PERFORMANCE OF ADJUSTABLE SPEED DRIVE UNDER THREE-PHASE VOLTAGE SAGS

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Abstract – **This work analyzes the effects of three-phase balanced voltage sags on ASD equipment using Simulink software. The simulation allows observing the behavior of currents, voltages, rotation and torque during the event of voltage sags. The main goal of these approaches is to measure the dc-link voltage and determine the limit voltage that permits a good performance of control motor. The control system adopted is the vector control available in the Simulink.**

Keywords - **Adjustable speed drive, Induction motor drives, Matlab, Power quality, Vector control, Voltage sags.**

I. INTRODUCTION

Voltage sag is a decrease in RMS voltage magnitude at the power frequency for durations of 0.5 cycles to 1 minute with a magnitude of 0.1 - 0.9 pu [1]. Despite a short duration, a small deviation from the nominal voltage can result in serious disturbances.

Voltage sags caused by transmission or distribution faults propagate long distances and affect all the connected power system parts. Events such as faults or insulator flashovers due to animals, trees, wind, automobile accidents, and lightning may cause a temporary magnitude reduction of the voltage on one or more phases [2]. The magnitude reduction depends of the short circuit level of the electrical system.

Also, inrush currents associated with motor starting and transformer energizing can cause voltage sags. Motors have the undesirable effect of drawing several times their full load current while starting. Transformers also exhibit inrush currents upon initial energization. In this case, the high currents occur to energize the transformer core. By flowing through system impedances, this large current will cause voltage sags.

One related problem to voltage sags is that there are no standards covering the complete issue, e.g. there are no descriptions on how to test and present the immunity in a three-phase system. Voltage sags normally do not cause equipment damage but can easily disrupt the operation of sensitive loads such as electronic adjustable speed drives (ASDs) [3].

As industrial plants move towards a globally competitive environment, achieving high levels of productivity becomes a critical factor. Therefore, it is important that processes operate essentially uninterrupted. The study of voltage sags is important because one of the dominant reasons for process interruption is due to voltage sags.

The pulse-width modulated (PWM) adjustable speed drive (ASD) systems provide improved efficiency, energy savings and process control in commercial and industrial facilities. However, ASD systems are often susceptible to voltage sags and others electric power quality disturbances because they are power electronic based technology.

Numerous power quality surveys have shown that utility transients are responsible for numerous nuisances tripping on ASD equipment installed in critical industrial continuous processes. PWM ASDs feeding induction motors from a constant dc-link voltage have matured as a standard drive technology [4].

In response to these concerns, this paper analyzes the effects of three-phase balanced voltage sags on adjustable speed drive equipment using Simulink software. The simulation allows observing the behavior of currents, voltages, rotation and torque during the event of voltage sags.

Variable frequency drives have different voltage sag and ride-through capabilities. Drive capabilities vary with design, internal programming, load inertia, and degree of loading. The use of simulation, if given the correct parameters, permits to measure the dc-link voltage and determine the limit voltage that permits a good performance of control motor. The control system adopted is the vector control available in the Simulink.

II. MODEL DESCRIPTION

As an extension of Matlab, Simulink adds many features specific to dynamic systems while retaining all of general-purpose functionality of Matlab [5]. The model available in the Simulink is a vector control of a variable-frequency induction motor drive. The d-q dynamic model is used because it's accurate in predicting the dynamics of the system.

A current-controlled PWM inverter that is built using a IGBT inverter block feeds the induction motor. The motor drives a mechanical load characterized by inertia, friction coefficient, and load torque.

The speed control loop uses a proportional-integral controller to produce the quadrature-axis current reference that controls the motor torque. The motor flux is controlled by the direct-axis current reference. Motor current, speed, and torque signals are available at the output to display the curves. The actual output voltage waveform is a pulse-width modulated (PWM) high-frequency waveform. Therefore, a sinusoidal waveform can be synthesized at the output terminals.

