Novel Analysis of Synchronous and Induction Generators in Parallel Operation Mode in an Isolated Electric System

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**ABSTRACT**

This paper presents an analysis of a parallel connection of one synchronous generator and one self-excited induction generator that feeds a resistive load and an Induction Motor. The system voltage and frequency are controlled by a voltage control loop and a speed control loop connected to synchronous generator. The induction generator speed is controlled by its primary machine that is fed by an autotransformer and a diodes bridge. Through by voltages applied by an adjustable tap autotransformer connected to induction generator's primary machine, it is possible widen the range of its shaft speed if compared with the shaft speed caused by only field flux variation method. Then, by the autotransformer method is possible to widen the speed and power limits from the induction generator what increases the induction generator contributions and relieves the power supply from synchronous generator. Analysis of generators power supply and its interactions in various operational scenarios are shown. The results enable comparisons of the two methods of induction generator speed control, either by auto-transformer method or by field flux variation method. The first results in larger range of speed and power from the induction generator. Therefore, it has more representative features of actual field conditions.

**Keywords:** Induction Generator, Isolated Electric System, Generators in Parallel, Synchronous Generator

**Nomenclature and Abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{SG} )</td>
<td>Synchronous generator voltage</td>
</tr>
<tr>
<td>( I_{SG} )</td>
<td>Synchronous generator current</td>
</tr>
<tr>
<td>( f_{SG} )</td>
<td>Synchronous generator frequency</td>
</tr>
<tr>
<td>( I_{IG} )</td>
<td>Induction generator current</td>
</tr>
<tr>
<td>( n_{IG} )</td>
<td>Induction generator speed</td>
</tr>
<tr>
<td>( V_{IG} )</td>
<td>Induction generator voltage</td>
</tr>
<tr>
<td>( f_{IG} )</td>
<td>Induction generator frequency</td>
</tr>
<tr>
<td>( R_{load} )</td>
<td>Resistors banks current</td>
</tr>
<tr>
<td>( Q )</td>
<td>Reactive power</td>
</tr>
<tr>
<td>( X_c )</td>
<td>Capacitive reactance</td>
</tr>
<tr>
<td>( pF, \cos \phi )</td>
<td>Power factor</td>
</tr>
<tr>
<td>( S_{G} )</td>
<td>Synchronous generator</td>
</tr>
<tr>
<td>( I_{fieldSG} )</td>
<td>Synchronous generator field current</td>
</tr>
<tr>
<td>( f_{DCMSG} )</td>
<td>Armature voltage of direct current motor coupled with synchronous generator</td>
</tr>
<tr>
<td>( I_{aDCMSG} )</td>
<td>Armature current of direct current motor coupled with synchronous generator</td>
</tr>
<tr>
<td>( I_{fDCMSG} )</td>
<td>Field current of direct current motor coupled with synchronous generator</td>
</tr>
<tr>
<td>( I_{WSG} )</td>
<td>SG active current</td>
</tr>
<tr>
<td>( I_{WIG} )</td>
<td>IG active current</td>
</tr>
<tr>
<td>( V_{DCMIG} )</td>
<td>DC armature voltage coupled with IG</td>
</tr>
<tr>
<td>( V_{DCMSG} )</td>
<td>DC armature voltage coupled with SG</td>
</tr>
<tr>
<td>( I_{DCMIG} )</td>
<td>Current of direct current motor coupled with induction generator</td>
</tr>
<tr>
<td>( I_{fieldDCMSG} )</td>
<td>Field current of direct current motor coupled with induction generator</td>
</tr>
<tr>
<td>( I_{loadR} )</td>
<td>Resistors banks current</td>
</tr>
<tr>
<td>( Q )</td>
<td>Reactive power</td>
</tr>
<tr>
<td>( X_c )</td>
<td>Capacitive reactance</td>
</tr>
<tr>
<td>( pF, \cos \phi )</td>
<td>Power factor</td>
</tr>
</tbody>
</table>

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C  Conjugate  
Xs  Synchronous reactance  
E  Back electromotive force  
$V_{ph}$  Phase neutral voltage  
FPSO  Floating production storage offloading  
IM  Induction Motor  
IdwMT  Motor reactive current  
IwMT  Motor active current  

1. Introduction  

This paper is an extension of work originally presented in PEDG conference [1].

The use of induction generators in generation systems is usual in wind plants [2-4] or eventually in small hydroelectric generation units [5]. Otherwise, from studies started in [1], it is shown a new knowledge border which consider the use of IG in parallel of SG in an isolated electric system. The first results and behavior of this kind of generation system were shown in [1] and are followed by this current article with original and deeper analysis.

Then, this work is composed of analysis over an expanded system that includes an induction motor, a resistive load, an autotransformer connected to a diodes bridge to feed the DCMIG armature and then permits to increase manually the output electric power limits if compared to flux variation method (3) presented in [1]. Therefore, this article shows the IG supplying more active power and the induction motor inserted in experiment what enables a novel analysis of the system behavior.

This paper presents results that show additional remarkable characteristics by operation in parallel mode among one SG and one IG. Some characteristics, such as reduced weight and size, easier maintenance, and shorter manufacturing and delivery time are more associated with induction generators and are relevant to oil platforms or offshore installation concerns. Besides, it has absence of dc supply for excitation and better transient performances [5].

One of the potential motivation for this study is to develop a potential alternative capable of optimizing the main electric system currently adopted in oil platforms and floating production storage and offloading (FPSO) ships to become cheaper, simpler, lighter, and more efficient.

