Analysis of Synchronous and Induction Generators in Parallel Operation Mode in an Isolated Electric System using a Ballast Load as a Regulation System under Transient Conditions

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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, which 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, it 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 balance and its interactions are presented in this paper in various operational scenarios. The results enable comparisons of the two methods of induction generator speed control, either by autotransformer method or by field flux variation method. The first one results in larger range of speed and power from the induction generator. Therefore, it has more confidence features of actual operational conditions. Besides, it presents a ballast load as contingency against a transient condition that consist on a great removal of loads considering the induction generation keeping on the same level of generation and it is higher than load demand. Synchronous generation pursues to regulate automatically decreasing its supply power but it is not enough due to high power supplied by induction generator. Then, there is a motorizing of the synchronous machine, and consequently its prime machine becomes generator what causes regenerating energy to the grid, because the supply converter of this machine operates as inverter, occurring the field inversing. This condition causes an increase of system frequency that should be regulated by a ballast load as described in this paper.

Nomenclature and Abbreviations

VSG  Synchronous generator voltage
I SG  Synchronous generator current
fSG  Synchronous generator frequency
IfieldSG  Synchronous generator field current
nSG  Synchronous generator speed
DCMIG  Direct current motor coupled with induction generator
DCMSG  Direct current motor coupled with synchronous generator
DCGSG  Direct current generator coupled with synchronous generator
IaDCMSG  Armature current of direct current motor coupled with synchronous generator
IfDCMSG  Field current of direct current motor coupled with synchronous generator

VIG  Induction generator voltage
fIG  Induction generator frequency
IIG  Induction generator current
fIG  Induction generator speed
IadCMIG  Current of direct current motor coupled with induction generator
IfadCMIG  Field current of direct current motor coupled with induction generator

C  Capacitor bank current
IloadR  Resistors banks current
Q  Reactive power

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I. INTRODUCTION

This paper is an extension of work originally presented in ASTESJ [11] which also calls [1] and [3].

The use of induction generators in generation systems is usual in wind plants [4-6] or eventually in small hydroelectric generation units [12]. 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 added by this current article.

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 an induction motor inserted in experiment what enables a novel analysis of the system behavior.

Besides, this paper presents a project to face a specific load transient shown in [2] which consist on a great load removal up to synchronous generator loses the capacity of frequency regulator. It happens because the generator reaches automatically the null generation and assumes the condition of motorizing; absorbing the energy from the induction generator because the induction generator keeps over the same generation level, and it is higher than the load demand. This condition leads to higher frequency scenario which requires a regulation way. This alternative consist on the insertion of a ballast load in the isolated system in order to decrease the system frequency when it rises or increase the system frequency when it falls. This complementary project is based on [2], [9] and [10].

This paper presents results that show additional remarkable characteristics by operation in parallel mode between 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, [7], [12].

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 [7].
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.

### 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.

### 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: DMC\textsubscript{IG} Dataplate

| Direct Current Motor \textsubscript{IG} |       |   |   |   |
|----------------------------------------|-------|---|---|---|
| V                                      | 220   | 7.5 A | 1.86 kW | 1410 rpm | 0.8 PF | 50 Hz |

#### Table 2: DMC\textsubscript{SG} Dataplate

| Direct Current Motor \textsubscript{SG} |       |   |   |   |
|----------------------------------------|-------|---|---|---|
| V                                      | 230   | 5.0 A | 2.0 kVA | 1800 rpm | 0.8 PF | 60 Hz |

#### Table 3: IG Dataplate

| Induction Generator (IG) |       |   |   |   |
|--------------------------|-------|---|---|---|
| V                        | 220   | 7.5 A | 1.86 kW | 1410 rpm | 0.8 PF | 50 Hz |

#### Table 4: SG Dataplate

| Synchronous Generator (SG) |       |   |   |   |
|----------------------------|-------|---|---|---|
| V                         | 230   | 5.0 A | 2.0 kVA | 1800 rpm | 0.8 PF | 60 Hz |

#### Table 5: Load Dataplate

| Resistive Load |       |   |   |   |
|----------------|-------|---|---|---|
| Load 1 (kW)   | 2/3   |   |   |   |
| Load 2 (kW)   | 2/3   |   |   |   |
| Load 3 (kW)   | 2/3   |   |   |   |

