Comparative Analysis of Stator Resistance Estimators in DTC-CSI Fed IM Drive

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Abstract
Stator resistance is the most importance to estimate torque, flux in direct torque controlled sensorless speed controlled induction motor drives. During low speed operation stator resistance inevitably varies due to temperature and low frequency. For stable and accurate operation at low speed requires an appropriate on-line identification algorithm for the stator resistance. This paper proposed to analyze stator resistance estimation by using proportional integral (PI) and MRAS schemes in CSI fed Induction motor drive with direct torque control during low speed operation. The performances of the two control schemes are evaluated in terms of torque, Speed and flux. The analysis has been carried out on the basis of the results obtained by MATLAB/simulink and hardware implementation.

Keywords: Current source Inverter, Direct torque control, Sensorless Speed, Stator resistance estimation, Digital signals processing.

INTRODUCTION
HIGH-POWER medium-voltage drives applications [1], the current-source inverter (CSI) fed drives are used increasingly. The current source inverters having simple converter topology, inherent four-quadrant operation, reliable fuse less short circuit protection, and motor friendly waveforms (with low \( \text{dv/dt} \)). Further improve the system performance, research efforts on CSI fed drives have been recently put on new current-source drive topology, advanced modulation scheme development [2]–[7], control performance [8]–[11], and efficiency [12], [13], etc.

DTC is recently developed in industrial drives due to generating fast torque responses. In DTC, the stator resistance is used to estimate the stator flux [14], [15]. The stator resistance is varying due to changes in temperature and low frequency; make the system becomes unstable at low speeds.

An accurate value of the stator resistance is of crucial importance for correct operation of a sensorless drive in the low speed region, since any mismatch between the actual value and estimated value may lead not only to a substantial speed estimation error but to instability as well [16]. As a consequence, numerous on-line schemes for stator resistance estimation have been proposed in recent past [16-27]. In this paper the PI and MRAS based compensation of stator resistance are analyzed for DTC-CSI fed induction motor during low speed operation and its performance results are verified by software and hardware.

SYSTEM CONFIGURATION AND CONTROL
Figure 1 shows the main circuit of the DTC-CSI-fed induction motor drive. \( L_L \) and \( C_L \) are the inductance and capacitance of the line filter and \( C_M \) is the filter capacitance in motor side. \( L_d \) is a smoothing inductor which is to minimize the current bearing problems of the motor drive [28]. Both the rectifier and the inverter are controlled with PWM and direct torque controller (DTC) respectively. The line side rectifier, left part in Figure 1 has to control the dc link current via the line side dc link voltage. Disturbance value is the machine side dc link voltage, produced by the induction machine via the inverter, right part in Figure 1. The control performance is basically influenced by the dc link inductance. The machine side inverter has to control the current in the motor to adjust the motor torque to the reference value. This is mainly a phase control, as the current amplitude in the machine is given according to the amplitude of the dc link current controlled by the rectifier.

Figure 1. Current source converter induction machine drive
Flux, Torque estimation

The functional block diagram of the Sensorless vector controlled drive is shown in Figure 2. It shown that the vector control algorithm requires rotor flux position $\theta_k$, which can be estimated from the stator flux space vector, $\lambda_s$ is estimated using

$$\lambda_s = \int \left[ V_s - R_i i_s \right] dt$$

(1)

Where $V_s$ and $i_s$ are the stator voltage and current space vectors. Superscript indicates that the variables are referred to stator axis. The rotor flux vector, $\lambda_R$ is obtained by subtracting the leakage flux from the stator flux vector as in

$$\lambda_R = \lambda_s - \sigma \lambda_{ls}$$

(2)

Where

$$\sigma = 1 - \frac{L_s^2}{L_{sr} L_{sr}}$$

$\sigma$ – Leakage factor

$L_s$ – Stator self Inductance

$L_{sr}$ – Rotor self Inductance and

$L_{m}$ - magnetizing inductance,

The rotor flux, rotor position angle, Torque is estimated from the stator voltage and current.

$$\theta_f = \tan^{-1} \left[ \frac{\lambda_{ds}}{\lambda_{qs}} \right]$$

(3)

$$T_e = \frac{3}{2} p (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

(4)

The motor speed estimated from the following

$$\omega_e = \omega_{sl} - \omega_{ad}$$

(5)

Where

$\omega_e$ = Stator frequency in rad/sec

$\omega_{ad}$ = slip frequency in rad/sec

The motor parameters employed in the control system may deviate from the real ones.