The potential application of this study is the replacement of one or two synchronous generators by one or two induction generators in oil offshore platforms or FPSO. A typical offshore electric system uses three or four turbo-generators in 13800 V, 60 Hz, driven by dual fuel (fuel gas or diesel oil) turbines. In typical operation, three main turbo-generators operate and can supply all unit consumers with the fourth in standby. During the peaks of load, the fourth main turbo-generator may be required to meet the demand. Therefore, the whole electric system shall be suitable for this operational condition.

Therefore, the study target is to analyze various aspects of topology and operating involving an induction generator in parallel with a synchronous generator for application in an isolated electric system, and to establish the operational viability, advantages and challenges.

2. Isolated Electric System  

The isolated electric system was sized as shown in the following equations and data. The automatic controls of the system consist of a voltage control loop and a speed control loop. Both are inserted in the SG scheme as shown in Figure 5 and Figure 6. The dataplates of the principal equipment are shown in Tables 1 to 6.

The parameterization used in both electronic control boards is indicated in [1], except for the references of voltage and speed for each of the control loops which are respectively 65.5 and 65.2 as shown in Figure 9.

2.1. Dataplate  

In tables 1 to 4 are shown the main equipment's dataplates and the tables 5 to 6 are shown the load's dataplates used in the experiments along this work.

### Table 1: DMCIG Dataplate

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
<th>Speed</th>
<th>Fieldmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 V</td>
<td>7.72 A</td>
<td>1.7 kW</td>
<td>1500 rpm</td>
<td>600 mA</td>
</tr>
</tbody>
</table>

### Table 2: DMCIG Dataplate

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
<th>Speed</th>
<th>PF</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 V</td>
<td>9.1 A</td>
<td>2.0 kW</td>
<td>1800 rpm</td>
<td>0.8</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

### Table 3: IG Dataplate

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
<th>Speed</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 V</td>
<td>1.86 kW</td>
<td>1410 rpm</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### Table 4: SG Dataplate

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
<th>Speed</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 V</td>
<td>2.0 kVA</td>
<td>1800 rpm</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### Table 5: Load Dataplate

<table>
<thead>
<tr>
<th>Load 1 (kW)</th>
<th>Load 2 (kW)</th>
<th>Load 3 (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
</tbody>
</table>

### Table 6: Load, Induction Motor Dataplate

<table>
<thead>
<tr>
<th>Power</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37 kW</td>
<td>1715 rpm</td>
</tr>
</tbody>
</table>

2.2. Equations - Part I  

Follow the main equations for analysis comprehension and to establish a studies base:

- Direct Current Motor

\[
\eta = \frac{E}{k \cdot \Phi} \tag{1}
\]

\[
n = \frac{U_a + (\sum R_a) + I_a}{k \cdot \Phi} \tag{2}
\]

\[
c_{\text{conjugate}} = k \cdot \Phi \cdot I_a \tag{3}
\]
• Synchronous Generator
  \[ \dot{E} = \dot{U}a + (Ra + jXa) \ast \dot{I}_a \]  
  (4)

• Induction Generator
  \[ S_{slip} = \frac{n_{nig} - n_s}{n_s} \ast 100 \]  
  (5)

\[ n_s = \frac{120f_{SG}}{p_{number \ of \ poles}} \]  
  (6)

2.3. Capacitor Bank Sizing

As informed at the IG dataplate

\[ \cos \phi = 0.8, \ \text{then} \ \sin \phi = 0.6 \] 

The reactive power is calculated to attend the reactive demand of the Induction Machine:

\[ Q = \sqrt{3} \ast V \ast I \ast \sin \phi \]  
  (7)

\[ Q = \sqrt{3} \ast 220 \ast 7.5 \ast 0.6 \Rightarrow 1714.7 \ VAr \] 

\[ Q_{\text{generated}} = Fc \ast Q \]  
  (8)

\[ Fc = 1.2 \ [6] \] 

For the machine coupled at a resistive load which requires 7.5A, it is necessary for the reactive power generation to be approximately 2057.6 VAr as demonstrated below.

\[ Q_{\text{generated}} = 1.2 \ast 1714.7 \Rightarrow 2057.6 \ VAr \]  
  (9)

\[ Q = \frac{3V^2}{Xc} \]  
  (10)

\[ Q = \frac{3 \ast 220^2}{Xc} \Rightarrow Xc = \frac{3 \ast 220^2}{2057.6} = 70.6 \ \Omega \]  
  (11)

\[ Xc = 70.6 \ \Omega \] 

\[ Xc = \frac{1}{2(\pi f \ast C)} = \frac{1}{2 \ast \pi \ast 50 \ast C} \Rightarrow \]  
  (12)

\[ C = \frac{1}{2 \ast \pi \ast 50 \ast 70.6} \approx 40 \mu F \ per \ phase \]  
  (13)

2.4. Resistive Divider Sizing:

• Field Control Loop Resistive Divisor as in Figure 5 and Figure 6.
  \[ (1 \ k\Omega + r_1) \rightarrow 300 \ V \ (brugge \ output \ voltage) \]  
  (14)

\[ r_2(1 \ k\Omega) \rightarrow 4V \ (MP \ 410^\prime \ voltage \ limit) \]  
  (15)

\[ r_1 = 74 \ k\Omega \ and \ r_2 = 1 \ k\Omega \]  
  (16)

• Resistor Power Sizing:

\[ P_{\text{power}} = \frac{300^2}{(75 \ast 10^3)} = 1.2 \ W \]  
  (17)

The resistors that were selected based on the sized resistor, were:

\[ r_1 = 79.1 \ k\Omega \ and \ r_2 = 947 \ \Omega \]  
  (18)

• Speed Control Loop Resistive Divisor as in Figure 5 and Figure 6.

