Effects of Voltage Sags on Induction Motors

M.A. ELGAMMAL, A.Y. ABOU-GHAZALA and T.I. ELSHENNAWY

Abstract *- Voltage sags are considered one of the most important Power Quality (PQ) problems in industrial plants. Voltage sags are defined as voltage reduction events, followed by restoration of the normal supply conditions after a short duration. During sag, induction motors may not continue its normal operation and may trip or shut down.*

Induction motors constitute a large portion of the loads in industrial power systems. The loss of their service in a continuous process plant (like a refinery) may result in a costly shutdown. The basic observed effects of voltage sags on induction motors are speed loss and current and torque transients associated with both voltage reduction and recovery. The response of induction motors to voltage sags differ depending on the characteristics of voltage sag such as sag magnitude and duration, as well as the electrical parameters of the motor and load characteristics.

This paper will focus on the response of the induction motors to voltage sags. In addition to the well-known parameters of voltage sags (magnitude and duration), other characteristics which drew a little or no interest in the literature will be investigated, such as pre-sag voltage, point on the wave at sag occurrence/recovery, percentage of loading, and presence of harmonic distortion. Other objective of this study is to investigate the motors ride through capability during different types of voltage sags. Finally, recommendations for adjusting the protection relays of the motors are pointed.

The industrial electrical distribution system at Alexandria National Refining and Petrochemicals Co. (ANRPC) is taken as a case study to investigate such effects through computer simulations using the MATLAB/SIMULINK toolbox. Validity of the simulations is verified by actual performance.

Keywords *- Power Quality, Voltage Sags, Induction Motors.*

1. INTRODUCTION

Alexandria National Refining and Petrochemicals Co. (ANRPC) is a refinery based in Alexandria, Egypt, with an average load of 10 MW. About 80% of the load consists of induction motors. The plant suffers from several voltage sags due to transmission system faults as well as faults from neighbouring customers on the common distribution system. Although lasting for durations in the range of a quarter second to barely more than one second, these voltage sags cause large induction motors connected directly to the supply bus to trip, either by undervoltage or by overcurrent relays, sometimes by the mechanical protection.

These unplanned shutdowns cost the plant tens of thousands of dollars for each shutdown in addition to material damage costs, restart charges, and any penalties due to delay in product delivery, shipping, etc.

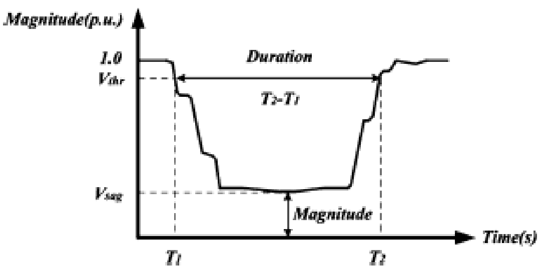

Fig. 1. Voltage sag.

The company asks for the advice of the faculty of engineering, and a joint group was formed from the faculty consultants and the electrical engineers at the company to thoroughly investigate and recommend solutions for this problem. This paper is part of this research work.

2. VOLTAGE SAGS AND INDUCTION MOTORS

2.1. Voltage Sags

IEEE defines voltage sag as: **A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min**. The amplitude of voltage sag is the value of the remaining voltage during the sag [1].

The IEC terminology for voltage sag is **dip**. The IEC defines voltage dip as: **A sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period of time, from half a cycle to a few seconds**. The amplitude of a voltage dip is defined as the difference between the voltage during the voltage dip and the nominal voltage of the system expressed as a percentage of the nominal voltage [2].

Fig. 1 shows an rms representation of voltage sag, the sag starts when the voltage decreases to lower than the threshold voltage Vthr (0.9 pu) at time T1. The sag continues till T2 at which the voltage recovers to a value over the threshold value, hence the duration of the voltage sag is (T2-T1) and the magnitude of the voltage sag is sag to Vsag [3].

