Ride-Through Study for Matrix-Converter Adjustable-Speed Drives during Voltage Sags

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***Abstract*—The ride-through capability issues associated with adjustable-speed drives (ASD) have become an important area of concern due to the susceptibility of ASD to power interruptions. Furthermore due to the absence of the dc link capacitor in matrix-converters (MC), MC adjustable speed drives are more vulnerable to such power disturbances. This paper presents a study of a ride-through strategy for MC adjustable-speed drives. With hysteretic control on the magnitude of motor currents, the strategy comprises of keeping the motor continuously operating through a combination of input voltage vector application, aligned in the flux direction, and zero vector application, along with discontinuation of MC switches. The strategy aims to enhance the ride-through duration and achieve minimum possible flux deviation during the voltage sag period to allow minimum transients during power system restoration. The paper also investigates the effect of different load torques and reference currents at different voltage sags on the maximum possible ride through time.**

I. Introduction

With the increase in application of ASD's in industrial and commercial facilities, in recent years, ride-through capabilities have become an important issue due to susceptibility of ASD's to voltage disturbances such as sags[1].Voltage sag is a sudden drop in the source voltage by a magnitude of 0.1-0.9 p.u. for a duration of 0.5 cycles-1min[2]. Research surveys have found voltage sags to be the major cause for disruption in industrial operations[3]. Through power quality surveys and questionnaires, it was determined that a ride-through duration of 0.5-5s at rated power withstanding a 50% sag would be beneficial[4].

If an ASD has no ride-through capability, then the drive might have to be restarted from zero speed and flux once the fault gets cleared and the power supply gets restored. In some cases this would also require some coordination and alignment with different industrial mechanisms involved in the task. All this might cause unwanted delays in the drive operation leading to production losses.

Thus, based on the requirements for ride-through capability for short power interruptions for the conventional ASD drive operation, different strategies were proposed .These were classified as employing or not employing external energy sources. Within the strategies that did not make use of external energy sources, the common approach was to cleverly manage the available system energy immediately after the power outage. This was done by decelerating the drive during voltage sag and receiving mechanical energy from the rotary part of the system. This energy was then used to maintain the dc link capacitor voltage which fed the control circuits and keep the motor magnetized[5].

But with matrix-converter fed ASD, ride through has become an even greater issue, because of the absence of dc link capacitor and the direct connection with the input grid phases. This makes MC more vulnerable to short term power interruptions at the input. Consequently as an effort to mitigate the impact of these disturbances on industrial production, different ride-through strategies for MC drives were developed.

This paper presents an alternate strategy to ride-through short term low voltage sags for MC adjustable speed drives. The proposed scheme makes use of the clamp circuit normally used with MC for protection against over voltage transients and commutation errors. The clamp circuit capacitor is used as the source for the control circuits and for sustaining the flux level in the motor as much as possible during the power disturbance duration. Using hysteretic control on the motor magnitude and applying the available grid voltage vector aligned in the flux direction alternately with clamp circuit voltage vector, ride through is achieved. To keep the flux level within limits when the drive decelerates to lower speeds, zero vector is applied alternately with active input voltage vector.

II. MC Drive Topology

The three-phase MC Drive Scheme as shown in Fig (1) clearly depicts all the different components of this integrated MC fed adjustable-speed drive system. Starting with the converter itself, it has nine four quadrant bidirectional switches which allow for high frequency switching operation. By use of an appropriate modulation scheme, a low frequency output voltage of variable amplitude and frequency can be obtained.

If viewed from the input supply side, the MC acts like a current source converter and therefore requires an LC filter to shape the current. For protection of MC, as already mentioned, a clamp circuit is used. This clamp circuit provides a current path for load de-energization if the switches are disconnected avoiding dangerous over-voltages. The same clamp circuit is also used by the proposed scheme to ride-through short term voltage sags discussed later in the paper. Because one of the advantages of MC is its lower weight due to absence of storage elements, care is taken while designing the passive filter components and the clamp circuit capacitor.

