Effects of Voltage Sags on a Refinery with Induction Motors Loads

M. A. El-Gammal, A. Y. Abou-Ghazala, and T. I. El-Shennawy

Abstract—Voltage sags are voltage reduction events, followed by restoration of the normal supply conditions after a short duration. Induction Motors (IMs) 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.

This paper will focus on the response of the IMs to various parameters of voltage sags; including magnitude, duration, effect of pre-sag voltage, loading percentage, point on the wave of sag occurrence, source harmonics, and three-phase unbalance. Other objectives of this study are to investigate the motors ride through capability during different types of voltage sags, and to establish guidelines for adjusting the protection relays of the IMs.

The industrial electrical distribution system of 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.

Index Terms—Induction Motors, power quality, voltage sags, power acceptability.

I. 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 connected directly online at different voltage levels. The plant suffers from several voltage sags due to upstream subtransmission system faults (66 kV) as well as distribution system faults (11 kV).

Although lasting for durations in the range of one second, these voltage sags cause large induction motors to trip, either by undervoltage or by overcurrent relays, sometimes by the mechanical protection to protect the motor shaft from any possible damage. 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. This paper thoroughly investigates and recommends solutions for this problem.

Fig. 1 shows an rms representation of voltage sag, the sag starts when the voltage decreases to lower than the threshold voltage \( V_{\text{thr}} \) (0.9 pu) at time \( T_1 \). The sag continues till \( T_2 \) at which the voltage recovers to a value over the threshold value, hence the duration of the voltage sag is \( (T_2-T_1) \) and the magnitude of the voltage sag is \( V_{\text{sag}} \) [3].

B. Effects of Voltage Sags on IMs

As the motor torque is directly proportional to the square of the applied voltage, therefore, as the supply voltage to the induction motor decreases, the motor torque will decrease drastically. For example, if the voltage decreases to 70% of its rated value, the motor torque will decrease to only 49% of its rated value. The speed also decreases with a decrease in torque. 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 speed may slow down and the torque exerted by the motor could not supply the load.
The motor will then be tripped to protect its shaft from any possible damage. Response 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. Curve A shows this relation during normal conditions. 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. Otherwise, the electric torque produced by the IM may become less than that of the load, the IM may decelerate, and the continuity of the output may be lost, as shown in curve C [5].

C. Effects of Voltage Recovery on IMs

Reappliciation 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. 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].

D. 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 torques after 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].

III. CASE STUDY

A. 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, whereas the protection settings of the motor are given in Table III.

B. Test Procedure

1-The motor is operated with normal (no sag) conditions. From this step, we can quantify the transient currents and torques that the motor is subjected to during starting.

2-A three-phase voltage sag is simulated with magnitude and duration equal to the existing settings of the undervoltage relay. From this step we can see the actual transient current and torque the motor is subjected to before tripped by the undervoltage protection.
The IM is subjected to a set of voltage sags in all three phases at different magnitudes (ranging from 0.1 p.u. to the voltage sag threshold of 0.9 p.u.) with a step of 0.05 pu, and for each sag value the duration is incremented gradually till the motor trips by overcurrent or locked rotor or mechanical protection relays. From this step, we can construct a table with the limiting values of accepted voltage during different sags affecting the IM under test.

3- From the previous step, we can construct a sag tolerance curve for the IM under test.

4- Parameters other than magnitude and duration of voltage during sag are tested to complete the sensitivity analysis.

C. Case Studies

1) Startup and Normal Conditions

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.

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. 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).
simulation continues till it ends at trigger signal comes out from the protection relays, the by overcurrent, locked rotor or mechanical protection. If no of the sag will increase gradually till the motor trips, either from 0.9 p.u. of the rated line voltage and decreases to 65% p.u., for a duration of 4.5 seconds. This shows that the voltage and below result in severe transient torques that trigger the mechanical protection relays. The criterion here is the speed loss, and it is of constant value. As the speed of the motor decreases below the threshold (95% of the normal speed), the motor trips by mechanical protection.

4) Voltage Sag Tolerance Curve

The voltage acceptability curves are aids in the determination of whether the supply voltage to a load is acceptable for maintaining the continuity of a load process [8]. Fig. 6 is the voltage sag tolerance curve (or ride through curve) of the IM under test. 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.

It should be noted that these results are motor and load dependant, and may vary from one motor to another. The motor under study is a large motor with high inertia, which is very helpful for riding through moderate sags and short interruptions. The load torque plays an important role in determining the sag tolerance curve for the induction motor. In this study, the load torque is directly proportional to the motor speed. In other cases, the load torque may be constant (optimistic case) or even varies in a quadratic proportion to the motor speed (pessimistic case).

For constructing a sag tolerance curve for the whole plant, each motor should be handled in the same way to get its own curve; the plant will be as sensitive as the most sensitive one piece of equipment to voltage sags.

Further work will be conducted to assess the effect of all the motors working together on the plant ability to withstand such sags. It is expected that the overall capability will be higher, on the expense of prolonging the motors’ recovery time after the sag event.

5) Recommended Undervoltage Settings

Based on the results obtained from Table IV, the recommended settings for the undervoltage relay are adjusted to (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 Fig. 7.