2.2. Effects of Voltage Sags on IMs

As the supply voltage to the induction motor decreases, the motor speed decreases. Depending on the depth and the duration of the voltage sag, the motor speed may recover to its normal value as the voltage amplitude recovers. Otherwise, the motor may stall. Responding in either case depends on the motor parameters and the torque-speed characteristic of the driven load [4].

Fig. 2 shows three different torque speed characteristics of an IM, along with a constant load torque. The upper curve (curve A) shows this relation during normal conditions (without a sag), where the normal operating point (speed) is determined by the intersection of the motor torque and the load torque. Voltage sag will reduce the motor torque proportional to the square of the motor terminal voltage. The IM may undergo a limited amount of retardation and may be able to reaccelerate on voltage recovery, as shown in curve B, during which there is a new operating point with slower speed and higher slip. Otherwise, the electric torque produced by the IM may even become less than that of the load, in such case the IM may decelerate, and the continuity of the output may be lost, as shown in the bottom curve (curve C) [5].

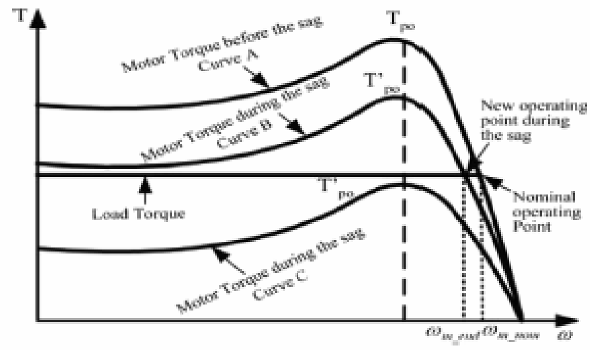

Fig. 2. Motor and Load Torques before and during different sags.

2.3. Effects of Voltage Recovery on IMs

Reapplication of out of phase voltage to a motor with a strong remaining rotor field may result in electromagnetic and shaft torque and current transients which may exceed the starting values by several times, and may be destructive. It must be decided whether to allow voltage to be reapplied to the motor terminals at whatever instant it is restored (often with the motor still running and the field still active), or whether to block reapplication of power until the motor rotor field has a chance to decay to a sufficiently low level. Depending upon the initial speed loss and the magnitude of the recovery voltage after fault clearance, the motors may accelerate, taking currents that may approach the starting currents of the motors. These starting currents of accelerating motors, flowing together through the supply system impedance, may prevent a fast recovery of voltage. The stronger the electrical system in relation to the size of the accelerating motors, the greater is the power available for the motors to accelerate and recover [6].

2.4. Effects of Protection Settings on Motor Performance

Motor recovering process after voltage sags is dynamically similar to motor starting process and is accompanied by large inrush currents. Depending on motor protection settings, these currents can trigger over current protection of the motor resulting in the tripping of the motor. Mechanical protection also can trip the motor if the motor torque becomes incapable of driving the load or if the transient torqueses on voltage recovery are too high.

Most of IM protection settings are too conservative. This leaves room for adjusting these settings without causing any threat to the motor safety. Many of the unnecessary motor tripping incidents can be avoided by simple adjustment to the motor protection settings [7].

3. CASE STUDY

ANRPC is an industrial facility located Alexandria, Egypt. About 80% of the load is directly on line started induction motors (IMs). The plant suffers from shutting down the whole complex due to tripping of undervoltage (or overcurrent) relays as a result of voltage sags.

These unplanned shutdowns cause the plant tens of thousands of dollars for each shutdown in addition to material damage costs. Additional costs include any penalties due to delay in product delivery, shipping, etc.

During the study, it is believed that the motor protection settings are too restricted. However, before adjusting these settings, it is required to thoroughly investigate any possible risks due to transient currents and torques the motor may be subjected to.

3.1. Test Circuit

The test circuit consists of a voltage source adjusted to simulate voltage sags with pre-determined magnitudes and durations affecting an induction motor, which drives a compressor load.

The load torque starts from a constant value of 2000 N.m., and then increases gradually in direct proportion to the speed, till it reaches its full load value (about 80 % of motor torque). Fig. 3 shows the implementation of this simple power system in the SimPowerSystems Blockset in the MATLAB workspace. The motor and load parameters are given in Tables I and II respectively. The existing settings for the motor protection relays are given in Table III.

