POWER QUALITY IMPACT ON PERFORMANCE AND ASSOCIATED COSTS OF THREE-PHASE INDUCTION MOTORS

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Abstract - This paper aims to present investigation results related to induction motors operation under non ideal supply conditions. The motors are of squirrel cage type and the non ideal conditions are associated to harmonics, unbalances, voltage sag and swell, etc. The studies are carried out using time domain modeling and the SABER simulator. Using this approach, computational results are derived in order to compare the non ideal motor performance to the ideal ones so that the real supply condition effect upon the motor behavior can be highlighted. In addition to technical aspects, the power quality impact on energy and financial waste and is also considered.

Keywords: Power Quality, Three-Phase Induction Motors, Computational Simulations

I. INTRODUCTION

Electric power quality has captured considerable attention from utility companies as well as their customers. The major reasons for the growing concerns are the continued proliferation of sensitive equipment and the increasing application of power electronics devices which result in power supply degradation. In addition, the customers have become less tolerant of any related power quality disturbances.

Many studies, researches and developments have been carried out in order to evaluate, assure and even to improve the quality of power necessary to a good behavior of the electric power system. However, what usually happens is that, for many industries, the system operation occurs without any concern about power quality problems [1][2].

On the other hand, it is quite well known that 80 % of the electric industrial load comprises three-phase induction motors. Therefore, any power quality and energy saving investigation procedure should take into consideration the performance of these devices under non-ideal supply conditions. As a matter of fact, in the literature [3][4], the effects of harmonic voltage distortion on the induction motor behavior and loss of life have been widely analyzed. However, the power quality context include other non-ideal conditions than only harmonic distortion. So, problems such as voltage unbalance, voltage variations, transients and others, should be necessarily evaluated.

Focusing in this direction, this paper aims to investigate the performance of squirrel-cage three-phase induction motors under non ideal voltage conditions. Using a time domain induction motor model, a computer program was developed in the SABER simulator platform. Besides the motor representation, the program is able to handle different power quality loss conditions in a simultaneous way. Using this, several studies were carried out to emphasize the relationship between power quality problems and motor behavior and additional costs associated to the increase in power consumption.

II. MATHEMATICAL MODEL OF THE INDUCTION MOTORS

The model implemented is the well known three-phase independent ABC reference frame model for a squirrel-cage induction motor. This model permits to represent the three-phase independently, so flexibility and versatility can be achieved to investigate the machine performance.

Electric Equation

According to ref. [5], by defining the stator phase as “abc” and rotor phases as “ABC”, the instantaneous voltage is given in the ABC reference frame by the well known expressions given below:

\[ v_i = r_i i_i + \frac{d \lambda_i}{dt} \]  

(1)

where:

\[ v_i \] - instantaneous voltage applied to phase i
\[ r_i \] - motor winding resistance
\[ i_i \] - motor instantaneous current of phase i
\[ \lambda_i \] - coil flux linkages with phase i

The subscripts i ("a, b, c, A, B and C") denote stator and rotor quantities respectively.

Mechanical Equation

The mechanical equations are then coupled to the electric system via the electromagnetic torque. This can be done on the basis of energy flow through the machine.

\[ T = \frac{p}{2} \sum_{i} \sum_{j} i_i j_j \frac{d \phi_y}{d \theta_R} \]  

(2)

with:

\[ p \] - number of poles
\[ \phi_y \] - electromagnetic flux
\[ \theta_R \] - rotor position
where:

- $L_s$ - phase leakage stator inductance
- $L_r$ - phase leakage rotor inductance
- $L_{mm} = L_{ss} = L_{sr} = 2/3$ of phase magnetizing inductance
- $M_{ss}$ - stator mutual winding inductance
- $M_{rr}$ - rotor mutual winding inductance
- $M_{sr}$ - phase A stator and rotor mutual inductance
- $M_{br}$ - phase B stator and rotor mutual inductance
- $M_{cr}$ - phase C stator and rotor mutual inductance

III. COMPUTATIONAL RESULTS

In order to investigate the induction motor behavior under voltage supply conditions with power quality loss, different computer simulations were then carried out using both ideal and non-ideal voltage conditions. The results obtained are related to time domain voltage, current, torque, active and reactive power, shaft power, shaft speed, etc. These and other variables can be easily derived from the simulator. The loss of power quality considered were related to voltage unbalance, voltage sag, voltage swell, etc. These will be specified later. The three-phase squirrel-cage induction motors’ parameters are given in table I. For simulation purposes, the motor load was taken as 50% of the rated value.

