Pulse Width Modulated Current Source Inverter fed Induction Motor Drive for Sub-sea Mining Application

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Abstract—Field Oriented Control (FOC) for Current Source Inverter (CSI) fed induction motor drive is presented for specifically subsea mining application. The system used for mineral harvesting mechanism at the seabed level will be driven by an induction motor. The induction motor in turn have to be driven from an inverter installed on a ship via a long power cable between them. For this method of application CSI fed drive system will be the best fit to avoid the effect of distributed parameters of the power cable. Also it necessitates the speed sensorless controller, to make it compact and cost effective. FOC is employed to have a decoupled control over the speed and the rotor flux. The control algorithm is implemented in digital platform, TMS320F28335 and the responses displaying better dynamics for both simulation and hardware are illustrated.

Index Terms—Sensorless field oriented control, space vector pulse width modulation, current source inverter, induction motor.

I. INTRODUCTION

Remote operated drives are mandatory for the process of sub-sea mining to retrieve minerals from sea bed. In such applications Current Source Inverter (CSI) fed induction motor drive has an important space as the CSI based drive system is less sensitive to system parameters compared to voltage source inverter (VSI) and hence by itself is a best fit for motor drive with long feeder cable. GTO based CSI topologies employing PWM techniques are presented in [1]–[5] to furnish sinusoidal voltage and current to motor and proved that CSI based drive is more efficient [1] than VSI based drive. In these works, only scalar methods of sensorless speed control are adopted without actual speed measurement. When compared to VSI fed drive, CSI fed induction motor can show reduced common mode voltage and lower insulation stress [6]. Further, it is shown that, the common mode voltage can be further optimized by choosing suitable switching pattern [7] of PWM CSI.

The primary control objective of CSI drive systems in [8]–[10], is not focused on regulating the motor speed. A control algorithm is implemented to reduce the losses in dc link inductor and CSI switches [11]. The loss reduction is attained by drawing minimum dc link current, since the controller can maintain the modulation index of CSI PWM at the maximum possible value while doing speed regulation. The dc current is further minimized by optimizing the rotor flux in [12]. The harmonic distortion in motor current is reduced, while regulating the speed with appropriate modification in control algorithm [13] or by using active filter at the motor terminals. Use of active filter will increase the cost and complexity of the overall system [14]. Moreover in these systems, speed measurement is done either using tacho-generator or speed encoder, which will be expensive for remotely operated drives.

In this paper, sensor less speed control of CSI fed induction motor drive is presented for subsea mining application. This is to avoid the communication cable between the motor and the drive that has to run for about 7km. this will reduce the installation cost. Field oriented control is implemented to employ decoupled control of flux and torque. The complete control algorithm with the support of Space Vector PWM (SVPWM) is incorporated in digital processor, TMS320F28335. This paper is supported by extensive simulation and hardware results.

Fig. 1. Power structure of CSI fed IM drive with 3φ SCR converter

The organization of the paper is as follows. The power circuit description is given in section II. Section III describes the control algorithm. The simulation and the hardware results are explained in section IV. Finally, the conclusion is given in section V.
II. SYSTEM DESCRIPTION

The power structure of CSI fed induction motor drive comprises of three phase SCR converter, a series inductor, inverter driving an induction motor. Fig. 1 shows the complete power structure. The SCR converter is fed from grid. The inductor with converter acts as a current source. The DC link current is controlled by controlling the firing angle of SCR converter. The PWM technique employed for the CSI drive is SVPWM. A three phase capacitor bank has been installed at the output of the inverter which assists commutation and in filtering of harmonics. The modulation index of the space vector pulse width modulation is maintained constant.

III. DESCRIPTION OF CONTROL ALGORITHM

The block diagram of complete control structure of CSI fed IM drive is shown in Fig. 2. The controller includes the speed estimation, the flux controlling segment, the speed controlling segment, the dc current controlling segment and SVPWM block. They are described as follows.

