CHAPTER -3

ROTOR FLUX ORIENTED CONTROL (RFOC) MODEL AND ROTOR RESISTANCE ESTIMATION USING PI ADAPTATION

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3.1 Introduction

The detuning effect of an RFOC induction motor drive due to parameter variations has been a major research topic over the last fifteen years. Many researchers have developed different solutions to this problem, which are reviewed in Chapter 2. The problem of detuning of an RFOC induction motor drive is revisited in this chapter. In order to study this problem in detail, a mathematical model of the RFOC induction motor drive has been developed in MATLAB/SIMULINK platform and discussed in this chapter. The main focus of this thesis is on investigating the rotor resistance identification for squirrel-cage induction motor. This chapter presents Rotor Flux based MRAS rotor resistance estimator for RFOC induction motor drive to overcome the detuning problem. A proportional-integral (PI) adaptation has been used for the estimation of the rotor resistance in section 3.3. The effectiveness of the algorithm has been demonstrated by MATLAB/SIMULINK results.

3.2 Analysis and Implementation of a RFOC Induction Motor Drive

The main focus of this thesis was to study the detuning effects of rotor resistance in a RFOC induction motor drive. It was thus necessary to develop both a mathematical model and simulation set-up for this system. The mathematical background of indirect or feed forward vector control (referred here as RFOC) has already been discussed in
Chapter 2. A block diagram of a conventional RFOC induction motor drive with Space Vector PWM Voltage Source Inverter is shown in Fig.3.1. The overall objective is to realize independent control of torque and flux for Induction Motor operation. The speed controller generates the input to the $i_{qs}$ controller and the flux controller generates the reference to the $i_{ds}$ controller. Both the currents $i_{ds}$ and $i_{qs}$ are controlled in the synchronously rotating reference frame. The decoupling unit removes the coupling caused by the $i_d$ and $i_q$ controllers. The flux model calculates the rotor flux based on the motor parameters. The estimated slip speed $\omega_{sl}$ is added to the measured rotor speed $\omega_r$ and integrated to get the position $\theta$, which is then used for transformation of currents from the stationary reference frame to synchronously rotating reference frame and vice versa. The complete drive system has been modeled using MATLAB/SIMULINK and the Simulink schematic of the same is given in Fig.3.2. The inverter block in the simulation schematic in Fig.3.2 contains subsystems for defining the DC link voltage, modulation index and sector definition. The overall schematic covers the problem of startup behavior and attaining the reference speed satisfying field orientation requirements. Here, the DC link voltage and load torque are specified apart from reference speed. The sampling time used for the speed controller is 200$\mu$seconds, and it is 20$\mu$seconds for the current controller. The parameters of the Squirrel-Cage Induction Motor used for this investigation are given in Appendix C.
Fig. 3.1 Block Diagram – Rotor Flux Oriented Vector Controlled Induction Motor Drive
3.3 Effect of Rotor Resistance variation on the performance of the RFOC Induction Motor Drive

The performance of the vector controlled drive depends on the accuracy of the estimated rotor flux from the measured stator currents. A mismatch between the actual rotor flux and the estimated rotor flux leads to error between the actual motor torque and the commanded torque which results in poor dynamic performance. The accuracy of the estimated rotor flux is greatly determined by the accurate value of rotor resistance used by the control algorithm. Rotor resistance may vary due to rotor heating and recovering this information with a temperature model or a temperature sensor is very inconvenient. In addition, rotor resistance can change significantly with rotor frequency due to skew/proximity effect in machines with double-cage and deep-bar rotors. The problems related
to rotor resistance adaptation have been reviewed extensively in [34]. This chapter presents Rotor Flux based MRAS rotor resistance estimation method using PI controller.

### 3.4 Rotor Flux based MRAS Rotor Resistance Estimation using PI Adaptation (RF-MRAS)

A model reference adaptive scheme has been presented in this section for $R_r$ estimation in which the adaptation mechanism is executed using PI-Controller. The performance of the estimator and torque and flux responses of the drive are investigated using MATLAB/SIMULINK simulations for variations in the rotor resistance value from the nominal value. When the estimator is integrated with the controller, the drive system performance is maintained even under variations of the rotor resistance. The estimation algorithm makes use of a PI controller for successive updation and convergence. The effectiveness of the estimation algorithm and its contribution for maintaining RFOC have been demonstrated by MATLAB/SIMULINK simulations.

