The contribution of asynchronous loads to pollutant and greenhouse gas emissions

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Abstract: - An algorithm to estimate the quantity of environmental emissions linked to the operation of asynchronous motors is reported. Emissions are those associated to the production of the electric energy necessary to supply the same asynchronous motors. The absorbed electric power depends on a number of elements, such as the motor rated quantities, its working conditions, the inertia moment of both the motor and mechanical load, the applied load torque, etc. First the consumed electric energy was estimated, either for a single motor or for an equivalent asynchronous load representing a number of motors, and afterwards the amount of linked pollution caused by a conventional thermal power plant was computed. Emissions due to electric energy generation were evaluated on the basis of statistics collected by the main electric utilities. The proposed algorithm was tested by means of laboratory tests performed on a single asynchronous motor.

Key-words: Electric motor speed estimate; Emissions and pollution; Environmental sustainability.

1 Introduction
In order to better understand the importance of the issue, it is useful to remember that in the industrialized countries asynchronous motors consume approximately 60% of the total used electric energy and some factories can consume even 90% of the proper used electric energy only to supply electric motors.

In the specialized literature, a number of works deal with motor energy consumption and efficiency. In some papers, even studies about the geographical distribution of different kinds of motors and their consumptions are reported [1]. In order to improve motor efficiency, many different solutions are proposed; in general, the basic idea is to reduce the absorbed electric energy while meeting construction constraints and assuring the minimum performances required [2]. Recently, even more than in the past, attention was addressed to digital control strategies and the use of power electronics devices. In this context, particularly successful procedures were adopted, such as the Vector Control (VC) and the Scalar Control (HVAC), [3].

On the other hand, also different algorithms were implemented with an aim to increase motor efficiency. In this field two main research approaches were followed. The former was directed to improve the motor constructive characteristics [4]. The latter was based on the implementation of control procedures aiming to improve the motor operating performances [5]. In addition, a number of studies were published addressing the errors performed in the estimate of motor efficiency; in this context, the approaches proposed were mainly the Maximum Estimated Error (MEE), the Worst Case Estimated Error (WCEE), and the Realistic Estimated Error (REE) [6].

2 The problem formulation
The issue here was to estimate the amount of emissions into the environment associated to the electric energy drawn by an asynchronous motor. The first step of the proposed procedure is the estimation of the $P_m$ mechanical power on the motor shaft:

$$P_m = C_m \cdot \omega_m \ [W]$$  \hspace{1cm} (1)

Where $\omega_m$ is the rotor speed and $C_m$ the electromagnetic torque. $C_m$ can be determined from the dynamic equilibrium equation:

$$C_m - C_r - C_a = J_T \frac{d\omega_m}{dt} \ [N \cdot m]$$  \hspace{1cm} (2)

$$C_m = C_r + C_a + J_T \frac{d\omega_m}{dt} \ [N \cdot m]$$  \hspace{1cm} (3)

The quantities $C_r$, $C_a$ and $J_T$ are the load torque, the friction torque and the moment of inertia, respectively; all of them are known quantities. $\omega_m$ is an unknown and can be estimated with the
algorithm illustrated in Section 4. From the knowledge of \( \omega_m \), Eq. (3) allows the evaluation of:

\[
\dot{C}_m = C_r + C_a + J_1 \frac{d\dot{\omega}_m}{dt} \quad [N \cdot m]
\]  

(4)

The value of \( \dot{C}_m \) introduced in eq. (1) allows the computation of \( \dot{P}_m \):

\[
\dot{P}_m = \dot{C}_m \cdot \dot{\omega}_m \quad [W]
\]  

(5)

Finally, the electric power drawn by the motor can be estimated from the knowledge of the \( \eta \) motor efficiency:

\[
\dot{P}_e = \frac{\dot{P}_m}{\eta} \quad [W]
\]  

(6)

\( \eta \) can be read from the motor label or evaluated with laboratory tests. It can also be estimated for an equivalent asynchronous load [10], [11].