A. Induction motor speed estimation

In sensorless operation, the rotor flux position and its derivative (synchronous speed) are estimated using the stator voltage and current information as shown in Fig. 3. Conventional voltage model is used to estimate the rotor flux. The terminal motor voltage is integrated followed by a high pass filter to obtain stator flux. The rotor flux position ($\psi_{mr}$, $\psi_{rb}$) is estimated from the stator flux. The slip speed is also estimated from (1).

$$\omega_{slip} = \frac{i_{sq}}{L_{mr}}$$  \hspace{1cm} (1)

The actual speed is the difference between the slip speed and the synchronous speed. The synchronous speed is obtained by differentiating the rotor position ($\rho_{mr}$). This estimated speed is used for the vector control drive.

B. Flux controller

According to Field Oriented Control (FOC) of induction motor, rotor magnetizing current ($i_{mr}$) can be controlled by controlling direct axis component of stator current ($i_{sd}$). The relation between $i_{mr}$ and $i_{sd}$ is illustrated by (2).

$$i_{sd} = i_{mr} + \frac{1}{L_{mr}} \frac{di_{mr}}{dt}$$  \hspace{1cm} (2)

The output of the flux controller is reference value for the direct axis component of stator current ($i_{sd}$).

C. Speed controller

Torque developed ($m_d$) by the induction motor depends on quadrature axis component of the stator current ($i_{sd}$) and the
rotor magnetizing current \( i_{mr} \).

\[
m_d \propto i_{sq} i_{mr}
\]  

(3)

As \( i_{mr} \) is controlled by \( i_{sd} \), torque developed by IM can be controlled by \( i_{sq} \). This results in decoupled control of flux and torque developed. The output of the speed controller is reference value of the quadrature axis component of stator current(\( i_{sq} \)).

The \( i_{sq}^* \) and \( i_{sd}^* \) are used to give modulation index of SVPWM and the dc current reference. The \( i_{dc}^* \) is obtained from (4).

\[
i_{dc}^* = \frac{2}{\sqrt{3}} \sqrt{(i_{sd}^*)^2 + (i_{sq}^*)^2}
\]  

(4)

D. DC link current controller

DC link current is controlled by gating pulses of 3\( \phi \) SCR converter. The output of DC link current controller is rectifier output voltage. The firing angle of SCR converter can be determined using rectifier output voltage and maximum gain of converter.

The bandwidths of the flux controller, speed controller and dc link current controller are 10Hz, 1Hz and 0.5Hz respectively.

E. Space Vector Pulse Width Modulation (SVPWM)

1) Space vector and Switching states: The switching constraint for CSI space vector PWM is that at any instant of time only two switches should conduct. One switch from the top commutation group and the other from bottom commutation group of CSI. Based on the constraint stated, 9 switching states are possible from a two level CSI [14]. Table 1 represents the current space phasors, corresponding switches to be turned on and the currents in three phases of inverter.

<table>
<thead>
<tr>
<th>Switching state</th>
<th>Switches to be turned on</th>
<th>Space Vector</th>
<th>( i_r )</th>
<th>( i_y )</th>
<th>( i_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>zero switching time</td>
<td>(1, 4)</td>
<td>( I_0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(2, 5)</td>
<td>( I_0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(3, 6)</td>
<td>( I_0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>active switching time</td>
<td>(6, 1)</td>
<td>( I_1 )</td>
<td>( I_{dc} )</td>
<td>( -I_{dc} )</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(1, 2)</td>
<td>( I_2 )</td>
<td>( I_{dc} )</td>
<td>0</td>
<td>( -I_{dc} )</td>
</tr>
<tr>
<td></td>
<td>(2, 3)</td>
<td>( I_3 )</td>
<td>0</td>
<td>( I_{dc} )</td>
<td>( -I_{dc} )</td>
</tr>
<tr>
<td></td>
<td>(3, 4)</td>
<td>( I_4 )</td>
<td>( -I_{dc} )</td>
<td>( I_{dc} )</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(4, 5)</td>
<td>( I_5 )</td>
<td>( -I_{dc} )</td>
<td>0</td>
<td>( I_{dc} )</td>
</tr>
<tr>
<td></td>
<td>(5, 6)</td>
<td>( I_6 )</td>
<td>( -I_{dc} )</td>
<td>( -I_{dc} )</td>
<td>( I_{dc} )</td>
</tr>
</tbody>
</table>