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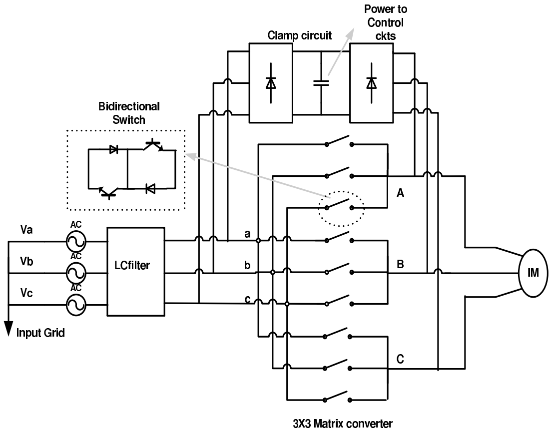

Fig. 1: Basic Matrix Converter Drive Topology

At the system end, we have the load driven motor supplied by the output voltage of the MC.

III. Existing Ride-Through Strategies

The first ride-through strategy developed for MC[6] uses an approach similar to the one discussed in the previous section for conventional back-to-back drives. The strategy now seeks to maintain the clamp capacitor voltage rather than the dc-link voltage, considering that all the control circuits are being fed by this capacitor voltage. During an under-voltage fault, the system is forced into the ride-through mode, where the motor circuit is separated from the input grid by disconnecting the MC switches. During this time the magnetic energy from the leakage inductances gets dumped into the clamp circuit in the form of electrostatic energy. This operation is then alternated with zero vector application during which rotor inertia gets converted to magnetic energy in the leakage inductances. The switching between the two states is controlled by the magnitude of the motor current vector. Consequently, with this kind of boost action scheme, Fig(2), ride-through is achieved. One distinctive feature of this scheme is that no active states are applied to the motor and hence the drive decelerates as the rotor flux cannot be controlled. Another feature worth mentioning is that since the input grid is separated from the motor terminal, the ride-through duration would be the same for all voltage sag%.

The next proposed ride-through strategy for matrix-converter fed ASD's involved enforcing constant volts/hertz operation through voltage sags with a minimum motor speed reduction[7]. To maintain constant V/f operation, first the modulation index of the MC was regulated which would counteract the dip in source voltage and secondly, the speed reference was lowered if required.Yet another ride-through approach was proposed in[8] which modified the conventional MC topology by adding extra IGBT switches and a dc-link capacitor. By making use of three of the nine switches MC switches and the additional IGBT's with the dc-link capacitor, a PWM VSI can be realized which in turn maintains rotor flux and enables continuous ASD operation.

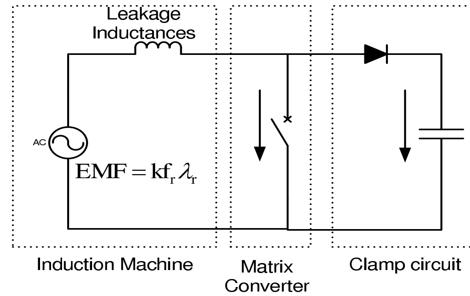

Fig. 2: Equivalent Boost Converter Circuit

IV. Proposed Ride-Through Strategy

The main ride-through objective of an MC driven ASD is to maintain current at a desired value and maintain flux in the machine at the closest possible value to the rated. But we are constrained by the drop in grid voltage, due to which we no more have the freedom to give the desired voltage vector at an arbitrary phase and amplitude. The electromagnetic machine dynamics, at any instant, is governed by the available voltage, speed of the rotor and the available flux in the machine. Before ride-through, in normal mode of operation all the quantities balance each other according to the motor model, and maintain certain steady state values. But during ride-through, when voltage at the grid drops by a sag amount, then the balanced steady state is no longer maintained. The system can then show large over-currents, due to low available grid voltages, because the back emf in the machine is no longer balanced by the available grid side voltage. In order to maintain current level and flux level within limit during ride-through, it is desirable to get additional voltage levels from the clamp circuit. But because clamp circuit allows uncontrolled rectification, therefore the phase and amplitude of voltages applied at the motor terminals, is no more in our control. This phase and amplitude of the voltage vector will entirely be governed by the phase of the stator current in the machine. Here we have two options available:

