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Low cost high performance self-starting sensorless single phase induction motor drive

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ABSTRACT

The present paper is directed to achieve a low-cost high-performance self-starting single phase induction motor (SPIM) drive system. A phase shifted pulse width modulation (PWM) trains feeding the motor will replace the starting and running capacitors. Adaptive sliding mode control, enhance with model reference adaptive control (MRAC), is implemented to achieve high performance sensorless SPIM drive. The obtained results confirm the feasibility of the proposed system in starting and fast tracking the reference speed with nearly zero percentage overshoot and zero steady-state error. Moreover, the proposed SPIM drive system is robust to external load torque disturbances and insensitive to system parameter variations. Extensive simulations have been conducted to confirm the validity of the proposed system.

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1. INTRODUCTION

Single-phase induction motors are widely used in residential industrial applications such as fans, washing machines, dishwashers, clothes dryers, compressors, heating pumps, refrigerators [1]–[4]. This is due to their merits over low rating DC motors including rigidness, low cost, high reliability, less maintenance requirement, no need for excitation. However, single phase induction motors (SPIMs) are not self-starting motors due to their stationary and pulsating air-gap magnetic field [5], [6] and therefore a mechanism for starting a SPIM is crucial. The SPIMs are classified according to their starting methods including two-capacitor SPIM, which combines the features of high starting torque and good running performance.

Improving SPIM performance during starting and running operation has attracted the attention of many researchers. The research [7], [8] have implemented an electronically controlled capacitor to improve the performance of SPIM. Liu [9] has used electronic switch to adjust the effective capacitance value of the capacitor for maximizing the starting torque of a SPIM. Liu *et al*. [10] have proposed a simple hardware circuit, including a digital signal processor DSP chip and one power electronic device, to improve a SPIM torque and its efficiency. The digital signal processor (DSP) controls the switching sequence of the power electronic device and this process leads to attain the required capacitance values for starting and running operation. The authors in [6] have proposed an arrangement to connect the main and auxiliary windings through a triode for alternating current (TRIAC) device and capacitor. With this arrangement, high starting torque is achieved by providing proper TRIAC switching sequences.

Sensorless speed estimation of electric drive has received a great concern of many researchers and several approaches have been found in the literature. The implementation of Kalman filter for speed estimation of three phase induction motor is presented in [11], [12]. The authors of the publications [13]–[15] have utilized fuzzy logic observer to estimate the speed of three phase induction motor drive. The use of sliding mode observer for speed estimation has been considered in [16], [17]. The implementation of model reference adaptive system (MRAS) for speed estimation of motor drives has attracted several researchers, because it is simple to design and utilize [18]. The implementation of MRAS for speed estimation of three phase induction motor is presented in [19], [20]. Khan and Verma [21] have implemented MRAS for speed estimation of direct controlled switched reluctance motor. Merrassi *et al.* [22] have combined MRAS and neural network to provide an observer for estimating the speed of three phase induction motor.

Sliding mode control has been extensively applied for speed control of three phase induction, some of these references are given here. On the other hand, the publications deal with the use of SLMC for speed control of single-phase induction motor are very few and the literature in this research area needs to be enhanced. The work presented in [23], [24] deals with the application of sensorless SLMC for three phase induction motor. The utilization of adaptive SLMC for three phase induction motor drives have been conducted in [25]–[27]. The research [28], [29] have utilized SLMC for single phase induction motor drive.

The current research work is devoted to develop a high-performance self-starting sensorless single phase induction motor drive with reduced cost. Instead of using two capacitors for starting and running, the two tasks are accomplished by a phase shifted pulse-width modulation pulse width modulation (PWM) train of pulses fed to the main and auxiliary windings through a single-phase bridge PWM VSI. The MRAS approach is utilized to estimate the motor speed with no need for a speed sensor, like shaft encoder or tach-generator. Robust motor speed control with minimized chattering and high time specifications is achieved using adaptive SLMC.

