Postprint of Improved Direct Torque Control System for Induction Motors

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Abstract

Sensorless direct torque control systems for induction motors based on three-level inverters suffer from issues such as complex inverter structure, excessive component usage, complicated flux calculation due to rotor-flux-oriented sensorless algorithms, and imprecise flux observation. To address these issues, the topology of the three-level inverter is simplified. Considering the characteristics of direct torque control, a stator-flux-based sensorless algorithm is adopted and combined with an improved flux observer for speed estimation, thereby constructing a sensorless direct torque control system for induction motors with improved topology and enhanced flux observation algorithm. Simulation experiments verify that the aforementioned improvements can reduce switching device losses while enhancing flux observation accuracy and achieving more precise speed estimation.

Full Text

Preamble

Improved Direct Torque Control System for Induction Motors

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Abstract

Direct torque control (DTC) systems for induction motors based on three-level inverters face several challenges when implemented as sensorless configurations: complex inverter structures, numerous components, complicated flux calculations due to rotor-flux-oriented sensorless algorithms, and inaccurate flux observation. To address these issues, this paper proposes a simplified three-level inverter topology and adopts a stator-flux-based sensorless algorithm combined with an improved flux observer for speed estimation. The resulting system integrates modified topology with enhanced flux observation algorithms for sensorless direct torque control of induction motors. Simulation experiments demonstrate that these improvements reduce switching device losses while enhancing flux observation accuracy and enabling more precise speed estimation.

Keywords: Induction motor, three-level inverter, model reference adaptive system, flux observer, direct torque control
Classification: TM343

1 Introduction

The integration of direct torque control (DTC) with multilevel inverters and sensorless technology represents a key development trend for high-voltage, high-power AC speed regulation systems. The diode-clamped three-level inverter, widely used in literature [2-4], offers superior reliability and performance metrics, making it the most representative and extensively adopted multilevel topology. However, conventional diode-clamped three-level inverters suffer from structural complexity and require numerous power electronic devices, making comprehensive component monitoring difficult during experimental implementation. This paper addresses these limitations by reducing the number of components per phase leg, thereby lowering costs, improving system reliability, and creating a simpler, more transparent topology without increasing control complexity. Compared to traditional diode-clamped three-level inverters, the proposed approach is better suited for high-voltage applications.

In sensored electric drive systems, speed detection relies on various sensors that are not only expensive but also vulnerable to temperature and environmental interference. Consequently, sensorless observation techniques have emerged as a practical solution. Literature [6-8] proposes numerous sensorless speed observation methods, among which the model reference adaptive system (MARS) presented in [6] stands out for its simple model structure, strong robustness, and ease of implementation, making it the most widely applied approach. However, conventional MARS structures based on rotor flux orientation cannot fully leverage the advantages of direct torque control in vector control systems and are susceptible to rotor-side parameter variations. This paper specifically addresses the characteristics of direct torque control strategies by directly employing a stator-flux-based model reference adaptive algorithm for sensorless speed identification, eliminating the need for rotor flux calculation and significantly simplifying the speed identification algorithm. Additionally, the flux observation component is improved by replacing the pure integrator with a low-pass filter, which avoids flux distortion caused by integrator saturation and enhances stator flux observation precision.

2.1 Analysis of Simplified Topology

Traditional neutral-point-clamped (NPC) three-level inverter topologies require numerous power devices, resulting in weak system stability. To retain the advantages while addressing these limitations, the topology is modified by eliminating the clamping diodes in the neutral point potential circuit and replacing them with a pair of anti-series switching devices. This reduces the power devices per phase leg from ten to eight, simplifying the circuit topology, reducing costs, decreasing circuit losses, and improving system operability for high-voltage, high-power applications. The single-phase circuit of the improved NPC three-level inverter is shown in [Figure 1: see original paper].

When subjected to external interference, NPC three-level inverters generate low-order harmonics that cause torque pulsation and degrade speed regulation performance. Therefore, it is essential to address issues such as high voltage jumps and neutral point potential imbalance during control. The priority levels of various influencing factors are presented in .

Table 1 Priority Levels of Various Factors

Factor	Impact
High voltage jump	Causes significant impact on inverter or load, damages insulation
Neutral point potential offset	Voltage offset may exceed IGBT or capacitor voltage ratings

2.2 Selection of Control Method for Improved Three-Level Inverter

After considering the system impacts of the factors listed in Table 1, the fixed resultant vector method is selected for three-level inverter control, employing hysteresis control for neutral point potential regulation. Fixed resultant vectors are composite vectors synthesized from a set of space voltage vectors in a fixed pattern, uniformly distributed across the coordinate plane with fixed directions and adjustable magnitudes. During synthesis, zero vectors are inserted to avoid excessive voltage jumps during vector transitions and to mitigate neutral point potential effects. One to two redundant small vectors are selected, ultimately yielding twelve fixed-position, adjustable-magnitude space voltage vectors.