\[ (1 \ k\Omega + r_2) \rightarrow 36 \ V \ (tacho \ generator \ output \ voltage) \]  
  (19)

\[ r_2(1 \ k\Omega) \rightarrow 4V \ (MP \ 410^\prime \ voltage \ limit) \]  
  (20)

\[ r_1 = 8 \ k\Omega \ and \ r_2 = 1 \ k\Omega \]  
  (21)

• Resistor Power sizing:

\[ P_{\text{power}} = \frac{36^2}{(9 \ast 10^3)} = 1.14 \ W \]  
  (22)

The resistors chosen, based on the sized resistor, were

\[ r_1 = 8.3 \ k\Omega \ and \ r_2 = 947 \ \Omega \] 

2.5. Equations - Port II

Follow the system equations base to calculate the power and efficiencies shown in Table 7 and Table 8 for each generator and entire group of machines.

\[ I_{SG}^2 = Iw_{SG}^2 + Ic_1^2 \]  
  (23)

\[ I_{IG}^2 = Iw_{IG}^2 + Ic_2^2 \]  
  (24)

\[ Ic - I_{\text{load}}MT = Ic_1 + Ic_2 \]  
  (25)

\[ I_{\text{load}}MT + IwMT = Iw_{SG} + Iw_{IG} \]  
  (26)

As \( I_{SG}, I_{IG}, Ic \) and \( I_{\text{load}} \) are measured values, shown in Table 7 and Table 8. \( IwMT(Motor’s \ reactive \ current) \) and \( IwMT(Motor’s \ active \ current) \) are values calculated in appendix 1. Then, the system has 4 four variables and 4-four equations. Then, for each scenario, the four variables \( Iw_{SG}, Ic_1, Iw_{IG} \) and \( Ic_2 \) were calculated by Matlab software and are shown in Table 7 and Table 8.

The entire group efficiency and the efficiency of each subgroup were calculated based on PIG, PSG, PDCMSG, and PDCMIG, as follows:

\[ P_{SG} = \sqrt{3} \ast V_{SG} \ast Iw_{SG} \]  
  (27)

\[ P_{IG} = \sqrt{3} \ast V_{IG} \ast Iw_{IG} \]  
  (28)

\[ P_{DCMSG} = Va_{DCMSG} \ast Ia_{DCMSG} \]  
  (29)

\[ P_{DCMIG} = Va_{DCMIG} \ast Ia_{DCMIG} \]  
  (30)

\[ \eta_{\text{group}}\% = \frac{P_{SG}+P_{IG}}{P_{DCMSG}+P_{DCMIG}} \ast 100 \]  
  (31)

\[ \eta_{SG}\% = \frac{P_{SG}}{P_{DCMSG}} \ast 100 \]  
  (32)

\[ \eta_{IG}\% = \frac{P_{IG}}{P_{DCMIG}} \ast 100 \]  
  (33)

2.6. Equations - Part III

The equations e calculus used to determined the IM parameters and IM equivalent circuit as primary, secondary
impedances and currents, including IM currents showed in Table 8 are calculated in item 5 of appendix 1.

2.7. The Experiment and Schemes

The experiment was mounted in the laboratory as shown in Figure 1 and Figure 2. The detailed circuit is shown in Figure 6. Figure 2 shows another experiment view, including the taco generator and its connections. The detailed circuit is shown in Figure 6. Figure 3 shows the typical connections of both circuit board MP 410T which are implemented in this experiment for the voltage loop and speed loop. They are also indicated in Figure 5 and Figure 6.

![Figure 1 Laboratory assembly](image1)

![Figure 2 Another view of laboratory assembly](image2)

![Figure 3. Connections arrangement of MP410T and devices](image3)

Figure 4 shows the 1B6C configuration used for the two thyristor converter bridges which were used in the control loops.

![Figure 4. Converters configuration used in voltage and speed loops](image4)

As seen in [1], the power from IG, PIG, was limited because the $I_{DCMIG}$ reached the maximum viable value in accordance with DCM$_IG$ current specifications. This limited speed from DCM$_IG$ was a challenge because it was not showing a representative contribution from PIG. It was necessary to elevate the DCM$_IG$ speed, $n_{IG}$.

Then, the methodology consists of implementing the comparative analysis of the power and efficiencies, starting with an analysis between the PIG from the scheme in [1] and PIG from the scheme in Figure 5 and Figure 6, covering the scenarios shown in Table 7 related to Figure 5 and Table 8 related to Figure 6. Finally, a comparative efficiency analysis was conducted for two subgroups, one composed of IG and DCM$_IG$ and the other composed of SG and DCM$_SG$ in scenarios related to the scheme in [1] and the schemes in Figure 5 related to Table 7 and Figure 6 related to Table 8.

Thus, the increase of DCM$_IG$ speed, increase of PIG contributions and improvement of IG subgroup efficiencies are shown in results.

Figure 6 shows the scheme implemented in the laboratory to overcome the challenge related to limitation of IG speed [1] and bring the experiment closer to actual offshore conditions, taking into advantages of IG power capacity. It was used as an autotransformer connect to a diodes bridge to vary the voltage applied on the DCM$_IG$ armature circuit and obtain a higher speed and PIG.

2.8. Voltage and Speed Control Loops

The Figure 7 and Figure 8 show the closed control loop used to control the SG speed and voltage via circuit boards.

Figure 9 (a) and Figure 9 (b) show the circuit boards with the respective working point or reference points defined during parameterization for the speed control loop, 65.2 and the voltage control loop, 65.5.