2. MATHEMATICAL MODELLING

2.1. Single phase induction motor

The voltages and flux linkages of a SPIM in stationary reference frame can be expressed in a matrix form as given in (1) and (2) [28]–[30]. The developed electromechanical torque is expressed in (3). The equation of motion of SPIM rotor is obtained by equating the inertia torque to accelerating torque as presented in (4), where T_{mech} is the externally applied mechanical torque, $D\omega_{rm}$ is the damping torque and D is the damping coefficient. The motor speed can be derived from (4), and it is given in (5).

$$\begin{bmatrix} v_{qs} \\ v_{ds}^{/} \\ v_{qr}^{/s} \\ v_{dr}^{/s} \end{bmatrix} = \begin{bmatrix} r_{qs} & 0 & 0 & 0 \\ 0 & r_{ds}^{/} & 0 & 0 \\ 0 & 0 & r_r^{/} & 0 \\ 0 & 0 & 0 & r_r^{/} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds}^{/} \\ i_{qr}^{/s} \\ i_{dr}^{/s} \end{bmatrix} + \begin{bmatrix} p/\omega_b & 0 & 0 & 0 \\ 0 & p/\omega_b & 0 & 0 \\ 0 & 0 & p/\omega_b & -\omega_r/\omega \\ 0 & 0 & \frac{\omega_r}{\omega_b} & p/\omega_b \end{bmatrix} \begin{bmatrix} \psi_{qs} \\ \psi_{ds}^{/} \\ \psi_{qr}^{/s} \\ \psi_{dr}^{/s} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \psi_{qs} \\ \psi_{ds}^{/} \\ \psi_{qr}^{/s} \\ \psi_{dr}^{/s} \end{bmatrix} = \begin{bmatrix} x_{lqs} + x_{mq} & 0 & x_{mq} & 0 \\ 0 & x_{lds}^{/} + x_{md} & 0 & x_{md} \\ x_{mq} & 0 & x_{lr}^{/} + x_{mq} & 0 \\ 0 & x_{md} & 0 & x_{lr}^{/} + x_{md} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds}^{/} \\ i_{qr}^{/s} \\ i_{dr}^{/s} \end{bmatrix} \tag{2}$$

$$T_{em} = \frac{P}{2\omega_b}(\psi_{qr}^{/s} i_{dr}^{/s} - \psi_{dr}^{/s} i_{qr}^{/s}) = \frac{P}{2\omega_b}(\psi_{ds}^{/} i_{qs} - \psi_{qs}^{/} i_{ds}^{/}) = \frac{P}{2\omega_b} x_{mq}(i_{dr}^{/s} i_{qs} - i_{qr}^{/s} i_{ds}^{/}) \tag{3}$$

$$J\frac{d\omega_{rm}}{dt} = T_{em} - T_{mech} - D\omega_{rm} \text{ N.m} \tag{4}$$

$$\omega_{rm} = \frac{1}{J}\int (T_{em} - T_{mech} - D\omega_{rm})\, dt \text{ N.m} \tag{5}$$

2.2. Model reference adaptive system

Model reference adaptive schemes have been utilized for various applications due to their attractive features of perfect response, robustness and stability [31]–[35]. Speed estimation process using MRAS observer can be accomplished through three inherent subsystems: reference model (RM), adaptive model (AM) and adaptation mechanism. The reference model can provide the reference rotor flux components based on the measured stator electrical signals. The RM is represented in stationary reference frame based on (1) and (2) as [36], [37]:

$$p\psi_{qr}^{/s} = \frac{X_r}{x_{mq}}[v_{qs}^s - (r_{qs} + \sigma X_s p) i_{qs}^s] \tag{6}$$

$$p\psi_{dr}^{/s} = \frac{X_r}{x_{mq}}[v_{ds}^s - (r_{ds} + \sigma X_s p) i_{ds}^s] \tag{7}$$

