Chapter 6

FIELD WEAKENING CONTROL OF INDUCTION MOTOR

6.1. Introduction

In specific applications such as propulsion purpose, the induction motor has to operate at speeds higher than the rated one, the field (flux) weakening is required which denotes the strategy by which the motor’s speed can be increased above the rated speed. To increase the produced torque to a maximum level in the field weakening region, it is essential to properly adjust the magnetic field by maintaining the maximum voltage and maximum current. The loss of torque and power in the case of not properly adjusting the machine flux is up to 35% [1]. So, the machine flux should be weakened in such a manner that it would guarantee a maximum possible torque in the whole speed range.

In this chapter, the basics of field weakening algorithms are studied along with the methods of field weakening for maximum torque capability. The FOC drive with sensor explained in chapter 2 and sensorless FOC drive with MRAS-SM developed in chapter 5 are extended to the field weakening region. The simulation models are validated and compared with extensive simulation results.

6.2. Field Weakening Control Methods

The basic principle for field weakening is that the magnetic field of the machine operating above rated speed level would be decreased due to the
limit in the machine’s voltage capability, which is imposed by a stator winding voltage limit and the DC link voltage.

The FW approach can be categorized as: i) variation of stator flux in inverse proportion to the rotor speed ($1/\omega_r$), ii) feed forward reference flux generation on machine equations or machine models and iii) closed loop control of the stator voltage or voltage detection model. The first approach as presented in [50] and [51], the most frequently used approach in FW control, the flux is established inversely proportional to the motor speed. Although the method is simple, it is justified only when considering the machine as a linear magnetic circuit. In real situations, the transition from nominal excitation to FW de-saturates the magnetic circuit. Thus the machine gets overexcited as the optimal balance occurs between the magnetizing and the torque producing current components. The method thus cannot produce maximum output torque for the available current and the full utilization of DC-link voltage.

The second approach, as presented in [52], [53], relies on the nonlinear equations of machine model and the constraints of voltage and current, which makes it parameter dependent. Thus the method can provide accurate results only if magnetic saturation is considered with known machine parameters of sufficient accuracy.

The third approach as described in [54]-[70], maximum available inverter voltage is utilized to produce maximum torque in FW region when the excitation level is adjusted by closed loop control of the machine voltage. Although it is not dependent on motor parameters and DC link voltage, it demands an additional outer loop which is to be tuned and requires intensive computation.

On comparing the above three approaches, the method based on machine model seems to be a more practical approach with reasonable results. The major problem of the machine model approach in the FW region is the substantial variation of magnetizing inductance which is considered constant in the base speed range. In the FW region, the rotor flux is getting reduced to below its rated value due to the increase of rotor speed than the base speed. The variable level of the main flux saturation in the machine
causes the variation of magnetic inductance [66]. Therefore, in model based approach, accurate speed estimation is possible only if the speed estimation algorithm is modified to account for the variation of magnetic inductance in the FW region.

6.3. Constraints of Voltage and Current to Induction Motor

Even though, the inverter has large enough voltage rating and current ratings, the induction machine itself has constraints in current and voltage rating because of insulation, magnetic saturation and thermal limit. Usually, the voltage rating of the inverter is set equal to the rated voltage of the induction motor. But, the current rating of the inverter is sometimes set as several times that of the induction machine to get higher acceleration and deceleration torque.

