using this angle, the flux sector number (1 to 6) is determined. The two digits produced by hysteresis comparators and one by flux position are collectively used to trigger the switches of the VSI (voltage source inverter) by selecting appropriate voltage vector (0,1,2,...,7) using the optimizing switching lookup table (Table(1)) shown below.

Table (1) ST (switching table) of DTC

ST inputs		ST Outputs sectors( $S_n$ )							
		1	2	3	4	5	6		
flux	torque								
		$\Delta\psi_s = 1$	$\Delta T_e = 1$	V2	V3	V4	V5	V6	V7
		$\Delta T_e = 0$	V7	V0	V7	V0	V7	V0	V0
	$\Delta T_e = -1$	V6	V1	V2	V3	V4	V5		
$\Delta\psi_s = 0$	$\Delta T_e = 1$	V3	V4	V5	V6	V7	V8		
	$\Delta T_e = 0$	V0	V7	V0	V7	V0	V7		
	$\Delta T_e = -1$	V5	V6	V1	V2	V3	V4		

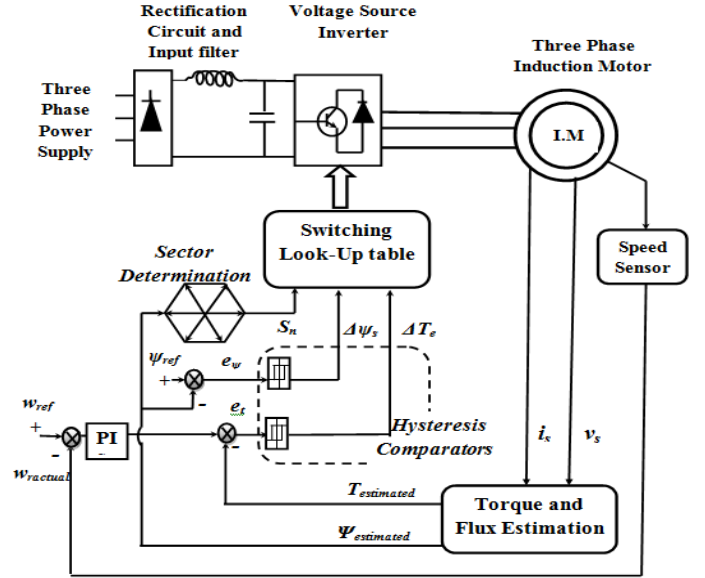


Fig (1) classical Direct Torque Control

## 3. MODEL REFERENCE ADAPTIVE SYSTEM OBSERVER.

MRAS speed observer is a simple kind of estimator because of its simple internal equations. There are many kinds of MRAS as rotor flux based; back e.m.f and reactive power based MRAS Ref. [19]. MRAS basic scheme is as shown in Fig (2). The scheme consists of two models, reference and adaptive one and the adaptation mechanism. The reference model ( $v_s - i_s$ ) depends on the voltages and current signals ( $v_s$  &  $i_s$ ) to estimate the rotor flux state components ( $\psi_r$ ). The adjustable one ( $i_s$  &  $w_r$ ) depends on the currents signals ( $i_s$ ) and estimated rotor speed ( $w_r$ ) from the adaptation mechanism (PI controller). And the adaptation mechanism estimates the required rotor speed based on PI controller. The difference between the reference and adjustable models state (errors) called the tuning signals which tune the adaptation mechanism. The adaptive model is updated by the adaptation mechanism to give the correct parameter (rotor speed or stator resistance) until satisfactory response is obtained. Fig (3) shows the block diagram of MRAS-DTC, the MRAS equations are as follows:

The reference model is given by[16] as:

$$\psi_{r\alpha} = \frac{L_r}{L_m} \left( \int_0^t (v_{s\alpha} - i_{s\alpha} R_s) dt - \sigma L_s i_{s\alpha} \right) \quad (13)$$

$$\psi_{r\beta} = \frac{L_r}{L_m} \left( \int_0^t (v_{s\beta} - i_{s\beta} R_s) dt - \sigma L_s i_{s\beta} \right) \quad (14)$$

Where  $\psi_{r\alpha}$ ,  $\psi_{r\beta}$  rotor flux alpha and beta components respectively

The adjustable model is given by:

$$\frac{d\psi_{r\alpha}}{dt} = \frac{1}{T_r} (L_m i_{s\alpha} - \psi_{r\alpha} - w_r T_r \psi_{r\beta}) \quad (15)$$

$$\frac{d\psi_{r\beta}}{dt} = \frac{1}{T_r} (L_m i_{s\beta} - \psi_{r\beta} - w_r T_r \psi_{r\alpha}) \quad (16)$$

The adaptive law for rotor speed is proved according to Popov's criterion of hyperstability.

$$w_r = w_{r0} + (k_p v_t + k_i \int_0^t v_t dt) \quad (17)$$

Where  $w_{r0}$  is the initial motor speed,  $k_p, k_i$  are the proportional and integral constants of the PI controller,  $v_t$  is the tuning signal from the error between reference and adaptive model.

$$v_t = (\psi_{r\beta} \hat{\psi}_{r\alpha} - \hat{\psi}_{r\beta} \psi_{r\alpha}) \quad (18)$$

Where  $\hat{\psi}_{r\alpha}$ ,  $\hat{\psi}_{r\beta}$  are the estimated rotor flux alpha and beta components respectively.