#### Table 6: Load: Induction Motor Dataplate

| Induction Motor |       |   |   |   |
|-----------------|-------|---|---|---|
|                 | 0.37 kW | 1715 rpm | Cos φ: 0.71 | 60 Hz |

### Equations - Part I

Follow the main equations:

- **Direct Current Motor**
  \[
  n = \frac{E}{k \times \phi} \tag{1}
  \]
  \[
  n = \frac{U_a - (\sum R_a) \times I_a}{k \times \phi} \tag{2}
  \]
  \[
  C_{\text{conjugate}} = k \times \phi \times I_a \tag{3}
  \]
- **Synchronous Generator**
  \[
  \dot{E} = \dot{U} + \sum (R + jX) \times \dot{I} \tag{4}
  \]
- **Induction Generator**
  \[
  \text{Slip \%} = \frac{n_s - n_{\text{IG}}}{n_s} \times 100 \tag{5}
  \]
  \[
  n_s = \frac{120 \times f_{SG}}{\text{number of poles}} \tag{6}
  \]

### Capacitor Bank Sizing

As informed at the IG dataplate \(\cos \phi = 0.8\), then \(\sin \phi = 0.6\)

The reactive power is calculated to attend the reactive demand of the Induction Machine:
\[ Q = \sqrt{3} \cdot V \cdot I \cdot \text{sen} \phi \]  
(7)

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

\[ Q_{\text{generated}} = F_c \cdot Q \]  
(8)

\[ F_c = 1.2 \]  
[13]

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.

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

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

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

\[ X_c = 70.6 \Omega \]

\[ X_c = \frac{1}{2 \cdot \Pi \cdot f \cdot C} = \frac{1}{2 \cdot \Pi \cdot 50 \cdot C} \Rightarrow \]  
(12)

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

**Resistive Divider Sizing:**

- Field Control Loop Resistive Divider as in Figure 5 and Figure 6.

\[ (1 \cdot k \Omega + r_1) \rightarrow 300 \cdot V_{\text{bridge output voltage}} \]  
(14)

\[ r_2(1 \cdot k \Omega) \rightarrow 4V_{\left(\text{MP 410 T voltage limit}\right)} \]  
(15)

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

- Resistor Power Sizing:

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

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

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

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

\[ (1 \cdot k \Omega + r_1) \rightarrow 36 \cdot V_{\text{tac k generator output voltage}} \]  
(19)

\[ r_2(1 \cdot k \Omega) \rightarrow 4V_{\left(\text{MP 410 T voltage limit}\right)} \]  
(20)

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

- Resistor Power sizing:

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

- The resistors chosen, based on the sized resistor, were

\[ r_1 = 8.3 \cdot k \Omega \land r_2 = 947 \Omega \]

**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.

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

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

\[ Ic - I_{dMT} = Ic_1 + Ic_2 \]  
(25)

\[ I_{wloadR} + I_{dMT} = I_{wSG} + I_{wIG} \]  
(26)

As \( I_{SG}, I_{IG}, Ic \) and \( I_{wloadR} \) are measured values, shown in Table 7 and Table 8, \( I_{wMT} \text{(Motor's reactive current)} \) and \( I_{dMT} \text{(Motor's active current)} \) are values calculated as [11]. Then, the system has 4 four variables and 4 four equations. Then, for each scenario, the four variables, \( I_{wSG}, Ic_1, I_{wIG} \) 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 \( P_{SG}, P_{DCMSG}, P_{DCMIG} \), as follows:

\[ P_{SG} = \sqrt{3} \cdot V_{SG} \cdot I_{wSG} \]  
(27)

\[ P_{IG} = \sqrt{3} \cdot V_{IG} \cdot I_{wIG} \]  
(28)

\[ P_{DCMSG} = V_{a_{DCMSG}} \cdot I_{a_{DCMSG}} \]  
(29)

\[ P_{DCMIG} = V_{a_{DCMIG}} \cdot I_{a_{DCMIG}} \]  
(30)

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

\[ \eta_{SG} \% = \frac{P_{SG}}{P_{DCMSG}} \cdot 100, \]  
(32)
\[ \eta_{IG} = \frac{P_{IG}}{P_{DCMIG}} \times 100 \]  

(33)

**Equations - Part III**

The equations and calculus used to determine the IM parameters and IM equivalent circuit as primary, secondary impedances and currents, including IM currents showed in Table 8 that were calculated in [11].