6.3.1. Voltage Constraints

The maximum phase voltage, \( V_{sm} \), is decided by DC link voltage, \( V_{DC} \) of a PWM inverter and the PWM method. If the output voltage vector is synthesized by means of sinusoidal PWM, the maximum magnitude of the stator voltage vector is:

\[
V_{sm} = \frac{V_{DC}}{2}
\]  

(6.1)

For SVM inverter, \( V_{sm} \) is equal to \( V_{DC}/\sqrt{3} \) in the linear control range. Considering some margins due to the dead time of the inverter and the control voltage for the current regulation,

\[
V_{sm} = \eta \frac{V_{DC}}{\sqrt{3}}
\]

(6.2)

where \( \eta = 0.90 - 0.95 \)

If \( V_{sm} \) is decided by the inverter as shown in Fig. 6.1, the \( d-q \) axis stator voltage should satisfy the following inequality condition, which sensibly influence the motor behaviour and the voltage limit ellipse equation as follows,
where $V_{sd}$, $V_{sq}$ are components of voltage vector in $d$-$q$ coordinates

$L_{3} = \sigma L_{3}$

### 6.3.2. Current Constraints

The maximum current to an induction motor, $I_{sm}$ is usually decided by the thermal limit of the inverter or the motor itself. If the constraint is decided by the inverter, then the limiting condition of the current is set by the heat dissipation of switching and conduction losses of the switching power semiconductors. If the constraint is decided by the motor itself, then limiting condition of the current is set by the heat dissipation from iron and copper losses of the motor. Thus, the maximum current to the motor is also limited and the current limit boundary is a circle, whose radius depends
only on the current rating $I_{sm}$. The current constraint of the inverter is shown in Fig. 6.2 graphically, and can be expressed as follows,

$$I_{sd}^2 + I_{sq}^2 \leq I_{sm}^2 \tag{6.5}$$

where $I_{sm}$ is the maximum current magnitude, $I_{sd}$, $I_{sq}$ are current vector components of the induction motor in the $d$-$q$ coordinate system.

![Fig. 6.2 Limiting condition for the reference vector of the stator current](image)

### 6.4. Operating Region under Current and Voltage Constraints

The voltage constraint in (6.4) and current constraint in (6.5) are expressed in the $d$-$q$ reference frame, but the constraints are presented in different planes, where one is voltage plane and the other in current plane. Hence, it is difficult to consider both constraints simultaneously. The constraints can be simultaneously depicted in the voltage plane or in the current plane by using the stator voltage equations of an induction machine. If the constraints are depicted in the voltage plane, though the voltage margin and phase of commanded voltage can be easily understood, the torque, which is usually expressed in terms of current, cannot be easily demonstrated in the voltage plane. In the synchronously rotating reference frame, the stator voltage can be represented in terms of the stator current.
and rotor flux linkage in (6.6) and in (6.7) under the assumption of the vector control based on the rotor flux linkage orientation.

\[
\begin{align*}
\tilde{V}_{sd} &= R_{s}i_{sd} + L_{s} \frac{di_{sd}}{dt} + L_{m} \frac{di_{rd}}{dt} - L_{s} \omega_{e} \sigma i_{sq} - L_{m} \omega_{e} i_{rq} \\
\tilde{V}_{sq} &= R_{s}i_{sq} + L_{s} \frac{di_{sq}}{dt} + L_{m} \frac{di_{rq}}{dt} + L_{s} \omega_{e} i_{sd} + L_{m} \omega_{e} i_{rd}
\end{align*}
\] (6.6) (6.7)

In (6.6) and in (6.7), the term due to the flux variation can be neglected under the assumption of relatively slow variation of the flux linkage. Also, the term due to the variation of current can be neglected with the assumption of slow enough current variation or under the steady state operation. The voltage drop due to the stator resistance can be neglected at higher operating speed, where field weakening occurs. With these assumptions, the stator voltage equation in (6.6) and (6.7) can be approximated in (6.8) and in (6.9).

\[
\begin{align*}
V_{sd} &\approx -\omega_{e} \sigma L_{s} i_{sq} \\
V_{sq} &\approx \omega_{e} L_{s} i_{sd}
\end{align*}
\] (6.8) (6.9)

By substituting (6.8) and (6.9) to the voltage constraint in (6.3), the following inequality can be obtained, which is the interior of an ellipse in the synchronous reference current plane.

\[
(\omega_{e} \sigma L_{s} i_{sq})^2 + (\omega_{e} L_{s} i_{sd})^2 \leq V_{sd}
\] (6.10)

The possible operating point of \(d\)-\(q\) axis current of the induction motor should lie in the common part of (6.3) and (6.10), which is the cross section of the ellipse and the circle.