The \( E_e \) energy supplied by the electrical system can be computed by the following integral:

\[
E_e = \int_{0}^{t} P_e \, dt \quad [W \cdot s]
\]  

(7)

If the \( t \) time is assumed (as a reference) as 1 h, the value obtained from Eq. (7) can be easily expressed in kWh. On the other hand, electricity companies are obliged to write a report of their emissions on the basis of a 1 kWh of produced energy.

3 Emissions compared to electric energy production

The emissions reported in the following are those produced by a traditional thermal power plant. In this case, emitted pollution can be primarily classified as solid, liquid and gas. Another frequently used classification subdivides the generated pollution as follows:

- emissions into the atmosphere;
- avoided CO\(_2\) emissions;
- outlet water;
- hazardous waste.

Emissions into the atmosphere include pollutant particles and greenhouse gases. The former category comprises:

- Sulphur dioxide (SO\(_2\));
- Nitrogen oxides (NO\(_x\));
- Powders.

The latter category comprises:

- Carbon dioxide (CO\(_2\));
- Sulphur hexafluoride (SF6);
- Methane (CH\(_4\)).

SO\(_2\) and NO\(_x\) come from a combustion process and as a consequence are produced by thermal power plants. In recent years SO\(_2\) and NO\(_x\) emissions were drastically reduced by means of advanced combustion processes and the use of desulphurators, deoxidizers and molecular sieves. Also CO\(_2\) emissions depend on combustion. Avoided CO\(_2\) emissions can be viewed as a useful indicator in quantifying the penetration level of renewable energy sources.

4 The implemented algorithm for the estimation of motor speed

The rotor \( \vartheta(t) \) position, \( \omega_m(t) \) speed and \( a_m(t) \) acceleration are linked by the following relations:

\[
\begin{align*}
\frac{d}{dt} \vartheta(t) &= \omega_m(t) \\
\frac{d}{dt} \omega_m(t) &= a_m(t) \\
\frac{d}{dt} a_m(t) &= 0
\end{align*}
\]  

(8)

where \( \frac{d}{dt} a_m(t) \) is an additional estimate equation that defines the acceleration as a state quantity. In order to implement the model on a DSC (Digital Signal Controller), a discretization of the (8) differential system must be made:

\[
\begin{bmatrix}
\Delta \vartheta(k) \\
\omega_m(k) \\
\epsilon(k)
\end{bmatrix}
= 
\begin{bmatrix}
0 & \frac{\Delta T}{2} & \frac{\Delta T^2}{2} \\
1 & \Delta T & \omega_m(k-1) \\
0 & 1 & a_m(k-1)
\end{bmatrix}
\begin{bmatrix}
\Delta \vartheta(k-1) \\
\omega_m(k-1) \\
a_m(k-1)
\end{bmatrix}
+ 
\begin{bmatrix}
\frac{\Delta T^2}{2} \\
\omega_m(k-1) \\
0
\end{bmatrix}
\]  

(9)

In the compact form, the same discretized model can be written as follows:

\[
y(k) = [A] \cdot x(k-1) + b \cdot u \quad \text{State equation} \quad (10)
\]

\[
y(k) = [\Delta \vartheta(k)] \quad \text{Output equation} \quad (11)
\]

On the basis of the previous model, an observer based on the Kalman filter can be implemented. Actually, the following non-linear and time-invariant system can be written:

\[
\begin{bmatrix}
x_k \\
y_k
\end{bmatrix}
= 
\begin{bmatrix}
f(x_{k-1}, u_k, k) + w_k \\
h(x_{k-1}, u_k, k) + v_k
\end{bmatrix}
\]  

(12)

Where \( x_k \) is the state equation, \( y_k \) is the output equation, \( f \) and \( h \) are generic equations, \( u_k \) is the input of the system, \( k \) is the sampling step, \( w_k \) is the noise produced by both disturbances and model accuracies, \( v_k \) is the noise on the output that is
linked to the measurement process. Noises are supposed Gaussian with zero mean.