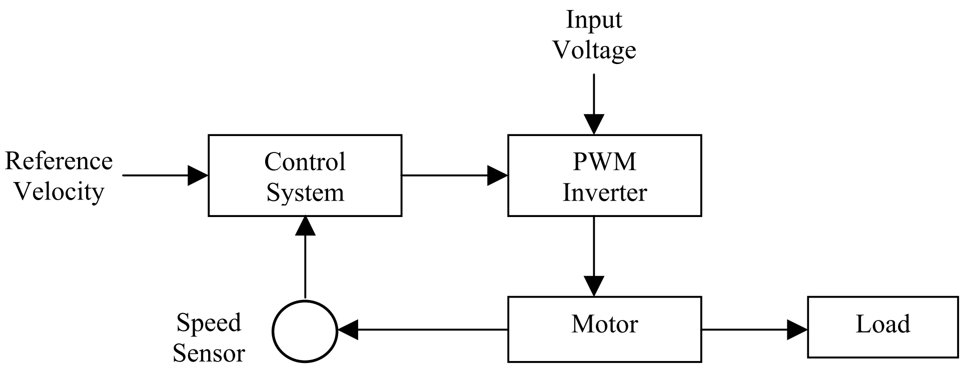

Fig. 1. Block diagram of drive system

The former circuit description is available as a demonstration model in Simulink. In this work, it was modeled a three-phase utility source in the Matlab and transferred to Simulink. This dedicated software was developed and added in the demonstration model available in Simulink. Therefore, it was possible to generate and control voltage sags in the magnitude and duration. Figure 1 shows the block diagram of drive system.

III. COMPUTER SIMULATION

A three-phase squirrel-cage asynchronous machine rated 50 HP, 460 V, 1780 rpm is fed by a sinusoidal PWM inverter.

The load torque applied to the machine's shaft is constant and set to its nominal value of 200 N.m. The speed set point is set to 1528 rpm therefore wave's frequency is nearly 52 Hz. The combined machine and load inertia coefficient is 1.662 kgm^2 and the combined viscous friction coefficient is 0.1 Nms.

The inverter is pulse-width modulated to produce a three-phase variable-voltage variable-frequency sinusoidal voltage to the load. The IGBT inverter is controlled in a closed loop with a PI regulator in order to maintain the reference velocity.

The frequency converter consists of a rectifier feeding an IGBT inverter through a DC link. The steady-state voltage waveform at DC bus exhibits only negligible change because the LC filter. The storage energy in capacitance provides operation continuity for ASD in the event of voltage sags, during some source cycles. This storage energy supplies power for a limited time during a power loss. This time depends on the capacitance value that is 5 mF in this simulation. The smoothing reactor, which is installed for other reasons, stores little energy and helps the operation continuity. In this simulation, the smoothing inductance value is 200 μH. Figure 2 shows the block diagram of frequency converter with LC filter.

There are several techniques to provide the ASD immunity or ASD ride-through capability to voltage sags and short-term power interruptions. This work discusses the performance of ASD without these techniques and uses only the storage energy in DC link. Therefore, the converter continues to supply power to motor and then the voltage at DC link decreases.

There is a critical DC voltage below which the mechanical system is adversely affected. This voltage value depends of the manufacturing plant sensibility. Therefore, this study is useful to determine when the tripping operation must be done.

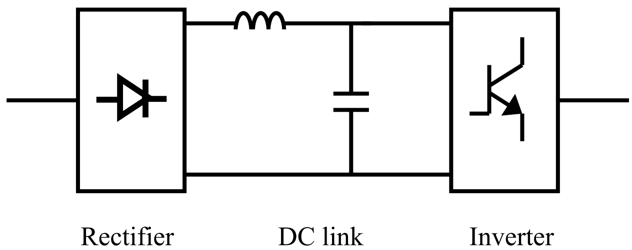

Fig. 2. Block diagram of frequency converter

IV. SIMULATION OF VOLTAGE SAG

There are two main parameters that can be defined to characterize the voltage sag event [6]. These parameters are the sag magnitude and the sag duration. In addition to these quantities, sags are also characterized by unbalance (asymmetry), nonsinusoidal waveshapes, and phase angle shift (phase jump). These factors are important in determining the behavior of motor drives during sags.

Voltage sags can be either balanced or unbalanced, depending on the causes. If the individual phase voltages are equal, the sag is balanced. If the individual phase voltages are different or the phase relationship is other than 120°, the sag is unbalanced. A three-phase short circuit or a large motor starting can produce symmetrical sags.