The size of the voltage constraint ellipse decreases as the operating speed increases as shown in Fig. 6.3. Also, current constraint can be represented as a circle in the current plane as shown in Fig. 6.3. The possible operating region is the cross section of the ellipse and the circle. The torque is depicted as a reciprocal proportion curve in the current plane as shown in Fig. 6.3.
For satisfying the voltage limit constraint, the command currents \( i_{sq} \) and \( i_{sd} \) should remain inside the voltage limit ellipse given at each operating frequency. The radii of ellipse become smaller as the operating frequency increases. The leakage factor of machine has influence on the area of ellipse at a specific frequency, it is because the shape of the ellipse is determined by its eccentricity \( e \), that depends on the leakage factor of the machine as:

\[
e = \sqrt{1 - \sigma^2} \tag{6.12}
\]

In case of machine with large leakage factor eccentricity is small, with small eccentricity, the area of ellipse is smaller than the case of the machine with a small leakage factor at the same operating frequency. Therefore at
the same operating frequency and the same voltage limit, in the case of machines with a large leakage factor, the area of the controllable currents is smaller.

The operating range of the induction motor can be divided into three regions: i) constant torque region or base speed region, ii) constant power region or field weakening region I and iii) constant slip frequency region or field weakening region II as shown in Fig. 6.4.

The available maximum torque and speed range of the induction machine in the torque-speed plane under the limited stator voltage and current magnitude, which is defined as the capability curve, can be obtained by controlling the airgap flux in constant up to the base speed and by reducing the airgap flux proportional to the speed above the base speed. Above the base speed, if the flux is kept as the rated value, the magnitude of the stator voltage increases above the rated value which is the maximum value accommodated by the machine itself or by the electric power supply of the machine. If the slip angular frequency increases, which is the value where the pull out torque occurs, then the torque would not further increase with the increase of slip angular frequency. Hence above that speed the slip
angular speed kept as constant and the magnitude of rotor and stator current decreases with further increase of speed.

### 6.4.1. Constant Torque Region or Base Speed Region

If $d$-axis current for the maximum torque, which is the current at the crossing point of the ellipse and the circle as shown in Fig. 6.5, is larger than the rated value of $d$-axis current of the induction motor, then the $d$-axis current reference should be set as rated value to prevent the magnetic saturation of the induction motor as in (6.13). The maximum available torque is decided only by the maximum $q$-axis current, which is obtained by the current constraint as (6.14). The maximum torque is always the same in this region and hence is called the constant torque region.

![Fig. 6.5 Constant torque region](image)

\[ i_{sd} = i_{sd,\text{rated}} \]  \hspace{1cm} (6.13)

\[ i_{sq} = \sqrt{I_{sm}^2 - i_{sd,\text{rated}}^2} \]  \hspace{1cm} (6.14)
As the speed increases, the size of the ellipse decreases and the constant torque region ends when \(d\)-axis current at the crossing point of the ellipse and the circle coincides with the rated \(d\)-axis current, \(i_{sd,\text{rated}}\). The angular frequency where the constant torque operation region ends is known as base speed, \(\omega_b\), which can be deduced as:

\[
\omega_b = \frac{V_{im}}{L_s \sqrt{[\sigma^2 (I_{sm}^2 - i_{sd}^2) + i_{sd}^2]}^{\frac{1}{2}}}
\]  

(6.15)

**6.4.2. Constant Power Region or Field Weakening Region I**

This operation region starts from the base speed and extended to \(\omega_1\), above which there is no more crossing point between the voltage ellipse and current circle. In this region, the \(d\)-axis current reference is always less than the rated \(d\)-axis current as shown in Fig 6.6. The \(d\)-axis current to maximize the torque can be derived as in (6.11) from the crossing point of the ellipse and circle and \(q\)-axis current is simply derived as in (6.17) from the current constraint.