**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 1: Laboratory assembly](image1)

Figure 1: Laboratory assembly

Figure 2 shows another experiment view, including the taco generator and its connections. The detailed circuit is shown in Figure 6.

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

Figure 2: Another view of laboratory assembly

As seen in [1], the power from IG, \( P_{IG} \), 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 5: Synchronous generator in parallel with induction generator and its dc motor _ 234 Vdc steady source for DCM$_{IG}$

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.

Figure 6: Synchronous generator in parallel with induction generator and its dc Motors _ Vdc variable source for DCM$_{IG}$
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 7: Speed Control Loop](image)

![Figure 8: Field voltage control loop](image)

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.

![Figure 9: Circuit boards MP410T used to implement the control loops](image)

The master and slave behavior between generators were realized, considering that the SG is master and the IG is slave. SG determines the frequency and voltage, while IG controls active power consumed at load.

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].

Experiment Data and Results

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 DCMIG field circuit for Figure 5 and Figure 6 and an additional motor as load in Figure 6.

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 into the rated values. Hence, the elevation of IG speed and power depend on just $V_{adCMI}G$, it means this method is different from the scheme presented in [1] that depends on the DCMIG field flux. Both $V_{adCMI}G$ and the DCMIG field flux are adjusted manually. In summary, the [1] shows the data obtained from the scheme that has the 234Vdc 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 are compared to data obtained from Table 7 related to scheme in Figure 5, which are 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 a 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 an induction motor, IM, as an additional load.
Table 7: Operational Scenarios in Controlled Mode and load being resistors bank

| Results       | Scenario 1B   | Scenario 2B   | Scenario 3B   | Scenario 4B   | Scenario 5B   | Scenario 6B   | Scenario 7B   | Scenario 8B   | Scenario 9B   |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $V_{SG}$ (V)  | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         |
| $f_{SG}$ (Hz) | 60            | 60            | 60            | 60            | 60            | 60            | 60            | 60,0          | 60,0          |
| $I_{feilds}$ (mA) | 190          | 320           | 300           | 300           | 320           | 350           | 370           | 340,100       |
| $V_{ADCMSG}$ (V) | 272.9       | 275.0         | 276.2         | 276.8         | 277.5         | 278.0         | 280.7         | 278.5         | 270.0         |
| $I_{ADCMSG}$ (A) | 2.0          | 2.5           | 3.8           | 4.7           | 6.2           | 7.4           | 9.5           | 10.6          | 2.0           |
| $V_{IG}$ (V)  | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | 220.0         | n.a.          | n.a.          |
| $I_{IG}$ (Hz) | 60            | 60            | 60            | 60            | 60            | 60            | 60            | n.a.          | n.a.          |
| $n_{IG}$ (rpm) | 1793          | 1896          | 1878          | 1857          | 1848          | 1821          | 1794          | n.a.          | n.a.          |
| $V_{ADCMSG}$ (V) | 291.3       | 323.6         | 316.7         | 308.3         | 301.3         | 293.0         | 284.1         | n.a.          | n.a.          |
| $I_{ADCMSG}$ (A) | 0.5          | 8.0           | 7.0           | 6.0           | 4.7           | 3.5           | 2.0           | n.a.          | n.a.          |
| $V_{IG}$ (V)  | 330.0         | 330.0         | 330.0         | 330.0         | 330.0         | 330.0         | 330.0         | n.a.          | n.a.          |
| $I_{loadR}$ (A) | 0.0          | 5.0           | 5.0           | 5.0           | 5.0           | 5.0           | 5.0           | 5.0           | 0.0           |
| $I_{IG}$ (A)  | 2.4           | 5.8           | 5.1           | 4.4           | 3.7           | 2.9           | 2.4           | 0.0           | 0.0           |
| $I_{IG}$ (A)  | 2.9           | 1.5           | 2.0           | 2.8           | 3.6           | 4.5           | 5.6           | 7.4           | 4.0           |
| $I_{IG}$ (A)  | 5.4           | 5.4           | 5.4           | 5.4           | 5.4           | 5.4           | 5.4           | 5.4           | 4.0           |
| $I_{WSG}$ (A) | 0.0           | 1.05          | 1.48          | 1.97          | 2.47          | 3.32          | 4.65          | 5.03          | 0.0           |
| $I_{WIG}$ (A) | 0.0           | 3.95          | 3.51          | 3.03          | 2.53          | 1.68          | 0.35          | 0.0           | 0.0           |
| $PSG$ (W)     | 0.0           | 400.5         | 565.5         | 750.0         | 939.8         | 1266.6        | 1770.1        | 1915.8        | 0.0           |
| $PIG$ (W)     | 0.0           | 1504.8        | 1335.8        | 1155.3        | 965.5         | 638.67        | 135.17        | 0.0           | 0.0           |
| $P_{ADCMSG}$ (W) | 545.8        | 687.5         | 1049.6        | 1301.0        | 1665.0        | 2057.2        | 2666.7        | 2962.7        | 543.4         |
| $P_{DCMSG}$ (W) | 145.7        | 2588.8        | 2216.9        | 1849.8        | 1416.1        | 1025.5        | 568.2         | 0.0           | 0.0           |
| $\eta_{GROUP}$ (%) | 0.0           | 58.15          | 58.33          | 60.47          | 61.84          | 61.80          | 58.89          | 64.66          | 0.0           |
| $\eta_{SG}$ (%) | 0.0           | 58.25          | 53.88          | 57.65          | 56.44          | 61.57          | 66.38          | 64.66          | 0.0           |
| $\eta_{IG}$ (%) | 0.0           | 58.12          | 60.43          | 62.45          | 68.18          | 62.28          | 23.79          | n.a.          | n.a.          |