In this simulation, it does not take into account the voltage asymmetry due to the difference in individual phase voltages and the phase-angle jump. This work analyzes the effects of three-phase balanced voltage sags.

Three simulations were run to determine ASD performance in the presence of different magnitude voltage sags. The variation of the nominal voltage magnitude of each simulation was 10%, 20% and 30%. Only the last simulation is presented in this paper. The voltage sag duration used was 5 cycles. This number of cycles is a normal interruption time of short-circuits. The opening time of the circuit breaker depends of how quickly the circuit breaker operates and others characteristics of the circuit that it will not be treated in this work.

Figure 3 shows the remaining voltage under the sag event with 70% of nominal magnitude and the duration of 5 cycles.

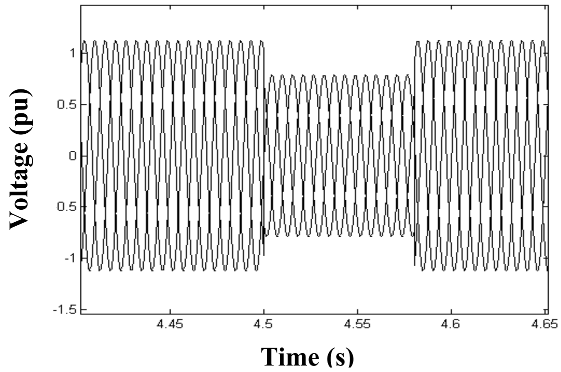

Fig. 3. Waveform of balanced 70% three-phase voltage sag

V. SIMULATION RESULTS

In this simulation, the drive and the motor are set to run from standstill to steady-state full speed and then the sag is initiated at 4.50 s and terminated at 4.58 s for a total of 83 ms.

The DC link voltage variation under voltage sag depends on source impedance, dc-link inductance and output load [7]. Therefore the sensitivity of the model to these parameters should be addressed. Therefore this task is not completed. However, it will be done in the future work.

Figure 4 shows the behavior of DC Link voltage. During the event, the DC link voltage drops from 650V to 450 V. This drop voltage may initiate a trip command that will take the equipment off-line and thereby disrupt the process.

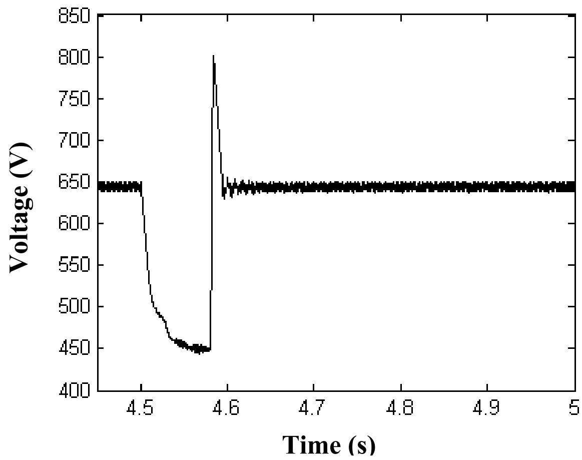

Fig. 4. DC Link voltage during the sag

Actually, when voltage sag begins the filter continues supplying current to motor; the voltage across the capacitor will draw down during the time no charging current flows through the rectifier. The input currents in the sagged phases completely drops out during 40 ms because, in this period, the dc-bus voltage drops down to a value which is still higher than the peak line-to-line voltage.

There is a peak voltage when sag event finish because voltage utility restores to normal levels and then a peak current occurs. The reactor inside link DC reduces diode peak current.

The inverter section converts this dc voltage back to a variable frequency and variable magnitude voltage using a pulse width modulated (PWM) control scheme.

Figure 5 shows the PWM output voltage (inverter PWM line to line output). The PWM pattern also changes because the voltage sag event. This changes on the PWM pattern may lead to mal-operation of the motor.