The space vector notation of current phasor is defined as,

\[
i_s = \frac{2}{3} \left( i_{sr} + i_{sy} e^{j\frac{\pi}{3}} + i_{sb} e^{j\frac{2\pi}{3}} \right)
\]  

(5)

When switches 1 and 6 of CSI are conducting, the resulting space vector is \( \vec{I}_1 \). At this instant, current through R-phase of CSI is \( I_{dc} \) and current through Y-phase of CSI is \( -I_{dc} \). The active space vector \( \vec{I}_1 \) is mathematically defined as,

\[
\vec{I}_1 = \frac{2}{\sqrt{3}} I_{dc} e^{j\frac{\pi}{6}}
\]  

(6)

The generalized expression for the active vectors of CSI space vector is mathematically defined as,

\[
\vec{I}_k = \frac{2}{\sqrt{3}} I_{dc} e^{-j((k-1)\frac{\pi}{6} - \frac{\pi}{6})}
\]  

(7)

where, \( k \) is the sector number of the current space phasor position. Therefore, the active vectors \( \vec{I}_1 \) to \( \vec{I}_6 \) form regular hexagon and zero vector \( \vec{I}_0 \) lies at the center of the hexagon. Fig. 4 represents the space vector diagram of CSI.

![Space vector diagram for CSI](image)

Fig. 4. Space vector diagram for CSI

![Synthesis of space vector using phasor](image)

Fig. 5. Synthesis of space vector using phasor

2) Dwell time calculation: Dwell time calculation is based on ampere-second balance. Product of current space phasor(\( \vec{I}_s \)) and switching period(\( T_s \)) is equated with the sum of the products of corresponding space vectors and corresponding time intervals i.e.,

\[
\vec{I}_s T_s = \vec{I}_1 T_1 + \vec{I}_2 T_2 + \vec{I}_0 T_0
\]  

(8)

and,

\[
T_s = T_1 + T_2 + T_0
\]  

(9)
Synthesis of space phasor using the active vectors($\vec{I}_1$ and $\vec{I}_2$) and zero vector($\vec{I}_0$) in sector-I is shown in Fig. 5. Decomposing current space phasor($\vec{I}_t$) into $\alpha\beta$ components, results in the following expressions.

$$I_s \cos(\theta)T_r = I_d(T_1 + T_2)$$

$$I_s \sin(\theta)T_r = \frac{1}{\sqrt{3}}I_d(-T_1 + T_2)$$

Dwell times $T_1$, $T_2$ and $T_0$ are calculated using Equations (7), (8) and (9). The expressions for dwell times $T_1$ and $T_2$ are defined as,

$$T_1 = m_d \sin(\frac{\pi}{6} - \theta)T_s$$

$$T_2 = m_d \sin(\frac{\pi}{6} + \theta)T_s$$

where $m_d$ is modulation index and is defined as,

$$m_d = \frac{I_s}{I_{dc}}; \quad 0 \leq m_d \leq 1$$

The generalized expression for finding dwell times $T_1$ and $T_2$ can be found by replacing $\theta$ with $\theta'$,

$$\theta' = \theta - (k - 1)\frac{\pi}{3}; \quad -\frac{\pi}{6} \leq \theta' \leq \frac{\pi}{6}$$

F. Design of Filter

For harmonic components(5th,7th and so on) of pulse width modulated current, slip of induction motor approximately equals one. Therefore, filter capacitance should be chosen such that harmonic components of pulse width modulated current flow through filter capacitance($C_f$) instead of magnetizing reactance ($L_m$). Therefore, choosing $\frac{L_m}{C_f} < \frac{1}{\pi m}$ for fundamental component of pulse width modulated current and $\frac{L_m}{C_f} > 10$ for harmonic components of pulse width modulated current gives

$$C_f = \frac{1}{\omega^2 L_m}$$

IV. RESULTS AND INFERENCE

The simulation and experimental results are discussed for 1h.p. induction motor drive with 10$\mu$F capacitor as CSI output filter and 30 mH as dc link inductor.