Table I - Motors parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>kW</td>
<td>100</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>V</td>
<td>440</td>
</tr>
<tr>
<td>Winding connection</td>
<td></td>
<td>delta</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>rpm</td>
<td>1773</td>
</tr>
<tr>
<td>Stator resistance - $R_s$</td>
<td>ohm</td>
<td>0.088</td>
</tr>
<tr>
<td>Rotor resistance - $R_r$</td>
<td>ohm</td>
<td>0.0615</td>
</tr>
<tr>
<td>Stator reactance - $X_s$</td>
<td>ohm</td>
<td>0.3019</td>
</tr>
<tr>
<td>Rotor reactance - $X_r$</td>
<td>ohm</td>
<td>0.7957</td>
</tr>
<tr>
<td>Magnetizing reactance - $X_m$</td>
<td>ohm</td>
<td>16.26</td>
</tr>
<tr>
<td>Iron losses reactance - $X_{lm}$</td>
<td>ohm</td>
<td>225</td>
</tr>
<tr>
<td>Moment of inertia - $J_m$</td>
<td>kg.m$^2$</td>
<td>0.9843</td>
</tr>
<tr>
<td>Number of poles - $p$</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

Table II summarises the different situations related to the loss of power quality considered.
Table II - Cases studied.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Motor supplied with a purely sinusoidal, symmetric and equilibrate voltage.</td>
</tr>
<tr>
<td>Case 2</td>
<td>Voltage supply with 5% of unbalance.</td>
</tr>
<tr>
<td>Case 3</td>
<td>Voltage supply with 14% of harmonic distortion.</td>
</tr>
<tr>
<td>Case 4</td>
<td>System supply with 15% of undervoltage.</td>
</tr>
<tr>
<td>Case 5</td>
<td>System supply with 10% of overvoltage.</td>
</tr>
<tr>
<td>Case 6</td>
<td>System supply with a mix of voltage quality problems: unbalance - 5%, harmonic distortion - 14%, undervoltage - 15%</td>
</tr>
</tbody>
</table>

**CASE 1**

This first situation aims to supply the motor electrical and mechanical main characteristics concerning the induction motor operation under ideal conditions. The voltage, current, torque and speed waveforms provide qualitative and quantitative information relates the machine behavior.

Figures 1 to 4 show the well known voltage, current and torque waveforms for both transient and steady state conditions.

![Fig. 1 - Steady state voltage supply.](image)

![Fig. 2 - Phase A line current.](image)

![Fig. 4 - Electromagnetic and load torque.](image)

**CASE 2**

The presence of voltage unbalance in any industrial power system complex is always certain. This item of power quality loss is well known for the power engineer and the corresponding effects are well established. By assuming the degree of asymmetry as being 5%, the investigations were carried out to illustrate the induction motor performance. Figure 5 shows the supplied three-phase line current. It is evident that the low level of voltage unbalance results in a high level of current unbalance. This phenomena is quite well known and it is related to the negative sequence impedance of the machine that is substantially lower than the positive sequence impedance. As a consequence of this negative current component, the motor windings can suffer overheating and this may result in loss of life expectancy.

The presence of negative sequence stator currents also affect the electromagnetic torque produced in the machine airgap. This, in its turn, creates negative sequence rotor currents. The final result is an oscillatory torque at the motor shaft and consequently mechanical problems may appear. Figures 6 and 7 illustrate this phenomena.

![Fig. 3 - Three-phase steady state line current.](image)
CASE 3
The power loss of quality to be analyzed in this case is related to the harmonic distortion imposed on the voltage supply. The strategy is to maintain the fundamental voltage magnitude and to add 5, 7, 11 and 13 harmonic order which will result in a total harmonic distortion (THDv) of 14%.

Figure 8 illustrates the distorted voltage supply and Figure 9 the corresponding line current. It can be seen that the current also shows some degree of harmonic distortion.

In figure 10 it is possible to see the effect of the distorted supply voltage on the motor shaft torque. As expected, the Fourier analysis of the oscillatory torque shows the presence of 6th, 12th, etc. harmonic components.

