Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM) Using Field Weakening

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INTRODUCTION

The utilization of an AC induction motor (ACIM) ranges from consumer to automotive applications, with a variety of power and sizes. From the multitude of possible applications, some require the achievement of high speed while having a high torque value only at low speeds. Two applications needing this requirement are washing machines in consumer applications and traction in powertrain applications. These requirements impose a certain type of approach for induction motor control, which is known as “field weakening.”

This application note describes sensorless field oriented control (FOC) with field weakening of an AC induction motor using a dsPIC® Digital Signal Controller (DSC), while implementing high performance control with an extended speed range.

This application note is an extension to AN1162: *Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM)*, which contains the design details of a field weakening block. The concepts in this application note are presented with the assumption that you have previously read and are familiar with the content provided in AN1162.

CONTROL STRATEGY

Sensorless Field Oriented Control

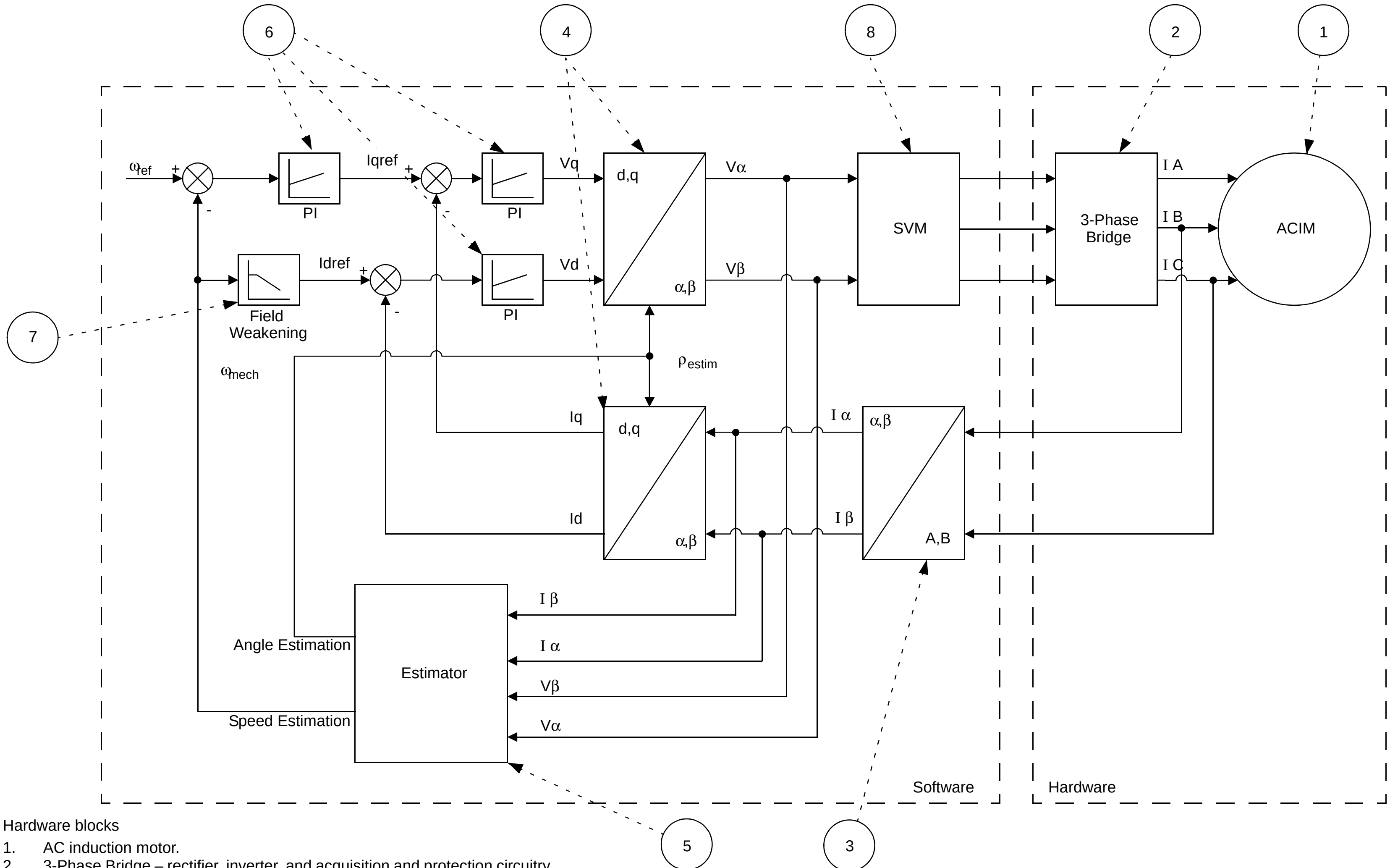
Field oriented control principles applied to an ACIM are based on the decoupling between the current components used for magnetizing flux generation and for torque generation. The decoupling allows the induction motor to be controlled as a simple DC motor. The field oriented control implies the translation of coordinates from the fixed reference stator frame to the rotating reference rotor frame. This translation makes possible the decoupling of the stator current’s components, which are responsible for the magnetizing flux and the torque generation.

The decoupling strategy is based on the induction motor’s equations related to the rotating coordinate axis of the rotor. To translate the stator fixed frame motor equations to the rotor rotating frame, the position of the rotor flux needs to be determined. The position of the rotor can be determined through measurement or it can be estimated using other available parameters such as phase currents and voltages. The term “sensorless” control indicates the lack of speed measurement sensors.

The control block diagram of the field oriented control is presented in Figure 1 with descriptions of each component block. In particular, the field weakening block has the motor’s mechanical speed as input, with its output generating the reference d-axis current corresponding to the magnetizing current generation.

For additional information on field oriented control of an AC induction motor, refer to AN1162 (see **“References”**).