The basic idea employed here is the comparison of the magnitude of rotor flux computed by using two models viz., the Voltage Model and Current Model [4]. Fig.3.3 shows the schematic diagram of the on-line rotor resistance tracking scheme for the indirect vector controlled induction motor drive. Equation (3.1) is based on stator voltages and currents, which is referred as the voltage model of the induction motor. Equation (3.2) is based on stator currents and rotor speed, which is referred as the current model of the induction motor [4]. Whenever there is variation in the real rotor resistance of the motor, the rotor flux estimated using the induction motor current model given in equation (3.2), differs from the rotor flux estimated from the induction motor voltage
model given in equation (3.1). This error is then used to update the control rotor resistance. Here, a PI controller is employed for adaptation process until the error between the two fluxes is zero.

The Voltage Model equations of the Induction Motor is given as

\[
\begin{bmatrix}
\frac{d\lambda_{dr}}{dt} \\
\frac{d\lambda_{qr}}{dt}
\end{bmatrix} = \frac{L_r}{L_m} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} - \begin{bmatrix} R_s + s\sigma L_s & 0 \\ 0 & R_s + s\sigma L_s \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \]

… (3.1)

The Current Model equations of the Induction Motor is given as

\[
\begin{bmatrix}
\frac{d\lambda_{dr}}{dt} \\
\frac{d\lambda_{qr}}{dt}
\end{bmatrix} = \begin{bmatrix} -1/T_r & -\omega_r \\ \omega_r & -1/T_r \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \frac{L_m}{T_r} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}
\]

… (3.2)

To verify the effectiveness and feasibility of the above rotor resistance estimation scheme, a simulation model has been developed in MATLAB/SIMULINK platform and the SIMULINK model is shown in Fig.3.4. The Space Vector PWM Inverter fed Squirrel Cage Induction Motor Drive is subjected to various changes in $R_r$ and the tracking capability of Rotor Flux based MRAS Rotor Resistance Estimator is tested. Simulations have been done for various changes in $R_r$ for the operating condition of 415V, 50Hz and rated load of 7.5Nm at 1000rpm. A PWM switching frequency of 5kHz, Modulation Index of 0.9 and DC link Voltage of 650V was used for simulations.
Fig. 3.3 Rotor Flux based MRAS Rotor Resistance Estimator

Fig. 3.4 MATLAB/SIMULINK Schematic of Rotor Flux based MRAS Rotor Resistance Estimator
3.5 Simulation Results

The Rotor Flux based Rotor Resistance Estimator was designed and tested for various operating conditions. Results obtained for three standard conditions are reported. Initially, the rotor resistance used in the controller was kept at the nominal value of 6.085\(\Omega\) and a step change of 100\% was applied to the value \(R_r\) of the motor model. Fig.3.5 shows the rotor flux based MRAS rotor resistance estimator output for step change in rotor resistance. The rotor resistance of 6.085\(\Omega\) is subjected to a step change to 12.17\(\Omega\) at 1 sec for 100\% step change in \(R_r\).

As the variation of the rotor resistance of an induction motor is rather slow, a corresponding ramp change in \(R_r\) has also been investigated. Fig.3.6 shows the rotor flux based MRAS rotor resistance estimator output for ramp change in rotor resistance. Here, the rotor resistance is varied in a ramp manner gradually during 0.5sec to 1.7sec and reaches the value 12.17\(\Omega\) from 6.085\(\Omega\) for 100\% change in \(R_r\). The simulation times are only to explain the concepts, the practical resistance variations depend on the load and thermal time constant of the motor.

![Graph](image)

**Fig.3.5** Actual and Estimated Rotor Resistance for 100\% **Step** change in \(R_r\)
Table 3.1 shows the error between actual rotor resistance and estimated rotor resistance, settling time for various changes in $R_r$ using Rotor Flux based MRAS Rotor Resistance Estimator. From the results obtained, it is observed that the maximum percentage error in estimation is 3% and settling time is found to be 0.13 sec.