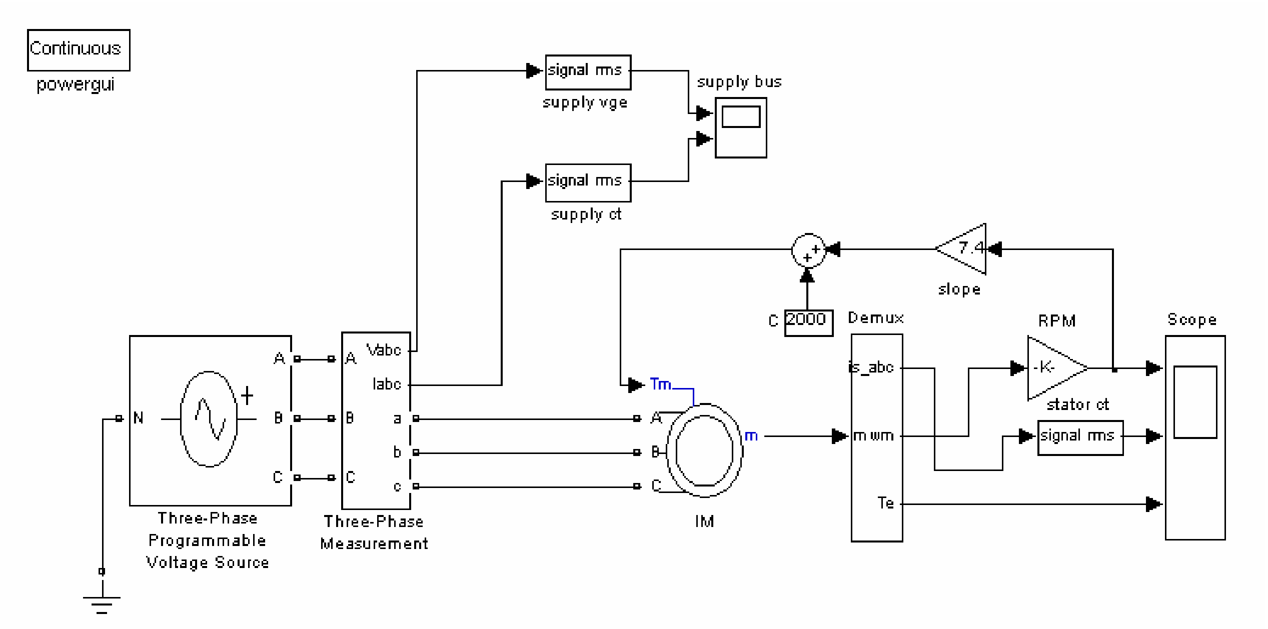

Fig. 3. Simulink model for the test circuit.

Table I. Motor Parameters.

Motor Parameters	
Rated Power	2500 kW
Rated Voltage	11000 V
Frequency	50 Hz
Full Load Current	153 A
RPM	1496
Starting Current	600% FLC
Starting time	22 sec
Locked Rotor P.F.	0.15
Power factor	0.9
Efficiency	95.5%
Moment of Inertia	560 kg.m^2
Rated Torque (T)	15959 N.m
Locked Rotor Torque	75%
Pull up Torque	65%
Breakdown Torque	270%
Stator Resistance	0.42 Ω
Stator Reactance	2.73 Ω
Rotor Resistance	0.62 Ω
Rotor Reactance	4.1 Ω
Magnetizing Reactance	197.8 Ω

Table II. Load Parameters.

Compressor Parameters	
Max. Absorbed Power	2057 kW
Maximum Torque	13092 N.m
Starting Torque	1960 N.m
Moment of Inertia	1000 kg.m^2

Table III. Motor Protection Settings.

