Improved scalar control based on slip compensation from virtual speeds in three-phase induction motor drives

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ABSTRACT

The typical scalar control method adjusts the speed based on changes in power frequency while maintaining a constant V/f ratio corresponding to the nominal flux. The disadvantage of the typical scalar method is that the motor operating speed is always less than the reference speed by a slip value. This research proposes an improved scalar control method based on slip compensation for speed control in the induction motor drive. A virtual speed according to the rotor flux-based model reference adaptive system (RF-MRAS) technique is applied to the current model to estimate the proper compensation of the rotor slip. The suitability of the control method is verified through comparative simulations between the typical and proposed methods under various operating conditions by the MATLAB/Simulink software.

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1. INTRODUCTION

Induction motors (IMs) are one of the most common types of electric motors that transfer electrical energy to mechanical energy in rotating of drive applications. IM applications cover the domestic, commercial, and industrial fields with flexible control ranges according to speed and torque requirements [1], [2]. A modern motor drive system includes a controllable power converter integrated sensors that provide voltage to the motor [3], [4]. Based on the precision requirements, two primary groups of methods are applied to the speed adjustment of the induction motor drive (IMD), including vector control (VTC), and scalar control (SLC) [5]–[7]. The vector control method group, including the field-oriented control (FOC) and the direct torque control (DTC), can precisely control motor speed in sensor or sensorless mode corresponding to the hardware structure and control algorithm [8], [9]. However, vector control requires a powerful hardware configuration for speed control aimed at high-precision applications [10], [11]. On the contrary, moderate precision applications should apply scalar control techniques to reduce hardware investment costs [12], [13].

The primary principle of IMD applying the SLC strategy in speed control is to keep the air gap flux as a constant value through the voltage/frequency (V/f) ratio [14], [15]. SLC is divided into two main branches: open-loop control and closed-loop control. In the SLC method using the open-loop method, the voltage will be supplied proportionately to the required control frequency, and no feedback signal from any sensor is needed [16]–[19]. In the SLC method, which uses a closed-loop structure, the control algorithm uses feedback signals from sensors to adapt the V/f ratio to control motor speed. Preview study [20], [21], the sensor's feedback rotor speed is compared with the reference speed to estimate a slip compensating for the asynchrony of the control frequency in the algorithm. SLC algorithms using feedback current signals without a speed sensor are called sensorless scalar control (SSLC). SSLC is a robust development direction in the SLC group because current sensors integrated inside the converter are less complicated than installing speed sensors at the motor shaft terminal. In a typical SSLC approach, feedback current signals are used to compensate for the voltage drop across the stator resistor and adjust the V/f ratio to match the slip to increase the accuracy of the control algorithm [22]–[25]. The preview study [26] proposes a hybrid voltage SSLC to control the motor speed. In this method, a boost voltage is used in the starting phase; a speed observer and a flux observer are used to calculate the estimated speed and estimated torque for the compensation algorithm in the V/f technique. The disadvantage of the method is that it must use the rotor current, which is difficult to measure in practice, for the compensation calculation.

This paper proposes an improved SSLC method; the feedback currents are applied in the RF-MRAS techniques [27]–[29] to estimate a virtual speed for determining the rotor slip in the frequency and voltage compensating. The rotor slip will be continuously updated every 1 second to ensure the motor operates stably and accurately when there are changes in control requirements. The mathematical method section of the paper will present the machine model of the IMD, typical SLC, and the proposed SLC technique. The simulation compares the typical SLC methods and the proposed SLC under similar operating conditions. The advantages and disadvantages of the proposed technique are analyzed in the discussion part.

2. SCALAR METHOD FOR SPEED CONTROL

In this section, the system of differential equations corresponding to the dynamic model of the IM is presented in the first sub-part. The open-loop SLC technique is briefly depicted in the second sub-part. Finally, a closed-loop SLC method using virtual speed is proposed to improve the SLC technique's effectiveness, performance, and stability.

