# Field Oriented Control of an Induction Machine with DC Link and Load Disturbance Rejection

B. J. Seibel, T. M. Rowan, R. J. Kerkman
Rockwell Automation
Allen-Bradley Standard Drives Business
6400 W. Enterprise Dr.
Mequon, Wisconsin 53092

***Abstract* - A method of actively maintaining voltage margin in field oriented induction machine controllers is proposed. A voltage margin controller is developed that rejects dc link and load disturbances such that current regulation and field orientation is maintained. In addition, the voltage margin controller coupled with rotor flux oriented control is shown to provide maximum torque capability equivalent to stator flux oriented control.**

## I. INTRODUCTION

AC drive users with sophisticated applications are demanding higher performance ac drives with greater reliability to avoid process interruptions and provide faster product throughput. Field oriented or “vector” controlled induction motor drives satisfy the performance requirements, however, they are susceptible to dc link and load disturbances. Dc link disturbances, which reduce the link voltage, can cause loss of current control and a fault may result or field orientation is lost. This is especially true when the drive is operating in the field weakening region.

Field oriented control of an induction machine in the field weakening region has received significant attention over the years [ 1 - 6 ]. The classical method of field weakening (i.e. adjusting the rotor flux inversely with the rotor frequency) does not achieve maximum torque. Joetten and Schierling [1] recognized this limitation and proposed using an observer to accurately profile the flux producing stator current and optimize the q-d stator voltage components to achieve maximum torque. An indirect field or rotor flux oriented (RFO) control scheme that reduced the dependencies on machine parameters and eliminated the observer in [1] was outlined in reference [2]. Xu, De Doncker, and Novotny presented a stator flux oriented (SFO) control scheme and compared it to classical RFO control; it was suggested the SFO was less sensitive to machine parameters in the field weakening region and produced more torque than RFO control with finite voltage and current limits [3-4]. Kim, Sul, and Park presented a RFO control method that achieves maximum torque in the field weakening region, while taking into account the current and voltage limits of the inverter and motor [5]. They discussed adjusting the base speed of the motor based on these limits in order to maintain a sufficient voltage margin to control the stator currents. In [6], Kim and Park present a voltage control method for maximum torque operation using RFO control. The authors of [6] limit the motor voltage to 91% of the dc link voltage - the linear region of pulse width modulation (PWM) operation using space vector modulation. In addition, the authors propose a voltage magnitude controller to regulate the flux producing stator current.

While the concept of voltage margin is discussed in the references cited above, a fixed dc link voltage is assumed and rejection of dc link disturbances has not been addressed. Dc link disturbances are a common occurrence at industrial sites [7],[8]. They can be a result of ac mains voltage sags, load transients, discontinuous conduction of the ac-dc converter power devices supplying the dc link voltage, or the opening of a fuse in the ac mains. Some methods of rejecting dc link disturbances have been proposed. They include momentarily regenerating energy from the load [9] or providing a means to boost the reduced line voltage using a power loss ridethrough converter - a costly solution. The former method requires that the load has sufficient inertia to provide energy to the dc link. In addition, the method of [9] regenerates even when ac-dc converters are operating in the discontinuous conduction mode (lower dc link voltage) or transient overloads are disturbing the dc link even though motoring is possible.

This paper proposes a RFO method to actively reject dc link and load disturbances while operating in the field weakening region. In addition, it will be shown that field orientation is maintained and maximum torque is produced when the disturbances occur. Operation of the proposed controller in the nonlinear or pulse dropping region of PWM is demonstrated. A steady state comparison of classical RFO, maximum torque RFO, and SFO controllers is also presented.

## II. VOLTAGE MARGIN

As reported in the literature, inverter voltage and current limits require a field weakening region [3-6]. The current limit, $I_{smax}$, is dictated by the current rating of the inverter and often is 150% of the induction machine’s rating. The voltage limit has been reported to be only limited by the induction machine’s rated voltage or nominal dc link voltage. However, the dc link voltage is seldom constant except in cases where a voltage source converter is applied to control the dc link voltage. Another way to guarantee a voltage margin is to use an induction machine with a significantly lower voltage rating as compared to the ac mains and resulting dc link voltage, which results in a cost penalty since higher current is required to develop the same power. Therefore, the challenge becomes one of providing a low cost, efficient, and robust solution to assure an adequate voltage margin as the dc link voltage is disturbed in a decreasing manner.

