A Diversity Based Reconfigurable Method for Fault Tolerant Control of Induction Motors

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Abstract—AC motor drive systems are sensitive to faults occurring at the power inverter, or at the control system. A novel fault tolerant Field Oriented Control system for induction motors is introduced. The system maintains speed control in the event of sensors malfunction and adverse signal conditions, providing enhanced reliability. The system comprises four different flux estimators which are fused by a Fuzzy aggregation system in order to give a reliable estimate of motor flux. The proposed control system is an effective and easy to implement method giving a potential for motor drive reliability enhancement.

Index Terms—Vector Control, Induction Motor, Fault Detection, Fault-Tolerant Control

I. INTRODUCTION

Field Oriented Control (FOC) is the industry standard for induction motor drives, where dynamic operation, and precise flux and torque control is required. FOC allows for decoupled torque and flux control, however, proper operation of the control system dependents on reliable operation of the feedback sensors. Faulty operation or disconnection of these sensors produces severe errors in the estimators which usually lead to drive shutdown by safety system. In some applications, In the event of sensor failures, it is desirable that the induction motor system continues to operate, even if under a diminished performance capacity. Research on fault tolerant control systems has received increased attention recently due to significantly increasing demand for reliability, maintainability and survivability of safety-critical systems, such as automotive and aerospace systems, nuclear power and hazardous chemical plants. Meeting these challenges demands highly sophisticated capabilities from these systems that traditional control technology is not offering.

This paper is concerned with developing an emerging control system for induction motor drive to mitigate the effects of different sensors failure. The system developed here, adaptively modifies control strategies in the event of sensor loss to attain the best performance given the complement of remaining sensors.

There are many literatures concerning fault tolerant control of induction motors [1-3], mostly focused on the failure of inverter and motor windings. Some literatures address sensor faults of an induction motor drive system [4, 5]. There are different control methods of induction motors from a high performance indirect vector control to a simple volts/hertz control with different dependency on the speed, current and voltage sensors. In a traditional redundant design, online switching of algorithm components and rapid redirection of the interconnections among them, as well as changing the priorities at which information is flowing, are employed in order to tolerate the faults. Nevertheless, immediate change of the operating regime may lead to unexpected catastrophic transients, because of uncertain state of variables following the sensor failure.

The proposed system in this paper coordinates distributed interaction among diverse components and supports dynamic reconfiguration and customization of the components in real time in the event of sensor failure. Multiple different implementations of the induction motor control is used like replicated systems to cope with errors in a specific implementation.

II. FLUX ESTIMATION

The conventional method for vector control is Field Oriented Control (FOC) along the rotor flux vector. In this method the motor model is described in a reference frame rotating with synchronous speed of motor with the real axis aligned with the rotor flux vector. It is convenient to use the two stator currents \((i_{SB}, i_{SA})\) as well as the two rotor fluxes \((\Psi_{2B}, \Psi_{2A})\) as state variables. As the stator current is impressed by the current control loop, the order of the system is virtually reduced from four to two. This way, the machine model is simplified [6].

Fig. 1 depicts the rotor flux vector \((\Psi_{2})\) in different reference frames. In this figure \(\beta_{1}\) is the flux angle with respect to stationary reference frame \((\alpha-\beta)\), \(\beta_{m}\) is the mechanical position of rotor and \(\beta_{2}\) is the slip angle. A crucial point in the development of field oriented control

![Fig. 1. The rotor flux vector in the stationary and rotating reference frames](image_url)
is determination of the flux angle ($\beta_1$). This is necessary to transform the variables from stationary frame to the rotating reference frame (A-B) and vice versa. The flux angle is derived from the measurable quantities of the IM by virtue of the machine model. There are several ways to estimate the rotor flux. They use different models for machine and require different quantities to be measured. Hence the dependency of each method to the sensors is different. Four methods are investigated here.

