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# A Novel Sensorless Vector Control of High-speed Hysteresis Motor Drive

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**ABSTRACT**

*Hysteresis motors are super high speed motors that used in special industries such as high-speed centrifuges, micro gas turbines, and etc. They are basically synchronous motors; however they can works in asynchronous mode. In most reported applications it is controlled in open-loop scheme and there isn't any considerable research on closed-loop control of this type of motor due to its special and limited applications. This papers presents a novel filed oriented (vector) control of a high-speed hysteresis motor. On this way, the rotor flux is oriented and indirect vector control is employed. Due to cost a difficulty of installation the rotor position/speed sensor in high speed hysteresis motors, the rotor position and speed is accurately estimated by employing a model reference adaptive system (MRAS). The validity of presented vector control and sensorless scheme is demonstrated via some simulations.*

***Keywords:*** *hysteresis motor; sensorless; vector control; model reference adaptive system (MRAS), drive*

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## 1. INTRODUCTION

The hysteresis motors are well-known for using them in super-high-speed applications like gas centrifuges or in low power (fractional horse-power) applications as video recorder that needs smooth torque.

These motors have simple structure, similar to induction motors: a winding stator with 3-phase sinusoidal distributed windings and a rotor that consists of a thin magnetic ring around a non-magnetic shaft. Figure 1 shows a cross section of a hysteresis motor [1, 2].

The torque of the motor is developed due to the hysteresis losses induced in the rotor. The starting current is at most 150% of its full load current that can pull into synchronism any load inertia coupled to its rotor. One of advantages of hysteresis motor is its noiseless operation because of having no teeth, saliency or winding on the rotor. In comparison with other types of motors, hysteresis motors have lower efficiency as high as 75% and low power factor less than 0.5.

When a hysteresis motor is operating at synchronous state there would be no needs of speed value notification [3].

But hysteresis motors can also operate at asynchronous condition and keep its stability. So in this case it is necessary to identify the rotor speed value. Using speed sensors to identify the rotor speed has high cost and reduces the reliability of control system. Moreover, in some cases, the rotor rotates in the vacuum and installation of position/speed sensor is impossible. Therefore, using a speed estimator is more convenient.

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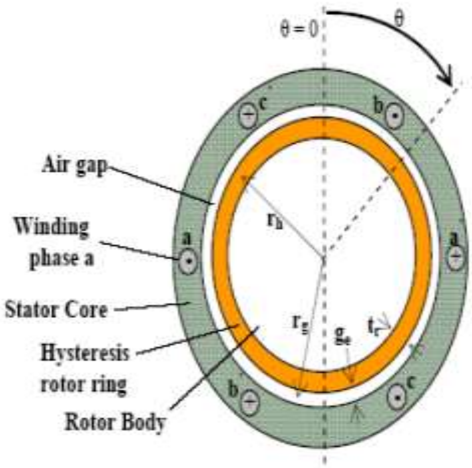


***Fig. 1:*** *Cross Section of a Circumferential-flux Hysteresis Motor.*

For applications that the reference speed and the load torque are constant or vary much slowly, the hysteresis motor is controlled as open-loop [4]. However for applications that motor may put at asynchronous conditions or load torque varies fast, open-loop control can't work well. In this situation, closed-loop control is more suitable. Field oriented control (FOC) is a well-known technique in motor drive designing. On the other hand, the rotor speed/position value is needed for field orientation and speed feedback of the system. In this paper, for the first time a novel speed sensorless vector control is developed and applied to a hysteresis motor. As follows, at first a dynamic model of hysteresis motor is presented. Then a model reference adaptive system (MRAS) is developed to speed estimation and to eliminate the speed/position sensor. Afterwards, a novel speed-sensorless drive for a hysteresis motor is presented on the basis of FOC method.

## 2. DYNAMIC MODELING OF HYSTERESIS MOTOR

Figure 2 shows the steady state equivalent circuit of a hysteresis motor [5]. Figure 3 shows its dynamic model in d-q reference frame [6]. This model is the general d-q model of a synchronous motor. The difference between the model of hysteresis and general synchronous motors comes from the modeling of rotor material that for the hysteresis motor is so different and has been proposed in [7, 8].

