Torque behaviour of a field oriented induction motor drive towards voltage sag conditions

Kurt Stockman, *Student Member, IEEE*, Frederik D'hulster, *Student Member, IEEE*, Jan Desmet, *Member, IEEE*,

and Ronnie J. M. Belmans, *Senior Member, IEEE*

***Abstract*—Industrial processes equipped with adjustable speed drives have shown to be very vulnerable towards voltage sags. In many applications, the control of torque and/or speed is the main interest in order to maintain correct operation. This paper investigates the behavior of a rotor flux oriented (RFO) induction motor drive under voltage sag conditions. The maximum torque as a function of the mechanical speed and dc-link voltage is determined. Finally, the results are used to set the under-voltage limit of the drive.**

***Index Terms*—Power quality, electric machine, field weakening, torque capability.**

I. Introduction

FIELD ORIENTED controlled induction motor drives are common practice in modern processes. High dynamic performances and flexibility are important advantages. On the other hand, the reliability of the processes equipped with adjustable speed drives has to be guaranteed in order to avoid process interruptions.

Adjustable speed drives are very susceptible to voltage sags and instantaneous supply interruptions. Measuring reports on standard induction motor drives show that voltage sags of 10 % or more can cause process interruptions [1]-[3]. The main reason for the interruption is the activation of the dc-link under-voltage protection voltage V_{DC}. This under-voltage protection level $V_{DC\,\min}$ can be adjusted in most commercial drives. Typical values of $V_{DC\,\min}$ range from 90 % to 50 % of the rated dc-link voltage.

This paper describes the behaviour of the steady-state torque in a common rotor flux oriented induction motor drive under voltage sag conditions. A voltage sag results in a reduction of the dc-link voltage V_{DC}. Due to the reduction of V_{DC}, it is shown that the field weakening region starts at speeds lower than the base speed ω_b.

Different field weakening techniques for induction motor drives have been described in literature [4]-[7]. In these publications, the field weakening region starts at the base speed ω_b. The extension of this region, due to voltage sags, reduces the maximum available torque even before the base speed is reached. Knowing the limits of the steady-state torque under voltage sag conditions can help to adjust the under-voltage protection level $V_{DC\,\min}$ of the drive for optimal operation. Activation of the under-voltage level with the proposed method means that the drive can no longer provide the torque needed by the application. At this instant, for applications where torque and/or speed fluctuations are not tolerated (weaving machines, paper industry, wire-drawing mills), the drive can be shut down in a controlled way without losing torque control and avoiding costly intervention by the operator . After the recovery of the supply voltage, the application can be restarted and normal operation is continued.

II. ROTOR FLUX ORIENTED DRIVE IN STEADY-STATE

The maximum torque that can be produced in a rotor flux oriented induction machine can be determined by examining the steady-state machine equations [4] :

$$V_{ds} = R_1 i_{ds} - \omega_e L_s^{'} i_{qs} \qquad (1)$$

$$V_{qs} = R_1 i_{qs} + \omega_e L_s i_{ds} \qquad (2)$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m^2}{L_r} i_{ds}\, i_{qs} \qquad (3)$$

where, V_{ds}, V_{qs} : *d*- and *q*-axis stator voltages
i_{ds}, i_{qs} : *d*- and *q*-axis stator currents
R_1 : stator resistance
L_s, L_r : stator and rotor inductance
$L_s^{'} = L_s - L_m^2 / L_r$: stator transient inductance
L_m : magnetising inductance
ω_e : rotor flux angular frequency
p : number of pole pairs
T_e : electromagnetic torque

To determine the maximum torque over the entire operating range of the machine, both voltage and current limits must be taken into account [4], [5].

A. Current limit

The current limit $Is_{\max}$ is set by the current rating of the inverter IGBT's. Typical values for the current limit are between 150 and 200 % of the rated motor current I_{rated}. The stator currents i_{ds} and i_{qs} are limited according to (4). Here the current limit is set at 150 %.

$$i_{ds}^{2} + i_{qs}^{2} \le Is_{max}^{2} \qquad (4)$$

The current limit can be represented by means of a circle (Fig. 1). The radius of the circle is independent of speed or voltage and will not be influenced by a voltage sag.