2.1. Mathematical equation system of the IM

The dynamic operating characteristic of IM is a system of non-linear equations. When an IM is supplied with an input voltage, the vector current and flux response will follow the system of differential equations, as shown in (1)-(4) [30], [31].

$$u_s^i = R_s i_s^i + \frac{d\Psi_s^i}{dt} \tag{1}$$

$$0 = R_r i_r^i - jp\omega_m \Psi_r^i + \frac{d\Psi_r^i}{dt} \tag{2}$$

$$\Psi_s^i = L_s i_s^i + L_m i_r^i \tag{3}$$

$$\Psi_r^i = L_r i_r^i + L_m i_s^i \tag{4}$$

Where: “i” corresponding coordinate system, including [α-β] stationary or [x-y] rotating coordinate. i_s^i, i_{sr}^i: stator, rotor current space vectors; Ψ_s^i, Ψ_r^i: stator, rotor flux space vectors; R_s, R_r: stator, rotor resistance; L_s, L_r, L_m: stator, rotor, magnetizing inductance; and p: number of pole pairs. After determining the stator current vectors and rotor flux vectors in the system of (1)-(4), by combining these two quantities in one calculation, the electromagnetic torque can be obtained through (5).

$$T_e = \frac{3p}{2} Im\{i_s^i . \Psi_r^{*i}\} \tag{5}$$

2.2. Typical open-loop scalar control

The advantage of the SLC method is its simplicity and independence from control algorithm parameters, but the accuracy of motor speed control is not high. The core principle of the open-loop SLC method is to adapt the ratio of voltage and frequency simultaneously corresponding to the demand motor speed. A general control structure of the SLC is shown in Figure 1. Reference speed is converted to the demand control frequency, and then this demand is used to determine the value of control voltage according to (6):

$$V_m = \frac{V_{m\_rated}}{f_{rated}} f \tag{6}$$

Reference three-phase voltages in the [abc] coordinate systems are determined from the amplitude “V_m” and the control frequency “f” sinusoidal pulse width modulation (SPWM) technique modulates the reference voltage signal into inverter switching pulses to supply power for the IM.

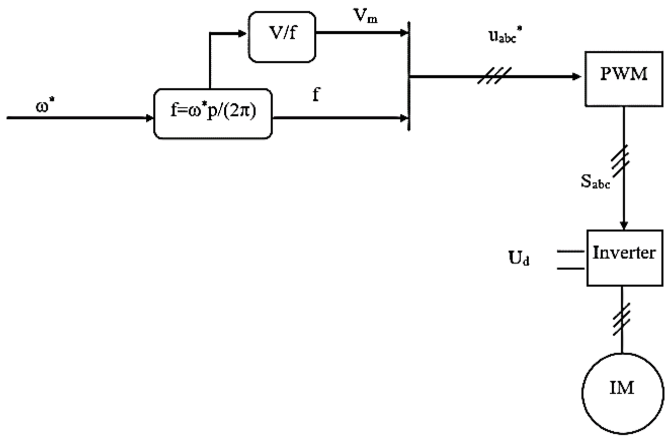

Figure 1. Block diagram corresponding to IMD using open-loop SLC

2.3. Closed-loop scalar control based on slip compensation using RF-MRAS speed sensorless

Closed-loop SLC is a more precise technique than open-loop SLC in speed control; however, the corresponding hardware must be more configurable with sensors integrated into the controller. This paper proposes using a virtual speed to estimate slip compensation for the SLC method to improve the speed control's precision. The proposed control structure of the closed-loop SLC is described in Figure 2.