FIGURE 1: SENSORLESS FOC FOR ACIM BLOCK DIAGRAM



Hardware blocks

1. AC induction motor.
2. 3-Phase Bridge – rectifier, inverter, and acquisition and protection circuitry software blocks (run by the dsPIC® DSC device).
3. Clarke forward transform block.
4. Park forward and inverse transform block.
5. Angle and speed estimator block.
6. Proportional integral controller block.
7. Field weakening block.
8. Space vector modulation block.

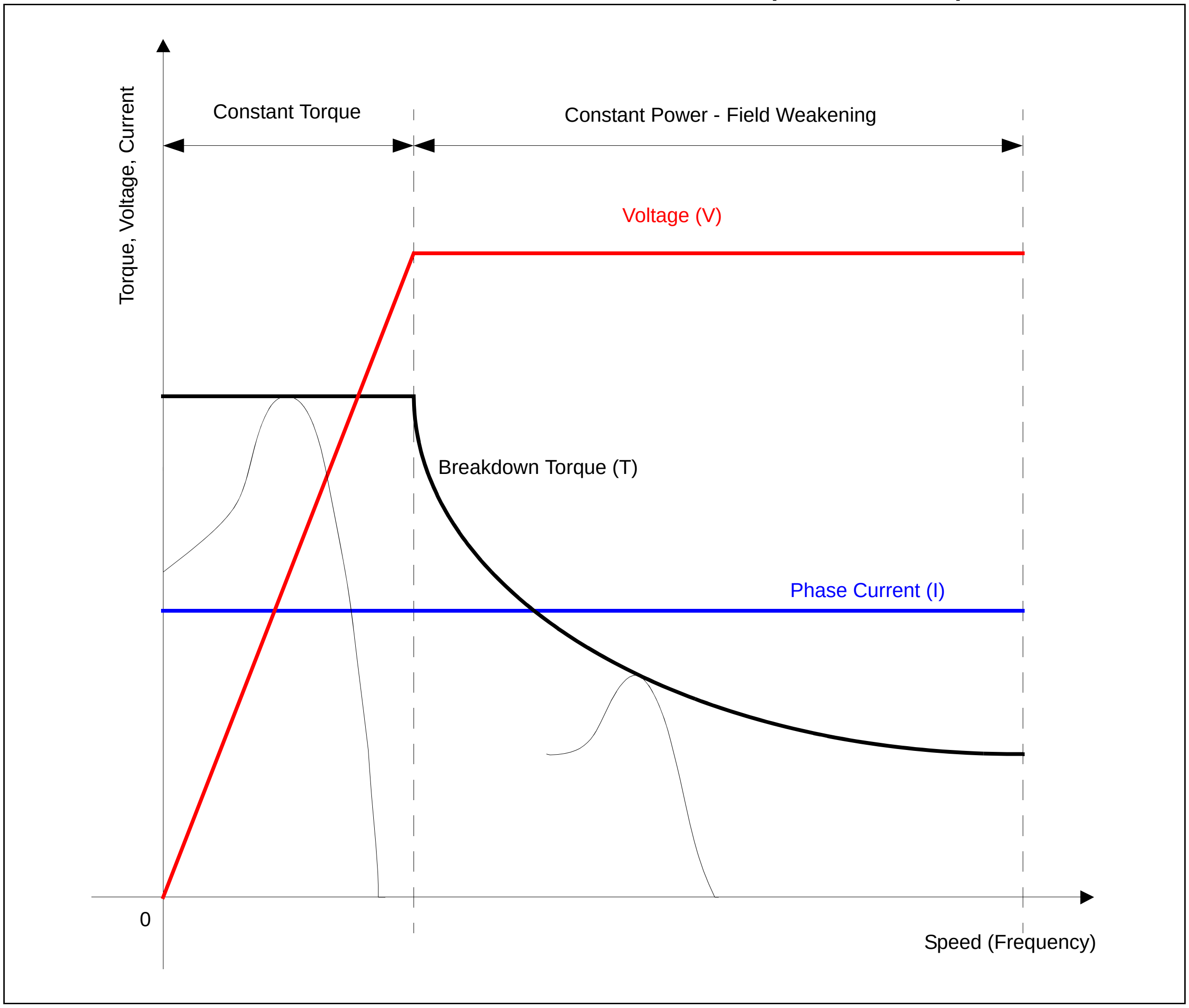
Field Weakening

Field weakening denotes the strategy by which the motor's speed can be increased above the value maximum achieved in the constant torque functioning region.

The constant torque region for field oriented control of the AC induction motor is delimited from field weakening – the constant power region by the maximum voltage that can be provided to the motor.

In the constant power region, the maximum voltage is a characteristic of the inverter's output in most cases. The breakdown torque is constant for the entire range of speeds below the field weakening region limit, and once the speed increases above this limit, the breakdown torque value will decrease, as shown in Figure 2.

FIGURE 2: CHARACTERISTIC OF AN INDUCTION MOTOR (THEORETICAL)



The torque of the induction motor is expressed by Equation 1:

EQUATION 1:

$$T = \frac{3}{2}\frac{P}{2}\frac{1}{1+\sigma_R}\Psi_{mR} \cdot i_{Sq}$$

where:

T = torque

P = number of poles

Ψ_{mR} = magnetizing flux

i_{Sq} = torque producing current component

$$\sigma_R = \frac{L_R}{L_M} - 1$$

L_R = rotor inductance

L_M = mutual inductance

The rated torque of the motor is obtained by selecting the magnetizing current to achieve the maximum torque per amp ratio. In theory, if the magnetic saturation is not taken into consideration, the maximum peak of torque per amp is achieved when the magnetizing current (i_{mR}) is equal to the torque-producing component of the stator current (i_{Sq}) at steady state condition for all permitted ranges of stator currents. The magnetizing current is responsible for the magnetizing flux generation. Its dependency on the d-component of the current is expressed by Equation 2.