B. Voltage limit

The voltage limit $Vs_{\max}$ depends on the dc-link voltage V_{DC} and the modulation strategy used. The maximum motor voltage value can be determined as :

$$Vs_{max} = \frac{2}{\pi} V_{DC} \qquad (5)$$

The induction machine voltages must satisfy equation (6):

$$V_{ds}^{2} + V_{qs}^{2} \le Vs_{max} \qquad (6)$$

Combining (1), (2) and (6) and neglecting the stator resistance, the voltage limit is represented by an ellipse:

$$\frac{i_{ds}^{2}}{\left(\frac{Vs_{max}}{\omega_e L_s}\right)^{2}} + \frac{i_{qs}^{2}}{\left(\frac{Vs_{max}}{\omega_e L_s^{'}}\right)^{2}} \qquad (7)$$

The shape of the ellipse depends on the angular speed of the rotor flux ω_e and the maximum motor voltage $Vs_{\max}$. The maximum motor voltage is related to the dc-link voltage V_{DC} by (5). Increasing the speed or reducing the dc-link voltage results in a smaller ellipse (Fig. 1 and Fig. 2).

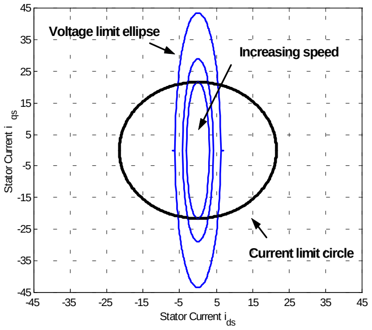

Fig. 1. Current limit circle and voltage limit ellipse with increasing speed.

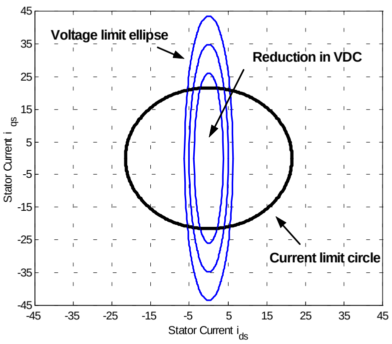

Fig. 2. Current limit circle and voltage limit ellipse with decreasing dc -link voltage V_{DC}.

To satisfy both current and voltage limit, the stator current i_S has to stay within the common area formed by the current limit circle and the voltage limit ellipse. As speed increases, the voltage limit ellipse becomes smaller, forcing the machine to operate in the field weakening region [4].

A reduction of the dc-link voltage also results in a smaller voltage limit ellipse (Fig.2). As a result, the machine operates in the field weakening region. The starting point of field weakening depends on the base speed ω_b and on the dc-link voltage V_{DC}.

C. Maximum torque of the FO drive

The maximum torque over the entire speed range as a function of the dc-link voltage V_{DC} can be applied by selecting the appropriate stator currents i_{ds} and i_{qs} in order to maximize equation (3) [4]:

In the field weakening, two regions can be distinguished. In region 1, the optimal stator current i_S yielding maximum torque is found at the intersection of the current limit circle and the voltage limit ellipse:

$$i_{ds\ region\ 1} = \sqrt{\frac{\left(Vs_{max}/\omega_e\right)^{2} - \left(L_s^{'} Is_{max}\right)^{2}}{L_s^{2} - L_s^{'2}}} \qquad (8)$$

$$i_{qs\ region\ 1} = \sqrt{\frac{\left(L_s Is_{max}\right)^{2} - \left(Vs_{max}/\omega_e\right)^{2}}{L_s^{2} - L_s^{'2}}} \qquad (9)$$

If the speed ω_e is further increased, the voltage limit will be included in the current limit circle (region 2). The stator current i_S for maximum torque is determined by solving the optimum problem described by (3) and (7):

$$i_{ds\,region\;2} = \frac{Vs_{max}}{\sqrt{2}\,\omega_e L_s} \quad (10)$$

$$i_{qs\,region\;2} = \frac{Vs_{max}}{\sqrt{2}\,\omega_e L'_s} \quad (11)$$

Equations (8) to (11) can be used to determine the available torque as a function of the angular speed ω_e and the dc-link voltage V_{DC}.