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. The inverter reference currents can be expressed as follows [29]:

$$i_{dw} = i_{cd} + i_{ds}$$

$$i_{qw} = i_{cq} + i_{qs}$$

(6)

where $i_{cd}$ 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:

$$i_{cd} = -\omega_q v_{qs} C_f$$

$$i_{cq} = \omega_q v_{dq} C_f$$

(7)

Where $C_f$ , $\omega_q$ , $v_{ds}$ and $v_{qs}$ are the inverter-side filter capacitance, motor electrical angular frequency, and stator d-axis and q-axis voltages, respectively.
DIRECT TORQUE CONTROLLER PRINCIPLE

The basic principle of DTC is to select stator current vectors according to the differences between the reference and actual torque and flux linkage. Stator flux and rotor flux are estimated from the Equation (8) (9), and (10) taking the integral of difference between the input voltage and the voltage drop across the stator resistance as,

\[ \dot{\lambda}_{ds} = \int \left( V_{ds} - \hat{R}_s i_{ds} \right) dt \]

\[ \dot{\lambda}_{qs} = \int \left( V_{qs} - \hat{R}_s i_{qs} \right) dt \]

\[ \dot{\lambda}_r = \int \frac{L_m}{L_r} \left[ i_q - \left( \hat{R}_s + cL_r p \right) i_s \right] dt \]

Where

- \( \lambda_{ds} \) - d-axis flux linkage.
- \( \lambda_{qs} \) - q-axis flux linkage.
- \( \hat{R}_s \) - estimated stator resistance.
- \( P \) - number of pole pairs

and then calculates the flux amplitude and find the sector of 60 degrees in a-β plane where flux vector resides, according to the partition shown in Figure 3.

In that case six intervals of 60 degrees can be defined in which the current and the voltage changes its values. In every interval the current from DC link flows through two inverter legs and two motor phase windings.

**EFFECT OF STATOR RESISTANCE VARIATION**

In DTC, the stator flux and rotor flux are estimated using the Equation (1) and (2) respectively. The variation of ‘Rs’ may influence the calculation of stator flux significantly and thereby the overall performance of the DTC system. At low speeds, the back EMF term is small, and the resistive drop ‘Rs*is’ is comparable with the supply voltage magnitude ‘Vs’. Therefore any change in stator resistance gives wrong estimation of stator flux and consequently of the electric torque and the stator flux position. An error in stator flux position is more important as it can cause the controller to select a wrong switching state which can result in failure of the controller. At high speeds, the stator resistance drop ‘Is*Rs’ is small and can be neglected. If increase stator resistance the stator current, flux and torque are oscillated. So a mismatch between the set value and actual value can create instability. So the parameter mismatch between the controller and motor makes the drive system unstable. So the stator resistance compensation is essential to overcome instability in DTC controlled IM drive system.

**Stator Resistance Compensation**

An observer has been designed to estimate the change in the actual stator resistance during operation of the machine. The estimator observes if any change is detected, a corresponding change in the stator resistance is made. The available stator resistance on-line compensation schemes can be classified into a couple of distinct categories. The stator resistance on-line compensation method is by far the most frequently met and it includes all the estimators where an updated stator resistance value is obtained through an adaptive mechanism. Proportional integral (PI) or integral (I) controllers are used for this purpose. In MRAS based systems the rotor flux estimated from the reference model and adaptive model which is used to estimate the stator resistance. This paper analyses the stator resistance on-line compensation on PI control and MRAS control schemes, as discussed below.

**PI Stator Resistance Estimator**

The block diagram of PI stator resistance compensator is shown in Figure 4. The error in the stator flux is used as an input to the PI estimator. The technique is based on the principle that the change in stator resistance will cause a change in stator current and stator flux linkage \( \lambda_s \). The error between the stator flux linkage \( \lambda_s \) and its reference \( \lambda_s^* \) is proportional to the stator resistance change. The equation for PI stator resistance estimator is given by

\[ \Delta R_s = \left( K_p + K_i \frac{1}{s} \right) \Delta \lambda_s \] (11)

Where, \( K_p \) and \( K_i \) are the proportional gain and integral gain of the PI estimator.
The error between the estimated stator flux \( \lambda_s \) and its reference \( \lambda_s^* \) is passed through a low pass filter with a very low cutoff frequency in order to attenuate high frequency component contained in the estimated stator flux. This filter time constant should be small compared to the stator resistance estimator time constant to overcome its effect on the stator resistance adaptation. Then the signal is passed through a PI estimator. The output of the PI estimator is the required change of resistance \( \Delta R_s \) due to change in temperature or frequency. The change of stator resistance \( \Delta R_s \) is continuously added to the previously estimated stator resistance \( R_s(K-1) \). The final estimated stator resistance \( \hat{R}_s \) is again passed through a low pass filter to have a smooth variation of stator resistance value. This updated stator resistance can be used directly in the controller.