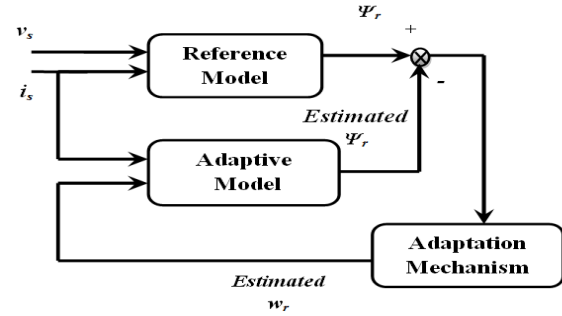


Fig (2) MRAS for  $w_r$  estimation

#### 4. SIMULATION RESULTS

The designed systems are tested to prove their effectiveness using the matlab / simulink program. The speed is set as a reference value as shown in fig.(4) load torque is set to the value of 10 N.m (constant load torque).

##### 4-1 The designed system for Sensorless control.

as shown in Fig (4), the speed is measured using encoder. Other system based on MRAS is able to track the rotor speed without using encoder with low steady state percentage error. Referring to the swing equation (5) the motor speed will reach to its steady state without oscillation if the difference between the electromagnetic and load torque is zero N.m.

**Acceleration speed region** the speed is increased from (0 to 1 seconds) then the electromagnetic torque is accelerated above the load torque to set the motor to the desired speed as shown in fig.(7 and 8).

**Constant speed region**, from (1 to 2 seconds ) the speed is constant then the electromagnetic torque and load torque are equal.

**Deceleration speed region**, from (2 to 3 seconds ) the speed is decreased then the electromagnetic torque is decelerated below the load torque to set the motor to the desired speed.

##### 4-2 Magnetic flux magnitude and components.

For classical and MRAS-DTC, the DTC controller is able to set flux magnitude to its reference value 1 wb as shown in fig.(5). The flux trajectory is near to be a circle as shown in figs (6.a & b).

##### 4-3 Electromagnetic torque ( $T_e$ ).

As shown in figs. (7&8) electromagnetic torque of the classical and MRAS-DTC is identical and generated according to the requirement of the load torque except for acceleration and deceleration region for the required speed.