Over Current Setting Time	168 A Inverse
Under Voltage Time	0.8 pu 1 sec
Mechanical speed loss	0.95 pu

3.2. Case Studies

3.2.1. Startup and Normal Conditions

The purpose of this step is to get the starting current and torque values for the motor. The motor ought to withstand these transients in its normal operation without affecting its operation. These values are considered the limiting values such that any safe operation of the motor during a sag event should not exceed these values.

The results of this normal situation are shown in Fig. 4. From these results, the following remarks are noted:

- The motor speed accelerates gradually during the starting period till it reaches its operating speed at 1486 rpm (slip=1% approximately) in about 20 seconds.
- The starting current of the motor rushes to about 930 A (approximately 600% of full load), then the current decreases to its normal current of about 118 A (the motor operates at 80% of its full load).
- The motor is subjected to a pulsating torque from +72,000 N.m to -54,000 N.m (peak to peak), for a period of 2 seconds. After which, these pulsations decay and the motor operates with increasing unidirectional torque until it reaches its maximum value of 50,000 N.m in 20 seconds. After which the motor torque intersects with the load torque at the operating point and the motor continues to deliver its normal torque of 13,000 N.m.

3.2.2. Sag to 80% pu & 1 sec

The motor is subjected to a three phase voltage sag with 80% magnitude and a duration of 1 sec. the sag starts at t=30 sec and recovers 1 sec later. This situation is presented in Fig. 5, and the following observations are noted:

- The speed drops to a value of 1477 rpm (99% of normal).
- The motor current increases on occurrence of the sag event reaching a value of 263 A (222% of normal and 28% of starting), then drops eventually since a new operating point is reached.

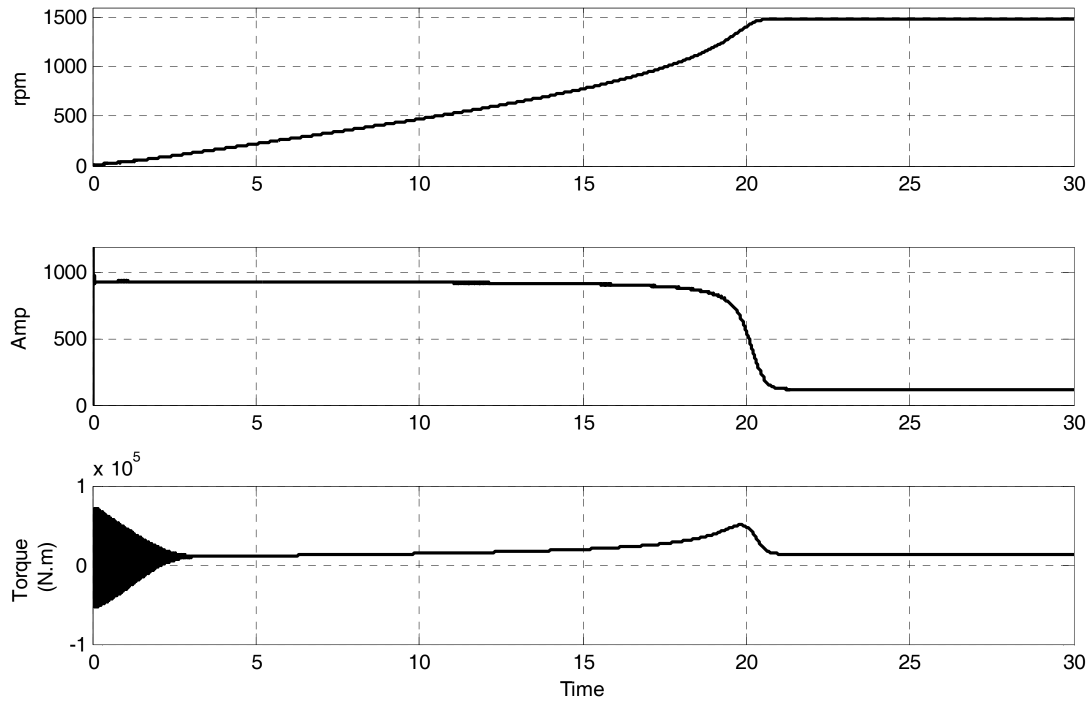

Fig. 4. Motor starting speed, current, and torque.