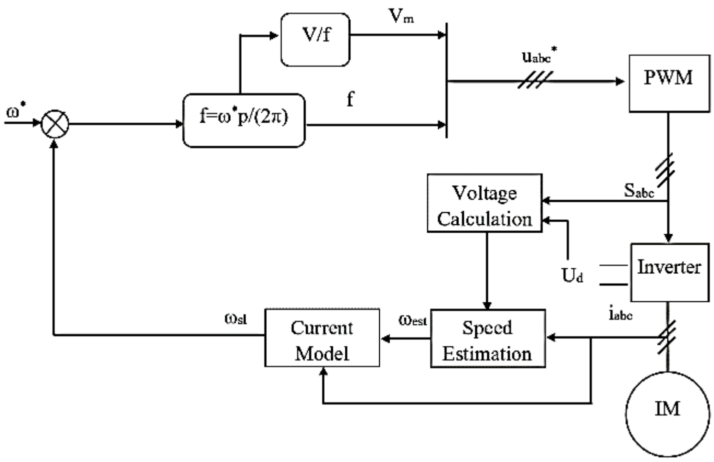

Figure 2. Block diagram corresponding to IMD using improved closed-loop SLC

The DC-link voltage combined with the inverter switching impulses determines the control voltage [32] for the speed estimation. Electrical signals, including voltage and current in the [abc] coordinate system, are converted to the [αβ] stationary coordinate using Clark's formula, as in (7).

$$\begin{bmatrix} X_{S\alpha} \\ X_{S\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \end{bmatrix} \tag{7}$$

Where X: u or i.

The speed estimation based on RF-MRAS [26] (or another proper estimation method) is applied to calculate the virtual speed "ω_{est}." Then, the current model uses the virtual speed from speed estimation and feedback current to calculate the rotor flux space vector, as shown in (8) and (9).

$$\Psi_{R\alpha} = \int (\frac{R_R L_m}{L_R} i_{S\alpha} - \frac{R_R}{L_R} \Psi_{R\alpha} - \omega_{est} \Psi_{R\beta}) dt \tag{8}$$

$$\Psi_{R\beta} = \int (\frac{R_R L_m}{L_R} i_{S\beta} - \frac{R_R}{L_R}\Psi_{R\beta} + \omega_{est}\Psi_{R\alpha})dt \quad (9)$$

The rotor angle can be determined from rotor flux components, using (10), and the synchronous speed "ω_s" of rotor flux can be calculated as in (11). The rotor slip can be calculated from the differences between synchronous speed and estimated speed, as shown in (12).

$$\gamma = arctg(\frac{\Psi_{R\beta}}{\Psi_{R\alpha}}) \quad (10)$$

$$\omega_s = \frac{d\gamma}{dt} \quad (11)$$

$$\omega_{sl} = \frac{1}{p}(\omega_s - \omega_{est}) \quad (12)$$

The rotor slip is fed back to compensate for the reference speed to achieve the demand operating speed of the IMD. As a result, the proposed SLC control method's operating characteristics are improved compared to the typical SLC method.

3. SIMULATION RESULTS

Two IMD models using typical SLC and rotor slip compensation SLC methods are simulated to evaluate the performance of the improved technique in controlling motor speed. The parameters of the IM in the model are listed: i) stator/rotor resistance (Ω): 3.18/2.12, ii) stator/rotor/magnetizing inductance (H): 0.21/0.21/0.19, iii) number of pole pairs: 2, iv) rated motor speed (rpm): 1420, and v) rated torque (Nm): 14.8.

3.1. Case 1

The reference speed of the motor is set at 1/3 of the rated synchronous speed value (500 rpm). The initial load torque is maintained at a value of 4 Nm; at 4 seconds, the load torque increases to 50 percent (6 Nm). Two control algorithms, including typical SLC, as shown in Figure 1, and rotor slip compensation SLC, in Figure 2, have been simulated to evaluate the performance in speed control. According to the typical SLC method, the motor operates stably, but the actual motor speed deviates from the reference speed by a rotor slip, described in Figure 3(a). As the load increases at 4 s, the rotor slip will increase, as shown in Figure 3(b).