The rotor flux components of AM are expressed in terms of stator current and mechanical rotor speed based on (1) and (2) [37] as given in (8) and (9). The third subsystem is the adaption mechanism producing the estimated speed value, which is treated to minimize the error between the reference and estimated fluxes. This task is accomplished using PI controller, which minimizes the tuning signal and feed it back to the adaptive model. The tuned and estimated speed signals are expressed in (10) and (11). A filter is added to minimize the oscillations which may occurs in the estimated speed.

$$p\psi_{qr}^{/s} = -\frac{1}{\tau_r}\psi_{qr}^s - \omega_r \psi_{dr}^s + \frac{x_{mq}}{\tau_r} i_{qs}^s \tag{8}$$

$$p\psi_{dr}^{/s} = -\frac{1}{\tau_r}\psi_{dr}^s + \omega_r \psi_{qr}^s + \frac{x_{mq}}{\tau_r} i_{ds}^{/s} \tag{9}$$

$$e_w = \psi_{qr}^s \psi_{dr}^{\wedge} - \psi_{dr}^s \psi_{qr}^{\wedge} \tag{10}$$

$$\omega_r^{\wedge} = (k_p + \frac{k_i}{p}) e_w \tag{11}$$

2.3. Adaptive sliding mode control

To acquire SPIM drive having the features of fast speed response, fast recovery for load torque changes and insensitivity to parameter variations adaptive sliding mode control is utilized. The chosen state variables to implement SLMC are speed error and its derivative, as expressed in (12). The developed torque of SPIM in field-oriented control can be given in (13) [38].

$$X_1 = \omega_{ref} - \omega_f \tag{12}$$

$$T_{em} = \frac{P x_{msrd}}{2\omega_b X_r}(\Psi_{dr}^s i_{qs}^s - \psi_{qr}^s i_{ds}^s) \tag{13}$$

Based on vector control concepts, the current i_{ds} and the rotor flux vector $|\Psi_r|$are aligned. In addition, the currents i_{qs}^s and i_{ds}^s are orthogonal to each other [25]. Under these circumstances, $\Psi_{qr} = 0$ and $\Psi_{dr} = |\Psi_r|$. Therefore, the developed torque equation can be simplified to that given in (14) [39], and the equation of the torque constant K_T can be expressed in (15). Based on (3) and (14) the state space SPIM drive system can be expressed in (16).

$$T_{em} = \frac{P x_{msrd}}{2X_r \omega_b}\Psi_{dr}^s i_{qs}^s = K_T i_{qs}^s \tag{14}$$

$$K_T = \frac{P x_{msrd}}{2X_r \omega_b}\psi_{dr}^{s*} \tag{15}$$

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{D}{J} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_T}{J} \end{bmatrix} u \tag{16}$$

To limit the motor acceleration and deceleration, fixed acceleration segments as part of sliding trajectory are used. The two segments are expressed in (17) and (18). The equation of the control structure in achieving the reaching and existing conditions is expressed in (19), where ϕ_1 and ϕ_2 are the controller gains, which are derived from the existing condition given in (20) [39]. To minimize the oscillations (chattering) and maintain the robustness feature of SLMC, the control function is modified to the one given in (21). The proportional factor K_d enables the controller to reject external disturbances and the damping factor e_1 enables the controller to minimize chattering in the system trajectory. The factor e_0 is added to prevent obtaining infinite when $S_i + e_1 . |X_1|$ becomes less than 1.

$$S_2 = X_2 - X_{2max} \tag{17}$$

$$S_3 = X_2 + X_{2max} \tag{18}$$

$$u = \varphi_1 X_1 + \varphi_2 X_2 \tag{19}$$

$$S_i \dot{S}_i < 0 \tag{20}$$

$$u = (\varphi_1 X_1 + \varphi_2 X_2)\frac{S_i(1+k_d)}{|S_i|+e_0+e_1.|X_1|} \tag{21}$$