The implemented algorithm, which is based on the EKF (Extended Kalman Filter), requires two separate processes:

1. Prediction
\[ \hat{x}_k = A \hat{x}_{k-1} + b \hat{a}_k \] (13)

2. Correction
\[ \hat{x}_k = \bar{x}_k + g(y_k - c^T \bar{x}_k) \] (14)

Where “g” is the gain vector assumed as \( c^T = [1 \ 0 \ 0] \). Fig. 1 shows a flow-chart of the implemented algorithm.

Fig. 1. The implemented algorithm.

5 Experimental validation of the model

Fig. 2 shows the configuration of a laboratory monitoring system that can be adopted to estimate the quantity of emissions released into the environment in consequence of 1kWh energy consumption of a single motor. The necessary data are acquired at the mechanical load side. In the laboratory test the motor speed is measured while in normal cases the speed is estimated using the algorithm of Fig. 1. In order to easily obtain the consumed electric energy in kWh, the operation time of the motor is established as 1h. For certain established \( \omega_m \) speeds, Tables 1 and 2 show a comparison of data either measured or estimated by a computation based on the implemented speed-estimate algorithm.

Table 1. Measured data.

<table>
<thead>
<tr>
<th>( P_e ) [W]</th>
<th>( P_m ) [W]</th>
<th>( \omega_m ) [rpm]</th>
<th>( \omega_m ) [rad/s]</th>
<th>( C + C_a ) [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3334.59</td>
<td>2734.36</td>
<td>1274.0</td>
<td>133.459</td>
<td>20.49</td>
</tr>
<tr>
<td>3401.58</td>
<td>2789.30</td>
<td>1300.0</td>
<td>136.137</td>
<td>20.49</td>
</tr>
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<td>3532.25</td>
<td>2896.45</td>
<td>1350.0</td>
<td>141.373</td>
<td>20.49</td>
</tr>
<tr>
<td>3270.65</td>
<td>2681.93</td>
<td>1250.0</td>
<td>130.900</td>
<td>20.49</td>
</tr>
<tr>
<td>3138.46</td>
<td>2573.54</td>
<td>1200.0</td>
<td>125.664</td>
<td>20.49</td>
</tr>
<tr>
<td>3009.03</td>
<td>2467.40</td>
<td>1150.0</td>
<td>120.428</td>
<td>20.49</td>
</tr>
</tbody>
</table>

Table 2. Estimated data.

<table>
<thead>
<tr>
<th>( \omega_m ) [rpm]</th>
<th>( \omega_m ) [rad/s]</th>
<th>( P_m )</th>
<th>( P_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1274.527</td>
<td>133.468</td>
<td>2734.763</td>
<td>3335.08</td>
</tr>
<tr>
<td>1299.921</td>
<td>136.127</td>
<td>2789.251</td>
<td>3401.53</td>
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<tr>
<td>1350.196</td>
<td>141.392</td>
<td>2897.127</td>
<td>3533.08</td>
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<tr>
<td>1249.613</td>
<td>130.859</td>
<td>2681.306</td>
<td>3269.88</td>
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<td>1200.036</td>
<td>125.667</td>
<td>2574.926</td>
<td>3140.16</td>
</tr>
<tr>
<td>1150.112</td>
<td>120.439</td>
<td>2467.806</td>
<td>3009.52</td>
</tr>
</tbody>
</table>

Tables 3 and 4 show the amount of the estimated particles emitted into the atmosphere as a consequence of the energy drawn and consumed by the tested motor.

Table 3. Estimate of the emitted particles.