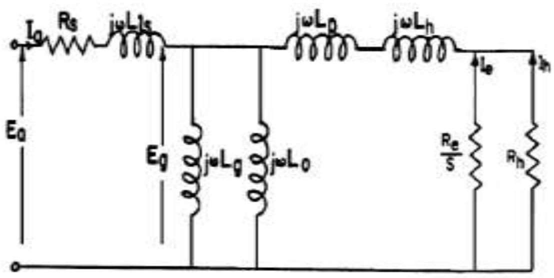


***Fig. 2:*** *General Equivalent Circuit of Hysteresis Motor.*

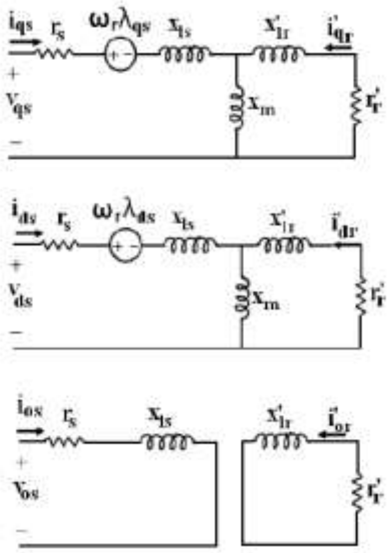

***Fig. 3:*** *Hysteresis Motor Dynamic Model in d-q Reference Frame.*

The hysteresis motor voltage and linkage flux equations in the synchronously d-q rotating reference frame is represented by [9]:

$$\begin{cases} v_{qs} = p\lambda_{qs} + \omega_r \lambda_{ds} + r_s i_{qs} \\ v_{ds} = p\lambda_{ds} - \omega_r \lambda_{qs} + r_s i_{ds} \\ v_{0s} = p\lambda_{0s} + r_s i_{0s} \end{cases} \quad (1)$$

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix} = \begin{bmatrix} L_{ls}+L_m & 0 & 0 \\ 0 & L_{ls}+L_m & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} \times \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \end{bmatrix} \quad (2)$$

$$\begin{cases} 0 = p\lambda'_{qr} + r'_r i'_{qr} \\ 0 = p\lambda'_{dr} + r'_r i'_{dr} \\ 0 = p\lambda'_{0r} + r'_r i'_{0r} \end{cases} \quad (3)$$

$$\begin{bmatrix} \lambda'_{qr} \\ \lambda'_{dr} \\ \lambda'_{0r} \end{bmatrix} = \begin{bmatrix} L'_{lr}+L_m & 0 & 0 \\ 0 & L'_{lr}+L_m & 0 \\ 0 & 0 & L'_{lr} \end{bmatrix} \times \begin{bmatrix} i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \quad (4)$$

Electromagnetic torque and rotor speed are obtained from:

$$T_{em} = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (5)$$

$$T_{em} - T_{mech} = \frac{2J}{P}\frac{d\omega_r(t)}{dt} \quad (6)$$

## 3. MRAS BASED SPEED ESTIMATOR

Model reference adaptive system (MRAS) scheme is an approach to estimate motor speed from measured terminal voltage and current for speed-sensorless motor control [10]. It is based on computation of the instantaneous reactive power. As illustrated in Figure 4 this system consists of two models: reference model and adaptive model. The outputs of reference model and adaptive model are real and estimated reactive power respectively. Figure 4 shows that the reference model inputs are stator voltage and current and adaptive model's are stator current and estimated rotor speed feedback. The error between outputs of two models is applied to a suitable proportional integrator (PI) controller which the output of this PI controller is estimated rotor speed.

In the d-q reference frame two sets of equation are developed to compare reactive power of the hysteresis motor in the reference model and adaptive model. The reference model equation does not involve the rotor speed value, while the adaptive model one needs the estimated rotor speed.

The reactive power in the reference model is calculated from cross product of the stator voltage and current as:

$$Q_{ref} = v_{qs} i_{ds} - v_{ds} i_{qs} \quad (7)$$

And the reactive power in the adaptive model is computed by substituting Eq. (1), Eq. (2) and Eq. (4) in Eq. (7) as follow:

$$Q_{est} = L_s \hat{\omega}_r (i_{ds}^2 + i_{qs}^2) + L_s (i_{ds}\frac{di_{qs}}{dt} - i_{qs}\frac{di_{ds}}{dt}) \quad (8)$$

As mentioned, the subtraction of $Q_{ref}$ and $Q_{est}$ is applied to a PI controller and the result is estimated rotor speed.