A. Simulation Results

Simulation results of sensorless PWM CSI vector controlled induction motor drive are presented below. The switching frequency is kept at 3kHz. Increase in switching frequency may lead to higher switching losses. The filter capacitor value is 0.54$\mu$F and the corresponding resonant frequency is around 300Hz. The reference speed is set to 1000rpm. The machine is loaded at time, $t = 3$ secs. Fig.6 represents the simulated steady state line voltages $v_{r\gamma}(red)$, $v_{r\phi}(green)$ and $v_{r\nu}(blue)$ across the terminals of induction motor. The frequency of voltage waveform is 33Hz for the reference speed of 1000rpm. The voltage waveforms contains ripple at the switching frequency of 3kHz. Fig.7 represents the steady state line currents flowing into the induction motor. The current ripple is high because

of lower capacitance (0.54$\mu$F) at the output ac terminals of inverter. The variation of reference value of direct axis component of stator current ($i_{s}\text{d}^*$) is shown in Fig.9 which is the output of speed controller. The speed of the motor is greater than the reference speed of the speed controller in between the time $t = 0$ seconds and $t = 3$ seconds. Fig.10 shows the variation of cosine and sine of

![Image](https://via.placeholder.com/150)

![Image](https://via.placeholder.com/150)

![Image](https://via.placeholder.com/150)
cos \rho_{mr} \quad \text{and} \quad \sin \rho_{mr}
\text{Scale: X-axis: 0.01sec/div; Y-axis: 0.5/div}

\text{Estimated mechanical speed of induction motor}
\text{Scale: X-axis: 1sec/div; Y-axis: 500rpm/div}

\cos \rho_{mr} = \frac{\psi_{r\alpha}}{\sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2}} \quad \sin \rho_{mr} = \frac{\psi_{r\beta}}{\sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2}} \quad (17)

The estimated mechanical speed of the induction motor is represented in Fig.11 which is used for implementing the sensorless speed control algorithm. The speed is estimated by using the line voltages and line currents. As the capacitance in simulation is small, the line voltages and line currents of induction motor are not pure sinusoidal resulting in the speed estimation with ripple. Fig.12 represents the steady state phase voltages (R-phase (blue) and Y-phase (pink)) of induction motor. The voltage waveforms are seen at the filter capacitor output. The capacitor attenuates the harmonic content of the load voltage. Fig.14 represents the sine (pink) and cosine (blue) waveforms of rotor flux position. These two signals are derived from stator measured voltages and the flux position is estimated.

**B. Hardware Results**

Sensorless field oriented control of induction motor and SVPWM techniques are implemented in digital platform using digital signal controller TMS320F28335. The complete hardware setup for PWM CSI fed induction motor drive of 1h.p. rating is built in laboratory. Hardware results are presented below. Fig.13 represents the steady state line currents (i_r (green) and i_y (blue)) of induction motor. Fig.15 shows the correlation between actual speed (pink) of motor and reference speed (blue) of speed controller. The drive is started after initial 0.8 seconds of operation. During this period the offsets of sensed voltages and currents are determined, and the reference speed is set to 400rpm. Then the reference speed is changed to 500rpm as soon as the gating pulses are fed to the inverter switches. Figure 16 shows the correlation between actual DC link current (I_{dc})(blue) and reference DC link current (I_{dc}^*)(green). By varying firing angle of SCR converter, I_{dc}^* tracks I_{dc}, but at a slower rate. Figure 17 shows the gating pulses for the inverter switches numbered 1 (blue) and 2 (pink) of CSI by implementing SVPWM technique.

The complete hardware setup is shown in Figure 18.

**V. Conclusion**

The Sensorless field oriented control of induction motor is successfully implemented on 0.75 kW induction motor. The switches for the Pulse width modulated CSI fed drive are realized by series connected IGBT and diode. The complete CSI with necessary protection circuit was built in the laboratory. Field Oriented Control of induction motor is implemented to achieve decoupled control of flux and torque. Sensorless operation is adopted to avoid the delay in operation and increase in installation cost. Space vector PWM technique is implemented for better dynamic response. Design of the filter capacitance is done analytically. The FOC of induction motor and sensorless operation are implemented on digital platform using micro-controller TMS320F28335.
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REFERENCES