<table>
<thead>
<tr>
<th>( P_e ) [W]</th>
<th>( SO_2 ) [g]</th>
<th>( NO_x ) [g]</th>
<th>( Powders ) [g]</th>
<th>( CO_2 ) [g]</th>
<th>( SF_6 ) [g]</th>
<th>( H_2S ) [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3532.25</td>
<td>3.2858</td>
<td>3.2858</td>
<td>1752.409</td>
<td>3.1798</td>
<td>14.132</td>
<td></td>
</tr>
<tr>
<td>3270.65</td>
<td>3.0409</td>
<td>3.0409</td>
<td>1621.863</td>
<td>2.9429</td>
<td>13.079</td>
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</tr>
<tr>
<td>3138.46</td>
<td>2.9203</td>
<td>2.9203</td>
<td>1557.516</td>
<td>2.8261</td>
<td>12.561</td>
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</tr>
<tr>
<td>3009.03</td>
<td>2.7988</td>
<td>2.7988</td>
<td>1492.722</td>
<td>2.7086</td>
<td>12.038</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Estimate of other emitted particles.

<table>
<thead>
<tr>
<th>( P_e ) [W]</th>
<th>Cells (pollutant load) [g]</th>
<th>Metals [g]</th>
<th>Nitrogen (total) [g]</th>
<th>Phosphorus (total) [g]</th>
<th>COD [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3334.59</td>
<td>1247.319</td>
<td>133403</td>
<td>4.002092</td>
<td>0.43356</td>
<td>17.3424</td>
</tr>
<tr>
<td>3401.58</td>
<td>1272.171</td>
<td>136061</td>
<td>4.081831</td>
<td>0.442198</td>
<td>17.6879</td>
</tr>
<tr>
<td>3532.25</td>
<td>1321.373</td>
<td>141323</td>
<td>4.239689</td>
<td>0.459301</td>
<td>18.3720</td>
</tr>
<tr>
<td>3270.65</td>
<td>1222.937</td>
<td>130795</td>
<td>3.923863</td>
<td>0.425085</td>
<td>17.0034</td>
</tr>
<tr>
<td>3138.46</td>
<td>1174.418</td>
<td>125606</td>
<td>3.768185</td>
<td>0.40822</td>
<td>16.3288</td>
</tr>
<tr>
<td>3009.03</td>
<td>1125.56</td>
<td>120381</td>
<td>3.611424</td>
<td>0.391238</td>
<td>15.6495</td>
</tr>
</tbody>
</table>
A validation procedure was performed also on the behaviour of the algorithm of Fig. 1. In this case the (9) equation model was implemented on a DSC where the quantities are expressed in per units. Fig. 3 shows a comparison between the speeds as estimated by the algorithm and as obtained from laboratory measurements. In the figure, the saw-tooth function represents the normalized pulses counted by the encoder and the horizontal line is composed of two overlapping straight lines representing the measured and estimated speeds, respectively. Two cases were examined assuming the rotor speed constant and equal to 1 and 0.5 p.u., respectively.

Fig. 3. Estimated and measured speeds vs. time as shown by a measurement oscilloscope; a) \( \hat{\omega}_{\text{rpm}} = 0.5 \text{p.u.} \) b) \( \hat{\omega}_{\text{rpm}} = 1 \text{p.u.} \)

As an example, Fig. 4 shows the results supplied by the estimate algorithm concerning the particles emitted into the atmosphere when the load torque is \( C_r = 18 \text{[Nm]} \) and the mechanical speed \( \omega_m = 1498 \text{[rpm]} \).

![Diagram](image1)

Fig. 4. Example of the estimated emissions for constant load torque (18Nm) and constant speed (1498 rpm).

6. Conclusions

On the basis of a method proposed for the speed estimate of an asynchronous motor, an algorithm was implemented in order to establish the amount of polluting emissions due to the production of electric energy required and consumed by the same motor. On the other hand, an everyday concern of electric production companies is to reduce pollution to levels below imposed limits, which are verified in real time by a number of national and international authorities. As a matter of fact, for this reason a number of measures are constantly enacted to improve the efficiency of both electric generation and electric end-uses. Of course these actions also involve benefits in contrasting the continuous growth of both consumptions and tariffs of primary energy resources. The method proposed to assess the contribution of asynchronous motors to environment pollution was validated by means of laboratory tests.

References