As [1], the master and slave behavior were verified by the generators, considering that SG is the master and IG is the slave. The frequency and voltage are determined by SG, while active power consumed at load is controlled by IG.
3. Experiment Data and Results

3.1. Experiment Data

The experimental data obtained in the laboratory are shown in Table 7 and Table 8. The Table 7 is referred to scheme in Figure 5 and Table 8 is referred to scheme in Figure 6. The unique difference is the presence of IM as additional load presented in Figure 6 scheme. Then, the Table 7 and Table 8 shows the data obtained from the scheme shown respectively in Figure 5 and Figure 6 which are similar to scheme shown in [1], except for the presence of an autotransformer in the DCM$_{IG}$ field circuit for Figure 5 and Figure 6 and an IM as additional load in Figure 6.

Note: For both regulators, the proportional gain P was experimentally set at 0.010 and, in the same manner, the time constant was set at 0.04 s as in [1].
The autotransformer is responsible for applying a voltage range directly on the DCMIG armature to obtain a larger speed range of the DCMIG and to push more power to the IG, keeping the DCMIG parameters in the rated values. Hence, the elevation of IG speed and power depend on just $V_{\text{DCMG}}$, it means this method is different from the scheme presented in [1] that depends on the DCMIG field flux. Both $V_{\text{DCMG}}$ and the DCMIG field flux are adjusted manually. In summary, the [1] shows the data obtained from the scheme that has the 234 Vdc steady source, Table 7 and Table 8 shows the data obtained from the schemes shown in Figure 5 and Figure 6, that has an autotransformer and a diodes bridge as substitute of the 234 Vdc steady source.

The data presented in Table 8 related to Figure 6 system performance results are compared to data obtained from Table 7 related to scheme in Figure 5 and also compared to data obtained from [1]. The scheme in Figure 5 and Table 7 shows the performance of the isolated electric system that considers the voltage application range on the DCMIG armature by an autotransformer and an diodes bridge. The scheme in Figure 6 and Table 8 shows the performance of the isolated electric system that considers the same scheme presented in Figure 5 added by a induction motor, IM, as an additional load.

4. Results

The results and comparative analysis from experiments shown in Figure 5, Figure 6 and the results obtained in [1] are presented in the following.

The results show graphs and analysis of system configurations presented in Figure 5 and Figure 6, data obtained in [1] and analysis of contribution from each generator for each arrange of load, that, in this case, is either just resistive banks or resistive banks added with an induction motor IM. It is noted that for all graphs obtained from [1] is related to a set system frequency of 55 Hz.

Table 7: Operational Scenarios in Controlled Mode and load being resistors bank

<table>
<thead>
<tr>
<th>Results</th>
<th>Scenario 1B</th>
<th>Scenario 2B</th>
<th>Scenario 3B</th>
<th>Scenario 4B</th>
<th>Scenario 5B</th>
<th>Scenario 6B</th>
<th>Scenario 7B</th>
<th>Scenario 8B</th>
<th>Scenario 9B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{SG}}$ (V)</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
</tr>
<tr>
<td>$I_{\text{SG}}$ (A)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$I_{\text{DCMG}}$ (mA)</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
<td>500.0</td>
</tr>
<tr>
<td>$V_{\text{IG}}$ (V)</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
</tr>
<tr>
<td>$I_{\text{IG}}$ (A)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>$I_{\text{PSG}}$ (A)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>$I_{\text{PSG}}$ (W)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>$P_{\text{DCMG}}$ (W)</td>
<td>545.8</td>
<td>545.8</td>
<td>545.8</td>
<td>545.8</td>
<td>545.8</td>
<td>545.8</td>
<td>545.8</td>
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<tr>
<td>$P_{\text{DCMG}}$ (%)</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
</tr>
<tr>
<td>$\eta_{\text{DCMG}}$ (%)</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
<td>545.8%</td>
</tr>
</tbody>
</table>
For all experiments shown in this paper, the system frequency is 60 Hz. Then, the synchronous speed for the experiments in [1] is 1650 rpm (6) and 1800 rpm for the experiments shown in this paper.

To highlight the contributions from autotransformer and diodes bridge in the experiments in relation to the experiments without these devices, it will be presented some analysis based on graphs and experiment results.

Figure 10 shows that the PIG was limited to 1164 W [1] in scenario 2 [1] because the over current of I_{DCMIG} 9.8 A [1] is a value greater than the rated I_{DCMIG} 7.72 A as Table 1. To overcome this barrier, an autotransformer and a diodes bridge were installed to widen the voltage range applied over the DCM armature, as shown in Figure 5 and Figure 6. The armature voltage range with the autotransformer and diodes bridge can vary from 0 to 336 Vdc. This range is greater than the previous V_{ADC} 234 Vdc. As the DCMG speed, n_{SG}, is directly proportional to V_{ADC}, as shown in (2), the n_{SG} is elevated proportionally with the V_{ADC} as shown in scenarios 2 to 8, in Table 7 and Table 8. Then, in this latter method, I_{DCMIG} variation only: as long as I_{DCMIG} decreases, I_{DCMIG} rises because of the load distribution to the generators, whereas the DCMG flux, \phi, remains constant as (3).