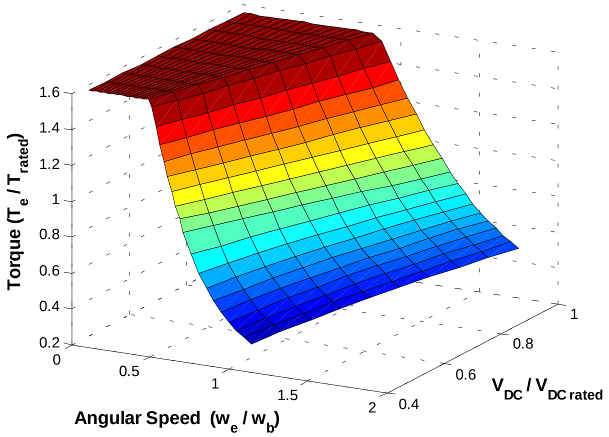

Fig. 3. Maximum torque for a FO induction motor drive at various speeds and motor voltages and a current limit of 150 % I_{rated}.

Fig. 3 shows the maximum steady-state torque for a RFO induction machine for various values of the angular speed ω_e and various values of the motor voltage limit $Vs_{\max}$. At high speeds and/or low motor voltages, the torque capability is reduced. The angular speed $\omega_{T_{\max}}$ where the torque starts to drop is:

$$\omega_{T_{max}} = \frac{(2/\pi)V_{DC}}{\sqrt{L_s^2 I_{ds\;rated}^2 + L_s'^2\left(Is_{max}^2 - I_{ds\;rated}^2\right)}}$$

(1

where $I_{ds\,rated}$ is the rated magnetising current.

In (12), the transition speed $\omega_{T_{\max}}$ varies linearly with the dc-link voltage V_{DC}. The transition speed $\omega_{T_{\max}}$ also determines the beginning of the field weakening (Fig. 3). For a dc-link voltage of 60 % of the rated dc-link voltage, field weakening starts at 45 % of the base speed ω_b.

III. VOLTAGE SAGS

The behaviour of an adjustable speed drive at the beginning of a supply voltage sag can be represented by an energy balance [2]:

$$E_C + E_{kin} = E_L \quad (13)$$

where, E_C : energy in the dc-link capacitors
E_{kin} : energy in the moving parts
E_L : load energy demand

All energy to drive the load has to be delivered by the dc-link or by regenerating the driven inertia. If speed fluctuations are not tolerated, kinetic buffering is not an option ($E_{kin} = 0$). In this situation, equation (13) can be revisited as (14):

$$V_{DC}\,C\,\frac{dV_{DC}}{dt} = T_L\,\omega_r \quad (14)$$

where, C : dc-link capacitor
T_L : load torque
ω_r : mechanical angular speed

Fig. 4 shows the dc-link voltage profile for a load with constant power demand during a 100 % voltage sag (outage). The discharge rate highly depends on the capacitor value C. Typical values for the dc-link capacitor range between 75 µF/kW and 360 µF/kW [3]. The under-voltage protection limit $V_{DC\,\min}$ in Fig. 4 sets the maximum ride-through time. The under-voltage limit can be adjusted. Typical values range between 90 and 50 % of the rated dc-link voltage.

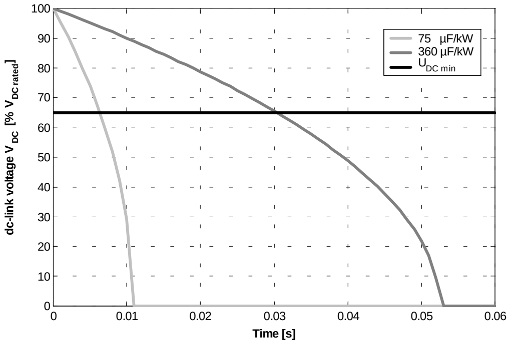

Fig. 4. Theoretical dc-link voltage profile V_{DC} for a constant power demand application.