A voltage margin must exist to support current regulation. To maintain current regulation, six-step voltage source operation is avoided, which implies a motor voltage limit, $V_{smax}$, must not be exceeded on the terminals of the induction machine. This maximum motor voltage is defined below by taking into account the dc link voltage, $V_{dc}$, and the rated machine voltage:

$$V_{smax} = \text{minimum}\left\{ \begin{array}{c} \frac{2}{\pi} * K_{utilization} * V_{dc} \\ \text{or} \quad V_{rated} \end{array} \right\} \tag{1}$$

where $K_{utilization}$ is a utilization constant dependent upon the desired transient and steady state response. This factor is also dependent on the modulation scheme and current control method(s) used [10]. Assuming the dc link voltage dominates in (1), the minimum voltage margin necessary to maintain current regulation can be calculated as follows:

$$V_{margin} = \frac{2}{\pi} * V_{dc} * \left(1 - K_{utilization}\right) \tag{2}$$

The magnitude of the induction machine voltage must not exceed the maximum voltage given in (1) and the following constraint must be met (see Appendix A).

$$\left|V_{motor}\right| \le V_{s\max} \text{ where } \left|V_{motor}\right| = \sqrt{v_{qs}^{e\,2} + v_{ds}^{e\,2}} \tag{3}$$

Assuming that the dc link voltage is the minimum from (1), the final form of (3) can be written as

$$\sqrt{v_{qs}^{e\,2} + v_{ds}^{e\,2}} \le \frac{2}{\pi} * K_{utilization} * V_{dc} \tag{4}$$

Finally, combining (1) and (4) into (5) describes a method of controlling the voltage margin.

$$v_{qs}^{e} = \sqrt{V_{s\max}^{\,2} - v_{ds}^{e\,2}} \tag{5}$$

The voltage margin controller is used to compensate for load disturbances as well as dc link disturbances since the torque producing current is reflected in the quantity $v^{e}_{ds}$ (see Appendix A).

## III. FIELD WEAKENING CONTROL

The field weakening operating range can be divided into two distinct regions. The first region begins at base speed and ends at the speed where current limit is unachievable due to the voltage limit. The second region extends beyond the first region with the voltage limit overriding the current limit and forcing a reduction in stator current below the current limit, $I_{smax}$. These two regions of field weakening are present in RFO and SFO controllers.

The SFO control regulates the q-axis stator flux to zero i.e. $\lambda^{e}_{qs} = 0$ [3,4]. In addition, SFO control requires a low pass filter that decouples the d-axis stator flux, $\lambda^{e}_{ds}$ , and q-axis component of stator current, $i^{e}_{qs}$. The decoupler's time constant is dependent upon four machine parameters (see Appendix A). A block diagram of the SFO control is illustrated in Fig. 1.

The RFO control method presented here is outlined in [2] and is comprised of a slip adaption regulator, flux regulator, and current regulated PWM (CRPWM) inverter (see Fig. 2). The flux regulator adjusts the flux producing stator current reference, $i^{e}_{ds\_ref}$, in response to an error in the q-axis stator voltage, $v^{e}_{qs}$. The rotor flux is reduced inversely proportional to rotor frequency to implement the classical method of field weakening. The slip adaption regulator adjusts the slip gain, $K_s$, in response to an error in the d-axis stator voltage, $v^{e}_{ds}$, to orient the rotor flux to the d-axis such that $\lambda^{e}_{qr} = 0$.

A block diagram that combines the voltage margin controller described by (5) with the RFO controller described in Fig. 2 is shown in Fig. 3. This block diagram illustrates the proposed method to maintain voltage margin while

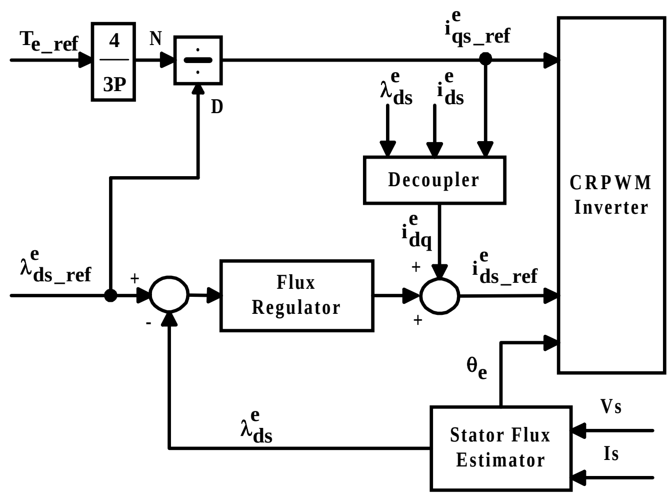


Fig. 1 - Block Diagram of a SFO Control System [3].