According to the proposed SLC, the differences between the actual motor speed and the reference speed are very high due to the starting phase, so the compensation mode will be performed when the motor has operated stably in a steady state. In this simulation, the compensation mode is delayed by 0.7 seconds and updated continuously with a 1-second cycle. At 0.7 seconds, the slip compensation mode is activated, the motor speed fluctuates due to changes in electrical frequency, and quickly returns to a stable state. The update cycles retain the same compensation value from 0.7 to 4 seconds during the operating time because the slip does not change, as shown in Figure 3(c). At 4 seconds, due to increased load, the motor speed decreases, the slip compensation algorithm is updated at 4.7 seconds, and a new compensation value is adjusted for the speed control. The IM quickly overcomes the transient process and operates stably with actual speed following the reference speed, described in Figure 3(d).

3.1. Case 2

The reference speed of the motor is set as a step function (300/600/900 rpm). The load torque is maintained at a value of 4 Nm during the operation. The motor works in a stable manner in the typical control method, corresponding to the various slips, as shown in Figures 4(a) and 4(b).

According to the proposed SLC, at 300 rpm, A compensation value is performed at 0.7 seconds; however, the actual speed is not immediately accurate, then the compensation slip is updated at the next cycle of 1.7 seconds, and the motor speed is tracked as the reference speed. According to the step function, the actual slip will change when the motor speed changes from 300 to 600 rpm and from 600 to 900 rpm. The slip compensation method has been continuously updated to calibrate the control process so that the motor's actual speed always follows the reference speed, as presented in Figures 4(c) and 4(d). Through simulation results in various operating modes, the proposed slip compensation SLC method has achieved the desired control effect; the motor speed closely follows the reference speed.

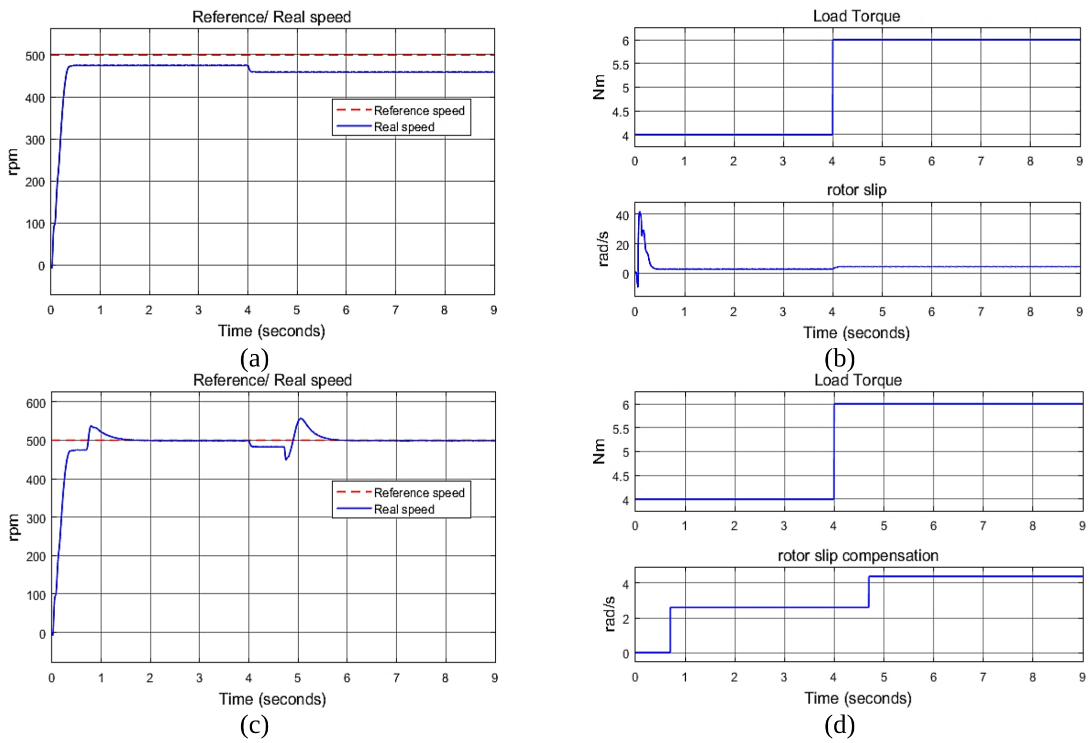

Figure 3. Performance of typical SLC and slip compensation SLC methods according to variable load mode: (a) motor speeds according to typical SLC method, (b) load torque and rotor slip according to IMD using typical SLC method, (c) motor speeds according to slip compensation SLC method, and (d) load torque and rotor slip according to IMD using slip compensation SLC method