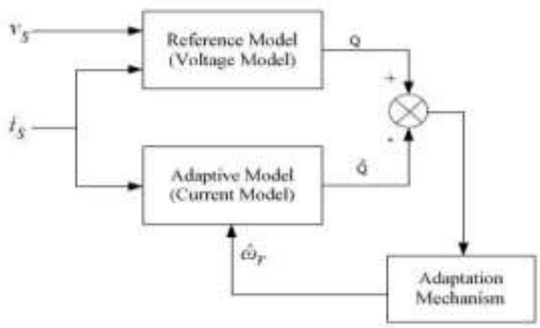


*Fig. 4: Block Diagram of MRAS based Speed Estimator.*

## 4. SPEED-SENSORLESS FOC FOR HYSTERESIS MOTOR

In a DC machine the rotor flux is controlled by adjusting the field current, $I_f$, and electromagnetic torque is controlled independently of flux by adjusting the armature current, $I_a$. But control of a three-phase ac machine, as hysteresis motor, is not as straightforward as that of a DC machine because of the interactions between the stator and rotor fields [6]. In a three-phase AC machine, by aligning the rotor flux with the d axis of d-q reference frame, the machine would be controlled as well as a DC machine. With this alignment that is called field orientation, the d-q components of rotor flux are as follow:

$$\lambda'_{dr} = \lambda'_r \qquad (9)$$

$$\lambda'_{qr} = L_m i_{qs} + L'_r i'_{qr} = 0 \qquad (10)$$

With $\lambda'_{qr}$ zero, the equation of electromagnetic torque reduced to:

$$T_{em} = \frac{3}{2}\frac{P}{2}\lambda'_{dr} i'_{qr} \qquad (11)$$

By substituting $i'_{qr}$ from Eq. (10) in Eq. (11), it can be written in the desired form of:

$$T_{em} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L'_r}\lambda'_{dr} i_{qs} \qquad (12)$$

It shows that independently of rotor flux, the torque can be controlled by adjusting the q component of stator current, $i_{qs}$. If $\lambda'_{dr}$ is to be constant, $d\lambda'_{dr}/dt$ must be zero. As this condition and that of $\lambda'_{qr}$ is zero, it would be found out that $i'_{dr}$ must be zero:

$$\underset{=0}{v'_{dr}} = r'_r \underset{=0}{i'_{dr}} + p\underset{=0}{\lambda'_{dr}} - (\omega_e - \omega_r)\underset{=0}{\lambda'_{qr}} \qquad (13)$$

If $i'_{dr}$ is kept to zero, then:

$$\lambda'_{dr} = L_m i_{ds} \qquad (14)$$

So the rotor flux can be independently controlled by tuning the other stator current component, $i_{ds}$. The block diagram of speed-sensorless vector control of a hysteresis motor by means of FOC method is illustrated in Figure 5. As it's shown in Figure 5 an indirect FOC method is used in this motor drive which does not rely on the measurement of the air gap flux situation. Electromagnetic torque can be controlled by regulating $i_{qs}$ and speed slip. Rotor flux can be controlled by regulating $i_{ds}$.