**MRAS Based Control**

The rotor speed and stator resistance estimation scheme is designed based on the concept of hyper stability [30] in order to make the system asymptotically stable. For the purpose of deriving an adaptation mechanism it is valid to initially treat rotor speed as a constant parameter, since it changes slowly compared to the change in rotor flux. The stator resistance of the motor varies with temperature, but variations are slow so that it can be treated as a constant parameter, too. The configuration of the proposed parallel rotor speed and stator resistance is shown in Fig. 5 and is discussed in detail next.

In this paper to analyze the speed estimator is originally proposed in [41] and illustrated in Figure 5, where the two left-hand side blocks perform integration of Equations (7) and (8). The reference (voltage) model and adjustable (current) models are derived by the stator voltage and currents. The estimator operates in the stationary reference frame (\( \alpha \)) and it is described with the following equations [41]:

\[
p\ddot{\lambda}_v = \frac{L_m}{T_r} \left[ V_v - (\hat{R}_s + \sigma \dot{\lambda}_v, p) \right] \tag{12}
\]

\[
p\ddot{\lambda}_l = \frac{L_i}{T_r} i_l \left[ \frac{1}{T_r} - j\omega \right] \dot{\lambda}_l \tag{13}
\]

\[
\dot{\omega} = \left( K_{mr} + K_{m\omega} \right) \omega \tag{14}
\]

\[
e_{sa} = \dot{\lambda}_s \times \dot{\lambda}_s = \dot{\lambda}_{sv} \dot{\lambda}_{sv} - \dot{\lambda}_{s\beta} \dot{\lambda}_{s\beta} \tag{15}
\]

A symbol \(^{\dagger}\) denotes in (12) - (15) estimated quantities, symbol \(^'p\) stands for \(d/dt\), \(T_r\) is the rotor time constant and \(\sigma = 1 - L_m / L_s L_c\). All the parameters in the motor and the estimator are assumed to be of the same value, except for the stator resistance (hence a hat above the symbol in (12)). Underlined variables are space vectors, and sub-scripts \( V \) and \( I \) stand for the outputs of the voltage (reference) and current (adjustable) models, respectively. Voltage, current and flux are denoted with \( v, i \) and \( \lambda \), respectively, and subscripts \( s \) and \( r \) stand for stator and rotor, respectively.

As is evident from (12)-(15) and Figure 5, the adaptive mechanism (PI controller) relies on an error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates. The second degree of freedom, the difference in amplitudes of the two rotor flux estimates, is not utilized. The parallel rotor speed and stator resistance MRAS estimation scheme, which will be developed, will make use of this second degree of freedom to achieve simultaneous estimation of the two quantities. The role of the reference and the adjustable model will be interchanged for this purpose, since the rotor flux estimate of (13) is independent of stator resistance.

Let \( R_s \) and \( \omega \) denote the true values of the stator resistance in the motor and rotor speed, respectively. These are in general different from the estimated values. Consequently, a mismatch between the estimated and true rotor flux space vectors appears as well. The error equations for the voltage and the current model outputs can then be written as:

\[
p e_{sv} = -\frac{L_m}{T_m} (R_s - \hat{R}_s) \tag{16}
\]

\[
e_{sv} = \lambda_{sv} - \dot{\lambda}_{sv} = \dot{e}_{sa} + j e_{sb} \tag{17}
\]

\[
p e_{sl} = \left( j\omega - \frac{1}{T_r} \right) e_{sl} + j (\omega - \dot{\omega}) \hat{\lambda}_{sl} \tag{18}
\]

\[
e_{sl} = \lambda_{sl} - \dot{\lambda}_{sl} = e_{sa} + j e_{sb} \tag{19}
\]