3. THE PROPOSED SYSTEM

The schematic diagram of the proposed SPIM drive system is shown in Figure 1. The measured stator currents and voltages I_a and I_b, V_a and V_b are supplied to MRAS block to estimate the rotor speed. The estimated feedback speed ω_f^* and the reference speed ω_{ref} is compared to provide the error signal. The error signal, which represent the state variable X_1 and its derivative X_2 are fed to the adaptive SLMC which provides the control signal u. This output signal is integrated and then multiplied by the torque constant K_T to obtain the electromagnetic torque T_e^*. This torque is used to evaluate the stator current command in synchronously reference frame I_q^*. The stator direct axis current in synchronously reference frame $I_d^*$is computed using the rated rotor flux linkage Ψ_r^*.

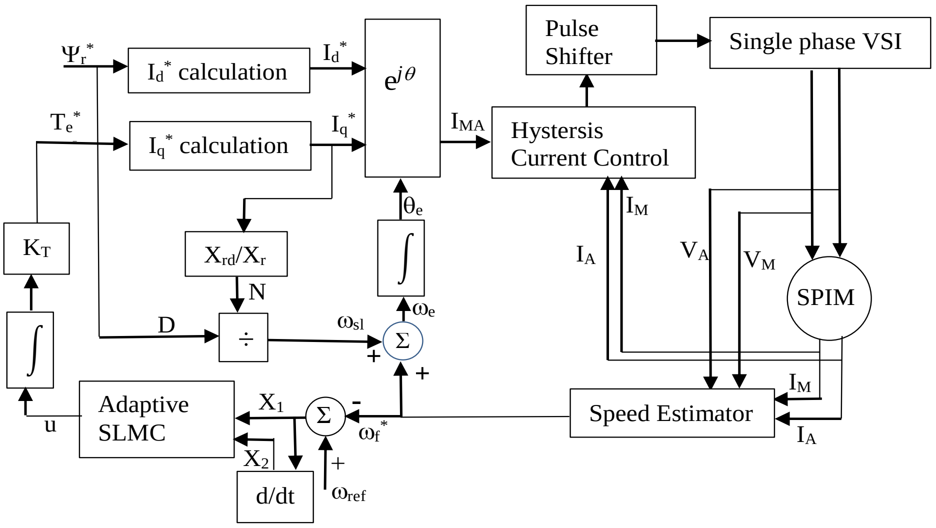

Figure 1. The schematic diagram of the proposed system

The slip speed ω_{sl} is found using the rotor flux linkage command Ψ_r^* and the computed current I_q^*. The estimated rotor speed is added to the slip speed to produce the synchronous speed ω_e, which is integrated to find the synchronous angular positron θ_e. Now the currents $I_q^*$and I_q^*can be transformed to stationary reference frame. These two currents are compared with the corresponding measured stator currents through two hysteresis controllers. The two outputs from the controllers are treated by applying appropriate shifting and the processed gating pulses are fed to the inverter to start and run the motor.

4. RESULTS AND DISCUSSION

Figures 2 to 4 are generated to examine the performance operation of both speed estimator and phase shifter of pulses fed to the VSI. It can be observed that the estimated speed is in close agreement with the simulated speed, even with step change in reference speed. Moreover, it can be seen that the utilized phase shifter has the capability to start and run the SPIM under speed changes. After having this confidence, a number of computer simulation have been conducted to examine the performance of the proposed SPIM drive system. Figures 5 to 7 are presented to test the robustness feature of the drive system in rejecting load torque disturbances. In this test, the motor is subjected to a step change in the load torque from no load condition at starting to full load torque at 3 second after starting, as shown in Figure 7. As can be noticed in Figure 5 the proposed controller can completely reject the applied disturbance torque. The response of the main and auxiliary currents to the applied step change in the motor's load is shown in Figure 6.

