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Current-Source-Inverter-Fed Induction Motor Drive PWM Using Zero-Speed Operation

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ABSTRACT

This project work is dedicated to investigating zero-speed operation characteristics of CSI-fed Induction Motor Drives (IMDs). General control strategies, pulse width modulation schemes, topologies, and efficiency evaluation. Zero-speed operation can greatly increase the competitive value of the drive and expand its range of applications to include cranes, hoists, and traction drives, where maintaining the desired torque down to zero speed or starting the load with a high torque from zero speed is highly desirable. The motor drive is controlled with rotor flux orientation, where stator currents and motor speed are employed for the rotor flux estimation. Simulation results show that the CSI-fed IMD works well at zero speed with promising speed dynamic performance.

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INTRODUCTION

Simple converter structure, motor-friendly waveforms, inherent four-quadrant operation capability, and reliable short-circuit protection are features that make Current-Source Inverter (CSI) well suited for medium-voltage drives applications. By adopting IGBT thyristors can achieve improved line/load current harmonics, superior power factor, and reduced costs with the possibility of eliminating the input transformer. Field-oriented control strategies are widely employed in the high-power current-source drives to improve system dynamics and reliability.

Recent work has focused on control strategies, PWM schemes topologies, and efficiency, for high-power current-source converters and drives, where significant improvements have been achieved such as harmonic distortion minimization, high input power factor, minimized dc-link current, and reduced switching frequencies. However, it seems that zero-speed operation of the high-power PWM CSI-fed Induction Motor Drive (IMD) has seldom been reported. Zero-speed operation plays an important role in applications such as cranes, hoists, and traction drives, where maintaining the desired torque down to zero speed or starting the load with a high torque from zero speed is highly desirable. This paper is therefore dedicated to exploring the zero-speed operation characteristics of the PWM CSI-fed IMDs.

In this paper, the drive is controlled with rotor flux field orientation, where the flux is identified by current model. In the system structure shown in Fig. 1, filter capacitors are connected at the output of the CSI to assist with current commutation and harmonics filtering. Thus, the inverter d, q-axis currents are different from the stator d, q-axis currents. The impact of the capacitors on the drive dynamic performance is systematically analyzed. Moreover, a classic load torque observer with feed forward control is adopted to improve the speed of dynamic response. Simulation and experimental results show that the CSI fed IMD work swell at zero speed with promising speed dynamic performance.

System Control Scheme:

A. Motor Control Scheme:

The induction motor control scheme is shown in Fig. 2, where rotor flux orientation is employed. The flux and speed controllers are utilized to generate the motor d-axis current (i_{ds}^*) and q-axis current (i_{qs}^*), respectively. The sum of stator d, q-axis currents and the compensated capacitor currents is used to produce the inverter reference d, q-axis currents (i_{dw}^* and i_{qw}^*). In order to minimize the dc-link current, the amplitude (i_{dc}^*) of the synthesized inverter reference current is served as the reference for dc-

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link current control of the current source rectifier, while the corresponding phase θ_w is added to the rotor flux angle θ_f for the modulation of the CSI.

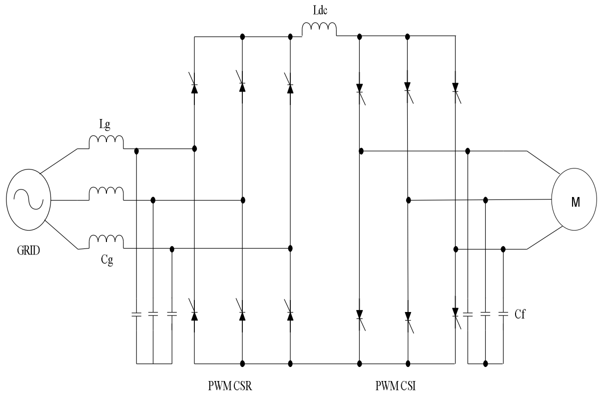

Fig. 1: PWM current-source converter based motor drive.