![Figure 10. PIG vs PSG with DCMG field flux variation and V_{ADC} kept constant](image)

Figure 11 and Figure 12 shows that the power range supplied from IG, PIG, through the autotransformer method, is greater than PIG of 234 Vdc through the steady source method. Consequently, the power complement from SG is

Table 8: Operational Scenarios in Controlled Mode and load being resistors bank and induction motor

<table>
<thead>
<tr>
<th>Results</th>
<th>Scenario 1C</th>
<th>Scenario 2C</th>
<th>Scenario 3C</th>
<th>Scenario 4C</th>
<th>Scenario 5C</th>
<th>Scenario 6C</th>
<th>Scenario 7C</th>
<th>Scenario 8C</th>
<th>Scenario 9C</th>
</tr>
</thead>
<tbody>
<tr>
<td>\eta_{SG} (%)</td>
<td>0.0</td>
<td>58.12</td>
<td>60.43</td>
<td>62.45</td>
<td>68.18</td>
<td>62.28</td>
<td>23.79</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>I_{DCMIG} (mA)</td>
<td>170</td>
<td>330</td>
<td>330</td>
<td>330</td>
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<td>330</td>
<td>330</td>
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<tr>
<td>V_{DCMIG} (V)</td>
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<td>277.5</td>
<td>280.5</td>
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<td>282.9</td>
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<td>I_{DCMIG} (A)</td>
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<td>4.0</td>
<td>5.0</td>
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<td>9.6</td>
<td>10.5</td>
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<tr>
<td>\eta_{IG} (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>n.a.</td>
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<tr>
<td>I_{IG} (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>n.a.</td>
</tr>
<tr>
<td>V_{IG} (V)</td>
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<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
<td>220.0</td>
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<tr>
<td>f_{IG} (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>n.a.</td>
</tr>
<tr>
<td>\eta_{IG} (W)</td>
<td>1803</td>
<td>1893</td>
<td>1868</td>
<td>1857</td>
<td>1843</td>
<td>1821</td>
<td>1793</td>
<td>n.a.</td>
<td>n.a.</td>
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<tr>
<td>V_{ADC} (V)</td>
<td>288.9</td>
<td>330.0</td>
<td>318.0</td>
<td>310.0</td>
<td>302.3</td>
<td>295.2</td>
<td>285.9</td>
<td>n.a.</td>
<td>n.a.</td>
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<tr>
<td>I_{ADC} (A)</td>
<td>1.0</td>
<td>8.0</td>
<td>7.0</td>
<td>6.0</td>
<td>4.7</td>
<td>3.5</td>
<td>2.0</td>
<td>n.a.</td>
<td>n.a.</td>
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<tr>
<td>I_{DCMIG} (mA)</td>
<td>330.0</td>
<td>330.0</td>
<td>330.0</td>
<td>330.0</td>
<td>330.0</td>
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<td>5.0</td>
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<td>5.0</td>
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<tr>
<td>I_{DCMIG} (A)</td>
<td>0.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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<td>1.23</td>
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<td>1.23</td>
<td>1.23</td>
<td>1.23</td>
<td>1.23</td>
<td>1.23</td>
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<tr>
<td>I_{SG} (A)</td>
<td>2.3</td>
<td>6.0</td>
<td>5.0</td>
<td>4.4</td>
<td>3.6</td>
<td>2.9</td>
<td>2.3</td>
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<td>0.0</td>
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<tr>
<td>I_{SG} (A)</td>
<td>2.8</td>
<td>0.7</td>
<td>1.6</td>
<td>2.3</td>
<td>3.3</td>
<td>4.1</td>
<td>5.3</td>
<td>6.7</td>
<td>4.0</td>
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<td>I_{SG} (A)</td>
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<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
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<td>5.4</td>
<td>5.4</td>
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<tr>
<td>I_{SG} (A)</td>
<td>0.9</td>
<td>0.46</td>
<td>1.29</td>
<td>1.99</td>
<td>3.04</td>
<td>3.74</td>
<td>4.95</td>
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<td>1.03</td>
<td>1.17</td>
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<td>1.88</td>
<td>4.2</td>
<td>4.0</td>
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<tr>
<td>I_{SG} (A)</td>
<td>2.46</td>
<td>3.91</td>
<td>3.14</td>
<td>3.00</td>
<td>2.88</td>
<td>2.51</td>
<td>2.29</td>
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<tr>
<td>\eta_{SG} (%)</td>
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<td>4.55</td>
<td>3.91</td>
<td>3.22</td>
<td>2.16</td>
<td>1.45</td>
<td>0.25</td>
<td>0.0</td>
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</tr>
<tr>
<td>\eta_{SG} (%)</td>
<td>0.0</td>
<td>30.87</td>
<td>44.17</td>
<td>53.75</td>
<td>65.35</td>
<td>66.88</td>
<td>69.51</td>
<td>67.59</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Obs.: 1- italic and bold text: calculated values by equations 23 to 33
2- Frequency was chosen based on the average between the SG and IG rated frequency
3- n.a: not applicable
lower than the PSG from 234 Vdc steady source method. Both methods feed the entire resistive load in Figure 10 and Figure 11, and resistive and motor load as shown in Figure 12.

In Figure 13, Figure 14 and Figure 15 shows the comparative results of IG and SG primary machine output power, $P_{\text{DCMIG}}$ vs $P_{\text{DCMSG}}$. These performances are similar to PIG and PSG performances shown in Figure 10, Figure 11 and Figure 12. The $P_{\text{DCMIG}}$ in Figure 13 elevates because the flux decreases and $V_{\text{aDCMIG}}$ is kept constant [1]. The $P_{\text{DCMIG}}$ in Figure 14 and Figure 15 elevates because of the $V_{\text{aDCMIG}}$ increases, which is manually adjusted by the autotransformer shown in Figure 5 and Figure 6.

The efficiency results shown in Figure 16, Figure 17 and Figure 18 present each subgroup efficiency for each scenario and load conditions. Each subgroup efficiency is resulted from relation between a generator and a DCM as shown in (32) and (33). In summary, the target scenarios are: 2 to 7 (without autotransformer) as in [1], scenarios 2B to 8B (with autotransformer and just resistive load) and scenarios 2C to 8C (with autotransformer, resistive load and induction motor).