EQUATION 2:

$$T_R\frac{di_{mR}}{dt} + i_{mR} = i_{Sd}$$

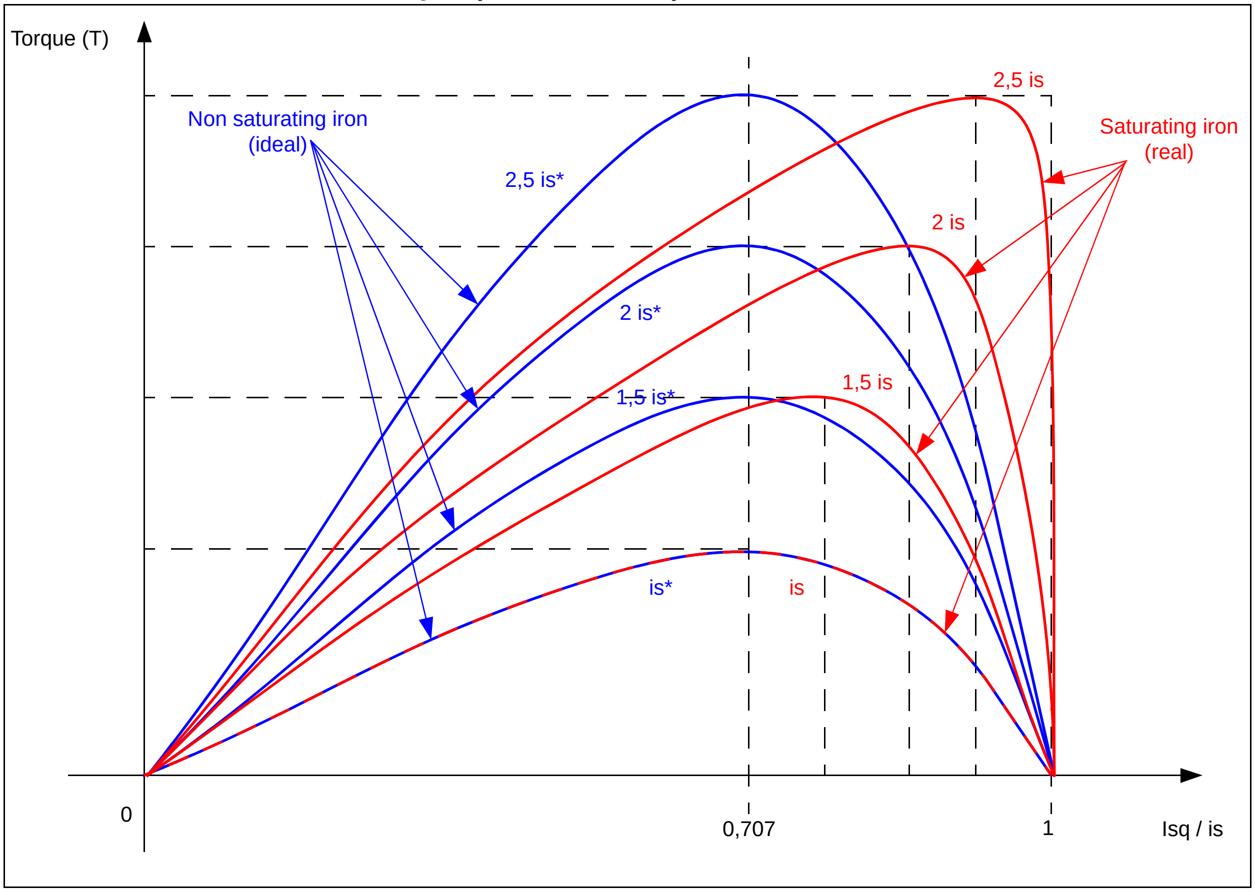
where:

T_R = rotor time constant

i_{mR} = magnetizing current

i_{Sd} = magnetizing flux-producing current component

FIGURE 3: MAXIMUM TORQUE (THEORETICAL)



In the real-world case of a saturating machine, the maximum torque per amp is no longer obtained at the same ratio of the magnetizing current per torque command current for the same range of stator currents.

The magnetizing flux increase has a nonlinear dependency on magnetizing current, which is a small flux increase requiring greater current needs. Therefore, to achieve a maximum torque per amp ratio, it is recommended to put most of the current increase in the torque-producing current component.

The power limit of the inverter and the necessity of speed increase can be achieved by delivering lower torque. Field weakening is well suited in the case of traction or home appliances where the high torque value is necessary only at low speeds.

When lowering the torque in field weakening, the same concerns of keeping a high ratio of torque per amp are considered. At the same time, considering Equation 3, the back electromagnetic force (BEMF) is proportional to the rotor speed. This limits the maximum reachable speed once the right term of the equation is equal to inverter maximum voltage (i.e., left term). A BEMF amplitude decrease, achieved by lowering the magnetizing current, would leave more space for speed increase, but at the same time, would lead to the torque decrease according to Equation 1.

EQUATION 3:

$$\underline{u}_S = (R_S + j\omega\sigma L_S)\underline{i}_S + \underbrace{j\omega(1-\sigma)L_S i_{mR}}_{BEMF}$$

where:

$\underline{u}_S$ = stator voltage vector

$\underline{i}_S$ = stator current vector

R_S = stator resistance

ω= angular speed

$$\sigma = 1 - \frac{L_M^2}{L_S \cdot L_R}$$

L_S = stator inductance

L_R = rotor inductance

L_M = mutual inductance

Figure 4 depicts the graphical representation of Equation 3, where U_{max} is the maximum voltage.