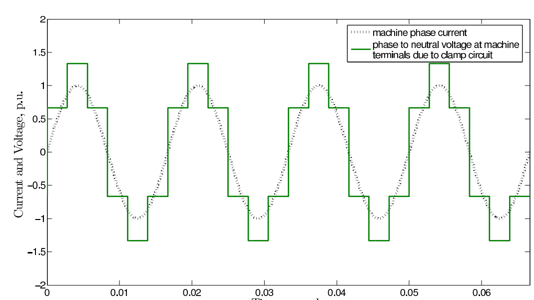

Fig. 3: Available Clamp circuit voltage vector according to the machine phase current

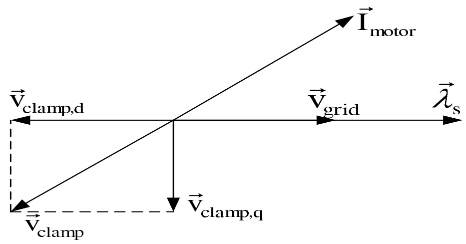

Fig. 4: Voltage vectors available from grid and clamp circuit during ride-through mode

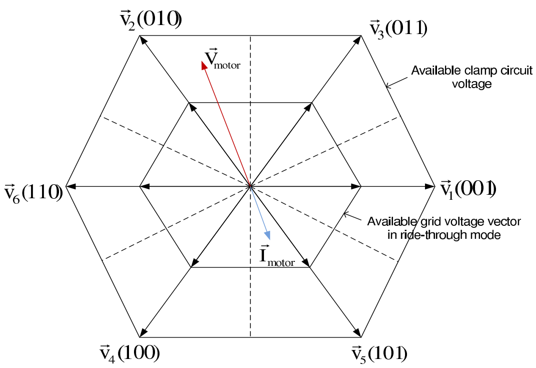

Fig. 5: Voltage vector selection during ride-through mode depending on the back emf of the motor

1. All switches of MC are forced to zero and machine current is controlled by clamp circuit.Fig(3) shows how the clamp circuit voltage will look like with the given machine current per phase.

2. In addition to clamp circuit voltage, we should use available grid voltage to control stator flux and stator current to best possible extent.

Traditionally, therefore zero vector was used to short circuit the motor terminals to control the motor currents within a limited range [6].

Unlike the traditional method, our strategy advocates use of the best possible voltages from the grid along with the clamp circuit voltages to control stator flux and current. During ride-through, the proposed controller uses hysteresis control to maintain the current amplitude from the clamp circuit voltages and voltages available from the grid. To control the hysteresis current, I_{motor} as shown in Fig(4), we need to give some grid voltage in the flux direction and clamp circuit voltage, unlike the old method of giving zero vector with the clamp circuit voltage. If applied current in the machine goes beyond rated value then clamp circuit voltages are applied and if current is below rated, then grid side voltage is applied. Another hysteresis block is used to control the flux amplitude in the machine. This flux magnitude determines whether zero vector should be used or voltage along flux direction, operated at maximum modulation range from the MC should be applied.

Fig(5) shows the average available grid voltage and clamp circuit voltage during ride-through. The voltage needed by the machine during this time is V_{motor} (back emf) which cannot be supplied by grid voltage alone, as can be seen, and hence clamp circuit voltage will also be applied alternately. The closer the V_{motor} to the clamp circuit voltage, the more the contribution of clamp circuit vector on an average over a cycle. With decrease in speed, as back emf decreases, voltage needed by the machine decreases. This means that V_{motor} is closer to the grid voltage vector envelope than the clamp circuit voltage vector envelope. Consequently, more grid voltage in the flux direction, would be applied than the clamp circuit voltage during low speed. Thus flux may tend to increase during low speed operation of the machine during ride-through, as we will see in the simulation results Fig(9).