![Figure 11. PIG vs PSG with $V_{\text{aDCMIG}}$ variation and field flux kept constant (Only resistive load)](image1)

![Figure 12. PIG vs PSG with $V_{\text{aDCMIG}}$ variation and field flux kept constant (Resistive load plus IM)](image2)

The IG subgroup efficiencies shown in Figure 17 and Figure 18 are bigger than IG subgroup efficiencies from similar scenarios in Figure 16. Moreover, the elevation of power from IG due to the increase of $n_{\text{IG}}$, $n_{\text{IG}}$, is more representative of actual offshore conditions. The turbines can assume whatever speed required from generators in offshore platforms.

The reduction of losses contributed to increased IG subgroup efficiency as shown in Figure 17 and Figure 18. Fig. 16 shows the machine’s efficiencies when the $I_{\text{DCMIG}}$ decreases to elevate the speed. The efficiency improves when the $V_{\text{aDCMIG}}$ elevation method is applied as shown in Figure 17 and Figure 18.
The Figure 17 and Figure 18 are higher than the efficiency presented in Figure 16 considering that the Figure 16 indicates a DCMIG speed range is more restricted as already clarified in [1].

The efficiencies from the $V_{adcmig}$ elevation method were greater than efficiencies from the scheme with Vdc steady source [1], as shown in Figure 17 and Figure 18. $V_{adcmig}$ elevation method does not have the additional current losses of Vdc steady source method. When the field flux $\phi$, $I_{dcming}$, is decreased, $I_{adcmig}$ is increased by (3) and IG speed, $n_{IG}$, is increased by (2). The main losses for the Vdc steady source method are related to higher $I_{adcmig}$ elevation, $P(w)=Ra*I_{adcmig}^2$. Then, by the Vdc steady source method, besides $I_{adcmig}$ be elevated due to the rise of PIG, $I_{adcmig}$ is also elevated due to reduction of $I_{adcmig}$. Higher $I_{adcmig}$ result in higher losses and lower efficiencies.

As shown in power performance graphs related to the $V_{adcmig}$ elevation method, Figure 11, Figure 12, Figure 14 and Figure 15, the PIG and $P_{adcmig}$ are more representative of actual operation conditions in offshore platforms.

In continuation of this content, a study of load and generation transients has been done and submitted to publication in COBEP, Brazilian Power Electronic Conference that took place in November, 2017.

In the next stage of this work, it will be studied energy regeneration and ballast load as a additional way to the system regulation.

5. Conclusion

The cited electric system shows voltage and frequency regulation for each scenario transition as demonstrated by results and respective analysis.

As it happened in [1], it was realized the master and slave behaviors to respectively SG and IG. SG controls the system voltage and frequency and IG follows the voltage and frequency defined by SG. The IG establishes the active power supplied to the system and the SG complements the rest of active power and reactive power required. The PIG depends on the IG shaft speed imposed by DCMIG. The PSG and the system voltage and frequency are controlled by voltage and speed control loops presented in Figure 5 and Figure 6.

It was realized a greater PIG range in the scenarios in Table 7 and in Table 8, than the scenarios from [1] due to $V_{adcmig}$ elevation method. The PSG complemented the PIG manually set to attend the load.

The $V_{adcmig}$ elevation method resulted in increase of $P_{adcmig}$ and PIG and higher IG subgroup efficiency than the $I_{adcmig}$ reduction method[1]. The increase of $P_{adcmig}$ and PIG were results of IG speed increase, $n_{IG}$, that was obtained by elevation of $V_{adcmig}$ as shown in Figure 11, Figure 12 and Figure 14. The use of $V_{adcmig}$ range instead of Vdc steady source enables to reach the $I_{adcmig}$ limit of 8.0 A and 1893 rpm shaft speed, it is 5.16% higher than synchronous speed. It is higher than Vdc steady source method limit that reached just 4.24% higher than synchronous speed, Figure 16 and [1].

As shown in power performance graphs related to the $V_{adcmig}$ elevation method, Figure 11, Figure 12, Figure 14 and Figure 15, the PIG and $P_{adcmig}$ are more representative of actual operation conditions in offshore platforms.

In continuation of this content, a study of load and generation transients has been done and submitted to publication in COBEP, Brazilian Power Electronic Conference that took place in November, 2017.

In the next stage of this work, it will be studied energy regeneration and ballast load as additional way to the system regulation.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

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References


Appendix 1_ Induction Motor Parameters

The follow calculus were developed on base in [7].

1. No Load and Locked Rotor Tests

The Figure 1 shows the circuit implemented in laboratory to no load test and locked rotor test.

The temperature during the test= 26ºC.

![Figure 1: No load test and locked rotor test circuit](image1)

The Figure 2 shows the induction motor IM equivalent circuit.

5.1. No Load Test

In this section, it will be presented the no load test and locked rotor test to calculus the IM parameters such as impedances, currents, losses and efficiency

The Table 1 presented the no load test measurements.