A. Flux Estimation by Feedback Current

In the proposed control system, the basic method is indirect field oriented control in which the slip derives from a current model of motor in rotor flux frame. This method incorporates rotor position feedback and motor current feedback to estimate the rotor flux angle ($\beta_1$) as depicted in Fig. 2. The flux equation can be written as below [6]:

$$\frac{d\psi_{2A}}{dt} + \frac{1}{T_2} \psi_{2A} = \frac{M}{T_2} i_{1A}$$

(1)

Where $M$ is the mutual inductance and $T_2$ is the rotor time-constant. Once the rotor flux is found from above equation, the rotor slip frequency ($\omega_2$) can be calculated as follows [6]:

$$\omega_2 = \frac{M}{T_2} \frac{i_{1B}}{\psi_{2A}}$$

(2)

The flux angle is then calculated by taking on the rotor speed.

The drawback of this method is that an error in estimating flux angle (e.g. due to wrong rotor resistance) yields error in $i_{1B}$ which further distorts $\beta_1$.

B. Flux Estimation by Feedforward Current Model

This method is the same as previous, but here the rotor slip frequency $\omega_2$ is calculated from reference values. No current sensor is required in this scheme. The drawback of feedforward technique is uncertain current quantities. Fig. 3 shows the block diagram of this method.

C. Flux Estimation by Voltage Model in the Stationary Reference Frame

All current models suffer from temperature (and saturation) dependent parameters.

In voltage model scheme, the flux angle is directly estimated via the integration of the measured voltages in stationary ($\alpha$-$\beta$) frame. The rotor flux equation can be expressed as:

$$\frac{M}{L_2} \frac{d\psi^*_{2A}}{dt} = -c_L \frac{d\psi^*_{1A}}{dt} + V_{1L}^* - R_{1i}^*$$

(3)

Where $V_{1L}^*$ and $i_{1L}^*$ are the stator voltage and current vectors respectively. The parameters $R_1$ and $L_1$ are the...
stator resistance and inductance. The parameter $\sigma$ is defined as:

$$\sigma = 1 - \frac{M^2}{L_2 L_1}$$  \hspace{1cm} (4)$$

The flux vector can be calculated from eq. (3) as below:

$$\Psi_2' = \frac{L_2}{M} [\sigma L_1 i_1' + \int (V_1' - R_1 i_1') dt]$$  \hspace{1cm} (5)$$

This way, no speed sensor is required. Furthermore, voltage models will prove less sensitive to rotor resistance variation compared with current models. Stator winding temperature however, may be measured (e.g. for motor protection) to allow for the influence in stator resistance ($R_1$). Fig. 4 shows the block diagram of this scheme.

This method fails at low speed where nearly all voltage is ohmic voltage drop without adequate information on the flux.

D. Flux Estimation by Feedforward Current Model with Feed-forwarding from Speed Reference (Sensor-free)

No sensor is employed in this method. To arrive at the constituent, the slip is calculated from load speed-torque characteristics and is added to reference speed to give the synchronous speed and then the flux angle. This, however, results in slow dynamics and sluggish response, since there is no feedback from the motor.

III. System Description

Fig. 5 depicts the proposed control system. Four different implementation of vector control is used. Although these methods look different, it can be shown that the entire problem is to estimate the rotor flux angle.

The flux angle estimates are fed to a fuzzy aggregation module where they are processed, validated, and fused to

![Fig. 4. Flux estimation by voltage model in the stationary reference frame](image)

![Fig. 5. The proposed fault tolerant vector control system for induction motor](image)
provide usable information to other control modules. Aggregating data using techniques such as averaging is an operation common to many information fusion processes. The Fuzzy logic gives more weight to consistent estimates and less weight to estimates that are far away from the consensus of the majority. Inputs are weighted and averaged to give the estimated angle.

\[
\beta_i = \frac{\sum_{j=1}^{4} w_j \beta_{ij}}{\sum_{j=1}^{4} w_j}
\]

(6)

Where \( w_j \) is the weight that the Fuzzy decision maker gives to the particular model. Fig. 6 depicts the membership functions used in Fuzzy weight generators.

The Fuzzy rules have been established on the basis of linguistic terms such as:

- In the event of current sensor failure, a feedforward current model is preferred, in which the reference torque and flux are used to estimate the slip.
- In the event of speed sensor malfunction, a voltage model of the motor has the largest weight in data fusion.
- When all sensors fail, the current feedforward method with additional feed-forwarding from speed reference is dominant, that implies the well known volt/hertz scheme.

