A Standstill Frequency Response Method for Large Salient Pole Synchronous Machines

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Abstract—In this article, a Standstill Frequency Response Test (SSFR) is proposed, with the aim of determining the direct and quadrature axis operational impedances for salient pole synchronous machines. The method is applied with the rotor at standstill in a given arbitrary position, thus avoiding the difficulties in rotor mechanical alignment and rendering it suitable for large salient pole synchronous machines of hydroelectric power plants.

Index Terms—Frequency response, parameter estimation, synchronous machines.

I. INTRODUCTION

There are many propositions for the determination of synchronous machine parameters. Among the modern techniques used are neural networks, finite elements, on-line and off-line statistical methods, frequency response, load rejection and others [1]–[5].

The frequency response method for parameters identification is a standard procedure that has been applied worldwide, mainly in countries where thermal generation is the main source of power. Thermal generation power plants use solid rotor generators with a small number of pairs of poles and relatively small dimensions. For this type of machine it is easier to align the rotor with the direct and quadrature axis for parameters identification.

Nevertheless, for heavy and large machines with a high number of pairs of poles—like those found in medium and low head hydro power plants—the application of this method brings an additional difficulty in the rotor mechanical alignment with the $d$- and $q$-axis.

The main reason for this difficulty is that even the smallest error in the mechanical alignment, when multiplied by the number of pairs of poles, results in a large error in the electrical degree.

Example Fig. 1 shows one of Itaipu power plant’s twenty generator rotors. The correct alignment of this rotor—which has 39 pairs of poles—with the $d$- or with the $q$-axis is a hard task. An error of only one mechanical degree will result in an error of 39 electrical degrees, which is inadmissable.

In this paper an extension of the Dalton and Cameron method [6] is proposed in order to overcome these problems and spread the usage of SSFR test in large salient pole synchronous machines. The two axis frequency response characteristics will be found using the same decomposition technique proposed in [6] over the data obtained by testing the machine with its rotor at standstill in an arbitrary position. Recent works have shown the need of further studies on this subject [7]–[9].

II. MACHINE IMPEDANCES EVALUATION

A. Dalton and Cameron Method

This method is recommended for the determination of the direct and quadrature subtransient reactances [1]. While keeping the rotor in an arbitrary position and having the field winding short-circuited, the test is performed applying a single-phase, rated-frequency, reduced-voltage source to the armature windings combined two-by-two.

When neglecting the armature resistance, this procedure leads to three reactances from which the subtransient reactances are calculated. These reactances are calculated using a simple decomposition technique described by the following equations [6]:

$$x''_d = \frac{k + M}{2}$$  \hspace{1cm} (1)

$$x''_q = \frac{k - M}{2}$$  \hspace{1cm} (2)

Fig. 1. Rotor of a 737MVA salient pole synchronous generator (reproduced with permission from ABB).
where

\[ k = \frac{A + B + C}{3} \]

(3)

and

\[ M = \sqrt{2(B - k)^2 + \frac{(C - A)^2}{3}}. \]

(4)

In these equations, \( A, B \) and \( C \) represent the measured reactances, \( k \) and \( M \) represent dummy variables, and \( x''_d \) and \( x''_q \) represent the direct- and quadrature-axis subtransient reactances.

B. Proposed Test Method

It is proposed to conduct the frequency response test with the machine at standstill, stopped in an arbitrary position, thus avoiding the presented rotor mechanical alignment difficulties. This method is an extension of that proposed by Dalton and Cameron [6].

A single-phase variable-frequency reduced-voltage source is applied to all armature windings combined two-by-two. The field winding must be short-circuited. This procedure defines three impedances \( A, B \) and \( C \), from which the \( d \)- and \( q \)-axis operational impedances are calculated for each frequency, using (3) and (4) and the following equations:

\[ z_d(s) = \frac{k(s) + M(s)}{2} \]

(5)

\[ z_q(s) = \frac{k(s) - M(s)}{2} \]

(6)

where \( s \) represents the complex frequency \((j\omega)\), \( k \) and \( M \) are obtained from (3) and (4).

By knowing the value of the armature resistance \((r_a)\) the \( d \)- and \( q \)-axis operational inductances can be calculated

\[ L_d(s) = \frac{z_d(s) - r_a}{s} \]

(7)

\[ L_q(s) = \frac{z_q(s) - r_a}{s}. \]

(8)

Once the operational inductances are obtained the other parameters of interest are assessed [10]–[12].

A hardware/software setup was developed for implementation and testing of the proposed method in an automatic way, as will be shown.