A. Analysis of machine dynamics during Ride-Through

The stator voltage equation for the induction machine in spacevector form is given in (1). In a stator flux oriented d-q frame, if stator resistance drop is neglected, (1) results in (2) and (3). (4) provides the flux linkage equation in this frame, and on assuming leakage inductances $L_{ls}, L_{lr} <<$ L_m(magnetising inductance) results in (5). (4) also results in (6), where $\bar{\sigma} = \left(\frac{L_s L_r}{L_m^2} - 1\right) \approx (L_{ls} + L_{lr})$.

$$\vec{V}_s = R_s \vec{i}_s + \frac{d}{dt}\vec{\lambda}_s \tag{1}$$

$$v_{sd} \approx \frac{d}{dt}\lambda_{sd} \tag{2}$$

$$v_{sq} \approx \omega_d \lambda_{sd} \tag{3}$$

$$\begin{pmatrix} \lambda_{sd} \\ 0 \\ \lambda_{rd} \\ \lambda_{rq} \end{pmatrix} = \begin{pmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{pmatrix} \begin{pmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{pmatrix} \tag{4}$$

$$i_{sq} \approx -i_{rq} \tag{5}$$

$$\lambda_{rq} = \bar{\sigma} L_m i_{sq} \tag{6}$$

Using equations (2) to (6) and assuming $\bar{\sigma}$ to be approximately zero, for short intervals of time (small compared to $\frac{\bar{\sigma} L_m}{R_r}$ or rotor leakage impedance time constant), the rotor voltage equations (7) and (8) results in (9) and (10). In this analysis, for short intervals of time during ride-through, as the inertia J is quite high, ω_m is assumed to be constant.

$$R_r i_{rd} - (\omega_d - \omega_m)\lambda_{rq} + \frac{d}{dt}\lambda_{rd} = 0 \tag{7}$$

$$R_r i_{rq} - (\omega_d - \omega_m)\lambda_{rd} + \frac{d}{dt}\lambda_{rq} = 0 \tag{8}$$

$$\bar{\sigma} L_m \frac{d}{dt} i_{sd} \approx v_{sd} \tag{9}$$

$$\bar{\sigma} L_m \frac{d}{dt} i_{sq} \approx v_{sq} - \omega_m \lambda_{sd} \tag{10}$$

During the voltage sag condition, the matrix converter is modulated to generate a voltage vector along the direction of $\vec{\lambda}_s$, (11). This results in linear increase in stator flux and d-axis component of the stator current (12). The stator flux-linkage vector stops rotating i.e. $\omega_d \approx 0$. Power is transferred from the input source to charge the magnetizing current or to maintain the machine flux during ride-through. $\tilde{i}_{sd}$, $\tilde{\lambda}_{sd}$ and $\tilde{i}_{sq}$ represent the variation in i_{sd}, λ_{sd} and i_{sq} respectively.

$$\begin{aligned} v_{sd} &= V_d^M \\ v_{sq} &= 0 \end{aligned} \tag{11}$$

$$\begin{aligned} \tilde{\lambda}_{sd}(t) &= V_d^M t \\ \tilde{i}_{sd}(t) &= \frac{V_d^M t}{L_m} \end{aligned} \tag{12}$$

During the clamp circuit mode, the applied voltage depending on the magnitude and direction of the input current space vector, results in applying a set of voltages to the stator as given in (13). This results in a decrease in stator flux linkage, (14) maintaining stator flux. By (10), assuming ω_m does not change appreciably during this time, we get (15). In this interval i_{sq} is negative, so the electromagnetically generated torque which depends on i_{sq}, is also negative. A part of the mechanical energy stored in the rotor inertia is transferred to clamp circuit through the electrical machine. This helps to maintain the clamp capacitor voltage during ride through period so that the control electronics could remain alive and a proper acceleraton of the machine to its rated speed is possible in a minimum amount of time without any current transient once the power comes back.

$$\begin{aligned} v_{sd} &= -V_d^R \\ v_{sq} &= -V_q^R \end{aligned} \tag{13}$$

$$\begin{aligned} \tilde{\lambda}_{sd}(t) &= -V_d^R t \\ \tilde{i}_{sd}(t) &= \frac{-V_d^R t}{L_m} \end{aligned} \tag{14}$$

$$\tilde{i}_{sq}(t) = -\left(\frac{V_q^R + \omega_m \lambda_{sd}}{\bar{\sigma} L_m}\right) t \tag{15}$$