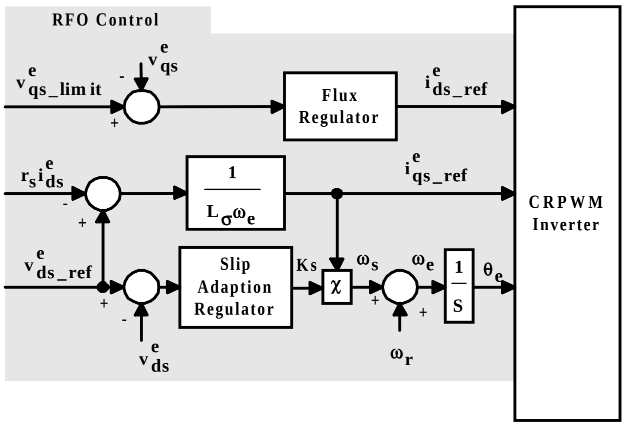


Fig. 2 - Block Diagram of a RFO Control System [2].

developing maximum torque by adjusting the flux and torque producing stator current references in response to dc link and load disturbances. The reference quantities $v^e_{ds\_nom}$ and $v^e_{qs\_nom}$ reflect nominal conditions and constraints i.e. $I_{smax}$ and $V_{rated}$. The terms $v^e_{ds\_max}$ and $v^e_{qs\_ref}$ reflect dc link disturbances . The blocks labeled "Min" select the input value with the minimum magnitude to enforce the appropriate voltage and current limits. When load changes or dc link disturbances occur, they are reflected in the reference quantities $v^e_{qs\_limit}$ and $v^e_{ds\_ref}$ and ultimately in $i^e_{qs\_ref}$ and $i^e_{ds\_ref}$ (see Fig. 2) and in the q-d stator voltage feedback quantities $v^e_{qs}$, $v^e_{ds}$.

*A. Steady State Operation*

Fig. 4 shows calculated steady state per unit (p.u.) values of torque, stator voltage, stator current, torque producing stator current, and flux producing stator current operating with a current limit of 1.5 p.u. and a voltage limit equal to the rated motor voltage (see Appendix B for motor data). Since field weakening is the area of interest, the stator resistance is neglected. Field weakening region one begins at 1 p.u. speed and region two begins at approximately 1.8 p.u. speed. Characteristics of the three different controllers presented above are plotted; SFO control, the voltage margin controller and RFO control with maximum torque capability (Max RFO), and classical RFO control.

Torque capability of each is illustrated in Fig. 4a. The SFO torque capability and the maximum torque RFO capability are identical while the classical RFO control produces significantly less torque. Fig. 4b shows the stator voltage magnitude and the q-d stator voltage components. The SFO control regulates all the stator voltage to the q-axis and contains no d-axis component. The classical RFO control limits the d-axis component of stator voltage by design to:

$$\left|v^e_{ds\_max}\right| = \left| r_s i^e_{ds} - \omega_{e\_base} L_\sigma \left( \sqrt{I^2_{smax} - \left(i^e_{ds\_base}\right)^2} \right) \right| \qquad (6)$$

This value represents the maximum allowable d-axis stator voltage magnitude at 1.5 p.u. current. For this particular motor, (6) yields 0.38 p.u. voltage. Once this level of d-axis stator voltage is reached, the torque producing stator current, $i^e_{qs}$, (see Fig. 4c) is reduced and the flux producing current, $i^e_{ds}$ (see Fig. 4d), is reduced to maintain constant q-axis stator voltage, $v^e_{qs}$ i.e. $\lambda^e_{dr} \propto 1/\omega_r$. The classical RFO control does not operate at current limit in field weakening as shown in Fig. 4e.

Unlike the classical RFO control, the maximum torque RFO control does not force a reduction in $i^e_{qs}$ (Fig. 4c) until a much higher speed since maximum torque is produced when the following constraints are met.

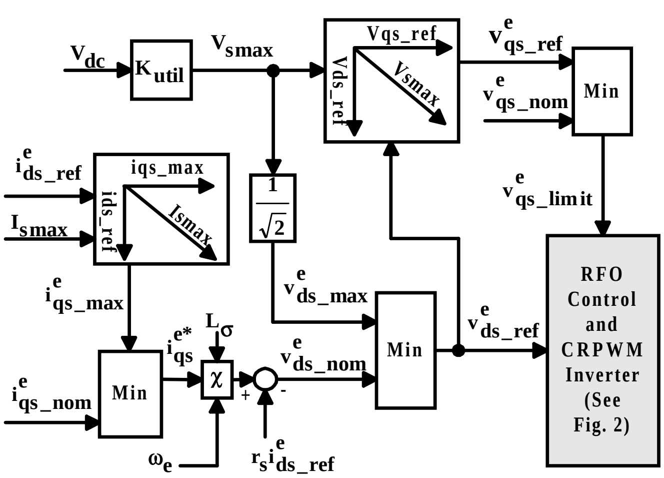


Fig. 3 - Voltage Margin Controller Including Current and Voltage Limits and RFO System.