**Table 3.1** Estimation Error and Settling Time for Various Changes in $R_r$ of Conventional MRAS (Rotor Flux Based)

<table>
<thead>
<tr>
<th>Change in $R_r$ (%)</th>
<th>Actual $R_r$ (ohms)</th>
<th>Estimated $R_r$ (ohms)</th>
<th>Settling Time (sec)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.694</td>
<td>6.91</td>
<td>0.10</td>
<td>3.125</td>
</tr>
<tr>
<td>20</td>
<td>7.302</td>
<td>7.515</td>
<td>0.11</td>
<td>2.834</td>
</tr>
<tr>
<td>30</td>
<td>7.910</td>
<td>8.124</td>
<td>0.11</td>
<td>2.634</td>
</tr>
<tr>
<td>40</td>
<td>8.519</td>
<td>8.734</td>
<td>0.11</td>
<td>2.461</td>
</tr>
<tr>
<td>50</td>
<td>9.127</td>
<td>9.341</td>
<td>0.12</td>
<td>2.290</td>
</tr>
<tr>
<td>60</td>
<td>9.736</td>
<td>9.943</td>
<td>0.12</td>
<td>2.081</td>
</tr>
<tr>
<td>70</td>
<td>10.34</td>
<td>10.54</td>
<td>0.12</td>
<td>1.897</td>
</tr>
<tr>
<td>80</td>
<td>10.95</td>
<td>11.14</td>
<td>0.13</td>
<td>1.705</td>
</tr>
<tr>
<td>90</td>
<td>11.56</td>
<td>11.73</td>
<td>0.13</td>
<td>1.449</td>
</tr>
<tr>
<td>100</td>
<td>12.17</td>
<td>12.31</td>
<td>0.13</td>
<td>1.137</td>
</tr>
</tbody>
</table>
3.6 Performance Evaluation of Vector Controlled Induction Motor Drive with Rotor Flux Based MRAS Rotor Resistance Estimator using PI Adaptation (RF-MRAS)

After establishing the validity of the proposed Rotor Resistance Estimation scheme described in Section 3.5 for a Squirrel-Cage Induction Motor, the same was integrated into the drive system for implementing indirect field oriented control and the performance was investigated. Fig.3.7 shows the combined block diagram covering Space Vector PWM inverter, Induction Motor, speed feedback and the estimator block. The SIMULINK schematic scheme of the whole setup is shown in Fig.3.8. The sampling time used for the speed controller is 200µseconds, and it is 20µseconds for the current controller. The sampling time for rotor resistance estimation was 2µseconds.

The performance of the Vector Controlled Induction Motor drive is examined for the following operating conditions:

**Operating Condition 1:**

- Reference Speed = 100 rad/sec
- Reference Rotor Flux = 0.9Wb
- Load Torque = 7.5Nm
- 100% Step change in Rotor Resistance is given at 1 sec.

The performance of the Vector Controlled Induction Motor drive system was simulated by applying an abrupt (100% step) change in $R_r$, from 6.085Ω to 12.17Ω at 1 second. Fig.3.9 (a) shows the actual and reference d-axis Rotor Flux when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed
that without Rotor Resistance Estimator, the actual rotor flux deviates from the reference rotor flux for the above step change in rotor resistance at 1sec. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was updated with the estimated value. The simulation results obtained for this case is shown in Fig.3.9 (b). From the result it is observed that with RF-MRAS based Rotor Resistance Estimator, the actual rotor flux is tracking the reference rotor flux.
Fig. 3.7 Block Diagram of the RFOC Induction Motor Drive with On-line PI Rotor Resistance Tracking
Fig. 3.8 MATLAB/SIMULINK schematic of the RFOC Induction Motor Drive with on-line PI Rotor Resistance Tracking
Fig.3.9 Actual and Reference d-axis Rotor Flux (a) Without RF-MRAS (b) With RF-MRAS

Fig.3.10 (a) shows the q-axis Rotor Flux when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed that without Rotor Resistance Estimator, the q-axis rotor flux is not zero for 100% step change in rotor resistance at 1sec indicating the absence of field orientation. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig.3.10 (b). From the result it is observed that with RF-MRAS based Rotor Resistance Estimator, the q-axis rotor flux returns to zero indicating field orientation even after $R_r$ has changed.
Fig. 3.10 q-axis Rotor Flux (a) Without RF-MRAS (b) With RF-MRAS

Fig. 3.11 (a) shows the actual and reference speed variations when the rotor resistance used in the RFOC controller was kept unaltered. It is observed that without RF-MRAS based Rotor Resistance Estimator, the actual speed deviates from the reference speed and takes some time to track the reference speed for 100% step change in $R_r$. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was concurrently updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig. 3.11 (b), Where it is observed that with RF-MRAS based Rotor Resistance Estimator the actual speed is tracking the reference rotor speed within a short period.
Fig. 3.11 Actual and Reference Speed (a) Without RF-MRAS (b) With RF-MRAS
Fig.3.12 Electromagnetic Torque (a) Without RF-MRAS (b) With RF-MRAS

Fig.3.12 (a) shows the electromagnetic torque developed when the rotor resistance used in the RFOC controller was kept unaltered. It is seen that without Rotor Resistance Estimator, the controller has slightly failed to maintain the torque for the step change in rotor resistance. Subsequently simulation was repeated after enabling the rotor resistance estimator block, updating $R_r$ with estimated value. The simulation results obtained for this case is shown in Fig.3.12 (b) which indicates that with RF-MRAS based Rotor Resistance Estimator, rapid torque control is achieved.