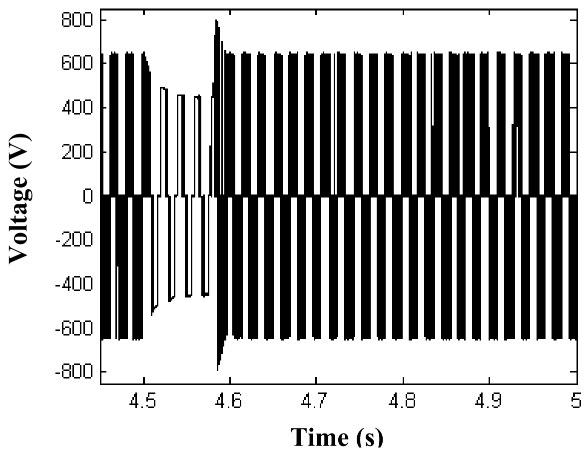

Fig. 5. PWM output voltage during the sag

There is a noticeable change in PWM pulse that is similar to dc-bus voltage drops down behavior. Whenever sag reduces the dc link voltage, the PWM pulse changes to more thin and low and fundamental voltage reduces in magnitude.

The motor torque can be seen in Figure 6. The torque magnitude decreases during voltage sag and recoveries with a bit increase. This increment observed on return of normal voltage after sag is good to process performance. The torque decreases in response to the decreasing of currents and increases with currents increment.

The P I controller operates on the speed error and outputs a torque command that is related to motor current. The energy storage in the DC Link is reduced during voltage sag and can't be satisfactorily utilized in order to compensate the speed-torque loss.

The behavior of motor speed can be seen in Figure 7. The speed decreases exponential during the event and increases also exponential when the event finishes.

Whether or not the response of an adjustable speed drive is acceptable depends upon the dynamic requirements of the process. For example, one process may not tolerate even moderate changes in torque and speed, while another may tolerate wide momentary swings in torque and speed. In fact, for some process, a drive may shut down and still meet the operational requirements of the process because the drive enables automatic restart or because the process does not require continuous control.

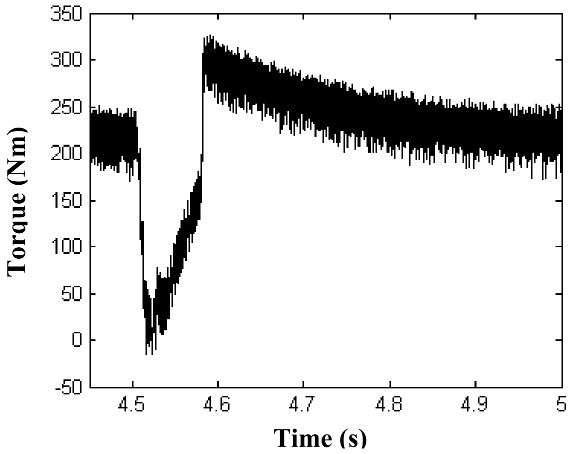

Fig. 6. Motor torque during the sag

Flying restart is not appropriate for processes that require precise regulation of speed and torque. This feature enables an ASD to restart while the motor is rotating.

To determine whether flying restart should be enabled, it's necessary understands the speed-torque requirements of the mechanical load.

Voltage sags and momentary interruptions can cause an ASD to drop its output power, causing a loss of motor torque and speed that can upset the entire process. The resulting downtime, restart time, and product damage are an unacceptable financial loss to end-users. The ability of an ASD to ride-through voltage sags and momentary interruptions without upsetting the process depends not only upon how sensitive the process is to variations in speed and torque but also upon the ASD energy-storage capacity.

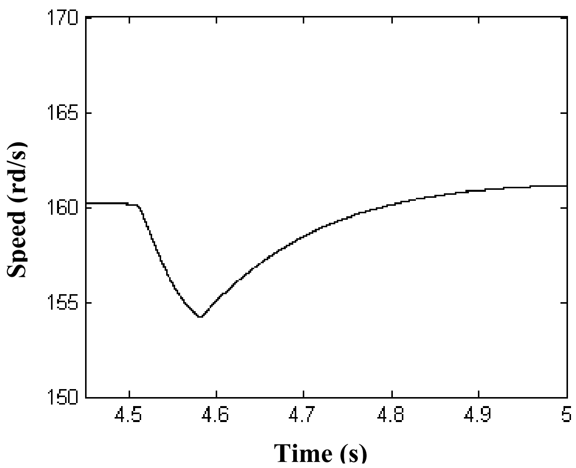

Fig. 7. Speed motor during the sag

Figure 8 shows the phase A current. All three-phase currents decrease with depth like the torque. The speed decreases slightly, only 3.6%, because kinetic energy is proportional to the square of the rotational speed. This mitigates the problem because the industrial process necessary energy is "self-generated" by the kinetic energy. However, this depends of process sensibility.