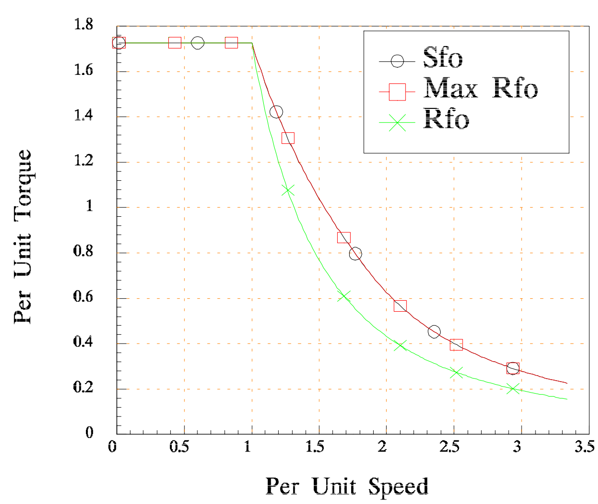


Fig. 4a - Steady State Torque Versus Speed.

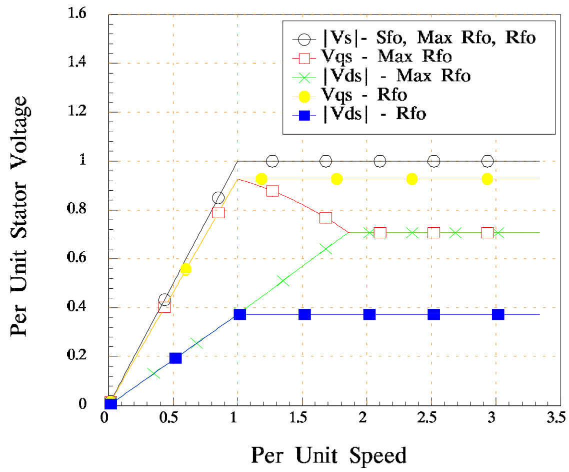


Fig. 4b - Steady State Stator Voltage Versus Speed.

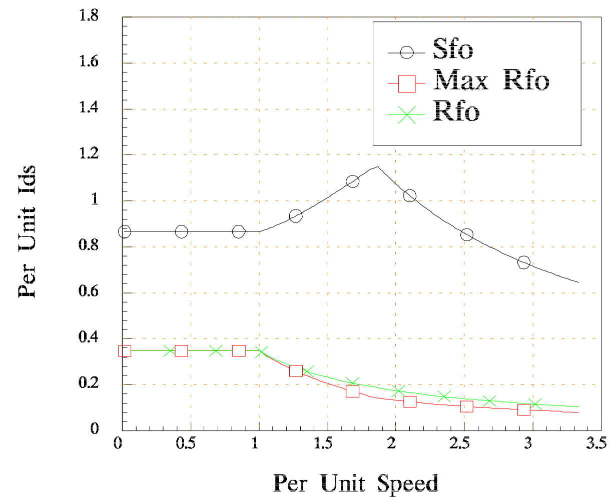


Fig. 4d - Steady State d-Axis Stator Current Versus Speed.

$$\left|v^e_{ds\_max}\right| = {V_{s\max}}/{\sqrt{2}} \quad and \quad \left|v^e_{qs\_ref}\right| = {V_{s\max}}/{\sqrt{2}} \tag{7}$$

In region one of field weakening, the maximum torque RFO control reduces the q-axis voltage ($\lambda^e_{dr}$ decreases at a rate greater than $1/\omega_r$) and allows the d-axis voltage to rise while in current limit as shown in Figs. 4b and 4e. Once the voltage limits given by (7) are reached, field weakening region two commences and the q-d stator currents are reduced (Fig. 4c and 4d) and current limit cannot be attained as shown in Fig. 4e.

The SFO control duplicates the maximum torque RFO control in torque capability, stator voltage magnitude, and stator current magnitude. Differences between them exist in the values of the q-d stator voltages and currents as depicted in Fig. 4b-4d. An interesting phenomena (not shown in Fig. 4) occurs in the constant torque region with SFO control that does not occur with any RFO method. The SFO control modulates both the q-axis and d-axis stator currents with changes in load.

*B. Simulated Transient Operation*

One of the benefits of field oriented control is the high dynamic response. To achieve good transient response to a step change in dc link voltage, the q-d voltage controllers need to be properly selected.