If the supply voltage is restored before reaching the under voltage limit $V_{DC\,\min}$, the dc-link is recharged and normal operation can continue.

IV. VOLTAGE TOLERANCE CURVE

The behavior of adjustable speed drives has been described using voltage tolerance curves [2], [3]. Fig. 5 gives a typical example of a voltage tolerance curve.

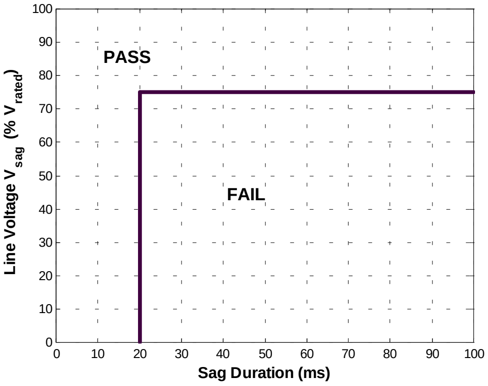

Fig. 5. Typical voltage tolerance curve for an adjustable speed drive.

The horizontal line in Fig. 5 is determined by the undervoltage protection limit $V_{DC\,\min}$ and can be user defined. The vertical line represents the maximum ride-through time for a supply voltage outage. This representation does not take into account the reduction of the maximum torque as described in previous sections.

The voltage tolerance curve can be adjusted by analyzing Fig. 6. Fig. 6 represents the maximum torque for different values of the dc-link voltage V_{DC} as a function of the angular speed. The voltage tolerance curves for a fixed speed can be deduced from Fig. 6 and are represented in Fig. 7. The horizontal lines in Fig. 7 represent the maximum steady-state torque that can be produced with a certain level of the remaining supply voltage, feeding the dc-link. As the torque demand becomes smaller, less supply voltage is needed to provide the torque. To generate each voltage tolerance curve in Fig. 7, constant torque and speed is assumed (constant power demand). As a result, the vertical line shifts to the right for lower torque readily seen from equation (14).

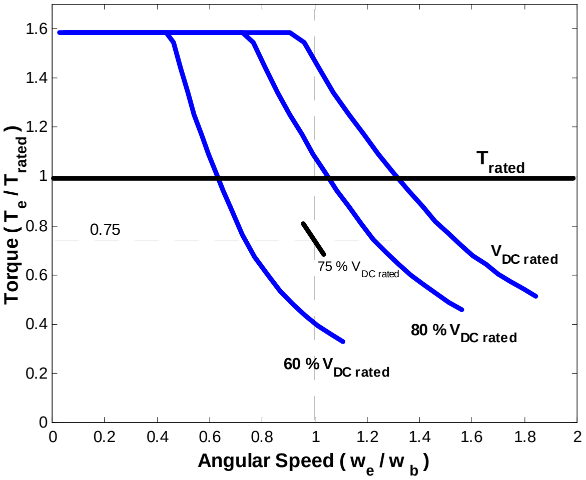

Fig. 6. Maximum torque curves for a FO induction machine for different magnitudes of the dc-link voltage V_{DC} .

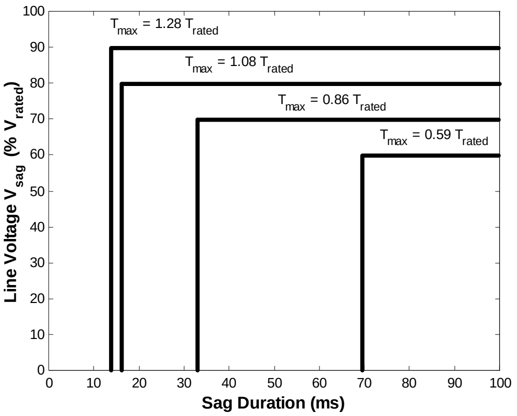

Fig. 7. Voltage tolerance curve for rated angular speed as a function of the torque demand.