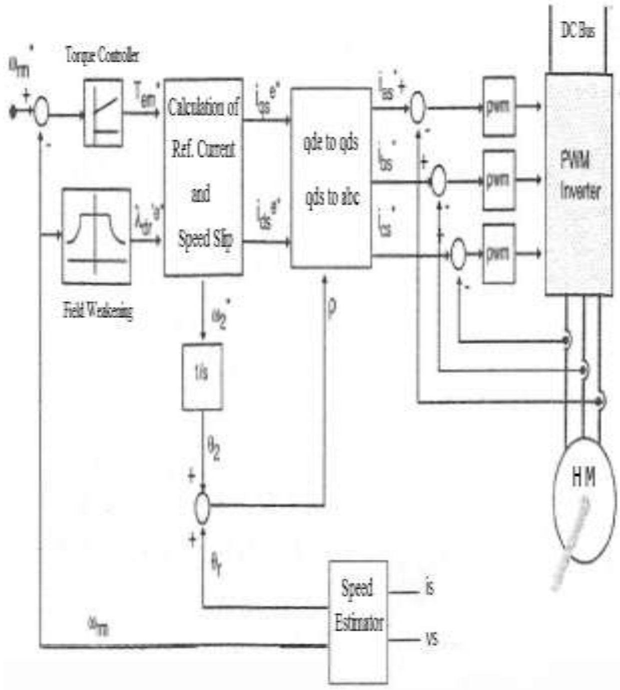


*Fig. 5: Block Diagram of Speed-sensorless FOC for Hysteresis Motor.*

## 5. SIMULATION RESULTS

The developed speed-sensorless hysteresis motor drive has been simulated for a 60000 rpm super-high-speed hysteresis motor in Matlab/Simulink. The corresponding parameters are summarized in Table I. Simulations are carried out at synchronous and asynchronous conditions by step changes in reference speed. Figure 6 shows the stator phase voltage ($v_{as}$) and its d-q components ($v_{ds}$ and $v_{qs}$). As it is shown $v_{ds}$ and $v_{qs}$ values would be constant when motor reaches steady state condition because the d-q reference frame rotates at synchronous speed. In Figure 7 stator phase current ($i_{as}$) and its d-q components ($i_{ds}$ and $i_{qs}$) are shown. The steady state values of d-q components depend on the B-H curve of the rotor material. In Figure 8 the electromagnetic torque, rotor speed and estimation error at synchronous condition are illustrated. As we see the estimated speed follows the real rotor speed accurately and the estimation error is about 0.17%. So it can be noticed that the speed-sensorless drive works properly at synchronous condition. To see that this drive also operate at asynchronous conditions as well as synchronous one, step changes have been applied to the reference speed. Figure 9 shows the electromagnetic torque, rotor speed and estimation error when a decrease step change is applied to reference speed and in this case the estimation error is about 0.15%, and Figure 10 shows the results for an increase change in reference speed. As it is illustrated also in asynchronous conditions the developed speed-sensorless drive operates properly and in this case the estimation error is about 0.20%.

***Table I:*** *Hysteresis Motor Parameters.*

| | | |
|---|---|---|
| Number of poles | p | 2 |
| Rated output power | P | 60 [W] |
| Rated voltage | $V_s$ | 400 [V] |
| Rated frequency | $f_s$ | 1000 [Hz] |
| Stator leakage reactance | $X_{ls}$ | 152 [Ω/ph] |
| Stator resistance | $r_s$ | 36 [Ω/ph] |
| Equivalent resistance due to eddy current | $R_e$ | 3288 [Ω/ph] |
| Equivalent resistance due to hysteresis ring | $R_h$ | 127 [Ω/ph] |
| Equivalent reactance due to hysteresis ring | $X_h$ | 163.7 [Ω/ph] |
| Unsaturated incremental reactance | $X_o$ | 451 [Ω/ph] |
| Saturated incremental reactance | $X_p$ | 13 [Ω/ph] |
| Air gap equivalent reactance | $X_g$ | 1217 [Ω/ph] |

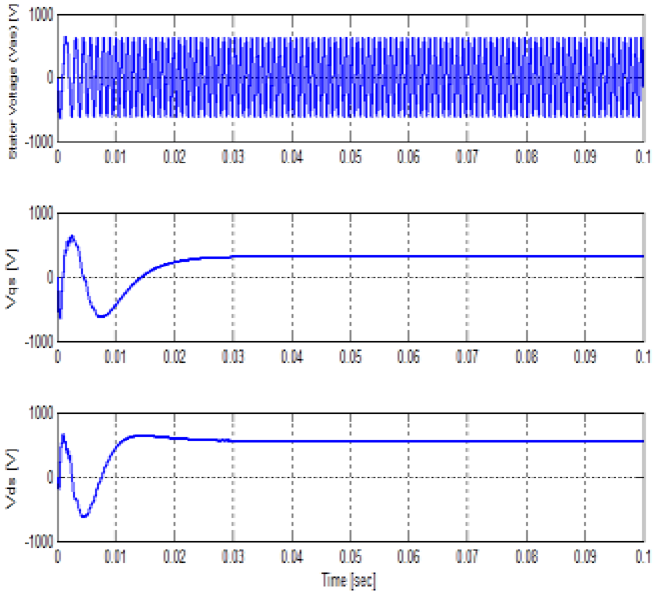


***Fig. 6:*** *Instantaneous Values of* $v_{as}$, $v_{ds}$ *and* $v_{qs}$.

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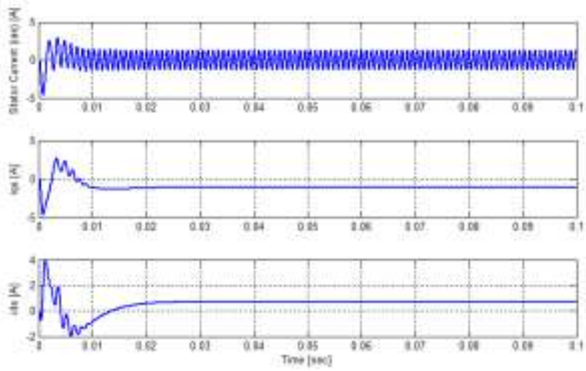