![Figure 2: Induction Motor Equivalent Circuit](image2)

<table>
<thead>
<tr>
<th>Vapply (V)</th>
<th>W1 (W)</th>
<th>W2 (W)</th>
<th>V (V)</th>
<th>A (A)</th>
<th>W1+W2 (W)</th>
</tr>
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<tr>
<td>240</td>
<td>-120.0 +220.0</td>
<td>240.2</td>
<td>1.50</td>
<td>100.0</td>
<td></td>
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<tr>
<td>220</td>
<td>-100.0 +170.0</td>
<td>220.8</td>
<td>1.35</td>
<td>70.0</td>
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</tr>
<tr>
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<td>1.15</td>
<td>60.0</td>
<td></td>
</tr>
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<td>180.3</td>
<td>1.00</td>
<td>50.0</td>
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<td>0.90</td>
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</tr>
<tr>
<td>140</td>
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<td>140.0</td>
<td>0.75</td>
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<td></td>
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<tr>
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<td>120.0</td>
<td>0.65</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>100</td>
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<td>100.1</td>
<td>0.55</td>
<td>15.0</td>
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<td>80.0</td>
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<td>10.0</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>-4.0 +12.5</td>
<td>60.0</td>
<td>0.25</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>40</td>
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<td>5.0</td>
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<tr>
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<td>0.05</td>
<td>2.0</td>
<td></td>
</tr>
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<td>0.0</td>
<td>0.0</td>
<td>1.99</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 shows the curve of voltage applied and power measured by wattmeter (w1) and (w2). Note that the cross of curve and vertical axe result in estimated attrition and ventilation losses (Pav). In this case Pav is 1 W as demonstrated.

![Figure 3: Results of no load test: W1+W2 vs Voltage applied](image3)

5.2. Locked Rotor Test

The Table 2 shows the locked rotor test measurements.

![Figure 4: Equivalent circuit - No load test](image4)

- Magnetization Current
  \[
  \text{Im} = \text{Magnetization Current} \\
  \text{Im}= 1.35 \text{ A as shown in Table 1.}
  \]

![Figure 2: Induction Motor Equivalent Circuit](image2)

\[
\text{Im}= 1.35 \text{ A as shown in Table 1.}
\]

- Rated Current
  \[
  \text{In} = \text{Rated Current} \\
  \text{In} = \frac{P}{\sqrt{3} \cdot V_{pp} \cdot \cos \phi \cdot \eta} \quad (1) \\
  \text{In} = \frac{370}{\sqrt{3} \cdot 220 \cdot 0.71 \cdot 0.76} \quad (2) \\
  \text{In} = 1.80 \text{ A}
  \]

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The Figure 3 shows the induction motor IM equivalent circuit during locked rotor test.

Figure 5: Equivalent circuit _ Locked rotor test

5.3. Magnetization Branch Parameters

- Motor Average Measured Resistance
- Phase resistance in star connection
- Phase resistance in delta connection

Table 3: Average Resistance

<table>
<thead>
<tr>
<th>RAA</th>
<th>RRH</th>
<th>RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>10.3</td>
<td>10.16</td>
</tr>
</tbody>
</table>

\[ R_m = \frac{(10.1 + 10.3 + 10.16)}{3} = 10.16 \Omega \]  

- r1 Calculus

Follow the calculus memory of stator winding resistor r1.

\[ R_m = \frac{rd * 2rd}{3rd} \]  
\[ R_m = \frac{2}{3} rd \]  
\[ rd = \frac{3}{2} rm \]  
\[ ry = \frac{1}{3} rd \]  

\[ ry = \frac{R_m}{2} = \frac{10.16}{2} \]  
\[ r1 = 5.08 \Omega \]  

- r2 Calculus

From Table XI, \( W1 + W2 = 85 \) W

\[ W1 + W2 = 3 \ast (r1 + r2) \ast \text{in}^2 \]  
\[ 85/(3 \ast 1.8^2) = 5.08 + r2 \]  
\[ r2 = 3.66 \Omega \]  

- Reactive Power

\[ Q = \sqrt{3} \ast V_{pp} \ast I_{dwMT} \ast \text{sen} \phi = \sqrt{3} \ast (W2 - W1) \]  

From Table XI, W2-W1=45

\[ Q = \sqrt{3} \ast (65 - 20) = 77.94 \text{Var} \]  
\[ Q = 3 \ast (x1 + x2) \ast \text{In}^2 \]  

(13) and (2) in (14)

\[ 77.94 = 3 \ast (x1 + x2) \ast 1.8^2 \]  
\[ (x1 + x2) = 8.01 \Omega \]  

\[ \begin{align*} 
& x1 \rightarrow x2 \\
& r1 \rightarrow r2 
\end{align*} \]  

\[ x1 = \frac{r1 \ast x2}{r2} \]  
\[ x1 = 5.08 \ast \frac{x2}{3.66} \]  

From (15) and (18), result in

\[ 5.08 \ast x2 + x2 \ast 3.66 = 29.32 \]  
\[ x2 \ast 8.74 = 29.32 \]  
\[ x2 = 3.35 \Omega \]  

(21) in (18), result in

\[ x1 = 5.08 \ast \frac{3.35}{3.66} \]  
\[ x1 = 4.65 \Omega \]
The $P_{av}$ was defined in Figure 3 and consist in 1 W and Pnl (no load losses) is no load test for 220 V, it resulted in 70 W ($W_1 + W_2$).