C. Hardware/Software

In the frequency response test, the machine impedance is obtained by applying a variable-frequency, reduced-voltage source and measuring the magnitude and phase of the resulting current for each frequency at a specified range. This is traditionally done by using conventional equipment, such as function generators, voltmeter, current, and phase angle meters, and occasionally, spectrum analyzers.

Fig. 2 shows the architectural concept of the developed equipment. An analogical I/O board is connected to one computer slot. The sinusoidal voltages—at various magnitudes and frequencies—are generated from the computer through the digital-to-analog (D/A) converter.

A linear IC power amplifier is used to achieve the necessary excitation power. The current and voltage are measured using an analog-to-digital (A/D) converter. The proper specification of the converters’ resolution and sampling rate are key factors in reaching the desired system performance.

Due to the low level of the applied voltage used in the test, no special signal conditioning is normally necessary. A Hall sensor is used as interface for the current measurement.

An off the shelf software platform was employed to control and automate the generation of the variable-frequency sinusoidal voltage, current and voltage measurements, and the calculus, graphical and measurement presentations.

The software used has visual programming capabilities, and programming is done by placing module icons on the screen and connecting them in a schematic diagram, which represents the flow of data through the system. The results of the data acquisition and calculations are displayed in tables, digital meters and \( Y/t \) graphs.

The voltage signal is generated with modulation not only in frequency, but also in amplitude, in order to maintain the magnitude of the current. Slide controls are used the first time to determine initial frequency and voltage values. After a suitable time period, the frequency is multiplied by a constant in order to span the total frequency range.

III. RESULTS

For proper evaluation of the method, measurements were applied with two salient pole synchronous machines: a micro alternator of 0.6 kVA and a medium sized machine of 900 kVA. The rated values are shown in Table I.

<table>
<thead>
<tr>
<th>Machine</th>
<th>#1</th>
<th>#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kVA)</td>
<td>0.6</td>
<td>900</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>220</td>
<td>4000</td>
</tr>
<tr>
<td>Current (A)</td>
<td>1.6</td>
<td>130</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1800</td>
<td>720</td>
</tr>
<tr>
<td>Field Voltage (V)</td>
<td>12</td>
<td>110</td>
</tr>
<tr>
<td>Field Current (A)</td>
<td>0.6</td>
<td>90</td>
</tr>
</tbody>
</table>
First, the stationary rotor aligned for $d$- and $q$-impedance evaluations were done using the standard procedure [1]. The impedances $zd$, $zq$ were determined for frequencies varying from about 1 to 300 Hz.

Next, the stationary rotor was moved to two arbitrary positions, and the $d$- and $q$-axis operational impedances were evaluated using the proposed procedure.

The obtained values of $zab$, $zbc$, $zca$ for machines #1 and #2 for two different rotor positions are shown in Tables II–V.

The final results of the operational impedances $zd$, $zq$ for machine #1 are shown in Tables VI and VII. The calculated results are compared with $d$- and $q$-axis impedances obtained by the standard procedure (2nd column).

One can observe that the results of the proposed technique do not match with those obtained by the standard procedure. For low frequencies, the errors are few, while for higher frequencies the errors grow considerably in number for both the $d$- and $q$-axis in both test positions.

Fig. 3 shows the screen, where one can see the voltage and current values, and the magnitude and angle of the measured impedance. A graph window shows the voltage and current wave forms. Note that the value of the voltage or the frequency can be manually modified at any time during the test by moving the slide controls on the screen.

Tables VIII and IX shows the results calculated for machine #2. In both cases, the results are compared with $d$- and $q$-axis impedances obtained by the standard procedure.

The results obtained by the application of the proposed methodology with a medium sized machine were better than that obtained with the micro alternator.
TABLE VIII
MACHINE #2—OPERATIONAL IMPEDANCE $z_d$

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>Rotor at $d$-axis Position #1</th>
<th>Rotor at $d$-axis Position #2</th>
<th>Error at Position #1 (%)</th>
<th>Error at Position #2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.150</td>
<td>0.72 ± 34.3°</td>
<td>0.69 ± 35.0°</td>
<td>4.33</td>
<td>2.36</td>
</tr>
<tr>
<td>4.640</td>
<td>1.11 ± 47.7°</td>
<td>1.05 ± 46.4°</td>
<td>8.8</td>
<td>3.0</td>
</tr>
<tr>
<td>10.00</td>
<td>1.93 ± 56.2°</td>
<td>1.79 ± 54.8°</td>
<td>7.63</td>
<td>1.25</td>
</tr>
<tr>
<td>21.54</td>
<td>3.37 ± 63.5°</td>
<td>3.07 ± 55.5°</td>
<td>11.0</td>
<td>2.94</td>
</tr>
<tr>
<td>46.52</td>
<td>6.04 ± 63.4°</td>
<td>5.62 ± 62.3°</td>
<td>7.20</td>
<td>3.71</td>
</tr>
<tr>
<td>100.0</td>
<td>10.6 ± 63.5°</td>
<td>9.97 ± 64.6°</td>
<td>6.23</td>
<td>1.96</td>
</tr>
<tr>
<td>215.4</td>
<td>18.0 ± 63.7°</td>
<td>17.1 ± 64.1°</td>
<td>4.52</td>
<td>2.23</td>
</tr>
</tbody>
</table>