Considering the two components of the stator voltage, d-q, their relation with respect to the stator voltage vector is expressed by Equation 4 (in modulus).

EQUATION 4:

$$u_S = \sqrt{u_{Sd}^2 + u_{Sq}^2}$$

where:

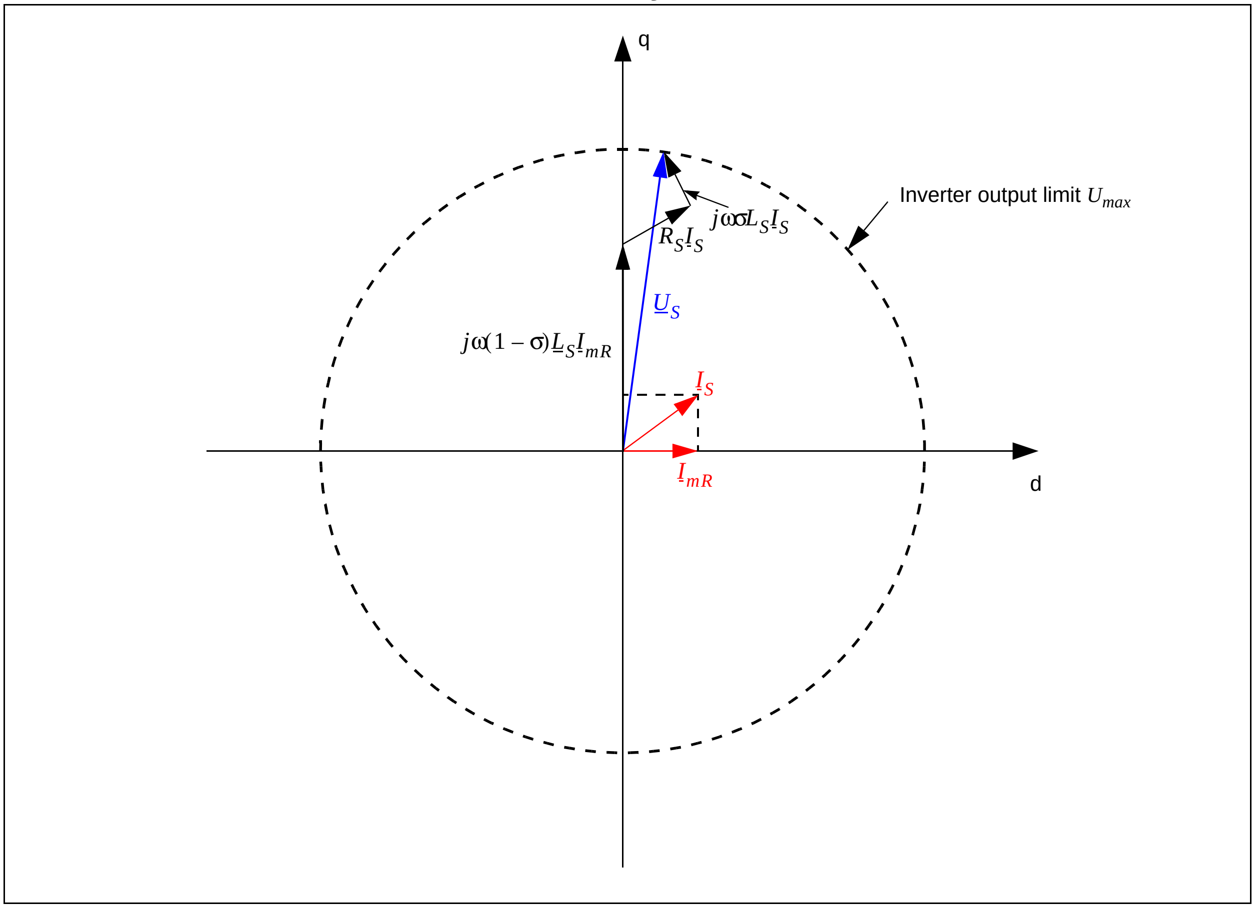
u_S = stator voltage

u_{Sd} = magnetizing flux-producing voltage component

u_{Sq} = torque-producing voltage component

The maximum stator voltage limitation is in fact a limitation of the two component terms, d and q, as resulting from Equation 4. Referring back to the control scheme, this limitation is confirmed by the fact that d-q current controllers are saturated. Decreasing the magnetizing current would unsaturate the controllers and get the system out of the limitation presented in Figure 4.

FIGURE 4: REPRESENTATION OF STATOR EQUATION



The presented solution uses the rotor speed as an input for the field weakening block. The magnetizing current is adjusted as a speed function so that the control system limitation described previously is avoided. The BEMF steady state amplitude value, which depends on the magnetizing current, must result so that the right term in Equation 4 is less than the maximum inverter voltage amplitude for the operating range. This is depicted in Figure 5.

Two criteria must be considered when determining the designated steady state feed voltage amplitude supplied from the inverter for field weakening operation:

- Having at any time the possibility to react on load change or on acceleration demand by increasing the output voltage – this being translated in maximum voltage reserve and;
- Having the maximum inverter output voltage to minimize the motor current resulting in high efficiency – this being translated in minimum voltage reserve

According to experience, the voltage reserve should be between 10% and 25% to fulfill both criteria. The current application choice of 15% voltage reserve is based on the consideration that the application does not require high dynamic or load change.

Since the variation of the speed is done slowly (i.e., low dynamic), there is no need for an additional flux controller. Instead, the output of the field weakening block is connected directly to the current controller.

The determination of magnetizing current as a function of rotor speed is achieved with a series of open loop V/Hz, no load experiments. For each series of experiments, the V/Hz ratio is modified. The experiments consist of varying the frequency, and at 85% of the maximum inverter voltage, the d-component of the current is measured (representing the magnetizing current at steady state). The assumption is that when the motor is running under no load, there is no torque produced (except the friction of the bearings, which is very small), so that at steady state, the d-current component is equal to the magnetizing current. As shown in Figure 6, the values obtained in several side experiments are summarized in a graph representing the magnetizing current function of the frequency.