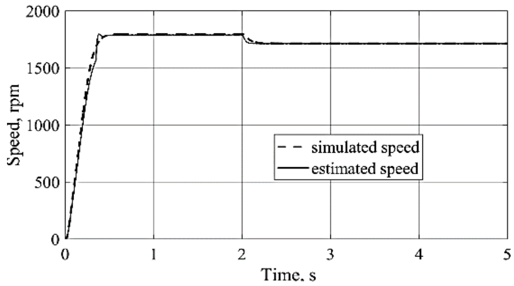

Figure 2. Comparison between simulated speed currents and speed under step change in speed

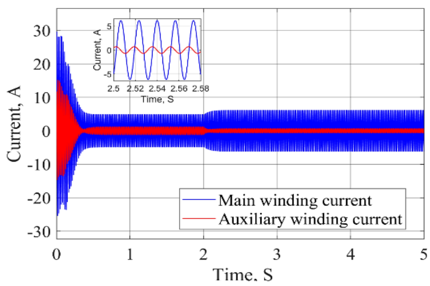

Figure 3. Main and auxiliary winding estimate under changes in reference speed

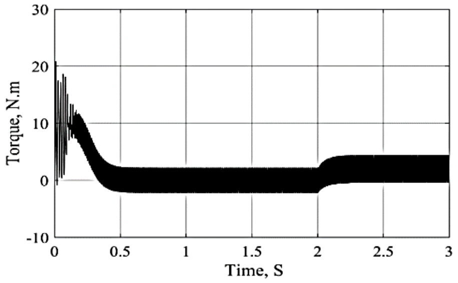

Figure 4. Torque response to step change in reference speed

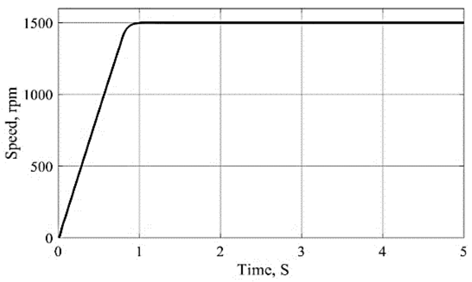

Figure 5. Speed response for step change in the load torque

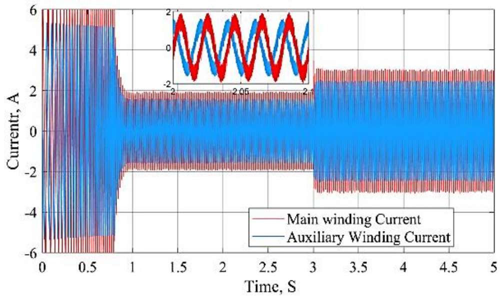

Figure 6. The responses of stator currents for load torque disturbance

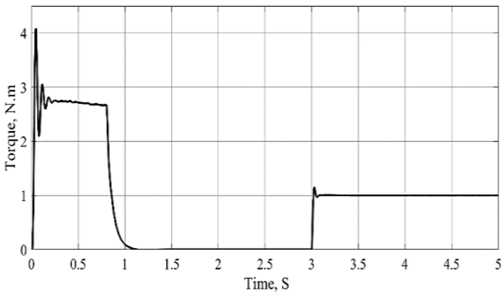

Figure 7. The load torque step response

Figure 8 shows the speed response for one step change in the load toruque of 1 N.m at two seconds after starting, as shown in Figure 9, and two step changes in the motor speed occurred after 3 and 6 seconds of starting. As can be noticed the motor can repond smoothely to the changes in the load torque and rotaional speed. The speed response to step changes has the features of fast response, zero percentage overshoot and zero steady state errors. Moreover, the recovery time of speed reponse to step in load torque is close to zero.

To examine the insensitivity of the proposed controller to system parameter variations, Figures 10 and 11 are created. Figure 10 shows the speed response for an increase of 10% in the main winding resistance and Figure 11 presents the speed response under 10% increase in the auxiliary winding inductance. In these figures one step change in the load torque at 2 s and two step changes in the speed command at 3 and 6 s are applied. As can be observed the controller follow the prescribed reference speeds smoothly and accurately with no effect due to system parameter variations.