Table 2 Fixed Resultant Vector Sequences

The fixed resultant vector sequences from Table 2 are adopted, with the zero vector 000 selected as the starting vector to achieve smooth transitions between vectors and minimize voltage amplitude jumps during adjacent vector switching. The dwell times for each component vector within one sampling period are 0.1Ts, 0.15Ts, 0.15Ts, 0.3Ts, 0.15Ts, and 0.15Ts, respectively.

The improved topology inverter maintains the same switching combinations as the conventional diode-clamped three-level inverter, without increasing control complexity.

3 Sensorless System Based on Stator Flux Model Reference Adaptive System

3.1 Principle of Model Reference Adaptive System

Conventional sensorless motor systems primarily employ model reference adaptive systems (MARS) based on rotor flux, where the reference model uses a voltage equation without the speed parameter to be identified, and the adjustable model uses a current equation containing the unknown speed. Both models output rotor flux, and the flux error between them is processed through an adaptive mechanism to obtain the speed estimate. The adjustable model parameters are continuously adjusted until the error between the two models converges to zero, yielding the actual speed value. The traditional MARS structure is illustrated in [Figure 2: see original paper].

3.2 Model Reference Adaptive Based on Stator Flux

Since direct torque control does not involve rotor flux, MARS based on rotor flux requires additional rotor flux observation, which increases system complexity and contradicts the main advantages of DTC. This paper proposes a MARS approach based directly on the stator flux model, eliminating the need to observe rotor flux and rotor current. When the error equation approaches zero, the estimated stator flux value can be considered equal to the actual flux value and used directly in subsequent flux control of the DTC system. This approach significantly reduces system complexity.

The derivation process is as follows. The stator and rotor flux and voltage equations of the induction motor are:

$$\psi_s = L_s i_s + L_m i_r \tag{1}$$

$$\psi_r = L_r i_r + L_m i_s \tag{2}$$

$$u_s = R_s i_s + p\psi_s \tag{3}$$

$$0 = R_r i_r + p\psi_r - j\omega_r \psi_r \tag{4}$$

From equation (1), the stator flux expression can be derived as:

$$\hat{\psi}_s = \frac{L_s}{L_m}\psi_r + L_\sigma i_s$$

where $L_\sigma = L_r L_s - L_m^2$. L_m is the mutual inductance between stator and rotor windings; L_s is the stator winding inductance coefficient; and L_r is the rotor winding inductance coefficient.

Differentiating both sides of equation (2) yields:

$$\hat{\psi}_s' = \frac{L_s}{L_m}\psi_r' + L_\sigma i_s'$$

Combining equations (1) and (3) gives:

$$\hat{\psi}_s' = \left(\frac{R_r L_s}{L_m^2} - \frac{R_s L_r}{L_m^2}\right)\psi_r + \left(\frac{R_r L_\sigma}{L_m} - j\omega_r \frac{L_s}{L_m}\right) i_s + u_s$$

Substituting equation (5) into equation (4) and rearranging equations (4) and (6) yields the adjustable model based on the stator side with stator current and stator flux as state variables:

$$\hat{i}_s' = \frac{1}{L_\sigma}\left(u_s - R_s i_s - \hat{\psi}_s'\right) \tag{5}$$

$$\hat{\psi}_s' = \frac{R_r L_s}{L_m^2}\hat{\psi}_s + \left(\frac{R_r L_\sigma}{L_m} - j\hat{\omega}_r \frac{L_s}{L_m}\right) i_s + u_s \tag{6}$$

The adaptive law derived from the adjustable model for the model reference adaptive system is:

$$\hat{\omega}_r = \int \left[k_p(i_{\alpha s} - \hat{i}_{\alpha s})\hat{i}_{\beta s} - (i_{\beta s} - \hat{i}_{\beta s})\hat{i}_{\alpha s}\right] dt$$

where $i_{\alpha s}$ and $i_{\beta s}$ are obtained from direct measurement of motor stator currents; $\hat{i}_{\alpha s}$ and $\hat{i}_{\beta s}$ are calculated from the adjustable model above. The block diagram of the stator-flux-based MARS is shown in [Figure 3: see original paper].

3.3 Improved Flux Observer in Stator Flux MARS

The stator-flux-based MARS method involves stator flux calculation, where the use of a pure integrator causes DC offset errors and initial integration errors in the flux observer. The improved method replaces the pure integrator with a low-pass filter to eliminate some DC error signals.