V. TRANSIENT BEHAVIOUR

So far, only the steady-state torque capability has been discussed. The change of the torque producing currents i_{ds} and i_{qs} in field weakening is limited by the dynamic behaviour of the induction machine. The dynamic behaviour is analysed by a Matlab/Simulink® simulation model making extensive use of the Power System Blockset.

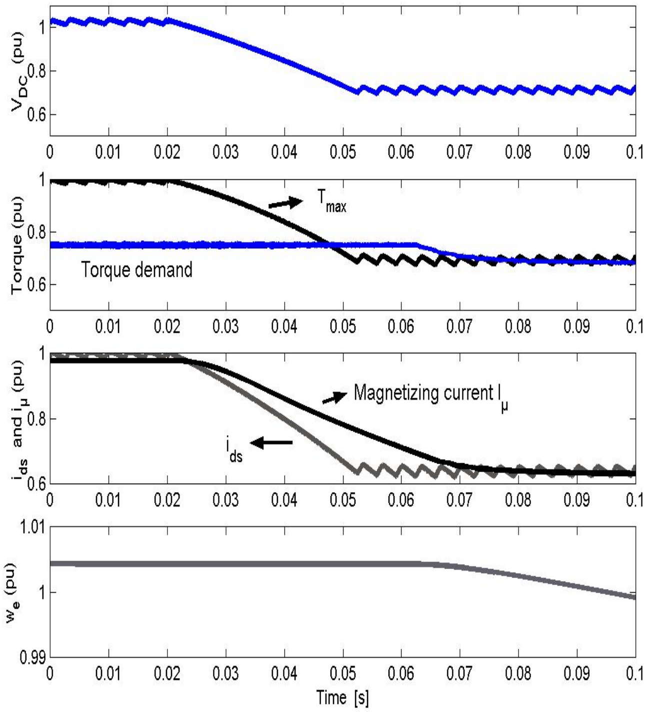

Fig. 8. Simulation results for a FO induction machine under voltage sag conditions : 30 % voltage sag, load torque $T_L = 0.75$ pu at rated speed.

Fig. 8 shows the simulation results for a 30 % voltage sag. The load torque T_L is 0.75 pu. The drop in dc-bus voltage causes a reduction in the maximum torque. In order to operate under maximum torque if needed, the control system reduces the stator current i_{ds}. Due to the dynamic behaviour of the machine, the reaction of the real magnetising current i_μ is delayed. The machine starts to slow down as soon as the load torque can no longer be supplied by the drive.

Fig 10. gives the results for a 20 % sag. For a 20 % sag, the drive is still able to produce the load torque.

For proper operation of the simulated application, the dc-bus undervoltage limit $V_{DC\,\min}$ should be set at approximately 75 % of the rated dc-link voltage. This optimal value for $V_{DC\,\min}$ can be derived from Fig. 6 (dashed lines).

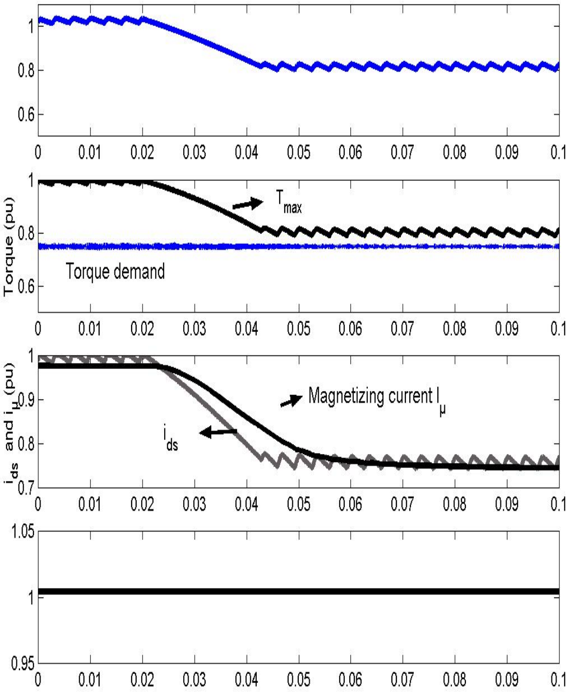

Fig. 10. Simulation results for a RFO induction machine under voltage sag conditions : 20 % voltage sag, load torque $T_L = 0.75$ pu at rated speed.