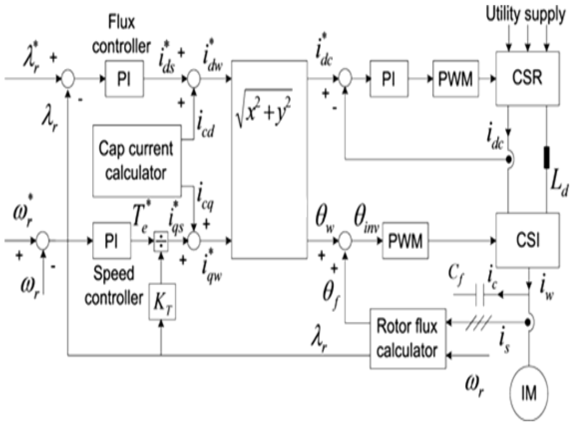

Fig. 2: Motor control scheme.

B. Current Flux Model:

The current model is utilized for the flux estimation, where the rotor flux components can be synthesized easily with the help of speed and current signals. The relationship among the rotor flux ($i_{\alpha r}$, $i_{\beta r}$), stator current ($i_{\alpha s}$, $i_{\beta s}$), and motor speed (ω_r) in two-phase stationary reference frame is shown.

$$\left.\begin{aligned}\left(p+\frac{1}{\tau_r}\right)\lambda_{\alpha r} &= \frac{L_m}{\tau_r} i_{\alpha s} - \omega_r \lambda_{\beta r} \\ \left(p+\frac{1}{\tau_r}\right)\lambda_{\beta r} &= \frac{L_m}{\tau_r} i_{\beta s} - \omega_r \lambda_{\alpha r}\end{aligned}\right\} \quad (1)$$

Where $\boldsymbol{\tau}_r = L_r / R_r$ is the rotor circuit time constant and p is the derivative operator.

Impact of Filter Capacitor on System Control:

CSI-fed motor drives have filter capacitors connected at the output of the inverter. This means that a portion of the inverter currents go through the capacitors. The influence of the filter capacitors on the system control is investigated in this section.

A. Coupling Analysis of Stator d, q-Axis Currents:

As mentioned previously, the inverter reference currents can be expressed as follows

$$\left.\begin{aligned} i_{dw}^* &= i_{cd} + i_{ds}^* \\ i_{qw}^* &= i_{cq} + i_{qs}^* \end{aligned}\right\} \quad (2)$$

i_{cd} and i_{cq} are the estimated capacitor d, q-axis currents. To reduce the sensitivity and noise caused by the derivative terms, the estimated capacitor currents are usually simplified as follows:

$$\left.\begin{aligned} i_{cd} &= -\omega_e v_{qs} C_f \\ i_{cq} &= -\omega_e v_{ds} C_f \end{aligned}\right\} \quad (3)$$

Where C_f, ω_e, v_{ds} and v_{qs} are the inverter-side filter capacitance, motor electrical angular frequency, and stator d-axis and q-axis voltages, respectively. The stator voltage equations of induction machine in synchronous reference frame can be expressed as follows:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} s\sigma L_s + R_s & -\omega_e \sigma L_s \\ \omega_e \sigma L_s & s\sigma L_s + R_s \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} \quad (4)$$

Where σ, e_d and e_q are the induction motor total leakage factor $(1-L_m^2/(L_S L_r))$, and d and q-axis back electromotive force (EMF), respectively. Under rotor flux orientation, the rotor flux vector is aligned with the d-axis and its amplitude is kept constant. Thus, the induction motor back EMF can be obtained as follows:

$$\left.\begin{aligned} e_d &= 0 \\ e_q &= (\omega_e \lambda_{dr} L_m)/L_r \end{aligned}\right\} \quad (5)$$

With the rotor flux orientation control, the detailed current controlled diagram of induction motor and the inverter is shown in Fig. 2, where T_{di} is the inverter processing delay.