![Fig. 6.6 Field weakening region I](image-url)
\[
    i_{sd} = \sqrt{\left(\frac{V_{sm}}{\omega_1}\right)^2 - (\sigma L_x i_{sm})^2} \quad (6.16)
\]

\[
    i_{sq} = \sqrt{I_{sm}^2 - i_{sd}^2} \quad (6.17)
\]

### 6.4.3. Constant Slip Region or Field Weakening Region II

If the operating frequency of the induction motor further increases from the field weakening region I and the ellipse shrinks further then the ellipse would be fully inside the circle as shown in Fig. 6.7. This operating region is referred to field weakening region II or characteristic region of the induction machine. Thus there is no crossing point of ellipse and circle in this region and the torque is limited only by the voltage constraint. The frequency, \( \omega_1 \), which separates the two regions, field weakening regions I and II can be expressed as [79].

\[
    \omega_1 = \frac{V_{sm}}{I_{sm}} \sqrt{\frac{1 + \sigma^2}{2(\sigma L_x)^2}} \quad (6.18)
\]

In this region, the reference current to maximize the torque can be represented in terms of the maximum voltage and the machine parameters as in (6.19).
\[ i_{sd} = \frac{V_{sm}}{\sqrt{2}\omega_c L_s} \]  

\[ i_{sq} = \frac{V_{sm}}{\sqrt{2}\omega_c \sigma L_s} \]

6.5. Four Quadrant Control Operation

The operating quadrants in the torque-speed plane correspond to the four possible combinations of polarities of torque and speed as shown in Fig. 6.8. Quadrant 1 shows forward speed and forward torque, where the torque is propelling the motor in the forward direction and is in ‘forward motoring’ mode. Conversely, In Quadrant 3, the motor is spinning backwards with the reverse torque. Now the motor is ‘backward motoring’ mode. Quadrant 2, where the motor is spinning in the reverse direction, but torque is being applied in forward direction. Torque is being used to ‘brake’ the motor and is in ‘generating’ mode. Finally, Quadrant 4 is exactly the opposite. The motor is spinning in the forward direction, but the torque is being applied in the reverse direction. Again, torque is being applied to attempt to slow the motor and change its direction to forward again. The power flow in the first and third quadrants is positive and is negative in the second and fourth quadrants.

![Fig. 6.8 Four quadrant motor operation](image-url)
For propulsion applications, both polarities of the motor speed are possible, forward and backward driving. Also, the motor torque can assume two polarities, agreeing with the speed, forward and backward braking known as ‘electrical braking’. Thus the two possible polarities of both the torque and speed make up four quadrant operation of the drive.

6.6. Implementation of FW Algorithm

Based on (6.13) to (6.20), the FW algorithm is formulated and presented as in Fig. 6.9. In the FW algorithm, the regions are identified using (6.15) and (6.18). The \( q \)-axis current control is determined in (6.14) in base speed region. In the field weakening regions, the current limitation in Region I is in (6.17) and in Region II in (6.20). The algorithm is written using \textit{m-functions} in MATLAB to reduce the usage of Simulink blocks.

The FW algorithm is implemented in the simulations models for FOC drive with sensor explained in chapter 2 and sensorless FOC drive with MRAS-SM developed in chapter 5. The block diagram of the simulation models incorporating the field weakening algorithms for FOC drive with sensor and sensorless FOC drive using MRAS-SM are as shown in Figs. 6.10 and 6.11 respectively.
Fig. 6.10 Block diagram of FOC with sensor in FW region

Fig. 6.11 Block diagram of sensorless FOC with MRAS-SM in FW region
6.7. Simulation Results and Discussion

The parameters of induction motor used for the simulation are presented in Appendix-I. For comparing the performance of the developed drive systems, simulation is carried out for both models, without sensor and with sensor using both SPWM and SVM inverters.