VI. CONCLUSION

The steady-state behaviour of a rotor flux oriented induction machine under voltage sag conditions has been investigated. The reduction of the dc-link voltage forces the drive to operate in the field weakening. Field weakening is activated at speeds well below base speed. As a result, classical field weakening has to be extended as a function of the voltage sag magnitude. In field weakening, the stator current is selected to produce maximum torque with regard to the voltage and current limit of the drive and the induction machine. The maximum torque is used to determine the voltage tolerance curves of the FO induction machine. Finally, adjusting the dc-link under-voltage limit of the drive, as a function of the minimum torque demand for the application under consideration, guarantees full torque control under voltage sag conditions.

VII. APPENDIX

MOTOR NAMEPLATE DATA AND PARAMETER VALUES

Rated output power	: 4 kW
Rated speed	: 1430 r/min
Rated voltage	: 400 V
Rated current	: 8.3 A
Number of poles	: 4
L_m	: 160 mH
L_s , L_r	: 13 mH
R_1	: 1.13 Ω
R_2	: 0.90 Ω

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IX. BIOGRAPHIES

Kurt Stockman was born in Kortrijk, Belgium, on September 24, 1972. He received the degree of industrial engineer in electrical engineering from "Provinciale Industriële Hogeschool", Kortrijk, Belgium, in 1994. Since 1995 he has been with the department of electrical engineering of the Hogeschool West-Vlaanderen, dept. I.&W., Kortrijk, Belgium. Currently he is performing his Ph.D.-study at K.U. Leuven. His interests are adjustable speed drives, voltage sags and control engineering.

Frederik D'hulster was born in Tielt, Belgium, on April 25, 1974. He received the degree of industrial engineer in mechanical engineering from the Katholieke Hogeschool in Ostend, Belgium, in 1996, and the M. Sc. Degree in mechanical engineering from Katholieke Universiteit Leuven, Heverlee, Belgium, in 1998. Currently he is performing his Ph.D.-study at K.U. Leuven. His interests are optimization and modelling of Switched reluctance machines and voltage sags.

Jan Desmet was born in Kortrijk, Belgium, on March 30, 1960. He received the degree of industrial engineer in electrical engineering from Provinciale Industriële Hogeschool, Kortrijk, Belgium in 1983. He received the M. Sc. degree in electrical engineering from the V.U. Brussels, Belgium in 1992. Since 1984 he is member of the staff of the Hogeschool West-Vlaanderen Dept. P.I.H. He is professor teaching power quality and industrial electric measurement techniques. His research interests include variable speed drives, rational use of electrical energy and power quality. He is also member of the SC77A (IEC), TC210 (CENELEC) and IEEE member. As steering member of the electrical engineering section of the Koninklijke Vlaamse Ingenieursvereniging (TI.KVIV) he works together with both university and industry.

Ronnie J. M. Belmans (S'77-M'84-SM'89) received the M.S. degree in electrical engineering and the Ph.D. degree from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1979 and 1984, respectively, and the special Doctorate and the Habilitierung from RWTH Aachen, Germany, in 1989 and 1993, respectively.

He is currently a Full Professor at the Katholieke Universiteit Leuven, teaching in the areas of electrical machines, power electronics, and variable-speed drives. His research interests include power quality, electrical energy systems, electrical machine design, and vibrations and audible noises in electrical machines. He was with the Laboratory for Electrical Machines of RWTH Aachen as a Von Humboldt Fellow from October 1988 to September 1989. From October 1989 to September 1990, he was a Visiting Professor at McMaster University, Hamilton, ON, Canada. He obtained the Chair of the Anglo-Belgian Society at London University for 1995-1996. He is currently a Visiting Professor at Imperial College, London, U.K.

Dr. Belmans is a Fellow of the Institution of Electrical Engineers, U.K., the International Compumag Society, and the Koninklijke Vlaamse Ingenieursvereniging.