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

| Results | Scenario | 1C | 2C | 3C | 4C | 5C | 6C | 7C | 8C | 9C |
|---------|----------|----|----|----|----|----|----|----|----|----|
| $V_{SG}$ (V) | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 |
| $f_{SG}$ (Hz) | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| $I_{felds}$ (mA) | 170 | 420 | 410 | 400 | 400 | 430 | 475 | 390 | 100 |
| $V_{adCMG}$ (V) | 278.9 | 277.0 | 277.5 | 280.5 | 281.0 | 281.1 | 282.9 | 279.2 | 271.7 |
| $I_{adCMG}$ (A) | 2.0 | 2.9 | 4.0 | 5.0 | 6.3 | 7.6 | 9.6 | 10.5 | 2.0 |
| $I_{IG}$ (mA) | 530.0 | 530.0 | 530.0 | 530.0 | 530.0 | 520.0 | 520.0 | 520.0 | 551.0 |
| $V_{IG}$ (V) | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 220.0 | 0.0 |
| $I_{IG}$ (Hz) | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| $n_{IG}$ (rpm) | 1803 | 1893 | 1868 | 1857 | 1843 | 1821 | 1793 | 0.0 | n.a. |
| $V_{adCMIG}$ (V) | 288.9 | 330.0 | 318.0 | 310.0 | 302.3 | 295.2 | 285.9 | 0.0 | n.a. |
| $I_{adCMIG}$ (A) | 1.0 | 8.0 | 7.0 | 6.0 | 4.7 | 3.5 | 2.0 | 0.0 | 0.0 |
| $I_{IG}$ (mA) | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 0.0 |
| $I_{loadIG}$ (A) | 0.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0.0 |
| $I_{CMIG}$ (A) | 0.0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 |
| $I_{CMIG}$ (A) | 0.0 | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | 0.0 |
| $I_{IG}$ (A) | 2.3 | 6.0 | 5.0 | 4.4 | 3.6 | 2.9 | 2.3 | 0.0 | 0.0 |
| $I_{IG}$ (A) | 2.8 | 0.7 | 1.6 | 2.3 | 3.3 | 4.1 | 5.3 | 6.7 | 4.0 |
| $I_{C}$ (A) | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 0.0 |
| $I_{WSG}$ (A) | 0.0 | 0.65 | 1.29 | 1.99 | 3.04 | 3.74 | 4.95 | 5.23 | 0.0 |
| $I_{CI}$ (A) | 2.94 | 0.28 | 1.03 | 1.17 | 1.29 | 1.66 | 1.88 | 4.2 | 4.0 |
| $I_{CI}$ (A) | 2.46 | 3.91 | 3.14 | 3.00 | 2.88 | 2.51 | 2.29 | 0.0 | 0.0 |
| $I_{WSG}$ (A) | 0.0 | 4.55 | 3.91 | 3.22 | 2.16 | 1.45 | 0.25 | 0.0 | 0.0 |
| $PSG$ (W) | 0.0 | 247.97 | 490.34 | 753.80 | 1156.9 | 1428.7 | 1887.8 | 1991.7 | 0.0 |
| $PIG$ (W) | 0.0 | 1733.5 | 1491.1 | 1227.7 | 824.52 | 552.74 | 93.68 | 0.0 | 0.0 |
| $P_{DCMSG}$ (W) | 557.8 | 805.30 | 1110.0 | 1402.5 | 1770.3 | 2136.4 | 2715.8 | 2931.6 | 624.5 |
| $P_{DCMSG}$ (W) | 288.9 | 2640.0 | 2226.0 | 1860.0 | 1420.8 | 1033.2 | 571.8 | 0.0 | 0.0 |
| $\eta_{GROUP}$ (%) | 0.0 | 57.55 | 59.40 | 60.73 | 62.09 | 62.52 | 60.27 | 67.59 | 0.0 |
| $\eta_{SI}$ (%) | 0.0 | 30.87 | 44.17 | 53.75 | 65.35 | 66.88 | 69.51 | 67.59 | 0.0 |
| $\eta_{IG}$ (%) | 0.0 | 65.66 | 66.99 | 66.00 | 58.03 | 53.50 | 16.38 | 0.0 | n.a. |