Symbols \( \dot{\lambda}_{sv}, \dot{\lambda}_{sv} \) in (17), \( \dot{\lambda}_{sl}, \dot{\lambda}_{sl} \) in (19) stand for true values of the two rotors flux space vectors which is obtained from reference model \( (V_s-I_s) \) and adaptive model \( (\omega-I_s) \) respectively. From equation (14) and (15) The adaptive mechanism for \( \omega \) is obtained and for \( R_s \) estimation

\[
\hat{R}_s = \left( K_{mr} + K_{m\omega} \right) e_{sr} \tag{20}
\]

\[
e_{sr} = i_{sa}(\dot{\psi}_{s\alpha} - \dot{\psi}_{s\alpha}) + i_{sb}(\dot{\psi}_{s\beta} - \dot{\psi}_{s\beta}) \tag{21}
\]

are proposed by Popov’s hyper stability theory.
RESULTS

Simulation Results
A sample of simulation results are presented here. Simulation results for a DTC system with resistance estimator were obtained using a 50-hp four-pole, induction machine. The machine parameters are shown in Appendix 1. The presented simulation results were made using MATLAB / Simulink software package. The sensor less DTC-CSI fed induction motor drive is operated with low speed with fast load changes is shown in Figure (6), is influence of inaccurate value of stator resistance. The estimation error is high and unstable in steady state and becomes higher at point of load changes. The simulation results of the presented control system with PI and MRAS estimated stator resistance tuning is shown in Figure (7) and (8) respectively. The actual and reference speed, torque, stator current and rotor flux are presented in Figure (7) and (8). The estimation error is very small and stable in steady state and becomes lower compared with stator resistance estimator is turned off at point of load changes

Experimental Results
Figure 10 shows a low-power prototype system is constructed for experimental verification with key parameters listed in Appendix 2. Although the rating of the laboratory prototype is lower than the practical high-power drive, their key parameters are similar. All measured and controller internal variables are accessible through the serial link to the PC.
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. The direct torque controller and resistance estimator were implemented with a single board computer that uses a 16-b TM320C14 digital signal processor (DSP). A 3-hp 420-V induction machine was used in the experiment. The stator resistance of the machine, calculated from tests on the machine, was found to be 0.435Ω. The machine currents and the dc bus voltage were interfaced into the controller through an analog-to-digital converter (A/D) built into the DSP board. The A/D and the multiplexer available were very slow. The command torque and command stator flux used are 11 Nm and 0.4 wb, respectively. The stator current vector at these values of command torque and command flux was found to be 10.4 A. The direct torque controller and the resistance estimator were programmed in assembly language. In actual operating conditions, the rate of change of temperature is very slow and so the stator resistance changes. Practically stator resistance changes in a nonlinear manner.
Figure 10. Experimental setup

Figure 11. Experimental results with PI Estimator (a) Stator Current (b) Rotor Speed (200rpm-10rpm) (c) Torque

Figure 12. Experimental results with MRAS Estimator (a) Stator Current (b) Rotor Speed (200rpm-10rpm) (c) Torque

Figure 13. Rs estimation with PI and MRAS Control when increases linearly.
CONCLUSION
The stator resistance has been estimated by using PI controller and MRAS controller and performance of controller analyzed during low speed operations of CSI fed drives. The simulation and experimental results shows that both estimators are able to compensate for the changes in stator resistance. The MRAS resistance estimator showed a better performance than the PI estimator. Also, robustness and ability to operate the controller with MRAS resistance estimator at very low speeds has also been shown experimentally.

APPENDIX 1 INDUCTION MOTOR PARAMETERS

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Rated Power</td>
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<tr>
<td>Rated Voltage</td>
<td>460 V</td>
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<tr>
<td>Stator Resistance</td>
<td>0.087 Ω</td>
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<tr>
<td>Stator Inductance</td>
<td>35.5 mH</td>
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<tr>
<td>Rotor Resistance</td>
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<tr>
<td>Rotor Inductance</td>
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<tr>
<td>Mutual Inductance</td>
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<tr>
<td>Moment of inertia</td>
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<td>Friction co efficient</td>
<td>0.1 N.m.s/rad</td>
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<td>Number of poles</td>
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APPENDIX 2 KEY PARAMETERS OF THE EXPERIMENT SETUP

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<tbody>
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<tr>
<td>Rated Voltage</td>
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<tr>
<td>Stator Resistance</td>
<td>0.435 Ω</td>
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<tr>
<td>Rotor Resistance</td>
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<tr>
<td>Stator Inductance</td>
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</tr>
<tr>
<td>Rotor Inductance</td>
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</tr>
<tr>
<td>Mutual Inductance</td>
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<tr>
<td>Moment of inertia</td>
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<td>Friction co efficient</td>
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<td>Number of poles</td>
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REFERENCES