Often times, the stator voltage magnitude is regulated by adjusting the flux producing stator current reference, $i^e_{ds\_ref}$ [5]. Fig. 5 illustrates a RFO control system with a voltage magnitude controller regulating $i^e_{ds\_ref}$. A voltage margin controller and RFO system incorporating the voltage magnitude controller can be designed by combining Fig. 5 and Fig. 6. Fig. 6 is a slightly modified version of the voltage

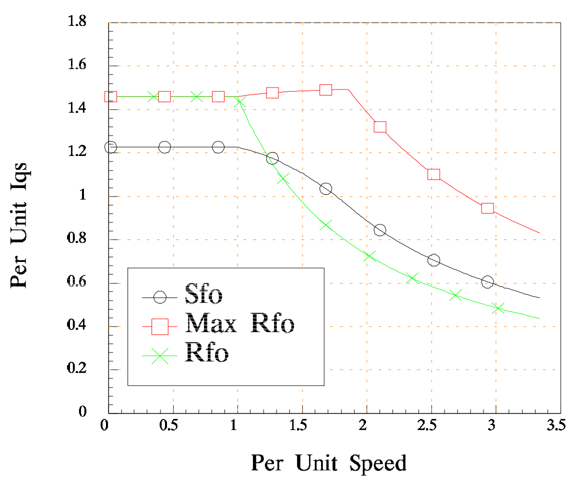


Fig. 4c - Steady State q-Axis Stator Current Versus Speed.

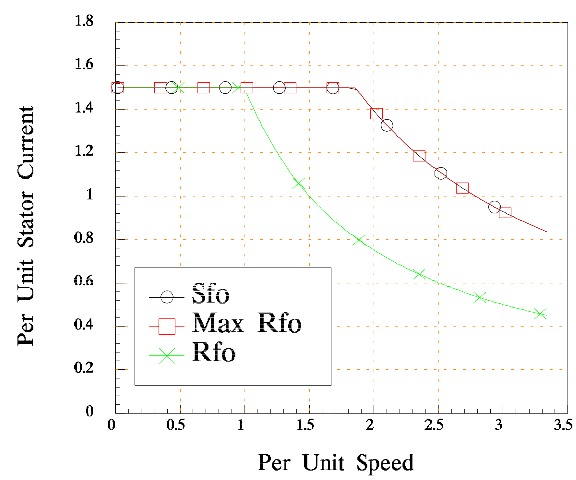


Fig. 4e - Steady State Stator Current Versus Speed.

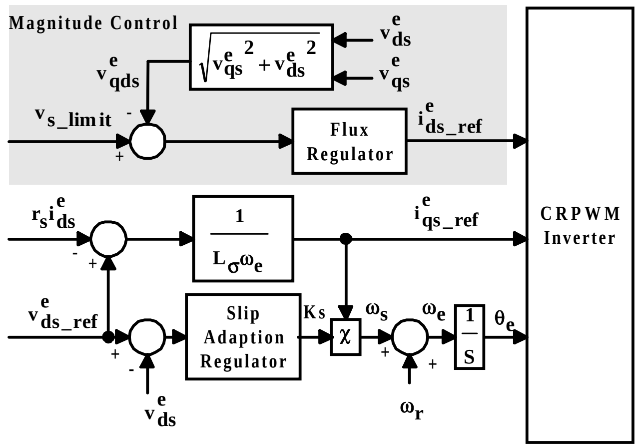


Fig. 5 - Block Diagram of a RFO System with Voltage Magnitude Control.

margin controller shown in Fig. 3.

A computer simulation of the voltage margin controller and RFO system with voltage magnitude control (Fig. 5 and Fig. 6) when subjected to a dc link disturbance is shown in Fig. 7a. The RFO system is initially operating as a torque regulator at 1.25 p.u. speed and 1.12 p.u. torque in region one of field weakening. The dc link voltage is stepped from 1.05 p.u. to 0.84 p.u. at approximately 0.065 seconds. A very large transient occurs in the q-d voltages and developed torque because the voltage magnitude flux regulator is coupled to the slip adaption regulator through the d-axis voltage component. Field orientation is lost as evidenced by the oscillation in the torque and q-d voltages at slip frequency. Notice the d-axis stator voltage is limited by the inverter voltage limit.