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
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 ether 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. 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 $I_{aDCMIG}$ 9.8 A [1] is a value greater than the rated $I_{aDCMIG}$ of 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 $V_{aDCMIG}$ of 234 Vdc. As the DCM speed, $n_{IG}$, is directly proportional to $V_{aDCMIG}$ as shown in (2), the $n_{IG}$ is elevated proportionally with the $V_{aDCMIG}$ as shown in scenarios 2 to 8 and Table 7 and Table 8. Then, in this latter method, $I_{aDCMIG}$ variation depends on the load conjugate variation only; as long as $I_{aDCMIG}$ decreases, $I_{aDCMSG}$ rises because of the load distribution to the generators, whereas the DCM flux, $\phi$, remains constant as (3).

Figure 10: PIG vs PSG with $DCMIG$ field flux variation and $V_{aDCMIG}$ kept constant

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 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.

Figure 11: PIG vs PSG with $V_{aDCMIG}$ variation and field flux kept constant (Only resistive load)
In Figure 13, Figure 14 and Figure 15 show the comparative results of IG and SG primary machine output power, $P_{DCMIG}$ vs $P_{DCMSG}$. These performances are similar to PIG and PSG performances shown in Figure 10, Figure 11 and Figure 12. The $P_{DCMIG}$ in Figure 13 elevates because the flux decreases and $V_{aDCMIG}$ is kept constant. The $P_{DCMIG}$ in Figure 14 and Figure 15 elevates because of the $V_{aDCMIG}$ 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).

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 DCMIG speed, $n_{IG}$, 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 $I_{DCMIG}$ decreases to elevate the speed. The efficiency improves when the $V_{aDCMIG}$ 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].

**Figure 16: $\eta_{IG}$ vs $\eta_{SG}$ with DCMIG field flux variation and $V_{aDCMIG}$ kept constant**

**Figure 17: $\eta_{IG}$ vs $\eta_{SG}$ with $V_{aDCMIG}$ variation and field flux kept constant (Only resistive load)**

**Figure 18: $\eta_{IG}$ vs $\eta_{SG}$ with $V_{aDCMIG}$ variation and field flux kept constant (Resistive load plus IM)**

Contingencies in face to Transient Conditions

In a specific load, transient condition [2] that consist on high removal of loads up to synchronous generation contribution reaches null value and induction generation keeps on the same level of generation contribution [2]. This condition causes an increase of system frequency that should be regulated by a ballast load as described below.

**Ballast Load and its Functioning**

As [2], in face to great removal of load and great power generated from induction generator, the synchronous generator loses its attributes as regulator of frequency. The figure 19 shows the removal of 2/3 kW load at a time up to full removal of load and the frequency increases what indicates that power generated is greater than power consumed in the isolated system. The power excess causes increase of frequency.