The stator flux calculation in the model is:

$$\psi_{s\alpha} = \int E_{s\alpha}\, dt \tag{7}$$

$$\psi_{s\beta} = \int E_{s\beta}\, dt \tag{8}$$

A first-order low-pass filter replaces the pure integrator, with input-output relationship:

$$\psi_{s\alpha} = \frac{1}{s+\omega_c} E_{s\alpha}, \quad \psi_{s\beta} = \frac{1}{s+\omega_c} E_{s\beta}$$

where ω_c is the cutoff frequency. The low-pass filter eliminates initial integration value errors, reduces system DC offset, narrows the flux hysteresis band, and prevents torque fluctuations and rotor vibration.

3.4 Structure of Improved Induction Motor Direct Torque Control System

The overall structure of the direct torque control system based on the improved three-level stator-flux sensorless technology is shown in [Figure 4: see original paper]. The estimated flux value approximates the actual stator flux value and is compared with the given stator flux value. The identified speed can be considered as the actual speed and is compared with the given speed. Through a PI regulator, the reference torque value is obtained. Simultaneously, the motor' s stator voltage and current signals are detected to calculate the actual torque, which is compared with the reference torque value. The resulting control signals are used to formulate the inverter switching table using the resultant vector method, ultimately outputting six PWM control signals to drive the three-level inverter, thereby controlling the motor' s stator flux and electromagnetic torque.

4 Simulation Experiment

To verify the above analysis, simulations were conducted in the Simulink environment. The inverter DC bus voltage was $U_d = 400$ V, and the flux reference value was $\Psi^* = 0.2$ Wb. The induction motor parameters were: pole pairs $n_p = 4$; stator resistance $R_s = 2.473\ \Omega$; rotor resistance $R_r = 2.473\ \Omega$; inductances $L_d = L_q = 0.991$ mH; rotor flux $\Psi_f = 0.215$ Wb; moment of inertia $J = 0.8 \times 10^{-4}\ \mathrm{kg \cdot m^2}$; friction coefficient $B = 0$.

Figure 5 compares the stator flux circle waveforms of the conventional DTC system and the improved DTC system at a reference stator flux amplitude of 0.2 Wb. The results show that the conventional DTC system exhibits flux circle radius fluctuations around 0.215 Wb, while the improved flux observer DTC system maintains a stator flux circle radius of 0.2 Wb with a narrower hysteresis band. This demonstrates that the low-pass filter effectively eliminates DC offset effects on flux, reduces stator flux pulsation, narrows the flux circle width, and improves flux observation accuracy.

Figure 6 presents the torque response curves when the reference speed changes from 50 r/min to 500 r/min at 0.1 s and the torque changes from 4 N•m to 10 N•m at 0.2 s. The improved DTC system exhibits reduced electromagnetic torque pulsation, faster dynamic torque response, and maintains better control performance under external disturbances compared to the conventional DTC system. This indicates that the improved system enhances anti-interference capability and achieves precise flux and torque control through accurate compensation of flux and torque errors.

The system was tested in low-speed mode with an initial speed of 50 r/min. **Figure 7** shows the low-speed response curves for both conventional and improved sensorless DTC systems. In high-speed mode with an initial speed of 1000 r/min, **Figure 8** presents the high-speed response curves.

Table 3 and **Table 4** compare the dynamic performance indices, showing that the improved DTC system achieves better performance across the entire speed range, with shorter settling times, reduced overshoot, and higher steady-state speed accuracy compared to the conventional sensorless DTC system. This improvement stems from the system' s integrated flux observer, which reduces complexity, shortens settling time, ensures flux observation accuracy, enhances control precision, and enables high-precision speed estimation.

These simulation experiments under various operating conditions validate the feasibility of the three-level inverter-based sensorless direct torque control system for induction motors. The system demonstrates accelerated dynamic response and enhanced anti-interference capability, offering significant cost savings and robustness against various operating disturbances, thus providing substantial practical value for engineering applications.

5 Conclusion

Simulation experiments confirm the effectiveness of the proposed improved direct torque control strategy for induction motors. The improved three-level power supply technology reduces power electronic component costs. The enhanced flux observer significantly mitigates DC offset interference, yielding smaller flux errors and providing reliable data for subsequent speed calculations. The stator-flux-based sensorless approach substantially simplifies system structure and improves anti-interference capability compared to rotor-flux-based methods. The overall system demonstrates enhanced value for engineering applications with both theoretical and practical significance.

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Note: Figure translations are in progress. See original paper for figures.