- The motor continues running with increasing current till the voltage recover. At this instant, the initial operating point is reached and the motor draws a transient current of 337 A (285% of normal and 36% of starting).
- The torque also shows two transients on sag occurrence and on full voltage recovery. The sag transient approaches 25,500 N.m (196% of normal and 35% of starting), whereas the recovery transient approaches 30,000 N.m (230% of normal and 42% of starting).

From these observations, it is clear that the undervoltage relay settings are too conservative for the motor operation. The faculty consultants recommends that the undervoltage relay settings should be readjusted, and considered as a backup protection for other motor protection relays. To determine the

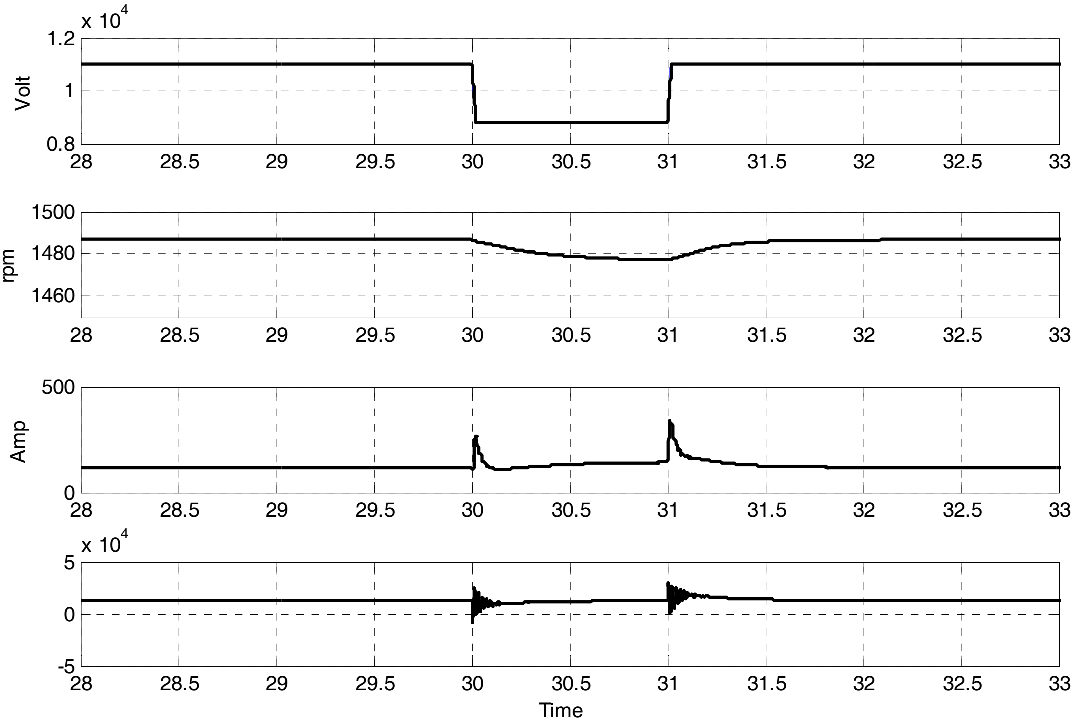

Fig. 5. Voltage, speed, current, and torque for a sag to 80%, 1 sec.

appropriate values for the new settings, a thorough investigation of the motor behaviour to different sags is carried out, and is explained in the next step.

3.2.3. Tripping the IM without Undervoltage Relay

The motor is subjected to three phase voltage sags at t=30 sec. The magnitude of the remaining voltage starts from 0.9 p.u. of the rated line voltage and decreases gradually in steps of 0.05 p.u. For each case, the duration of the sag will increase gradually till the motor trips, either by overcurrent, locked rotor or mechanical protection. if no trigger signal comes out from the protection relays, the simulation continues till it ends at t=40 sec. The results of this step are presented in Table IV.

Table IV. Limiting Values Tripping the IM.