The rotor flux controller and speed controller provide the motor d, q-axis reference currents i_{ds}^* and i_{qs}^* respectively. After the capacitor current compensation, the inverter reference currents i_{dw}^* and i_{qw}^* are generated. Subsequently, the inverter real currents i_{dw} and i_{qw} can be obtained with an inverter processing delay of T_{di} and then supply the filter capacitor and motor.

Improvement of Speed Dynamic Performance:

Referring to Fig. 2, the CSI modulation index is fixed at 1and the stator current amplitude is regulated by varying the dc-link current. With a considerably large dc-link current, the CSI modulation index control may improve the speed dynamic performance; however, the losses will increase. Therefore, the load torque feed forward control is employed as a compromise.

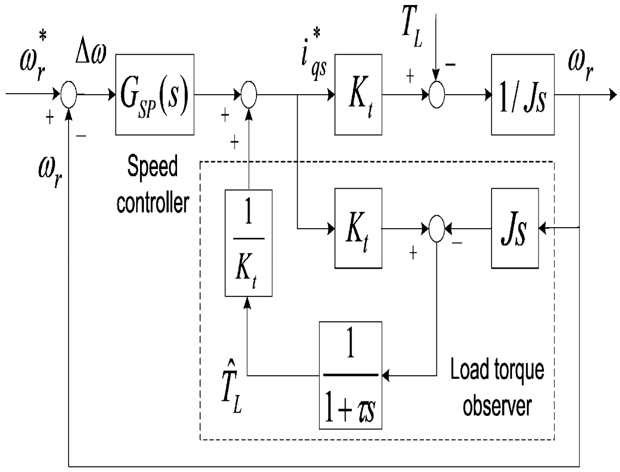

Fig. 3: Speed control block diagram with classic load torque feed forward control.

The classic load torque disturbance feed forward compensation scheme is shown in Fig. 3. The estimated load torque $\hat{T}_r$ is calculated according to the motors mechanical equations follows:

$$\hat{T}_L \approx K_t i_{qs}^* - Js\omega_r \tag{6}$$

Where J is the inertia of the motor and load, and K_t is the equivalent torque constant with definition as follows:

$$K_t = \frac{3P}{2}\lambda_r \tag{7}$$

Where P the number of pole pairs. Considering the HF harmonics and noises presented in the measured speed signal, a low-pass filter with time constant of **τ** is employed to filter the estimated load torque $\hat{T}_r$. After dividing by the equivalent torque constant K_t, the estimated load torque $\hat{T}_r$ is fed forward in the controller.

Simulation and Results:

In order to illustrate the feasibility of the zero-speed operation control scheme, a CSI-based ac drive model is developed with MATLAB/Simulink to feed induction motor. The control scheme presented in Fig. 4 is employed for the drive system. The drive performance under step torque variation is shown in Simulation result. The stator flux is initially established through dc current, while the stator *q*-axis current is zero. At 0.6 s, a rated load torque is suddenly addressed and the stator q-axis current is increased to handle it. The stator d-axis current varies a little and recovers quickly. This verifies that the coupling between stator q-axis currents has negligible impact on the system control.

In order to improve the system dynamic performance, the load torque feed forward control is employed. The corresponding system waveforms are shown. With the load torque feed forward control, the stator q-axis reference current responds faster to the load torque variation and the real q-axis current exhibits a little transient oscillation. The faster variation of the q-axis current will increase the coupling effect on the d-axis current.

A low-power prototype system is constructed for experimental verification with key parameters. Although the rating of the laboratory prototype is lower than the practical high-power drive, their key parameters are similar. A dc motor is coupled to the shaft of the induction machine. It is supplied by a dc drive to generate the step load torque. This is mainly introduced by the speed derivative, which highly depends on the encoder resolution and measurement noises. A comparatively large time constant **τ** is adopted for the low-pass filter to suppress such effect, which contributes to larger speed recovery overshoot. This same time constant is adopted for the speed controller and the induction motor initially operates at zero speed with no load.