Fig.3.13 (a) shows the q-axis stator current when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed that without RF-MRAS based Rotor Resistance Estimator, the q-axis stator current deviates from the reference value for 100% step change in rotor resistance at 1sec. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig.3.13 (b), where it is observed that with RF-MRAS based $R_r$ Estimator, the q-axis stator current is tracking the reference.
value closely. The current $i_{qs}$ was also found to follow a profile similar to the motor torque.

**Operating Condition 2:**

- Reference Speed = 100 rad/sec
- Reference Rotor Flux = 0.9Wb
- Load Torque = 7.5Nm
• 100% **Ramp change** in Rotor Resistance is given at 1 sec.

The temperature rise and the change in rotor resistance of the Squirrel-Cage Induction Motor are very slow. To investigate this situation, a simulation was carried out introducing a 100% ramp change in the rotor resistance. The performance of the drive system was examined by changing the rotor resistance by 100%, from $6.085\Omega$ to $12.17\Omega$ over an interval of 1 sec to 2.5 sec.

Fig.3.14 (a) shows the actual and reference d-axis Rotor Flux when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed that without Rotor Resistance Estimator, the actual rotor flux deviates from the reference rotor flux for 100% Ramp change in rotor resistance at 1sec. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig.3.14 (b). Here, it is observed that with RF-MRAS based Rotor Resistance Estimator, the actual rotor flux is tracking the reference rotor flux closely.
Fig.3.14 Actual and Reference d-axis Rotor Flux (a) Without RF-MRAS (b) With RF-MRAS

Fig.3.15 (a) shows the q-axis Rotor Flux when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed that without Rotor Resistance Estimator, the q-axis rotor flux deviates significantly away from zero, following the ramp change, indicating loss of field orientation. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was concurrently updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig.3.15 (b) which indicate retention of field orientation even after the $R_r$ change.
Fig. 3.15 q-axis Rotor Flux (a) Without RF-MRAS (b) With RF-MRAS
Fig. 3.16 Actual and Reference Speed (a) Without RF-MRAS (b) With RF-MRAS

Fig. 3.16 (a) and (b) show simulation of shaft speed of the motor corresponding to ignoring and accounting ramp variation of $R_r$ respectively. It is seen that the mechanical behavior of the machine is similar in both the cases, though case (b) indicates a marginally better response. The variation of the electromagnetic torque of the machine without and with $R_r$ estimator are shown in Fig. 3.17 (a) and (b). These indicate similar behavior and generally corroborate the conclusions regarding speed variation.
Fig. 3.17 Electromagnetic Torque (a) Without RF-MRAS (b) With RF-MRAS

Fig. 3.18 (a) shows the q-axis stator current when the rotor resistance used in the RFOC controller was kept unaltered. From the result it is observed that without RF-MRAS based Rotor Resistance Estimator, the q-axis stator current deviates from the reference value for the Ramp change. Subsequently simulation was repeated after enabling the rotor resistance estimator block, so that the rotor resistance in the controller was updated with the estimated rotor resistance. The simulation results obtained for this case is shown in Fig. 3.18 (b), which indicate that with RF-MRAS based Rotor Resistance Estimator the q-axis stator current is tracking the reference value closely.
3.7 Conclusion

In this Chapter, the mathematical model of the RFOC Induction Motor drive has been presented. The essential mathematics involved in modeling the whole drive system incorporating RFOC along with speed feedback is presented. The MRAS based $R_r$ estimator using rotor flux is presented and implemented through MATLAB/SIMULINK simulation. Based on a model reference adaptive system, a rotor resistance estimation scheme has been developed with the help of PI adaptation. The tracking capability of the above algorithm for step and ramp changes in $R_r$ is studied. The benefits of incorporating rotor resistance variation in the closed loop control of a Cage Induction motor drive system are evaluated. From the results obtained, it is observed that the percentage error in estimation of RF-MRAS is 3% and settling time is found to be 0.13sec. Although the PI controller is capable of tracking the $R_r$ value without any large deviation, the choice of gain values in the controller require to be obtained using repeated trials. To overcome this problem, an alternate approach using ANN which is easy to design is developed and presented in Chapter 4.