FIGURE 5: VOLTAGE RESERVE FOR STATOR EQUATION

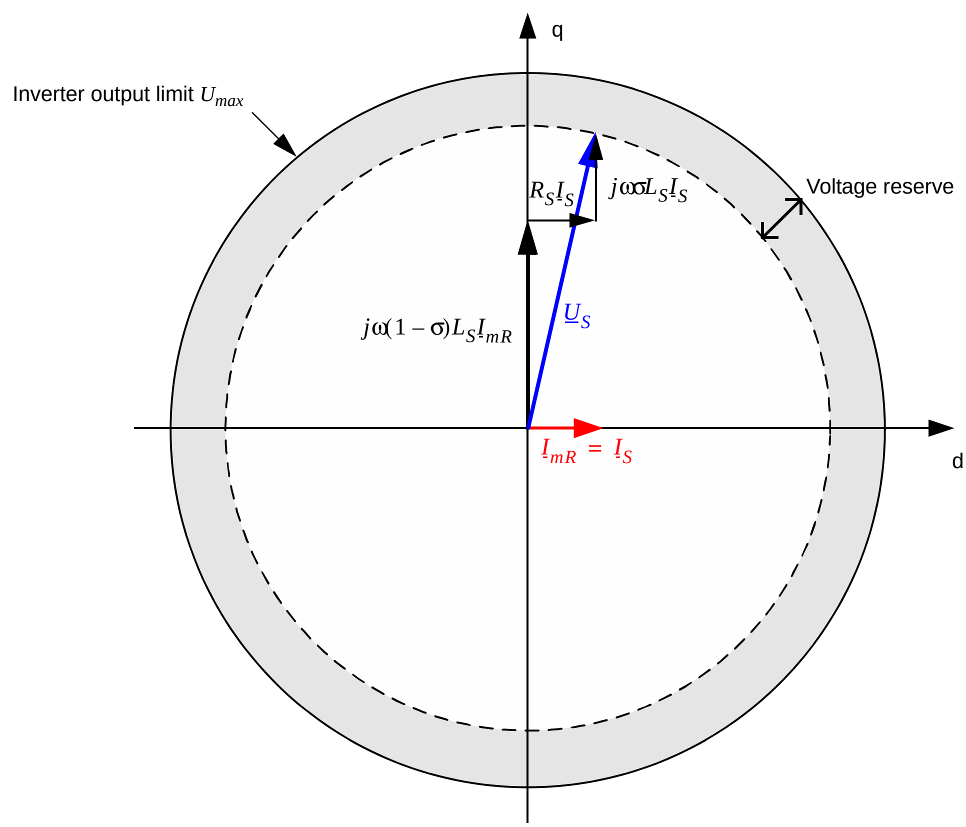
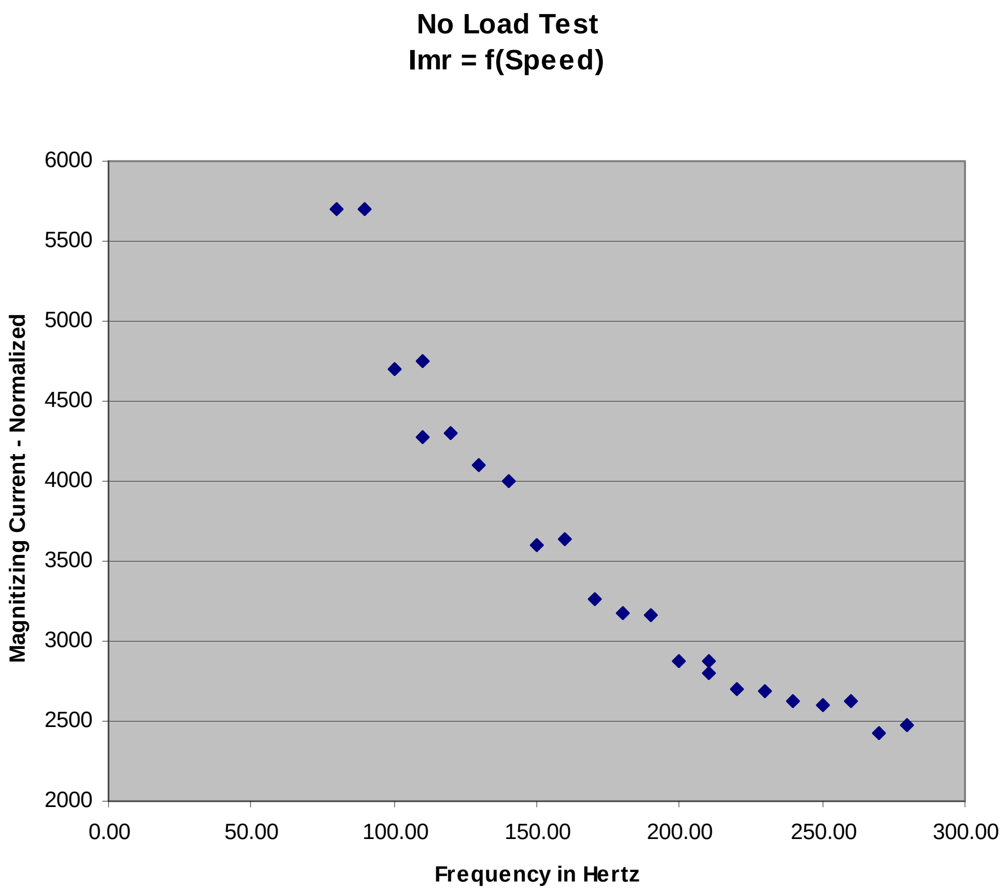


FIGURE 6: MAGNETIZING CURRENT FUNCTION OF SPEED (EXPERIMENTAL)



As indicated previously, the variation of rotor flux with the magnetizing current is not linear, since the saturation of iron is implied. Equation 5 expresses the relation between the rotor flux, magnetizing current, and mutual inductance.