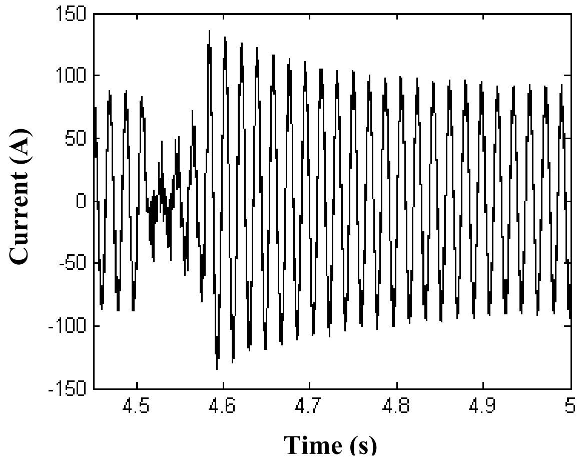

Fig. 8. Phase A current motor during the sag

Table I illustrates the performance of adjustable speed drive under three-phase voltage sag. The minimum values reached during the sag for each variable is showed in this table.

The motor currents and shaft torque magnitudes are severally reduced. DC link voltage and fundamental voltage of PWM pulse are moderately reduced. Note that speed decreases slightly (3.6%) although other variable decrease more than 24%.

TABLE I
Variable values results

Variable	Set value	Disturbed output	Dropped value (percentage)
DC Link (V)	650	450	30.7
$V_{ab,ef}$ (V)	460	346	24.7
I_s a,b,c (A)	56	14	75.0
Torque (Nm)	200	50	75.0
Speed (rd/s)	160	154	3.6

VI. VOLTAGE REGULATION

Sag correction may be provided directly on adjustable speed drive. Correction may also be chosen for large portions of a facility or for the entire facility. The selection of sag mitigation technolology will depend on cost verses advantages gained.

Various solutions are commercially available for correcting voltage sags. These include tap changing transformers with static switches, saturable reactor regulators, and ferroresonant transformers. Some of the advantages and disadvantages of using these solutions are given by the following examples.

Tap changing transformers is rather simple in concept and uses established thyristor technology. Electronic tap changing is achieved via the use of back-to-back thyristors with a tap changing transformer. This technique has a reasonable response time (1 cycle) and is used for medium power applications. The drawbacks of this scheme include the large number of thyristors and its susceptibility to high transients.

Saturable reactor regulators control the output voltage by varying the impedance of a saturable reactor. This scheme is simple in concept and has a good line transient rejection. The drawbacks of this technique include slow response (10 cycles) and high output impedance, which gives high distortion with non-linear loads.

Ferroresonant transformer is operated in the saturated flux region. As a result, the output waveforms are not sinusoidal especially with non-linear loads. The transformer operation can be sensitive to circuit capacitance and frequency deviations. In addition, the output voltage can collapse under heavy loading such as motor starting and high inrush currents. This technique offers good line transient suppression.

VII. CONCLUSION

Power quality problems, which compromise industrial productivity, include mainly voltage sags and power interruptions. The potentially most serious power quality problem is the occurrence of voltage sags. Voltage sags are inevitable on the power system, even in the most advanced utility networks.

The biggest problem associated with voltage sags is the tripping of sensitive equipment such as motor drives. This occurs because of insufficient voltage that reduces dc bus voltages in adjustable speed motor drives. Also, contactor and relay coils, programmable controllers and other electronic loads are sensitive equipment.

An adjustable speed drive system has been analyzed for voltage sag studies using Simulink software. Three-phase balanced voltage sag of 70% remaining has been applied to ASD during 5 cycles. The behavior of currents, voltages, rotation and torque during the event has been simulated. It has been shown that the performance of vector control is good enough in the simulation conditions. The speed has been decreased slightly as a consequence of sag although the torque has been decreased with depth.

In this study, others simulations with different magnitudes and durations of voltage sags have been performed and the conclusion is that the effect of magnitude is worst than the duration.

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