***Fig. 7:*** *Instantaneous Values of $i_{as}$, $i_{ds}$ and $i_{qs}$.*

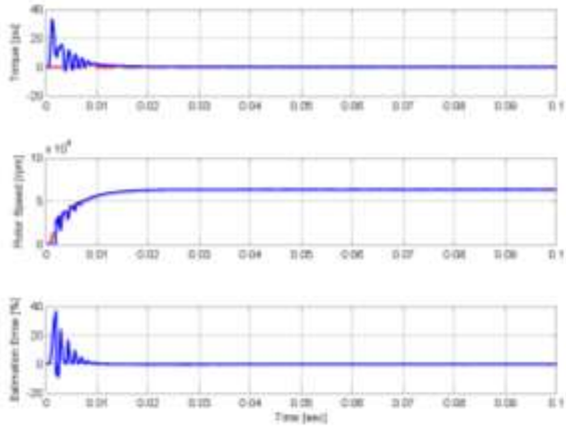

***Fig. 8:*** *Electromagnetic Torque, Rotor Speed and Estimation Error at Synchronous Condition.*

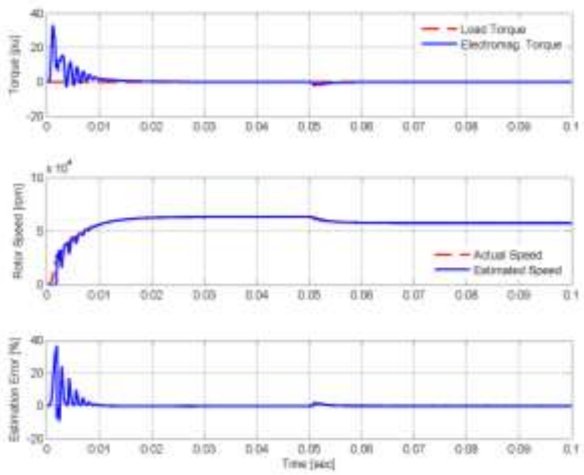


***Fig. 9:*** *Electromagnetic Torque and Rotor Speed in Ref. Speed Decrease.*

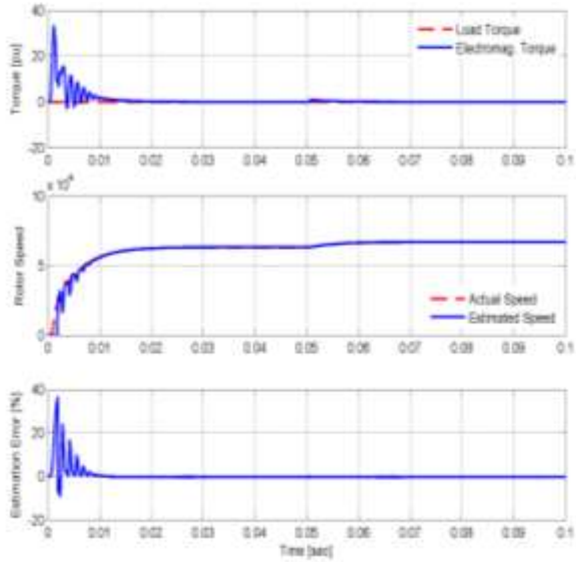


***Fig. 10:*** *Electromagnetic Torque and Rotor Speed in Ref. Speed Increase.*

## 6. CONCLUSIONS

A speed-sensorless field oriented control drive for a high-speed hysteresis motor has been developed and implemented in Matlab/Simulink. In this investigation a dynamic model of hysteresis motor based on d-q theory has been used. To eliminate the speed-sensor usage a MRAS based speed estimator has been improved and applied to a FOC speed control system of hysteresis motor. It has been shown that this speed-sensorless drive operates properly in any condition of hysteresis motor function.

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