V. MC Drive Ride-Through Performance

A. Implementation

The proposed ride-through strategy was simulated and tested in MATLAB/Simulink. Using the Induction Motor dynamic equations, the motor model was created with the specifications given in Table(1). This motor drive system was vector controlled and the initial conditions were calculated from the applied phasor voltages using phasor analysis and the dq equations. The MC and the Clamp circuit were modeled using SimPowerSystem Toolbox.

During normal mode operation, the input grid supplies voltages switched by the MC to get the desired output voltages and currents at the motor terminals. The clamp circuit operates only during the dead time (if any) during this mode. The desired control voltages feed the appropriate modulation index to the MC during this time. When suddenly the voltage at the input grid drops below its nominal voltage, sag detect flag gets enabled and the system now starts operating in ride-through mode. During ride-through mode, as explained in the previous section, vector control is no longer into action. Hysteresis control is now used to sustain flux in the machine, and keep it online during the STPI period. The stator flux position is estimated, and with the idea of applying voltages in the direction of flux, the voltage sector is determined. Using this information, the MC voltage vector is then appropriately switched to apply the active voltage vector that is available from the grid. The hysteretic current controller and the flux controller together manage to sustain the current and hence the flux in the machine.

Motor Parameters	Specifications
Power	19KW
$V_{LL,rms}$	250 V
R_r	0.125Ω
R_s	0.19Ω
f_{sw}	15kHz
f_o	60Hz
X_m	13.9Ω
X_{lr}	0.603Ω
X_{ls}	0.641Ω
J	$0.7kgm^2$

TABLE I: Induction motor specifications taken for the simulation

B. Simulation Results

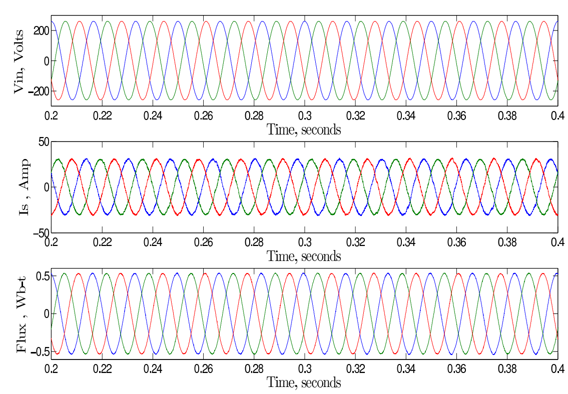

Fig. 6: Simulation results in normal mode (a) Input Grid Voltage vs Time (b) Motor currents vs Time (c)Stator Flux Linkage vs Time

The steady state waveforms of the MC-drive, in normal mode of operation, are shown in Fig(6). It shows the available input grid voltages to be around 260V peak. The motor currents and stator flux are seen to be sinusoidally varying with a peak of around 36A and 0.53 Wb-t respectively. The next set of waveforms in Fig(7) show the transient response, when the input voltage at the grid suddenly falls down to 50% of its nominal voltage. The stator currents and stator

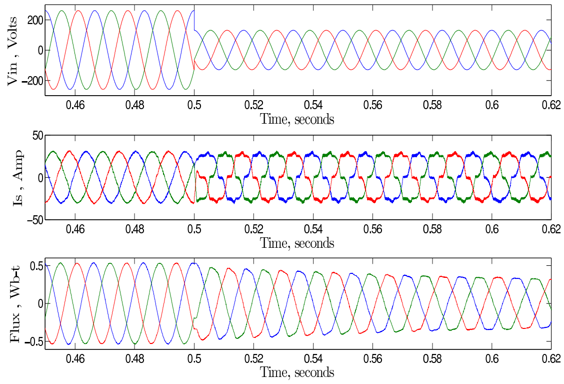

Fig. 7: Simulation results during transition to ride-through mode (a) Input Grid Voltage vs Time (b) Motor currents vs Time (c)Stator Flux Linkage vs Time