- **Stator Joules Losses**
  
  $$P_{jstator} = \text{Stator Joule Losses} = 3 \times r_1 \times \text{i} \text{m}^2$$  
  $$(24)$$
  
  $$P_{jstator} = 3 \times 5.08 \times 1.35^2$$  
  $$(25)$$
  
  $$P_{jstator} = 27.77 \text{ W}$$  
  $$(26)$$

- **Phf_ histerese and foucault losses**
  
  $$P_{hf} = (W_1 + W_2) - 3 \times r_1 \times \text{i} \text{m}^2 - P_{av}$$  
  $$(27)$$
  
  $$P_{hf} = 70 - 3 \times 5.08 \times 1.35^2 - 1$$  
  $$(28)$$
  
  $$P_{hf} = 41.23 \text{ W}$$  
  $$(29)$$

5.4. **No Load Reactive Power**

$$Q_o = \sqrt{3} \times (W_2 - W_1)$$  
$$(30)$$

From Table 1, $W_2 - W_1 = 270\text{ W}$

$$Q_o = \sqrt{3} \times 270 \text{ W}$$

$$Q_o = 467.65 \text{ Var}$$  
$$(31)$$

5.5. **Magnetization Branch**

- **No load Reactive Power in Magnetization Branch**
  
  $$Q_m = Q_o - 3 \times X_1 \times \text{i} \text{o}^2$$  
  $$(32)$$
  
  $$Q_m = 467.65 - 3 \times 4.66 \times 1.35^2$$  
  $$(33)$$
  
  $$Q_m = 442.23 \text{ Var}$$  
  $$(34)$$

- **Magnetization Branch Power Factor Angle**
  
  $$\theta_o = \arctg \frac{442.23}{41.23}$$  
  $$(35)$$
  
  $$\theta_o = 84.67^\circ$$  
  $$(36)$$

- **Magnetization Branch Currents**
  
  $$I_{rm} = I_m \times \sin \theta_o$$  
  $$(37)$$
  
  $$I_{rm} = 1.35 \times \sin 84.67^\circ$$  
  $$(38)$$
  
  $$I_{rm} = 0.1254 A$$  
  $$(39)$$

- **Magnetization Branch Resistance**
  
  $$r_m = \frac{P_{hf}}{3 \times I_{rm}^2}$$  
  $$(42)$$
  
  $$r_m = 41.23 \div (3 \times 0.1254^2)$$  
  $$(43)$$
  
  $$r_m = 873.97 \Omega$$  
  $$(44)$$

- **Magnetization Branch Reactance**
  
  $$x_m = \frac{Q_m}{3 \times I_{rm}^2}$$  
  $$(45)$$
  
  $$x_m = 442.23 \div (3 \times 0.1254^2)$$  
  $$(46)$$
  
  $$x_m = 82.10 \Omega$$  
  $$(47)$$

3. **Parameters of Induction Motor**

Figure 8 shows all IM parameters calculated as resisters, reactance and currents as data obtained during experiment, without temperature correction because the motor operated no load.

4. **Induction Motor Efficiency**

It will be calculated the temperature correction factor, corrected resistences to 40ºC, corrected winding losses, $P_{wind40^\circ C}$, and total losses, $P_{tl}$, before induction motor efficiency calculus.

5.6. **Temperature Correction Factor and Resistance Correction**

- **Temperature Correction Factor Kt 40ºC**
  
  $$Kt 40^\circ C = 234.5 + 40 \div (234.5 + 26)$$  
  $$(48)$$
  
  $$Kt 40^\circ C = 1.054 \text{ to } r_1 \text{ and } r_2$$  
  $$(49)$$

- **Resistance Correction**
  
  $$r_1 40^\circ C = r_1 26^\circ \times 1.054$$  
  $$(50)$$

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5.7. Corrected Winding Losses and Total Losses

- Winding Losses

The winding losses, $P_{\text{wind}}$, measured in locked rotor test, Table 2, need to be corrected to 40°C. Follow the corrected winding losses.

$$ P_{\text{wind}40^\circ} = k t_{40^\circ} \cdot P_{\text{wind}26^\circ} \quad \text{(locked rotor test)} $$

$$ P_{\text{wind}40^\circ} = 1.054 \times 85 W $$

$$ P_{\text{wind}40^\circ} = 89.59 W $$

- Total Losses

The total losses, $P_{\text{tl}}$, calculus:

$$ P_{\text{tl}} = P_{\text{hf}} + P_{\text{av}} + P_{\text{wind}40^\circ} $$

$$ P_{\text{tl}} = 41.23W + 1W + 89.59W $$

$$ P_{\text{tl}} = 131.82 W $$

5.8. Rated Motor Efficiency Estimate

$$ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} $$

$$ P_{\text{in}} = P_{\text{out}} + \text{losses} $$

$$ P_{\text{in}} = 370 W + 131.82 W $$

$$ P_{\text{in}} = 501.82 W $$

$$ \eta = 0.7373 \text{ %} $$

5. Induction Motor Currents

Follow the calculus of IM reactive and active currents ($I_{\text{dwMT}}$ and $I_{\text{wMT}}$). This values are shown in Table 8 for all scenarios tested.

- Reactive Current

$$ Q = \sqrt{3} \times 220 \times I_{\text{dwMT}} = \sqrt{3} \times (W2 - W1) $$

$$ \sqrt{3} \times 220 \times I_{\text{dwMT}} = 467.65 $$

$$ I_{\text{dwMT}} = 1.23 A $$

** The difference between $I_{\text{dwMT}}$ and $I_{\text{wMT}}$ is perfectly acceptable. The difference close to 0.1 A between expected and found values is due to small measurements errors and instruments precision and accuracy errors. It does not impact the presented modeling. Therefore, the results and modeling continue valid.

- Active Current

$$ P = (W1 + W2) = 70.0 W $$

$$ Q = \sqrt{3} (W2 - W1) = 467.6 W $$

$$ S = \sqrt{70.0^2 + 467.6^2} = 472.86 VA $$

$$ \cos \emptyset = \frac{P}{S} = \frac{70}{472.86} $$

$$ \cos \emptyset = 0.148 $$

$$ I_{\text{wMT}} = I_o \times \cos \emptyset = 1.35 \times 0.148 $$

$$ I_{\text{wMT}} = 0.20 A $$

In Figure 9 are shown resistor banks current and no load IM current.

![Figure 9: Resistors bank and IM currents in scenarios C](image-url)