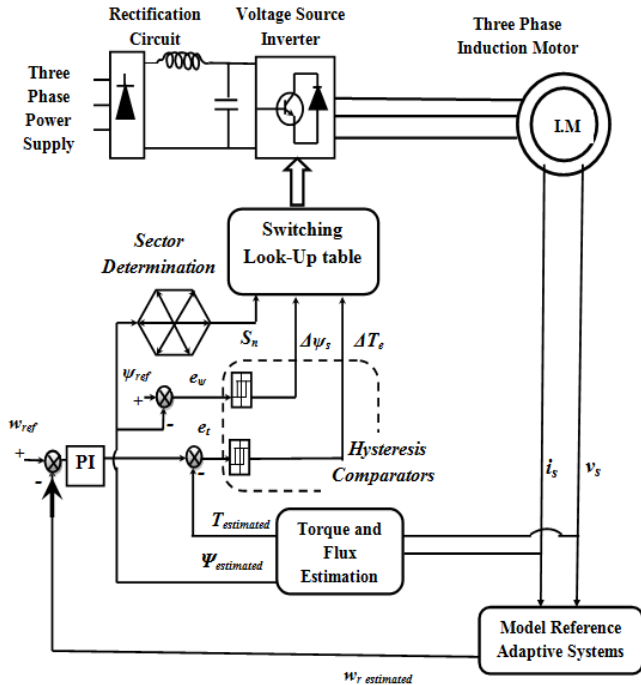


Fig (3) Direct Torque Control Based on MRAS observer

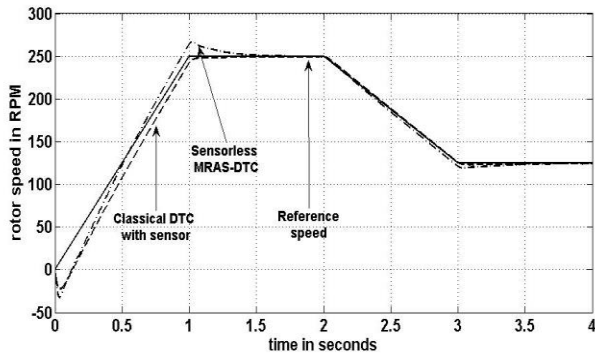


Fig (4) Illustrates speed estimation using classical and MRAS DTC

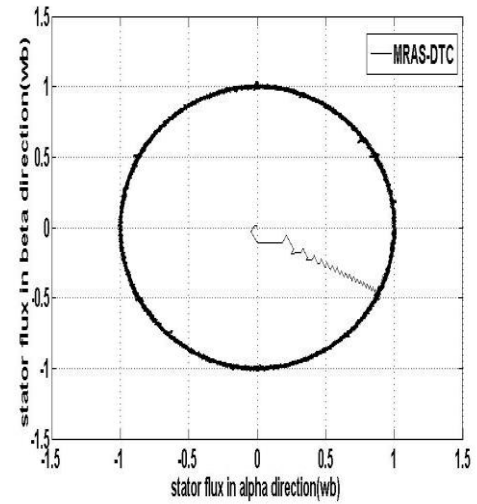


Fig (6-b) Flux trajectories for MRAS-DTC

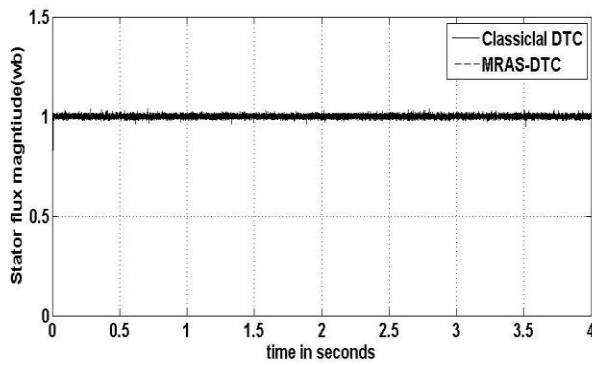


Fig (5) Stator flux magnitude for all systems

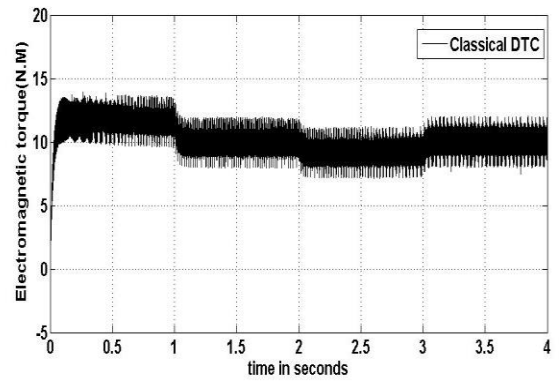


Fig (7) Electromagnetic torque for classical system

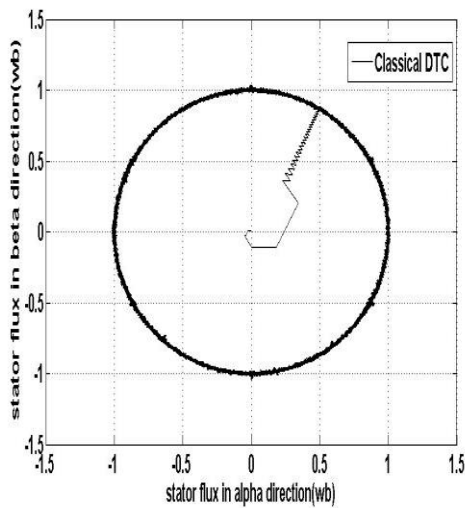


Fig (6-a) Flux trajectories for classical system

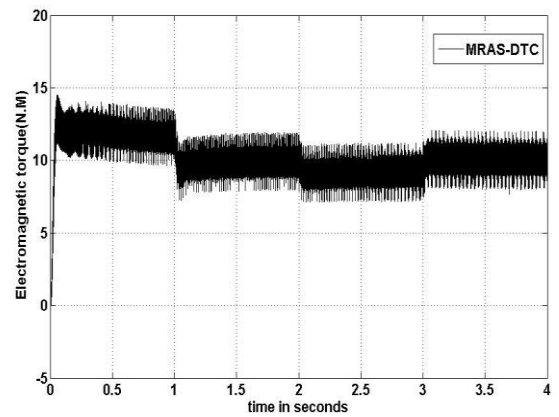


Fig (8) Electromagnetic torque for MRAS-DTC system

## 5. CONCLUSION

In this paper the proposed systems based on MRAS is effective in the speed sensorless system for DTC scheme. Simulation shows that these systems are robust in the estimation and tracking of the rotor speed. This eliminates the need for using encoder which has many problems such as noise, large space for its components and connections cables, data lost in case of any problems. So these systems have a wide attention nowadays with the combination with DTC system.

The comparison between the designed systems proves that the MRAS system has main improvements to the DTC scheme.

- Low complexity because of equations simplicity
- Speed estimation without using encoders.
- Better rotor speed response.
- No dropping in flux trajectory (circular path)
- High robustness in the DTC scheme because of the above points.

## Appendix

Induction motor details are as in Table (2):

Table (2) induction motor name plate data

$P$ (kw)	$f$ (Hz)	$Jl$ (kg.m <sup>2</sup> )	$Bl$ (N.m /r/s)	$Pp$	$V$ (volt)	$I$ (amp)
3	50	0.006	0.001	2	380	6.9
$R_s$ ( $\Omega$ )	$R_r$ ( $\Omega$ )	$L_s$ (H)	$L_r$ (H)	$L_m$ (H)	$Nm$ (rpm)	$Te$ (N.m)
2.283	2.133	0.231	0.231	0.22	1430	20

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