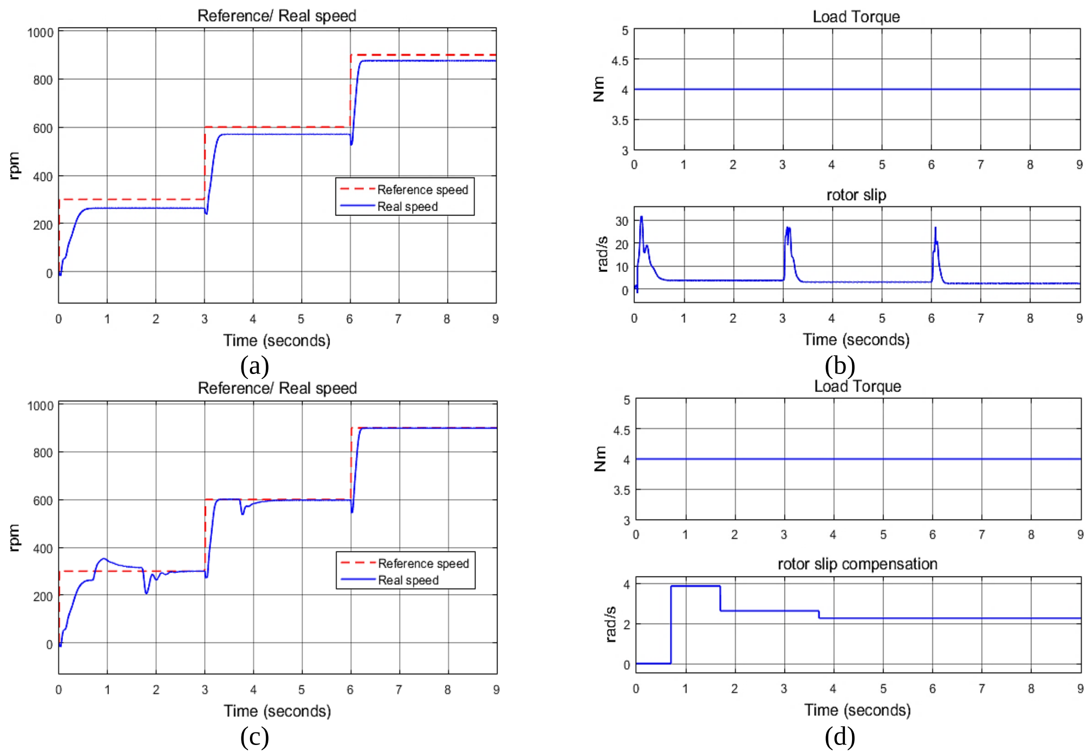

Figure 4. Performance: typical SLC and slip compensation SLC methods according to variable speed mode: (a) motor speeds according to typical SLC method, (b) load torque and rotor slip according to IMD using typical SLC method, (c) motor speeds according to slip compensation SLC method, and (d) load torque and rotor slip according to IMD using slip compensation SLC method

4. CONCLUSION

A method to improve SLC using slip compensation technique from estimating deviation of virtual asynchronous rotor speed and synchronous rotor speed. Here, the estimated speeds correspond to the rotor speed, which can be estimated using the RF-MRAS or other proper techniques. The synchronous speed can be obtained by calculating the derivative of the rotor flux. The compensation method is updated at preset intervals so that the performance of the control method is always maintained as operating conditions change. However, updating the rotor slip leads to a sudden change in the electrical frequency, creating a short-term transient period affecting the control quality if the applications have continuously changed operating modes. Future research can aim to reduce the effects of this transition.

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