EQUATION 5:

$$\Psi_{mR} = L_0 \cdot i_{mR}$$

where:

Ψ_{mR} = magnetizing flux

$L_0 = L_M$ (mutual inductance)

i_{mR} = magnetizing current

To determine the L_0 inductance, it can be assumed that $L_S = L_R$. Under a no load condition, L_S can be calculated, as shown in Equation 6:

EQUATION 6:

$$L_S = \frac{1}{\omega_S}\sqrt{\frac{u_S^2}{i_S^2} - R_S^2}$$

where:

u_S = stator voltage

i_S = stator current

L_S = stator inductance

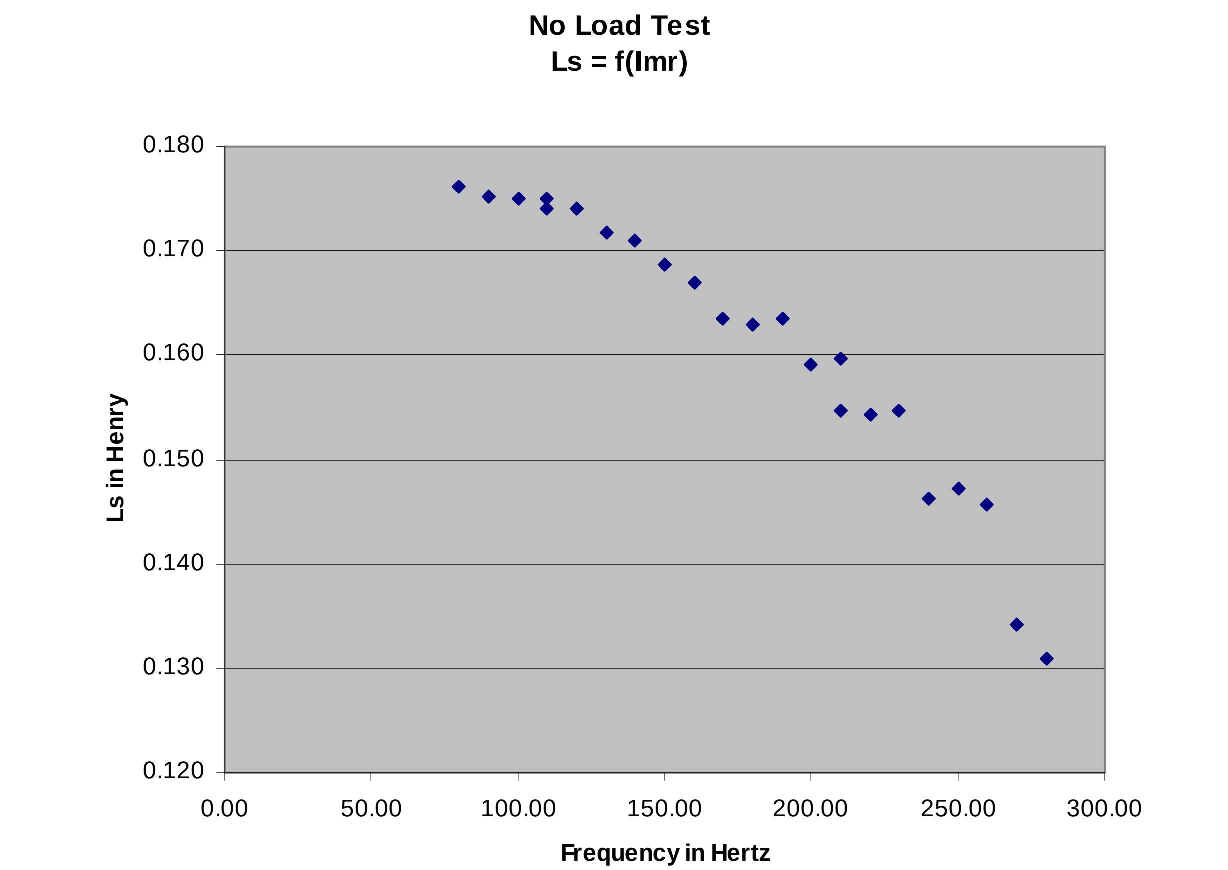
R_S = stator resistance

ω_S = angular stator speed

Considering that the variations of L_S, L_R, and L_0 are supposed to be identical, the determination of L_S variations would be sufficient to extrapolate the results to the other inductances. Figure 7 shows the experimental results, and it can be observed that a maximal variation of approximately 25% can be measured between the inductivity at base and at maximum speed.

The experimental results for obtaining both the magnetizing curve and the stator inductance (L_S) variation, are presented as an example in the Excel file, `MagnetizingCurve_FW.xls`, which is provided in the software archive (see **Appendix A: "Source Code"**).

FIGURE 7: VARIATION OF INDUCTANCE WITH SPEED (EXPERIMENTAL)



SOFTWARE IMPLEMENTATION

This application note represents an enhancement to AN1162, *Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM)* (see **"References"**). The enhancement effort consists in designing the new field weakening block and the adaptation of the existing variables, which are affected by the field weakening.

C Programming Functions and Variables

The field weakening block has as input, the reference mechanical speed and as output, the reference for the magnetizing current. The function is called every 10 milliseconds, the call frequency being set by the `dFwUpdateTime` constant defined in the include file, `UserParms.h`. The magnetizing curve is defined as a lookup table in `UserParms.h`. Field weakening is applied when the reference speed (output of a ramp generator) is above a defined lower limit determined by the constant torque functioning region.

