Voltage Sag Effects on the Process Continuity of a Refinery with Induction Motors Loads

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Abstract: Voltage sags are voltage reduction events, followed by restoration of the normal supply conditions after a short duration. Voltage sags can cause induction motors (IM) which constitute a large portion of the loads in industrial power systems to trip by protection relays to protect the motor from any possible damage. These numerous trips in a continuous process plant (like a refinery) may result in a costly shutdown. The purpose of this research work is to decide whether the protection settings are too conservative or the plant requires a sag mitigation device.

This paper will focus on the response of the IM to voltage sags. 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. Other objectives of this study are to investigate the motors ride through capability during different types of voltage sags, and guidelines for adjusting the protection relays of the IM.

The basic observed effects of voltage sags on IM are motor speed loss and current and torque transients associated with both voltage reduction and recovery. The behavior of the motor depends on the sag characteristics (magnitude and duration) and motor and load parameters. Other factors that affect this behavior are pre-sag voltage, percentage of loading, type of sag, and point on the wave at sag occurrence and at voltage recovery.

From the results obtained, it was suggested the usage of undervoltage relays with inverse voltage-time characteristics to protect motors from voltage sags instead of using the typical constant voltage relays. A procedure for constructing the voltage tolerance curve for the IM under study was proposed and could be extended to the whole refinery. In most cases, readjusting of the protection relays may be adequate to counteract voltage sags. No additional custom power equipment is required.

Keywords – Power Quality (PQ), Voltage Sags, Induction Motor (IM), Continuous Process.

I. INTRODUCTION

A. Voltage Sags

The 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 \( V_{th} \) (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 \( V_{sag} \) [3].

B. Effects of Voltage Sags on IM

As the supply voltage to the IM 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. 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 retard 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].

![Figure](image.png)

**Figure (2). Motor and Load Torques before and during different sags**

**C. Effects of Voltage Recovery on IM**

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, 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, or to block reapplication of power until the motor rotor field has a chance to decay to a sufficiently low level [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 [8].

**II. 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).

![Figure](image.png)

**Figure (3). Simulink model for the test circuit**

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 [7].

![Table](image.png)

**TABLE I

MOTOR PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>2500 kW</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>11000 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Full Load Current</td>
<td>153 A</td>
</tr>
<tr>
<td>RPM</td>
<td>1496</td>
</tr>
</tbody>
</table>

Tables I and II, and the protection relays settings are given in Table III respectively.
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 balanced 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 it reaches its normal current of about 118 A (the motor operates at 80% of its full load).

3. 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.

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

5. The undervoltage relay is readjusted using results of the previous step, and the new setting is verified by new simulation.

6. Parameters other than magnitude and duration are tested to complete the sensitivity analysis:
   i. Effect of other types of sags
   ii. Effect of pre-sag voltage.
   iii. Operating the motor at ¾ and ½ full load.

   iv. Effect of source harmonic distortion.
   v. Effect of point on the wave.

III. RESULTS

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 263 A (222% of normal) 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).

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 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) 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>
<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</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>0.00</td>
<td>0.900</td>
<td>Speed loss</td>
<td>1410 rpm</td>
</tr>
</tbody>
</table>

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 the existing settings for the undervoltage relay is too conservative, and that many shutdowns due to motor tripping could have been avoided.
- As the remaining voltage during the sag decreases (voltage drop increases), the tripping time decreases. This is predicted as the criterion used to trip the motor is the inverse current-time characteristics. Since the motor voltage decreases, the motor tries to supply the load power by drawing higher current, thus triggering the overcurrent protection.
- 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, 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 aides in the determination of whether the supply voltage to a load is acceptable for maintaining the continuity of a load process [9]. Fig. 6 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.

Note that this curve, constructed from Table IV, is based on the two main parameters of the voltage sag; magnitude and duration. Other factors characterizing voltage sag such as unbalance of the three phases, point on the wave of sag occurrence and recovery, pre-sag voltage, loading percentage, etc… are discussed in the next section.

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>
<thead>
<tr>
<th>Under Voltage Time</th>
<th>Limiting value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 pu</td>
<td>1.5 sec</td>
</tr>
</tbody>
</table>

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 7. 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 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).

IV. SENSITIVITY ANALYSIS

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.
Sensitivity Analysis

<table>
<thead>
<tr>
<th>Sag Voltage (pu)</th>
<th>0.1</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-sag 1.05 pu</td>
<td>1.473</td>
<td>0.323</td>
<td>0.405</td>
<td>0.280</td>
<td>0.335</td>
<td>0.500</td>
</tr>
<tr>
<td>Pre-sag 0.95 pu</td>
<td>1.483</td>
<td>0.225</td>
<td>0.255</td>
<td>0.300</td>
<td>0.280</td>
<td>0.140</td>
</tr>
<tr>
<td>¾ load operation</td>
<td>1.481</td>
<td>0.317</td>
<td>0.238</td>
<td>0.260</td>
<td>0.300</td>
<td>0.260</td>
</tr>
<tr>
<td>½ load operation</td>
<td>1.489</td>
<td>0.315</td>
<td>0.236</td>
<td>0.240</td>
<td>0.260</td>
<td>0.260</td>
</tr>
<tr>
<td>Harmonic polluted sag</td>
<td>1.469</td>
<td>0.325</td>
<td>0.405</td>
<td>0.290</td>
<td>0.340</td>
<td>0.200</td>
</tr>
<tr>
<td>90° Phase shift</td>
<td>1.473</td>
<td>0.180</td>
<td>0.284</td>
<td>0.280</td>
<td>0.335</td>
<td>0.500</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

Upon the occurrence of a voltage sag, the induction motor speed drops, the motor is subjected to transient currents and 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 VI. It is clear that the possibility of the IM to survive a sag increases by decreasing the loading conditions.

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.

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 will be those presented in Table VI.

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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. 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. Instead, relays operating on an inverse voltage-time criterion should be used.
- 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.
- Motors operating at lower loading ratios are less sensitive to voltage sags.
- Redausting of the protection relay settings may be adequate to counteract voltage sags. No additional power conditioning equipment is required.

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