Sag voltage (pu)	Sag duration (sec)	Motor tripped by	Limiting value
0.90	> 10 sec	No trip	-
0.80	> 10 sec	No trip	-
0.70	> 10 sec	No trip	-
0.65	4.488	overcurrent	181
0.60	2.550	overcurrent	195 A
0.55	2.093	overcurrent	204 A
0.50	1.935	overcurrent	209 A
0.45	1.900	overcurrent	212 A
0.40	1.760	Speed loss	1410 rpm
0.35	1.443	Speed loss	1410 rpm
0.30	1.252	Speed loss	1410 rpm
0.25	1.127	Speed loss	1410 rpm
0.20	1.040	Speed loss	1410 rpm
0.15	0.980	Speed loss	1410 rpm
0.10	0.937	Speed loss	1410 rpm
0.0	0.900	Speed loss	1410 rpm

From Table IV, the following remarks are noted:

- The first sag event that trips the motor occurs for a sag to 65% p.u., for a duration of 4.5 seconds. This shows that how the existing settings for the undervoltage relay is too conservative, and that many shutdowns due to motor tripping could have been avoidable.
- As the remaining voltage during the sag decreases (voltage drop increases), the tripping time decreases. As the criterion used to trip the motor is the inverse current-time characteristics, and as the voltage decreases, the motor tries to supply the load by drawing higher current, triggering the overcurrent relay.
- All sags with remaining magnitude 40% of p.u. voltage and below result in severe transient torques that trigger the mechanical protection relays. The criterion here is the speed loss. As the speed of the motor decreases below the threshold (95% of the normal speed), the motor trips by mechanical protection.

3.2.4. Recommended Undervoltage Settings

Based on the results obtained from Table IV, the recommended settings for the undervoltage relay are shown in Table V.

Table V. Recommended Undervoltage Settings.

Under Voltage Time	0.75 pu 1.5 sec

To verify these new settings, a new simulation with these values as the sag magnitude and duration is carried out and is shown in Figure 6. It is clear that the current, the torque, and the speed do not approach their limiting values of starting. The speed drops to 1473 rpm (99% of normal speed). The current transients are 323 A on sag start (273% of normal and