The previous obtained results confirm that the proposed control system possess the features of fast dynamic response with no overshoot and zero steady-state error. Moreover, it is robust to external load disturbances and insensitive to system parameter changes. It can be stated that all aimed targets in the proposed SPIM drive system are achieved.

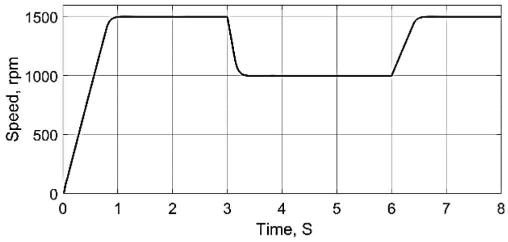

Figure 8. Speed response for two speed step changes and one torque step change

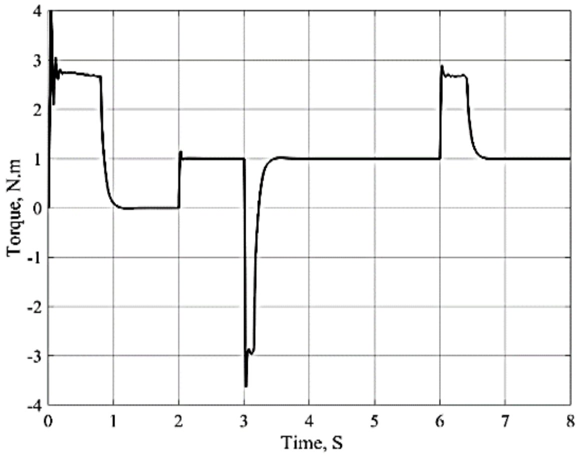

Figure 9. The torque response for two step change in speed and one torque step change

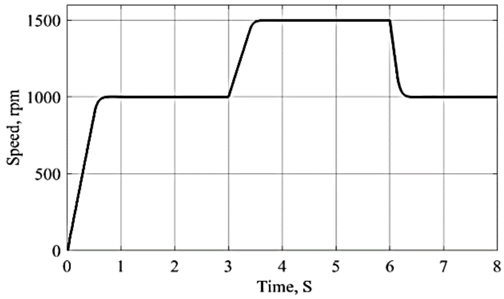

Figure 10. Speed response for an increase of 10% in the main winding resistance

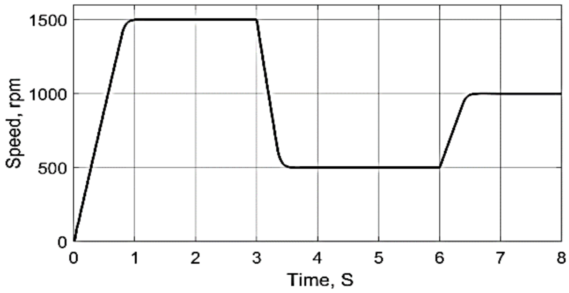

Figure 11. Speed response for an increase of 10% in the auxiliary winding inductance

5. CONCLUSION

The performance of the proposed low cost sensorless self-starting SPIM drive system, under different operating conditions, has been assessed by conducting extensive MATLAB/Simulink simulations. Self-starting and smooth running are achieved via the phase shifter to the pulses supplied to VSI inverter. The motor speed is estimated using MRAS observer and adaptive SLMC is utilized to acquire the robust speed controller. The obtained results show that the motor can start and run smoothly, and the speed is accurately estimated, even under step changes in speed and torque commands. Moreover, the speed controller provides results confirming that a high-performance control system, in terms of time specifications and robustness, is reached. The features of fast dynamic response, very fast recovery time for step changes, zero parentage overshoot, zero steady-state error, rejection for load disturbances and insensitivity to parameter variations are all achieved.

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