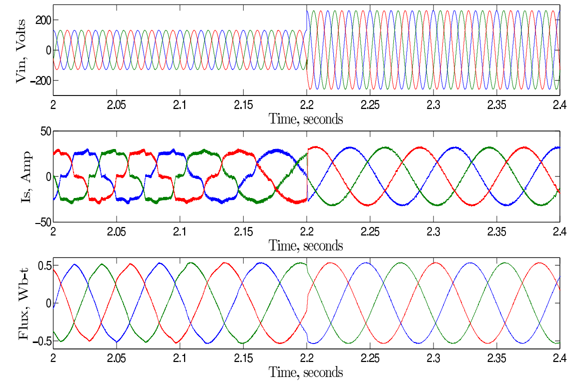

Fig. 8: Simulation results during system recovery at rated flux (a) Input Grid Voltage vs Time (b) Motor currents vs Time (c)Stator Flux Linkage vs Time

flux do not see any overshoots in their response. The current waveform has some harmonics due to some numerical issues in the simulation, and improper tuning, to be improved in the future. But the currents can be seen to be maintained around the reference rated current magnitude set by the hysteresis controller. The stator flux waveform gradually decreases immediately after the under-voltage fault appears.

After the flux has risen to its rated value during ride-through time, the system is recovered. Fig(8) show the system recovery instant when the fault is cleared and the voltage at the grid appears suddenly. The current and flux waveforms are seen to come back to their initial operating conditions with minimum transient. Fig(9) shows the motor current and flux waveforms for the entire duration of the normal mode operation, transition to ride-through mode, ride-through mode operation and power recovery transition back to normal mode. The flux waveform show how the flux values decrease, and try to sustain at a certain level during the ride-through. But because of the low speeds, its value starts increasing, due to increased stator voltages applied at the motor terminals. Finally the flux reaches the rated value and is sustained at that level, till the entire ride-through duration, which is limited by the system inertia. The waveforms shown in Fig(10) and Fig(11), show the variation in ride-through duration, with different reference currents, and different percentage of voltage sag (V/Vn *100). At a particular reference current, the 10%sag has lower ride-through duration as compared to 20% sag and so on. For 50%sag and beyond, the ride-through durations are limited by the mechanical energy of the system. This means that for an infinite inertia machine (hypothetical case), the flux can be sustained for infinite time using this strategy.As the reference currents are lowered the ride-through duration increases, because now, with lower current values in the machine, the torque values decrease due to which speed decreases at a slower rate. Fig(11) shows a similar waveform but at no load condition. Waveforms of stator flux versus percentage of voltage dip (V/Vn *100) in Fig(12), show the flux levels maintained during the ride-through duration for different voltage sags and different values of reference currents. For very low voltage dip values as the reference currents are decreased below the rated, the flux levels are seen to increase, never falling to zero for 50% and 25% reference current values.

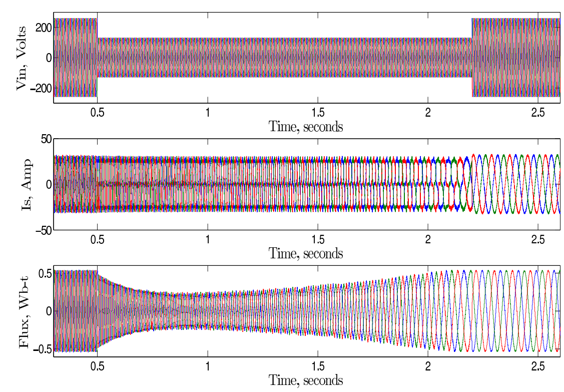

Fig. 9: Simulation results during ride-through mode (a) Input Grid Voltage vs Time (b) Motor currents vs Time (c)Stator Flux Linkage vs Time

The final waveform in Fig(13) shows the ride-through profile of the given machine under different voltage sag% .With a minimum of 200ms at 10% sag and increased durations for subsequent higher percentage sag(V/Vn) value.