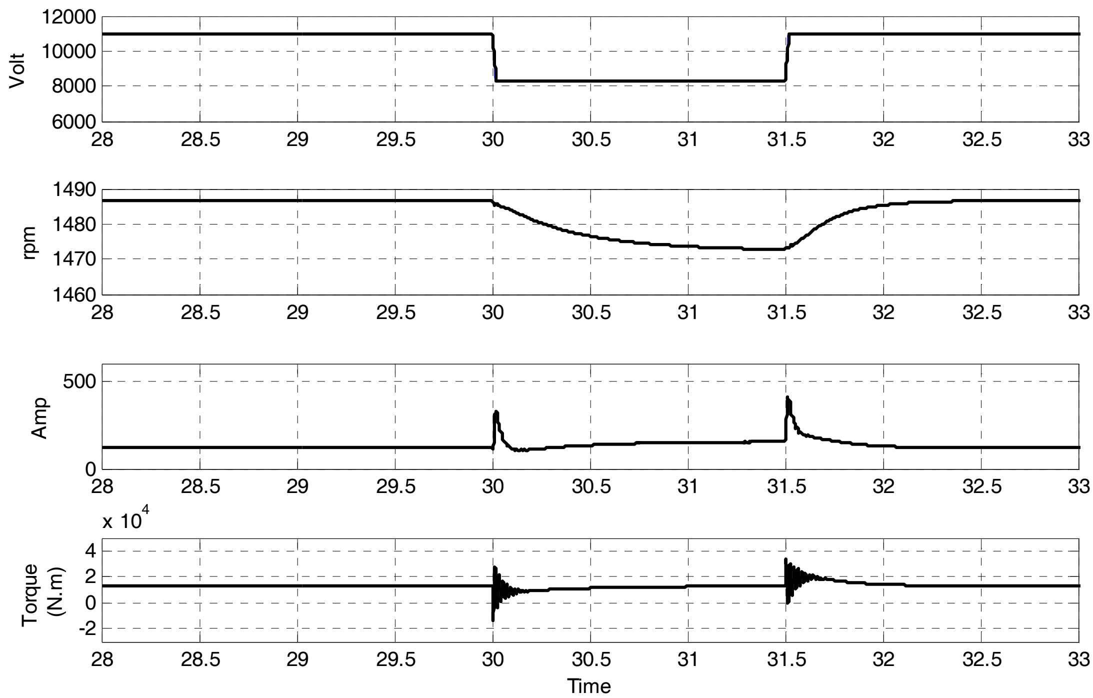

Fig. 6. Voltage, speed, current, and torque for a sag to 75%, 1.5 sec.

35% of starting) and 405 A on voltage recovery (342% of normal and 43% of starting). The torque transients are 28,000 N.m on sag start (215% of normal and 38% of starting) and 33,500 N.m on voltage recovery (258% of normal and 46% of starting).

3.2.5. Voltage Sag Tolerance Curve

The voltage acceptability curves determine whether the supply voltage to a load is acceptable for maintaining the continuity of a load process [8]. Fig. 7 is the voltage sag tolerance curve (or ride through curve) of the IM under test. This curve may not necessarily apply to similar motors. It is expected that each motor (and any piece of equipment) has its own curve. The whole plant is sensitive to, and may shut down as a result of, the most sensitive piece of equipment.

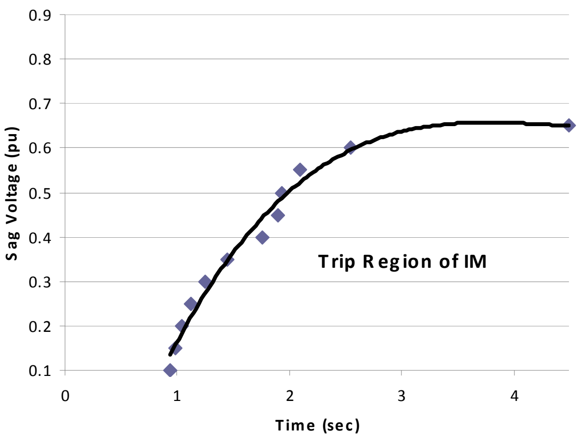

Fig. 7. Voltage tolerance curve for the IM.

4. SENSITIVITY ANALYSIS

The voltage acceptability curve of Fig. 7 is based only on the two main parameters of the voltage sag; magnitude and duration.

Factors other than magnitude and duration may have effect on the response of the IM to the voltage sag. Some of these factors are examined and discussed in this section.

4.1. Unbalanced voltage sag

Although the severity of the three phase voltage sag is expected to be more than that of the single phase sag, yet the latter is more frequent especially on the distribution circuits. Step 4 is repeated for the new situation and the results are presented in Table VI, and compared with results of Fig. 6.

Table VI. Effect of Unbalanced Sag.

	Speed	Sag current	Recovery current	Sag torque	Recovery torque
Three phase sag	1473	323	405	28,000	33,500
Single phase sag	1483	225	255	30,000	28,000

As expected, the single phase sag is less severe than the three phase one. This can be interpreted, as the full voltage present on the other two healthy phases will support the motor during the sag and at recovery [9].

4.2. Effect of pre-sag voltage

As the supply voltage may range from 1.05 p.u. to 0.95 p.u., transient currents and torques may vary substantially for such tolerance. A summary of the IM response to these sags are shown in Table VII.

Table VII. Effect of Pre-sag Voltage.

	speed	Sag current	Recovery current	Sag torque	Recovery torque
Pre-sag voltage 1.00 pu	1473	323	405	28,000	33,500
Pre-sag voltage 1.05 pu	1473	385	405	32,000	33,500
Pre-sag voltage 0.95 pu	1473	264	405	24,400	33,500

Comparing with the reference 1.0 pu pre-sag, there is almost no change in the IM speed. However, transient currents and torques on occurrence of sag differ noticeably; transient currents and torques for voltage difference of 20% are less than those for voltage difference of 30%. This may be attributed to the fact that the difference in voltage is what makes the transient. Note that this situation does not hold in case of voltage recovery, since in both cases the voltage recovers to 1.0 pu. This may explain why the IM may trip (by the overcurrent relay) on a voltage drop to 75% lasting for 1.5 sec in case of pre-sag voltage equals 1.05 pu, while the same IM may survive the same voltage sag in case of pre-sag voltage equals 0.95 pu. Similar results are represented in [10].