IV. FAULT IDENTIFICATION

Sensors are always subjected to errors such as noise, offset, drift, and disconnections. The fault diagnosis is obtained from the comparison between the measured and predicted quantities for normal operation.

A. Current Sensors Fault Identification

Three sensors are employed for measuring of motor currents. When sensors are sound, the sum of the measured currents returns null. If one or two sensors fail, the sum is a non-zero sinusoidal signal. This signal is rectified and averaged to give a touchstone for identification of current sensors failure.

B. Voltage Sensors Fault Identification

Since the output voltages of the inverter are balanced, the deviation in sum of three voltages from zero is observed as the required error signal. To remove the switching ripples the respective voltages are filtered beforehand.

C. Speed Sensor Fault Identification

Fault detection of speed sensor is accomplished by comparing the sensed speed with the speed history. In transients, however there is a deviation, even when the sensor is perfect. Nevertheless, this makes no problem as the speed sensorless methods are emphasized by the fuzzy aggregation system.

V. SIMULATION RESULTS

The effectiveness of the proposed system was investigated by conducting a series of computer simulations. For better illustration of results, they are compared with a conventional indirect rotor FOC. The parameters of the motor that is used for simulation purpose are tabulated in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>( P_n )</td>
<td>15kW</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>( V_n )</td>
<td>460V</td>
</tr>
<tr>
<td>Rated Current</td>
<td>( I_n )</td>
<td>72A</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>( f_s )</td>
<td>60Hz</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>( R_s )</td>
<td>0.2761 ( \Omega )</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>( R_r )</td>
<td>0.1645 ( \Omega )</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>( L_s )</td>
<td>2.191mH</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>( L_r )</td>
<td>2.191mH</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>( L_m )</td>
<td>76.14mH</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>( J )</td>
<td>0.1kgm²</td>
</tr>
</tbody>
</table>

Three severe conditions of losing current, speed and both speed and voltage sensors are investigated by computer simulation as follow:

A. Current Sensors Failure:

The first simulation run involves disconnection of one of current sensors. The drive is intended to follow the base speed. After 8 seconds, a fault of missing one of current sensors is introduced. The results are illustrated in Figs. 7 and 8. With the conventional vector control the motor can no longer keep running. The stator currents substantially exceed their nominal values. This will usually leads the inverter shut down by the protection circuit. The proposed method, on the other hand, keeps the motor speed thoroughly near the speed reference. The speed is lightly diminished at the beginning of transition, but after that the system identifies the existing of a malfunction in the current sensor; the error is remedied in fractions of a second. No significant increases in currents are observed.
B. Speed Sensor Failure:

Next simulation performs the effect of speed sensor malfunction.

Simulation results are depicted in Figs. 9 and 10. One can see that the control system successfully prevents the drive stopover. No significant transients in currents occur. The conventional FOC method however, halts the motor. The currents are excessively increased beyond the safe operation limits.

Fig. 7. Motor speed after loss of current sensor; a) conventional vector control, b) proposed method

Fig. 8. Stator currents after loss of current sensor; a) conventional vector control, b) proposed method

Fig. 9. Motor speed after loss of speed sensor; a) conventional vector control, b) proposed method

Fig. 10. Stator currents after loss of speed sensor; a) conventional vector control, b) proposed method
C. Failure of Both Speed and Voltage Sensors:

The final simulation performs losing of both speed and voltage sensors. There is no feedback in this case and the system use the open loop method to control the motor. The simulation results are depicted in Figs. 11 to 13. The speed sensor fails after 6 seconds and the voltage sensors 2 seconds later. The deviation in speed is acceptable and no significant transient appears in motor currents and torque.

VI. CONCLUSIONS

A fault tolerant vector control system for induction motor was introduced. A multi-sensor data fusion method was used in order to estimate the flux angle. The investigation proved the effects of the proposed control system on preventing the motor drive from falling into catastrophic conditions in the event of losing some or all sensors. The smooth and rapid reconfiguration of control system ensures seamless operation of motor drive in a stable and robust manner and maintain viability in the event of unpredictable sensors failure. The resultant drive provides slightly degraded performance in the case of some faults, but still allows crucial limp home capability. The investigation proved the controller effectively prevents the drive from stop even on all sensors completely destroyed.

REFERENCES