In the first phase of simulation, the motor starts from a standstill state to reference speeds of 0.8 p.u. (Base speed region), 2.2 p.u. (FW-I region) and 3.5 p.u. (FW-II region) with a rated speed of 136 rad/sec in no load conditions. Figures 6.12 (a) and 6.12 (b) show the rotor speed responses with time for cases with and without sensors using both SPWM and SVM. Table 6.1 presents the time elapsed to attain the above speeds for both cases using SVM and SPWM inverters. The results show MRAS-SM observer estimates the rotor speed well and close to that of with sensors in all ranges. SVM fed inverter improves the performance of tracking the reference speed compared to that of SPWM in FW region for sensorless case. The speed tracking rate is more or less same for both the inverters in the case of drive with sensor.

Table 6.1 Rotor speed response with time

<table>
<thead>
<tr>
<th>Rotor speed (p.u.)</th>
<th>Time taken to attain reference speed (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sensorless</td>
</tr>
<tr>
<td></td>
<td>SVM</td>
</tr>
<tr>
<td>0.8</td>
<td>0.40</td>
</tr>
<tr>
<td>2.2</td>
<td>1.40</td>
</tr>
<tr>
<td>3.5</td>
<td>3.85</td>
</tr>
</tbody>
</table>

The response of electromagnetic torque as the rotor speed changes from zero to the maximum attainable rotor speed in FW region is presented in Figs. 13 (a) and 13 (b). The maximum speed attained in sensorless case is 3.8 p.u. and 3.6 p.u. for SVM and SPWM respectively. Maximum speed of 4.15 p.u. for SVM fed inverter and 3.75 p.u. for SPWM respectively are achieved in the case of drive with sensor.
Fig. 6.12 Rotor speed vs. time (in three regions)
(a) Sensorless using MRAS-SM

(b) With sensor

Fig. 6.13 Torque vs. Rotor speed
The maximum torque attained to the rated value in the base speed region for the SVM and lesser values in the case of SPWM in both base speed and FW-I regions compared to SVM for sensorless case. But, in FW-II region, both have same performance. Torque-speed characteristic is more or less same in both base speed and FW-1 regions for the case of drive with sensor. But, SVM fed inverter improves the torque capability in FW-II region compared to SPWM. Table 6.2 presents the values of torque for various rotor speeds for both cases.

Table 6.2 Torque - Speed response

<table>
<thead>
<tr>
<th>Rotor speed (p.u.)</th>
<th>Torque (p.u.)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sensorless</td>
<td>with sensor</td>
<td></td>
</tr>
<tr>
<td>SVM</td>
<td>SPWM</td>
<td>SVM</td>
<td>SPWM</td>
</tr>
<tr>
<td>0.8</td>
<td>1.00</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>2.2</td>
<td>0.45</td>
<td>0.46</td>
<td>0.45</td>
</tr>
<tr>
<td>3.5</td>
<td>0.18</td>
<td>0.25</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Variation of magnetizing current with respect to rotor speed is shown in Figs. 6.14 (a) and 6.14 (b) for drives without sensor and with sensor respectively. Fig. 6.15 shows the estimated rectangular components of rotor flux in the steady state condition in the time range between 5.0 sec and 5.05 sec for the three reference rotor speeds in base speed, FW-I and FW-II regions for both cases using SVM and SPWM inverters. Rotor flux locus for the speed range from 0 to 3.5 p.u. is shown in Figs. 6.16 and 6.17.