4.3. Loading Percentage

In some cases, the industrial process operates the motor at ¾ or ½ its full load. Note that the basic parameters of the motor are now changed. In case of ¾ load, there will exist a new operating point, for which the normal speed increases to 1489 rpm, the normal current decreases to 95 A, and the normal torque is reduced to 10,000 N.m. In case of ½ load, the normal speed increases to 1493 rpm, the normal current decreases to 73 A, and the normal torque is reduced to 7500 N.m.

The IM response to both situations is presented in Table VIII. It is clear that the possibility of the IM to survive a sag increases by decreasing the loading conditions.

Table VIII. Effect of Loading Conditions.

	speed	Sag current	Recovery current	Sag torque	Recovery torque
Full load operation	1473	323	405	28,000	33,500
¾ load operation	1481	317	380	26,000	30,000
½ load operation	1489	315	360	24,000	26,000

4.4. Effect of source harmonic distortion

Consider again the test signal of Fig. 6. Assume that there are some harmonics present at the supply bus. Normally triplen harmonics are eliminated in the power transformer. What really matters is the distortion level of the 5^{th} and sometimes the 7^{th} harmonics. Now, if we introduce a 5th harmonic with 20% p.u. and a 7th with 15% p.u. to our test signal, the results will be that of Table IX.

Table IX. Effect of Harmonic Distortion.

	speed	Sag current	Recovery current	Sag torque	Recovery torque
Reference sag	1473	323	405	28,000	33,500
Harmonic polluted sag	1469	325	405	29,000	34,200

Minor differences are there between the two results, with the exception of bold torque. This boldness refers actually to the power frequency oscillations in the motor torque due to presence of harmonic distortion.

4.5. Point on the wave

In all the previously simulated sags, the sag starts at t=30 sec, which corresponds to zero phase angle. Moreover, the voltage recovers at t=31.5 sec, again corresponding to zero angle. Consider now that the sag occurs at any instant (angle other than zero) which is almost the actual case, and recovers at a different angle. A new set of simulations is carried out with the same sag magnitude and duration, but at different instants. Comparison between the reference sag and the most significant case (with angle = 90°) is given in Table X.

Table X. Effect of Point on the Wave.

	speed	Sag current	Recovery current	Sag torque	Recovery torque
Reference sag	1473	323	405	28,000	33,500
Phase shifted	1473	180	284	28,000	33,500

5. CONCLUSIONS

The influences of voltage sags on the behavior of induction motors are investigated. Upon the occurrence of a voltage sag, the induction motor speed drops, the motor is subjected to transient currents and torques depending on the drop in voltage and the motor and load parameters. Upon voltage recovery, the motor is subjected once more to transient currents and torques, exceeding in many cases the previous transients, but still lower than transients during starting process.

The following are the main contributions of this research work:

- Undervoltage protection with fixed magnitude and duration should not be the main protection relay of the induction motors. It can serve as a backup protection with proper setting.
- Transient currents are directly proportional to the voltage drop, not to the remaining voltage magnitude.
- Three-phase voltage sags are the most severe events, and should be taken in consideration for any evaluation of sag effects on induction motors. Single-phase sags are the least severe.
- Sags occurring at the voltage zero- crossing instants are the most severe, and should be taken in consideration for the worst case in any evaluation. Sags occurring at the peak of the voltage waveform are the least severe.
- Motors operating at lower loading percentages are less sensitive to sags.
- Harmonic distortion in the supply source has no noticeable effect on the motor performance during sags.
- It can be concluded that, in industries with large portion of its load consisting of induction motors, readjusting of the protection relay settings may be adequate to counteract voltage sags.

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