In contrast, the RFO control shown in Fig. 2 uses the q-axis stator voltage regulator to adjust $i^{e}_{ds\_ref}$. A computer simulated transient response of the proposed voltage margin control and maximum torque RFO system (RFO control of Fig. 2 and voltage margin controller of Fig. 3) to a dc link disturbance is shown in Fig. 7b. The initial conditions are the same as described above for Fig. 7a. The dc link voltage

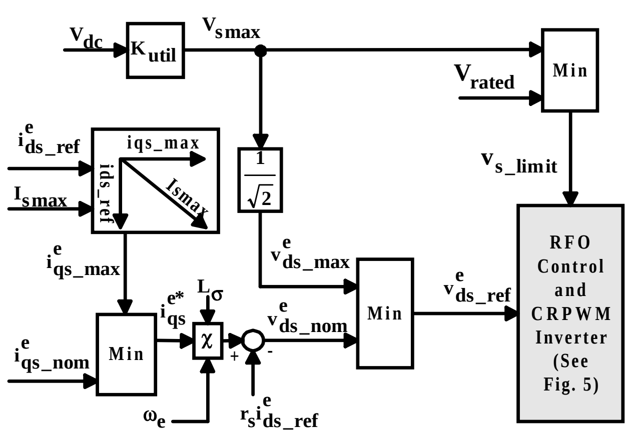


Fig. 6 - Voltage Margin Controller Including Current and Voltage Limits and RFO System with Voltage Magnitude Control.

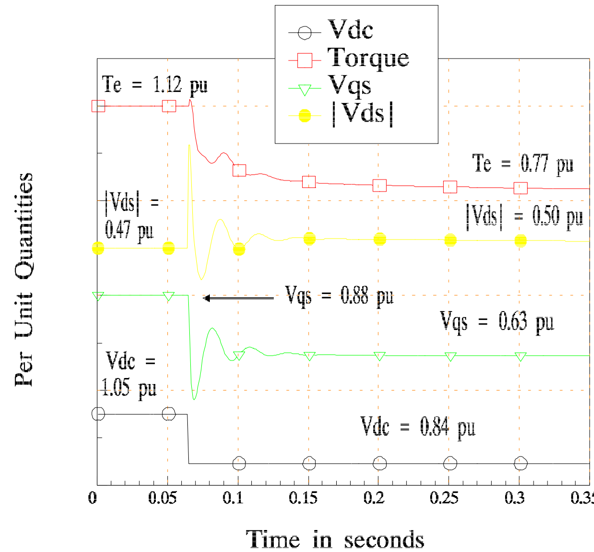


Fig. 7a - Transient Response of the Voltage Magnitude Controller to a DC Link Disturbance.

is stepped from 1.05 p.u. to 0.84 p.u. at 0.065 seconds. A transient occurs but the q-d voltage response is much less oscillatory and the torque reduction is much more controlled because of the decoupling of the two components of stator voltage. Unlike the magnitude controller, field orientation is maintained and no inverter voltage limit is reached. It is clear that decoupled flux and slip adaption regulators provide a much more robust RFO voltage margin control system.

### C. *Experimental Transient Operation*

The dc link disturbance rejection capability of the voltage

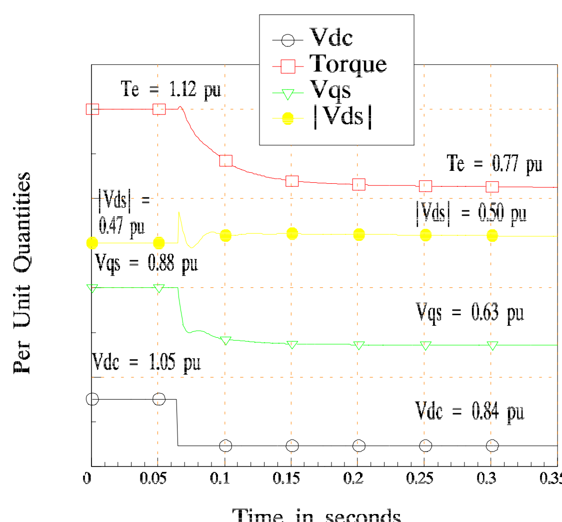


Fig. 7b - Transient Response of the q-d Voltage Controller to a DC Link Disturbance.

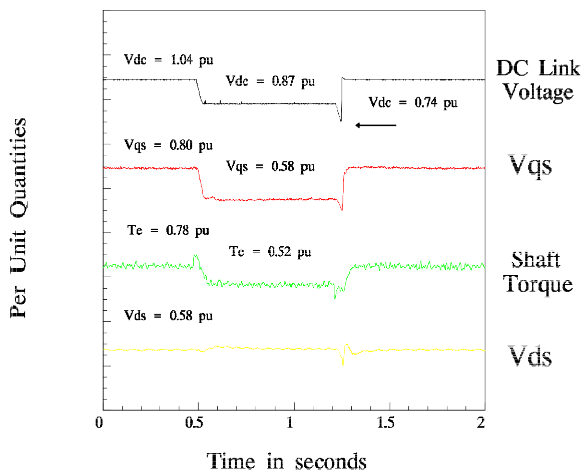


Fig. 8 - DC Link Disturbance Rejection.