Conclusion:

In this project, the zero-speed operation of PWMCSI-fed IMD with speed senor is investigated. The motor is controlled with rotor flux orientation, where the rotor flux is estimated using stator currents and motor speed. Due to the CSI-side filter capacitors, the stator currents are a portion of the inverter output currents. The influence of these capacitors on the motor control performance is systematically evaluated. A load torque observer with feed forward control is also utilized to improve the speed Dynamic response. Simulation and experiments show that the CSI-fed IMD works well at zero speed with promising speed dynamic performance.

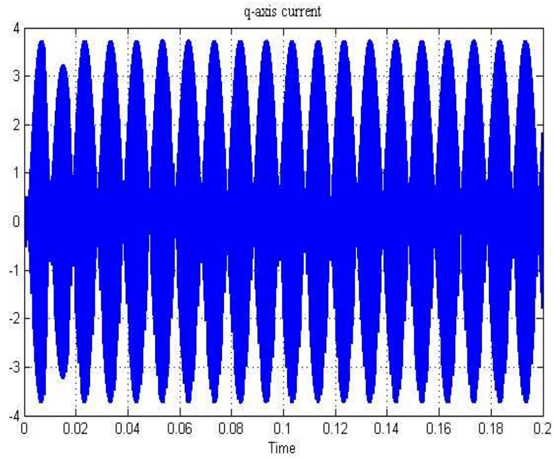

Fig. 4: Simulation result for q axis.

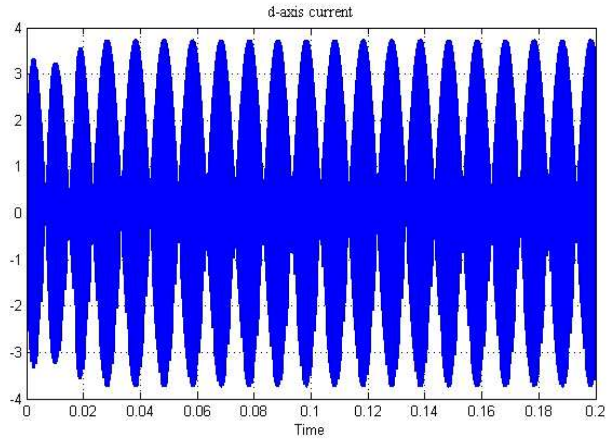

Fig. 5: Simulation result for d axis.

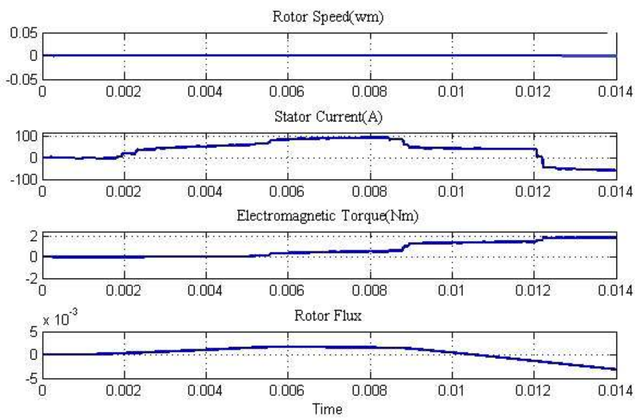

Fig. 6: Simulation result.

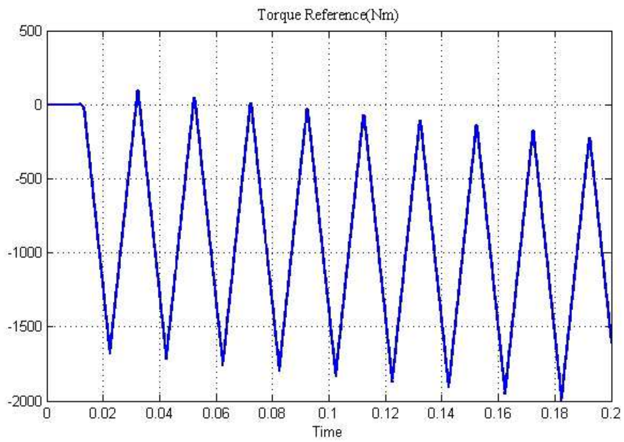

Fig. 7: Reference torque.

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