Channel 1: Transducer  
Input: 0 to 100 Hz and Output: 0 to 10 V (Yellow line)

Channel 2: Amperimeter allocated in the load  
Current up to 10 A, 100 mV/A (Green line)
From this scenario, it is necessary the inclusion of frequency regulation system in order to keep the frequency stable in rated values. In this case, it will be used a ballast load to control the frequency. This option showed in figure 20 will be able to control the load seen by generators in such manner that frequency will be controlled within the rated values. The ballast load will be connected in parallel to principal loads of generators. In the frequency control loop, it will be set a reference frequency and the feedback frequency will be obtained by signal from frequency transducer connected to principal generator terminals as showed in figure 20.

The control system will actuate on ballast load switching the thyristors, as result from increase or decrease of system frequency and will result in a set of grid frequency. It consist of increase of the load when the system frequency is beyond the reference frequency and vice versa. The figure 21 is a summary of load control configuration.

The figures 22, 23 and 24 show the frequency control technique of ballast load. In figure 21 is shown the target phase RMS value control of ballast load through by fire angle from thyristors connected in antiparallel configuration as shown in figure 23. In figure 24is shown the target voltage waveform applied on ballast load when the fire angle is 90 degrees.

**Figure 19: Frequency transients in face to load removal**

**Figure 20: Scheme to be implemented in laboratory_ Ballast Load**

**Figure 21: Ballast Load Control.**
The figure 25 is identical model that shown in figure 9. It shows the electronic board MP410 that will be used in scheme in figure 20.

The voltage set circuit shown in figure 20 gets voltage signal Vt from transducer and generates a 10 V minus Vt as output signal. It is implemented to correct the functioning of control system. If this circuit is out, the frequency increases in opposition of expected results [10].

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 respectively by field 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 Vadmig elevation method. The PSG complemented the PIG manually set to attend the load.

The Vadmig elevation method resulted in increase of PDCMig and PIG and higher IG subgroup efficiency than the IfDCMig reduction method[1]. The increase of PDCMig and PIG were results of IG speed increase, nIG that was obtained by elevation of Vadmig as shown in Figure 11, Figure 12 and Figure 14. The use of Vadmig range instead of Vdc steady source enables to reach the IsDCMig 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].

The efficiencies from the Vadmig elevation method were greater than efficiencies from the scheme with Vdc steady source [1], as shown in Figure 17 and Figure 18. Vadmig elevation method does not have the additional current losses of Vdc steady source method. When the field flux ϕ, IsDCMig, is decreased, IsDCMig is increased by (3) and IG speed, nIG, is increased by (2). The main losses for the Vdc steady source method are related to higher IsDCMig elevation, P(w)=Ra* IsDCMig². Then, by the Vdc steady source method, besides IsDCMig be elevated due to the rise of PIG, IsDCMig is also elevated due to reduction of IsDCMig. Higher IsDCMig result in higher losses and lower efficiencies.

As shown in power performance graphs related to the Vadmig elevation method, Figure 11, Figure 12, Figure 14 and Figure 15, the PIG and PDCMig are more representative of actual operation conditions of offshore platforms.

As response of a load transient [2], it were been developed projects of schemes, using ballast load(energy dissipation) able to regulate the system frequency when load is removed and induction generator keeps on supplying the loads with its generation higher than load demand what results in motorizing of synchronous machine and increase of system frequency. This project is being implemented and tested in laboratory and its results will be published soon.
It will be also developed another scheme capable to regulate the system frequency in an interconnected system returning the excess of generated power to the interconnected grid using the followings changes and complements such as to include an external speed control loop in cascaded with inner DCMMSG current control loop [8]. It is done to set the converter firing angle upper than 90 degrees when system generation is greater than load demand so that the converter operates as inverter and DCMMSG field should be inverted via contactors when the DCMMSG turn a DCGSG [8]. All of these complements will be done to permit the DCMMSG operates as generator and to push the excess of power to grid and to avoid over frequency in the system. This experiment will be done in a future work, with the electric system of the workbench of the laboratory, connected to the external grid.

Conflict of Interest
The authors declare no conflict of interest.

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