margin controller and maximum torque RFO control is shown in Fig. 8. Operation of the control as a torque regulated system begins at 1.5 p.u. speed, 1.04 p.u. dc link voltage, 1.5 p.u. torque current reference, and shaft torque of 0.78 p.u. Refer to Appendix B for induction machine nameplate data. At approximately 0.5 seconds, an ac mains power loss occurs for 43 milliseconds followed by a transition to a low ac mains input voltage resulting in a dc link voltage of 0.87 p.u. During the dc link disturbance, the margin controller lowers the q-axis stator voltage (rotor flux) by 28% while the q-d stator voltages experience a transient until the slip gain and flux regulators damp out and the dc link stabilizes. The developed torque is reduced by 28%, too. Next, at roughly 1.2 seconds the input power is again interrupted for approximately 33 milliseconds followed by a transition back to 1.07 p.u. input voltage. During the ac mains loss, the dc link voltage drops to 0.74 p.u. and again the margin controller successfully reduces the q-d stator voltages to avoid loss of current control. Once the nominal

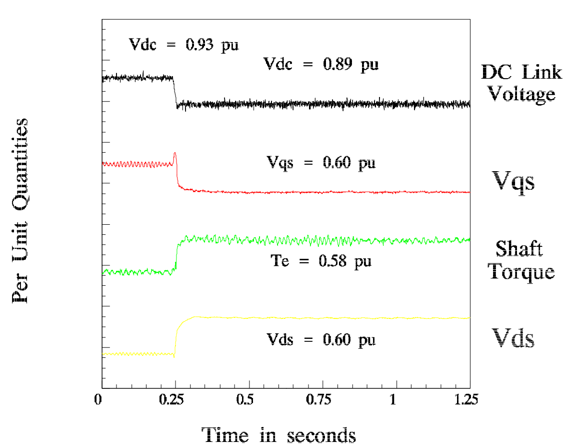


Fig. 9 - Load Disturbance Rejection.

ac mains voltage is reapplied, the q-axis stator voltage (rotor flux ) returns to its nominal value. The voltage margin controller successfully rejected the dc link disturbances.

The load disturbance rejection capability of the voltage margin controller and maximum torque RFO control is shown in Fig. 9. The system is operating as a torque regulator at 1.5 p.u. speed, 0.93 p.u. dc link voltage, and shaft torque of zero. At 0.25 seconds a 1.5 p.u. torque step is applied to the induction machine. The dc link voltage drops to 0.89 p.u. due to the load. The d-axis voltage reflects the commanded step change and increases in magnitude to $v^{e}_{ds\_max}$ as defined in (7). The slight disturbance in dc link voltage is reflected in $V_{smax}$ and the q-axis stator voltage changes according to (5) and (7), too. Once $v^{e}_{ds\_max}$ and $v^{e}_{qs\_ref}$ are altered, the q-d stator currents and voltages are reduced to maintain current regulation and develop maximum torque.

The experimental results obtained in Figs. 8 and 9 use a voltage utilization constant of 0.92. A utilization factor of 0.92 coupled with a sine-triangle PWM algorithm results in operation in the overmodulation region at a modulation index of 1.16. Use of a more efficient modulation scheme could provide significantly higher voltage utilization with acceptable transient response.

## IV. CONCLUSION

The voltage margin controller has been shown to effectively maintain current regulation and field orientation when subjected to dc link and load disturbances. In addition, the voltage margin controller can be used to provide maximum torque capability with RFO control that equals the torque capability of the SFO control. Application of the voltage margin controller to the SFO control would be straightforward as well.


## V. ACKNOWLEDGMENT

The authors would like to thank their colleague Mr. David Schlegel for his technical assistance in preparing this manuscript.


## APPENDIX A

### *A. Rotor Flux Oriented Equations*

The steady state equations describing a rotor flux oriented induction machine are given below:

$$v^{e}_{qs} = r_s i^{e}_{qs} + \omega_e \lambda^{e}_{ds} \quad \text{where} \quad \lambda^{e}_{ds} = L_s i^{e}_{ds} \tag{8}$$

$$v^{e}_{ds} = r_s i^{e}_{ds} - \omega_e \lambda^{e}_{qs} \quad \text{where} \quad \lambda^{e}_{qs} = L_\sigma i^{e}_{qs} \tag{9}$$

$$T_e = \frac{3 * poles}{4}\left(\lambda_{ds}^e i_{qs}^e - \lambda_{qs}^e i_{ds}^e\right) \tag{10}$$