CASE 4
Another significant item of power quality to be investigated is the effect of undervoltage upon the motor performance. Figures 11 and 12 show the induction motor behavior with 15% of undervoltage.
According to the results, the motor starting time has been extended due to the lower voltage level applied. Besides, the current and torque level are correspondingly modified.

**CASE 5**

This case aims to investigate the induction motor performance under sustained overvoltage conditions. Although this situation is not as frequent as the previous one, it may occur in a real system and deserves consideration.

Figures 13 and 14 show line currents and motor torque, respectively, under 10% of overvoltage.

![Fig. 13 - Three-phase line currents.](image1)

![Fig. 14 - Motor and load torque.](image2)

As given in the previous figures, the motor starting time has been accelerated and the current, torque, etc. are correspondingly affected.

**CASE 6**

This last study aims to investigate the induction motor behavior when the voltage supply comprises a mixture of power quality disturbances. Although this could be considered quite a rare operational condition, the situation is not absolutely theoretical. Besides, when one considers the case of induction motor applications supplied by frequency inverters, maybe this case will become closer to real conditions.

Figure 15 shows the three-phase voltage supply. The harmonic distortion, unbalance and the undervoltage can be easily seen.

![Fig. 15 - Three-phase voltage supply.](image3)

The corresponding line current supplying the induction motor is shown in figure 16. The unbalance and harmonic distortion are quite clear.

![Fig. 16 - Three-phase line current.](image4)

The shaft and load torque are shown in figure 17 where the significant oscillation presented in the time behavior can be easily seen.

![Fig. 17 - Motor and load torque.](image5)

In order to provide means of comparison, table III gives a summary of the main variables and their numerical values, for the different cases studied.

**Table III - Main Variables and their Numerical Values**

795
IV. ENERGY AND ECONOMIC ANALYSIS

Besides the previous results, which are useful to illustrate the effect of power quality upon the several variables associated to the motor operation, the studies were carried on towards the investigation of the relationship between power quality and energy consumption. To achieve this target, using the SABER simulator and its calculator facilities, the motor supplied active power, the mechanical power and the general motor efficiency for each situation were evaluated. Table IV gives a summary of the results. The ideal voltage supply can be considered as the basis for analysis.

Table IV - Induction motors energy analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>( P_{\text{motor}} ) - kW</th>
<th>( P_{\text{losses}} ) - kW</th>
<th>Efficiency</th>
<th>( \eta % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.13</td>
<td>38.07</td>
<td>38.06</td>
<td>37.86</td>
</tr>
<tr>
<td>2</td>
<td>42.77</td>
<td>43.01</td>
<td>43.72</td>
<td>42.47</td>
</tr>
<tr>
<td>3</td>
<td>89.15</td>
<td>88.51</td>
<td>87.05</td>
<td>89.14</td>
</tr>
</tbody>
</table>

According to the figures given in Table IV, it can be seen that the motor power consumption and consequently the efficiency are substantially affected by the loss of power quality. This will, of course, cause internal overheating and loss of life expectancy. As a result under the specified operating conditions, either power quality solutions and/or derating procedures must be sought so that the motor may work without thermally affecting its performance.

In addition to the above analysis, it follows that the increase in power consumption leads to further financial expenditures. By assuming the ideal supply condition as the reference case, then the power increase for the individual cases of loss of power quality can be easily considered and converted in US$. Using a typical Brazilian cost for the energy as being US$0.14 per kWh, and the motor in operation for 24 hours a day, it is possible to convert the increase in power consumption to US$ per year. Figure 18 shows the values obtained from this calculation. Since the above results express extra financial amount in the electricity bill they must be considered during power quality solutions pay-back studies.

V. CONCLUSIONS

This paper focused on the behavior of induction motor under different and simultaneous power quality loss conditions. By using the SABER simulator and a time domain motor model, a computer program was elaborated to represent three-phase independent situations. Then, a set of non-ideal operating conditions were established and computational studies were carried out. The results were clear enough to illustrate the effect of power quality on the motor performance. In addition to technical aspects, the paper went into the direction of considering the increase in losses and the corresponding financial impact. It has been shown that not only motor life expectancy reduction may be affected, but also substantial increase in the electricity bill may occur. These are of importance when considering power quality pay-back solutions.

VI. REFERENCES


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Biographies

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