![Fig. 6. Voltage tolerance curve for the IM.](image)

![Fig. 7. Voltage, speed, current, and torque for a sag to 75%, 1.5 sec.](image)

<table>
<thead>
<tr>
<th>Sag voltage (pu)</th>
<th>Sag duration (sec)</th>
<th>Motor tripped by</th>
<th>Limiting value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90</td>
<td>&gt; 10 sec</td>
<td>No trip</td>
<td>-</td>
</tr>
<tr>
<td>0.80</td>
<td>&gt; 10 sec</td>
<td>No trip</td>
<td>-</td>
</tr>
<tr>
<td>0.70</td>
<td>&gt; 10 sec</td>
<td>No trip</td>
<td>-</td>
</tr>
<tr>
<td>0.65</td>
<td>4.488</td>
<td>overcurrent</td>
<td>181 A</td>
</tr>
<tr>
<td>0.60</td>
<td>2.550</td>
<td>overcurrent</td>
<td>195 A</td>
</tr>
<tr>
<td>0.55</td>
<td>2.093</td>
<td>overcurrent</td>
<td>204 A</td>
</tr>
<tr>
<td>0.50</td>
<td>1.935</td>
<td>overcurrent</td>
<td>209 A</td>
</tr>
<tr>
<td>0.45</td>
<td>1.900</td>
<td>overcurrent</td>
<td>212 A</td>
</tr>
<tr>
<td>0.40</td>
<td>1.760</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.35</td>
<td>1.443</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.30</td>
<td>1.252</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.25</td>
<td>1.127</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.20</td>
<td>1.040</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.15</td>
<td>0.980</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.10</td>
<td>0.937</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>0.0</td>
<td>0.900</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
</tbody>
</table>
IV. Sensitivity Analysis

The curve of Fig. 6 is based only on magnitude and duration. Other factors characterizing voltage sag are discussed in this section.

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. The test is repeated for a sag on one phase and the results are presented in Table V, and compared with results of Fig. 7. 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].

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 VI.

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 explain why the IM may trip (by the overcurrent relay) on a voltage drop to 75% 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 [10].

3) Operating the Motor at 3/4 and 1/2 of the Full Load

In some cases, the industrial process operates the motor at 3/4 or 1/2 its full load. Note that the basic parameters of the motor are now changed.

In case of 3/4 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 1/2 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 VII. It is clear that the possibility of the IM to survive a sag increases by decreasing the loading conditions.

4) Effect of Source Harmonic Distortion

Consider again the test signal of Fig. 7. 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 5th and sometimes the 7th 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 show minor differences between the two cases, 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.

5) Point on the Wave

In all the previously simulated sags, the sag starts at \( t = 30 \text{ sec} \), which corresponds to zero phase angle. Moreover, the voltage recovers at \( t = 31.5 \text{ sec} \), 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 VIII.

It is clear that when the sag occurs at 90° angle in the voltage signal, this corresponds to near zero angle in the current signal, current transients in this case are minimum.

6) Other Factors

Several other factors may affect the behavior of the IM during voltage sags, and are not discussed here for reasons of limited space, and are preserved for future research work. Of these factors are:

- Effect of motor parameters, especially motor inertia.
- Effect of load torque and its relation to motor speed.
- Effect of several motors rotating together on the same bus.

Table V

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sag Current</th>
<th>Recovery Current</th>
<th>Sag Torque</th>
<th>Recovery Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three Phase Sag</td>
<td>1473</td>
<td>323</td>
<td>405</td>
<td>28,000</td>
</tr>
<tr>
<td>Single Phase Sag</td>
<td>1483</td>
<td>225</td>
<td>255</td>
<td>30,000</td>
</tr>
</tbody>
</table>

Table VI

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sag Current</th>
<th>Recovery Current</th>
<th>Sag Torque</th>
<th>Recovery Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-sag 1.05 pu</td>
<td>1473</td>
<td>385</td>
<td>405</td>
<td>32,000</td>
</tr>
<tr>
<td>Pre-sag 0.95 pu</td>
<td>1473</td>
<td>264</td>
<td>405</td>
<td>24,400</td>
</tr>
</tbody>
</table>

Table VII

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sag Current</th>
<th>Recovery Current</th>
<th>Sag Torque</th>
<th>Recovery Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>¾ Load Operation</td>
<td>1481</td>
<td>317</td>
<td>380</td>
<td>26,000</td>
</tr>
<tr>
<td>½ Load Operation</td>
<td>1489</td>
<td>315</td>
<td>360</td>
<td>24,000</td>
</tr>
</tbody>
</table>

Table VIII

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sag Current</th>
<th>Recovery Current</th>
<th>Sag Torque</th>
<th>Recovery Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° Phase Shift</td>
<td>1473</td>
<td>180</td>
<td>284</td>
<td>28,000</td>
</tr>
</tbody>
</table>
• Effect of power factor correcting capacitors.
• Effect of loads other than the IM loads, such as heaters and furnaces.

V. CONCLUSIONS
The influences of voltage sags on the behavior of induction motors are thoroughly 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 sag magnitude, duration, 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 observations of this research work:
• Three-phase voltage sags are the most severe events, and should be taken in consideration for any evaluation.
• Undervoltage protection with fixed magnitude and duration should not be the main protection relay of the induction motors.
• Transient currents are directly proportional to the voltage drop, not to the remaining voltage magnitude.
• Sags occurring at the voltage wave zero crossing are the most severe, and should be taken in consideration for any evaluation.
• Motors operating at lower loading ratios are less sensitive to voltage sags.
• Harmonic distortion in the supply source has no noticeable effect on the motor performance during sags.
• Readjusting of the protection relay settings may be adequate to counteract voltage sags. No additional power conditioning equipment is required.

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REFERENCES

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