TABLE IX
MACHINE #2—OPERATIONAL IMPEDANCE $z_q$

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>Rotor at $q$-axis Position #1</th>
<th>Rotor at $q$-axis Position #2</th>
<th>Error at Position #1 (%)</th>
<th>Error at Position #2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.150</td>
<td>0.55 ± 15.5°</td>
<td>0.57 ± 18.4°</td>
<td>6.31</td>
<td>5.69</td>
</tr>
<tr>
<td>4.640</td>
<td>0.66 ± 31.9°</td>
<td>0.69 ± 32.5°</td>
<td>4.67</td>
<td>2.19</td>
</tr>
<tr>
<td>10.00</td>
<td>0.98 ± 50.8°</td>
<td>1.03 ± 50.9°</td>
<td>5.11</td>
<td>1.23</td>
</tr>
<tr>
<td>21.54</td>
<td>1.77 ± 62.9°</td>
<td>1.83 ± 58.5°</td>
<td>8.51</td>
<td>3.16</td>
</tr>
<tr>
<td>46.52</td>
<td>3.39 ± 68.7°</td>
<td>3.51 ± 65.6°</td>
<td>6.54</td>
<td>1.23</td>
</tr>
<tr>
<td>100.0</td>
<td>6.21 ± 71.1°</td>
<td>6.72 ± 71.9°</td>
<td>8.34</td>
<td>1.56</td>
</tr>
<tr>
<td>215.4</td>
<td>12.2 ± 72.7°</td>
<td>12.8 ± 71.3°</td>
<td>4.77</td>
<td>3.32</td>
</tr>
</tbody>
</table>

It should be noted that aligning a micro alternator with $d$- or $q$-axis is not a simple task. As a result of the small diameter, even a little deviation in the mechanical angle can result in a large error in the electrical angle.

As an example, consider a micro alternator with two pairs of poles and a diameter of 100 mm. In a mechanical alignment, an error of only 5 mm in its perimeter will result in an error of about 10 electrical degrees.

The results are summarized in Figs. 4–9.

Although graphically the errors seem to be small, when the calculated values are compared with that obtained by the standard procedure, numerically they are not so negligible, increasing with the frequency as shown in previous tables.

Nevertheless, if one compares the calculated results for the two stationary positions, the conclusion is that they have quite the same value, i.e., large errors are found when the results obtained by laborious rotor mechanical alignment are used as a reference base.

Based on the statements above, one can conclude that the main source of error when testing salient pole synchronous machines with a large number of pairs of poles is the great difficulty...
in obtaining a correct mechanical alignment of the rotor with the \( d' \)- or with the \( q' \)-axis.

The error between the impedances obtained by the proposed technique in relation to their mean for each frequency is presented in Figs. 8–11.

In general, the errors found in the analyses were less than \( \pm 5\% \), which is acceptable in parameter estimation, and thus demonstrates the efficiency of the proposed procedure.

IV. CONCLUSIONS

A new methodology for the evaluation of the \( d' \)- and \( q' \)-axis operational impedances of synchronous machines was presented. The methodology combines the frequency response test and the Dalton and Cameron methods to derive the test procedure. This method is suitable for large salient pole synchronous machines.

The great advantage of the proposed technique is that the machine can be tested with the rotor at standstill, stopped at an arbitrary position. This avoids the need of a precise rotor mechanical alignment with the \( d' \)- or with the \( q' \)-axis, as these results are obtained from a proper decomposition.

It was also shown that the test can be carried out in an automatic mode using appropriate available hardware and software facilities.

When conducting research on small machines it can be seen that some errors are found when comparing the proposed methodology with the standard methodology/procedure. For medium-sized machines these errors were smaller.

Nevertheless these errors are very small when comparing the results of the proposed technique for two different positions in both machines, conducting to admissible errors in synchronous machines parameter identification.

REFERENCES