An 18x integer array is defined and initialized with the lookup table. To calculate the reference value for magnetizing current i_{mR}, an interpolation is used to ensure smooth field variation. For every speed reference an index for access to the lookup table can be calculated, as shown in Example 1.

In Example 1, `qMotorSpeed` represents the speed reference and `qFwOnSpeed` is the speed from which the field weakening strategy is begun. Their difference is divided by 2^{10} to get the index in the lookup table.

The division term is a measure of the granularity of the samples obtained experimentally from the magnetizing curve as previously described.

The reference value of the magnetizing current is between `FdWeakParm.qFwCurve[ FdWeakParm.qIndex ]` and `FdWeakParm.qFwCurve[ FdWeakParm.qIndex + 1 ]`.

`MotorEstimParm.qL0FW` represents the division of stator inductance (L_S), which results from the magnetizing curve determination experiments with the double of base speed value for the stator inductance (L_{S0}). In order to have more accurate results, L_S is computed as an interpolation between two consecutive experimental results for determination of stator inductance variation.

The interpolation part is calculated, as shown in Example 2.

The function implementing the field weakening functionality, `FieldWeakening`, is defined in the C file, `FieldWeakening.c`, and has the following performances:

- Execution time: 51 cycles
- Clock speed: 7.2-8.5 µs @ 29.491 MHz
- Code size: 212 words
- RAM: 46 words

As indicated in the previous section, the mutual inductance must be adapted when running in the field weakening region. The adaptation law for mutual inductance, considering the premise that all inductance variation is identical, follows in Equation 7. Figure 8 depicts the mutual inductance (L_0) variation according to the motor's speed variation.

EXAMPLE 1:

```
// Index in FW-Table

FdWeakParm.qIndex = (qMotorSpeed - FdWeakParm.qFwOnSpeed ) >> 10;
```

EXAMPLE 2:

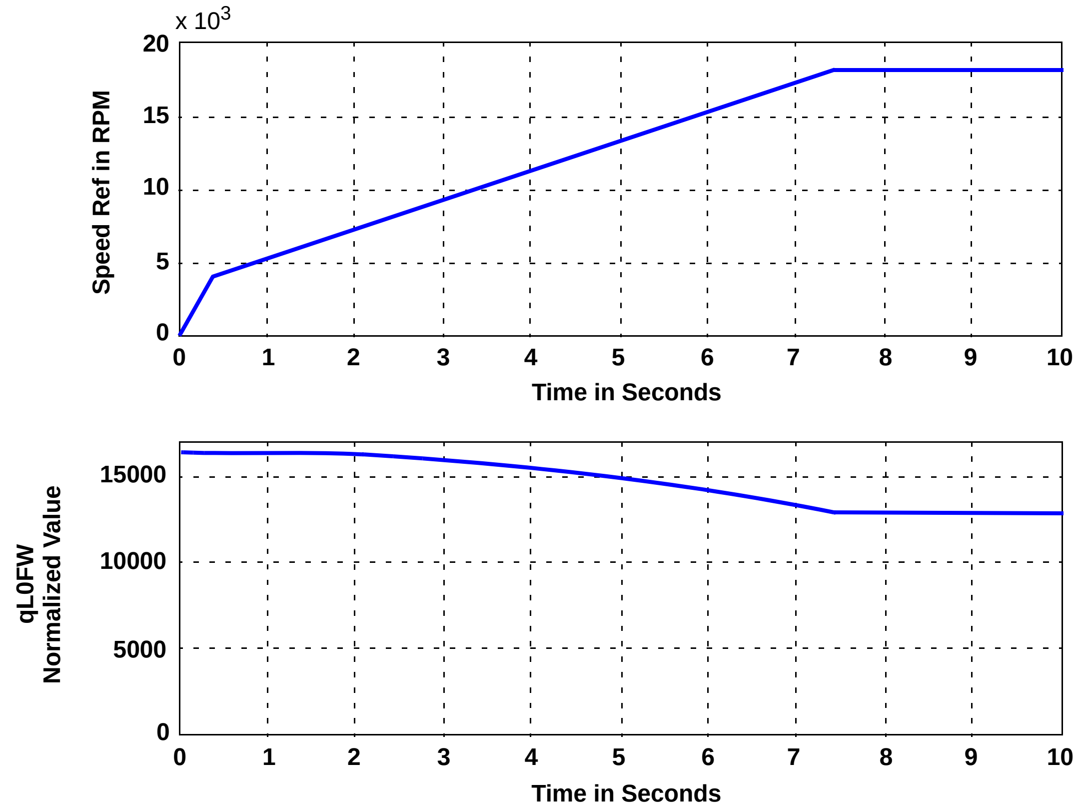
```
// Interpolation between two results from the Table
FdWeakParm.qIdRef=
FdWeakParm.qFwCurve[FdWeakParm.qIndex]-
(((long)(FdWeakParm.qFwCurve[FdWeakParm.qIndex]-
FdWeakParm.qFwCurve[FdWeakParm.qIndex+1])* (long)(qMotorSpeed-
((FdWeakParm.qIndex<<10)+FdWeakParm.qFwOnSpeed)))>>10);
```

EQUATION 7:

$$MotorEstimParm.qL0Fw = 2^{14}\frac{L_S}{L_{S0}} \cong 2^{14}\frac{L_R}{L_{R0}} \cong 2^{14}\frac{L_M}{L_{M0}}$$

Where the measures having index 0 are the base speed corresponding values.