VI. Conclusion

This paper presents a ride through strategy for matrix converter driven ASD's for general purpose applications. The proposed strategy is based on the alternative switching of the MC between the active voltage available from the grid and the MC disconnect state such that the stator currents are maintained and stator flux has minimum deviations from its rated value even at low voltage sags. The strategy also seeks to enhance the ride through period. Moreover, the converter never loses synchronization with the drive, so it is capable of restoring to initial conditions, after the disturbance, with minimum transient. An additional zero vector state helps control flux and keeps it within limits, if the flux increases beyond the rated value. This may happen due to over-compensation of flux at higher voltage sags, when the speed decreases to low values. Through the simulation results and waveforms obtained, an investigation into the strategy was made and dependence of ride-through duration on sag% and reference currents was analysed. The ride-through profile of the machine under study was plotted and was found to be satisfactory in terms of its ride-through performance. In future, experimental verification of the strategy needs to be done and further modifications for improvement to the strategy needs to be made, after further insight is obtained.

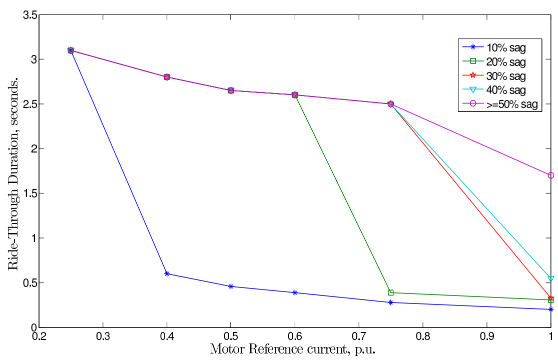

Fig. 10: Ride-through Duration Vs Current Reference at Full Load Torque

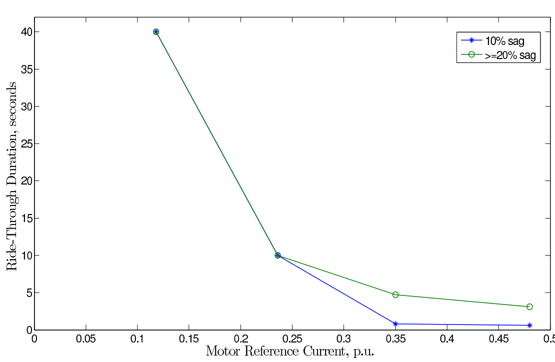

Fig. 11: Ride-through Duration Vs Current Reference at Zero Load Torque

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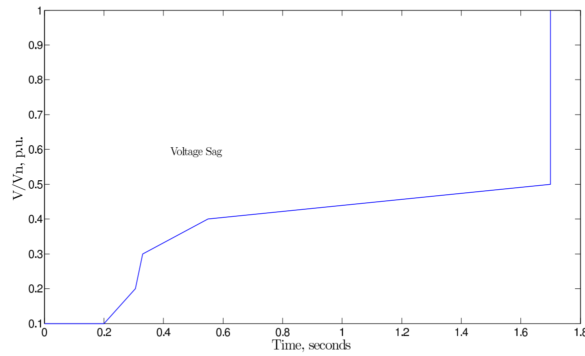

Fig. 12: Stator Flux Vs Voltage sag % at Different Motor Current References

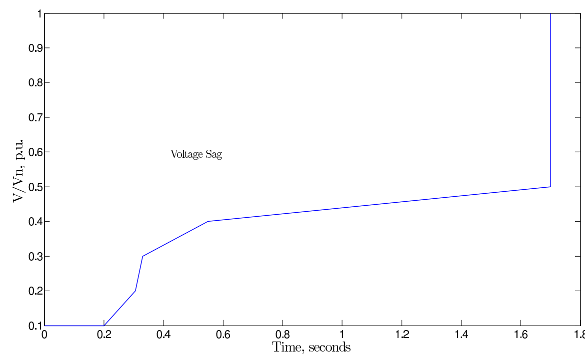

Fig. 13: Ride through profile with Rated Load Torque

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