*B. Stator Flux Oriented Equations*

The steady state equations describing a stator flux oriented induction machine are given below:

$$i_{ds}^e = \frac{\lambda_{ds}^e}{L_s} + \sigma T_r \omega_s i_{qs}^e \tag{11}$$

$$i_{qs}^e = \frac{4}{3 * poles} \frac{T_e}{\lambda_{ds}^e} \tag{12}$$

$$\lambda_{qs}^e = 0 \tag{13}$$

$$\lambda_{ds}^e = \lambda_s \tag{14}$$

$$v_{ds}^e = r_s i_{ds}^e \tag{15}$$

$$v_{qs}^e = r_s i_{qs}^e + \omega_e \lambda_{ds}^e \tag{16}$$

$$\omega_s = \frac{L_s i_{qs}^e}{\tau_r \left(\lambda_{ds}^e - \sigma L_s i_{ds}^e\right)} \tag{17}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{18}$$

$$T_r = \frac{L_r}{r_r} \tag{19}$$

$$T_e = \frac{3 * poles}{4}\left(\lambda_{ds}^e i_{qs}^e\right) \tag{20}$$

The decoupler for proper transient response is as follows:

$$i_{dq}^e = \frac{\sigma T_r \omega_s i_{qs}^e}{1 + \sigma T_r p} \quad \text{where } p = d/dt \tag{21}$$

The quantities in (8) - (21) are as follows: $v^e{}_{qs}$, $v^e{}_{ds}$ are the q-d axis stator voltages, $i^e{}_{qs}$, $i^e{}_{ds}$ are the q-d axis stator currents, $\sigma$, the total leakage factor, $\omega_e$ is the stator frequency, $\omega_s$ is the slip frequency, $L_s$, is the stator inductance, $L_r$, is the rotor inductance $L_m$, is the magnetizing inductance, $L_\sigma$, the stator transient inductance, $T_r$, and $T_e$ the electromagnetic torque.

**APPENDIX B**

Motor Nameplate Data and Parameter Values:

| | |
|---|---|
| Rated output power: 7.5 Hp | $L_m$ = 179.1 mH |
| Rated speed: 1745 rpm | $L_{ls}$ = 9.2 mH |
| Rated voltage: 460 volt | $L_{ls}$ = 9.2 mH |
| Number of poles: 4 | $r_r$ = 0.881 Ω |
| Design Type: NEMA B | $r_s$ = 1.135 Ω |

## REFERENCES


[1] R. Joetten, and H. Schierling, “Control of the Induction Machine in the Field Weakening Range”, in *Proc. IFAC Cont. Power Electron. Elect. Drives,* (Lausanne, Switzerland), 1983, pp. 297-304.

[2] R. Kerkman, T. Rowan, D. Leggate, “Indirect Field-Oriented Control of an Induction Motor in the Field-Weakening Region”, *IEEE Tran. on Industry Applications*, Vol. 28, No. 4, pp. 850-857, July/August 1992.

[3] X. Xu, R. De Doncker, D. Novotny, “Stator Flux Orientation Control of Induction Machines in the Field Weakening Region”, in *Conf. Record 1988 IEEE-IAS Ann. Mtg.* pp. 437-443.

[4] X. Xu, D. Novotny, “Selection of the Flux Reference for Induction Machine Drives in the Field Weakening Region”, *IEEE Trans. on Industry Applications*, Vol. 28, No. 6, pp. 850-857, November/December 1992.

[5] S. H. Kim, S. K. Sul, M. H. Park, “Maximum Torque Control of an Induction Machine in the Field Weakening Region”, in *Conf. Record 1993 IEEE-IAS Ann. Mtg.* pp. 437-443.

[6] S. H. Kim, S. K. Sul, “Voltage Control Strategy for Maximum Torque Operation of an Induction Machine in the Field Weakening Region”, in *Conf. Record 1994 IEEE-IECON Ann. Mtg.* pp. 599-604.

[7] P. Kingsley, “A-S Drive Ride-Through Saves Critical Processes”, *Power Transmission Design*, April 1993, Vol. 35, No. 4.

[8] IEEE Project 1346 Working Group, “Electric Power System Compatibility with Industrial Process Equipment - Part 1: Voltage Sags”

[9] J. Holtz, W. Lotzkat, “Controlled AC Drives with Ride-Through Capability at Power Interruption”, in *Conf. Record 1993 IEEE-IAS Ann. Mtg.* pp. 629-636.

[10] J. Holtz, B. Beyer, “The Trajectory Tracking Approach - A New Method for Minimum Distortion PWM in Dynamic High-Power Drives”, in *Conf. Record 1992 IEEE-IAS Ann. Mtg.* pp. 331-338.