FIGURE 8: ADAPTATION OF MUTUAL INDUCTANCE IN FIELD WEAKENING



All others variables used in field oriented control that incorporate the motor's constants are also adapted to minimize the errors in the case of field weakening. The variables are:

- `MotorEstimParm.qInvTr`
- `MotorEstimParm.qLsDt`
- `MotorEstimParm.qInvPsi`
- `MotorEstimParm.qRrInvTr`

All of the software functionality was initially designed for a constant power region, which takes into consideration the motor parameter's constant; therefore, an adaptation function was designed to consider the variation of the parameter's value with the speed increase in the field weakening region. The function implementing the adaptation functionality, `AdaptEstimParm`, is defined in `FieldWeakening.c` and has the following performances:

- Execution time: 1800 cycles
- Clock speed: 7.2-8.5 µs @ 29.491 MHz
- Code size: 218 words
- RAM: 62 words

The experimental results in Figure 9 show high stability and proper trajectory of the speed control with field weakening.

FIGURE 9: EXPERIMENTAL RESULTS OF SENSORLESS FOC OF AN ACIM WITH FIELD WEAKENING

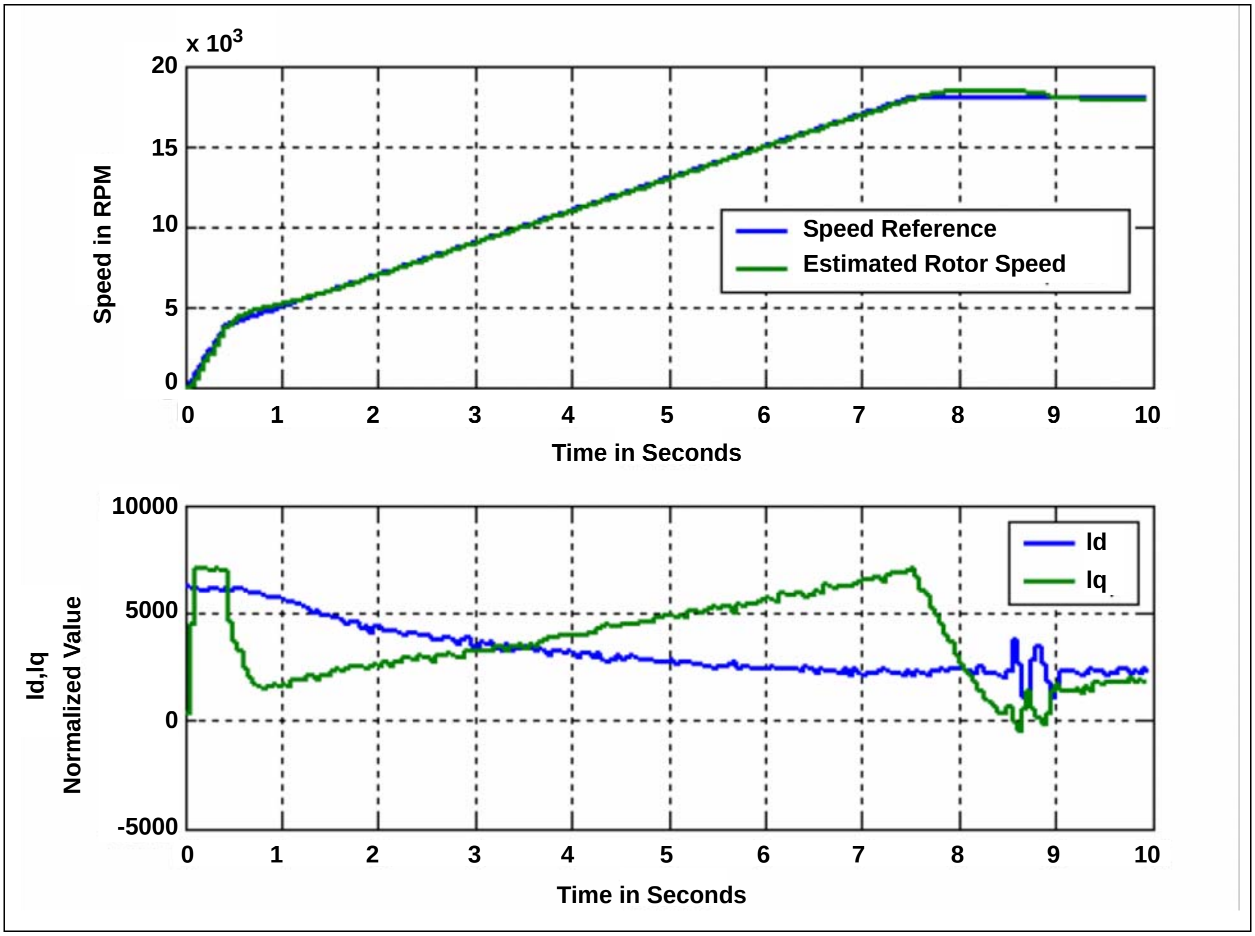


Table 1 presents the experimental results in terms of torque-speed and efficiency (calculated for both the inverter and the motor).

TABLE 1: EXPERIMENTAL RESULTS OF TORQUE-SPEED

Speed (RPM)	Torque (N*m)	Mechanical Power (W)	Electrical Input Power (W)	Efficiency (%)
9400	0.147	146	237	61.6
8500	0.172	153	234	65.4
6800	0.5	360	470	76.6
1100	1.15	135	250	54.0

CONCLUSION

This application note presents a solution for implementing field weakening in a sensorless field oriented control of an ACIM using Microchip's dsPIC30F and dsPIC33F digital signal controllers. It was developed as an addendum to the previously published application note AN1162, which offers a solution for high-performance, high-speed control of an induction motor drive.

REFERENCES

AN1162 - *Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM)* (DS01162), Microchip Technology Inc., 2008

APPENDIX A: SOURCE CODE

All of the software covered in this application note is available as a single WinZip archive file. This archive can be downloaded from the Microchip corporate Web site at:

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