By observing all these simulation results, it ensures that the ability of MRAS -SM observer to adapt the actual saturation level in the induction machine and hence provide an accurate speed estimation for any operating point in both base speed and FW regions. SVM inverter improves the performance of the FOC drive compared to SPWM in both cases. It is also observed that SVM inverter can respond quickly in both base speed and FW regions.
(a) Sensorless using MRAS-SM

(a) With sensor

Fig. 6.14 Magnetizing current vs. rotor speed
Fig. 6.15 Rotor flux vs. time (for sensorless case with SVM)

i) Base speed region

ii) FW-I region

iii) FW-II region

Fig. 6.16 Rotor flux locus with SVM inverter
In the second stage of simulation, the motor is operated in the four quadrants with no load condition. Rotor speed responses in four quadrants with a speed reversal of +3.5 p.u. to -3.5 p.u. is demonstrated in Fig. 6.18. The difference between the actual and the estimated speed defined as the speed error expressed as percentage is shown in Fig. 6.19. Table 6.3 presents the reference, estimated and actual rotor speeds and corresponding speed error for base speed, FW-I and FW-II regions. The average speed estimation error is found to be negligibly small in all regions.

Table 6.3 Rotor speed response

<table>
<thead>
<tr>
<th>Reference speed (p.u.)</th>
<th>Estimated speed (rpm)</th>
<th>Actual speed (rpm)</th>
<th>Speed error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1040</td>
<td>1039</td>
<td>1041</td>
</tr>
<tr>
<td>2.2</td>
<td>2860</td>
<td>2868</td>
<td>2862</td>
</tr>
<tr>
<td>3.5</td>
<td>4550</td>
<td>4552</td>
<td>4557</td>
</tr>
</tbody>
</table>
Figure 6.18 shows the speed tuning signal with respect to time. From the simulation results, it can be seen that estimated speed tracks the actual speed very well in all the regions of four-quadrants except during the first part of base speed region.
Figure 6.21 demonstrates the electromagnetic torque-speed curve as the rotor start up from zero to +3.5 p.u., +3.5 p.u. to -3.5 p.u. and -3.5 p.u. to zero. This resembles the typical torque capability curve of the induction machine in four quadrant operation.

![Fig. 6.20 Speed tuning signal vs. time](image1)

![Fig. 6.21 Torque-speed curve in four quadrant operation](image2)

The dynamic behavior of field weakening algorithm in the models is evaluated by applying a sequence of multiple and single step changes of the speed reference signal between 0 to 4 p.u. (4 times rated value) in four quadrant. The induction motor used for simulation is 10 kW having the motor parameters as given in Appendix I. The speed responses for SPWM and SVM inverters are shown in Figs. 6.22 and 6.23 respectively. The results show that MRAS-SM observer estimates the rotor speed well and
close to that of with sensors in all ranges of speed and SVM inverter catches better performance in tracking the speed command compared to that of SPWM inverter.

Fig. 6.22 Rotor speed vs. time
(Four quadrant operation in single step)

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a) with SPWM inverter

b) with SVM inverter

Fig. 6.23 Rotor speed vs. time
(Four quadrant operation in multiple steps)
The electromagnetic torque (p.u.) vs. rotor speed (p.u.) characteristics of the four models is presented in Fig. 6.24. The torque attainability rate is slightly less for sensorless case compared to drive with sensor for both type of inverters and the characteristics is more or less same in all quadrants. But, SVM inverter improves the torque capability in all quadrants compared to SPWM inverter.

Fig. 6.24 Torque vs. rotor speed (Four quadrant operation)
6.8. Summary

In this chapter, a novel adaption technique is proposed for sensorless operation of FOC induction motor using MRAS-SM in FW region. The adaption mechanism is based on Lyapunov theory to ensure stability with fast error dynamics. MATLAB/Simulink models of FOC induction motor drives with and without sensors using SPWM and SVM inverters are developed for wide ranges of speed including FW region and the performance of the models compared in four quadrant operation. The speed estimation by the rotor flux MRAS with SM observer using SVM inverter, instead of conventional SPWM inverter, ensured very good accuracy in all ranges of speed control of four quadrants. In this method, the transition speed between base speed region and FW region is smooth, depending upon the voltage and current limits.

6.9. Publications Related to this Chapter

**International Conference:**


**Transaction:**