Repowering and Evaluation of New Power of Synchronous Generators

L. M. Neto¹, J. R. Cardoso², S. P. Santos³, E. Delbone⁴

¹Uberlândia Federal University, MG, Brazil ²Sao Paulo University, USP, Brazil ³Santa Cecília University, Santos/SP, Brazil ⁴Paulista University, Santos/SP, Brazil

ABSTRACT: Useful life of winding insulation is about 30 years. This may be reduced when it is overloaded or when it works in aggressive environments. When retrofitting is undertaken an increase to a higher insulation class is recommendable. So the generator’s capacity should be increased, and this will not just more than fully compensate for the investment made it will also result in a more efficient use of the raw materials used and thus contribute to sustainable development. Our Brazilian experience shows that retrofitting with repowering is successful. The objective of this study is to present two cases of repowering, in which the old insulating materials were replaced by other, modern ones. So, eight SG of a Power Plant in Cubatão, S.P and two SG of CEMIG, MG had its power increased up to 40%. The discussion also deals with how to determine the new power obtained after the repowering, before the final load tests. In large machines, the load tests are critical. In order to calculate the field current of the full load SG to determine the temperature rise in field, indirect tests are undertaken. Which are the methods that present reliable results? This study compares three study methods, ASA, IEEE 115, and the General Method with their theoretical analyses. The ASA method is now regarded as normal in many countries. According to Brazilian Standards it is given under NBR-5052. In the IEEE 115, this method is named “Phasor Diagram Analysis—Salient-Pole Machines”. The General Method is an academic treatment with a better theoretical basis.

KEY WORDS: Synchronous Generator (SG), Repowering, American Standard Association (ASA), General Method, Synchronous Reactance (S R).

Symbols:
S G – Synchronous Generator
MC – Magnetic Circuit
mmf - Magnetomotive force
xₜ – Synchronous Reactance S R
xₐ – Direct axis SR
xₐ(s)/xₐ(ns)–Saturated/not saturated D A
xₙ – Quadrature axis S R
xₙ(s)/xₙ(ns)–Saturated/not saturated QA
x”ₐ – Direct axis transient reactance
x”ₐ – Direct axis sub-transient reactance
x”ₚ – Quadrature axis transient reactance
x₀ – Sequence zero reactance
x₂ – Sequence negative reactance

Table 1: Generators repowered to CEMIG.

| GENERATOR | 1 | 2 |
|-----------|---|---|
| Earlier power (MW) | 28.241 | 28.241 |
| After Repower (MW) | 36.948 | 36.948 |

It is also based on eight 20-pole, 11-kV, EMAE SG, which were repowered from 1995 until 2007 to obtain new power with an increase of up to 40%.

Table 2: SG repowered in Hydroelectric Henry Borden Power Plant – Cubatão/SP

| GENERATOR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-----------|---|---|---|---|---|---|---|---|
| Earlier Power | 33 | 33 | 55 | 55 | 55 | 55 | 55 | 55 |
| After Repower | 43 | 39 | 69 | 78 | 69 | 76 | 66 | 69 |
2- Methods used to confirm new power
After repowering, the result must be confirmed with final tests with nominal load so as to guarantee the new projected values.

In large machines, the test with nominal load implies putting it in parallel with an electrical network system. Before the test, it is to be recommended that the new parameters be guaranteed as well so as to confirm the planned range of temperature. This is possible with normalized tests but not with loaded ones. The purpose of this study is to contribute to a discussion on better ways to determine the correct field current with no load tests. Methods are to be applied under steady state conditions, everything being modeled in frequency dominion.

2.1- Stator
According to the IEEE 115-1995 Guide [2], determination of Stator temperature rise may be undertaken by various methods. However, the load tests are to be preferred. Alternatively, good results can also be obtained by indirect tests, with no load and in short circuit, as presented by the IEEE 115 Method 4: Open Circuit and Short Circuit Loading, page 73. In Brazil, it is described by NBR 5052 on page 22. It consists of determining the rise in temperature obtained with no load and short circuit tests. The sum of the temperature rise, after deducting a value of the rise caused by ventilation, determines a rise in the stator\(^a\).

2.2-Rotor
The determination of the rise in the temperature of the rotor may be calculated as follows:

- a) The field should be fed with a current equal to that necessary to keep the generator in a condition of rated load. This can be done with the SG excited on no load or in short circuit, but either of the two tests could cause damage to the generator.

- b) We can undertake extrapolation using the data obtained with no load or short circuit tests in order to obtain the rise of temperature at full load. The problem consists, therefore, in accurately determining the value of the full load excitation current. IEEE 115 presents two methods for determining load field current. ABNT-NBR5052 presents several methods, with emphasis on the ASA method.

Finally, a discussion of the General Method which is understood as theoretically the correct one. The next item presents a discussion of the three above-mentioned methods.

2.2.1- EC Determination by Phasor Analysis Method for Salient Poles
This method corresponds to the reactance or flux superposition method. Magnetic and electrical parameters are decomposed into direct and quadrature axes.

This description is similar to that given by IEEE-115 item 5.3.3: Suppose SG to have V, I and cos \(\phi\). Current is to be decomposed into the d axis (\(I_d\)) and q axis (\(I_q\)). I forms an angle \(\delta\) with the q axis, and can be calculated as:

\[
\Delta \text{Arc tan} (d+f) = \frac{(V_{sen}\phi + I_q)}{V}\cos\phi \quad (1)
\]

\(\delta\): the power angle (between \(E_f\) and V):

Thus, \(I_q\) and \(I_d\) current can be calculated:

\[
I_q = I \cos(\delta + \phi)\Delta\delta \quad (2)
\]

\[
I_d = I \sin(\delta + \phi)\Delta(\delta - 90^o) \quad (3)
\]

The no-load voltage to maintain V at the SG terminals can be calculated by:

\[
E_{fns} \Delta \delta = V \Delta 0^o + r I \Delta \phi + j x_{qns} I_q \Delta \delta + j x_{dns} I_d \Delta(\delta - 90^o) \quad (4)
\]

Error correction due to saturation:

\(E_{fns}\) is determined on the air gap linear curve, thus MC is supposed to be Linear.

It is possible to obtain \(F_{fns}\) and \(E_{fns}\) from figure 2. The correction of the saturation effect is obtained by the voltage corresponding to resultant flux \(F_R\). This voltage, named \(E_R\), is determined as presented in (5):

\[
E_R = V + rI + jx_I I \quad (5)
\]

---

\(\Delta\) In machines with water-cooled armature only the rise of the short circuit test must be considered, because the coolant practically eliminates the iron heating influence in the winding.

Figure 1: determination of \(E_{fns}\)
The correction is the difference between the air gap and the saturation curve in Figure 2. \( \Delta F_{f} + F_{fns} = F_{fs} \) is the mmf field necessary to maintain the alternator under specified conditions. If no saturated is obtained from the saturation curve.

\[
E_{fns} \angle \delta = V \angle 0^\circ + r I_a \angle \varphi + j x_q I_q \angle \delta 
\]

Another way to consider the saturation effect is to suppose linear MC in \( E_R \). Correction is made with \( K = E'_{fns}/E_R \).

\[ x_{q} \] is calculated from the project or experimentally determined for example by the Poitier Method which presents some errors but is acceptable for almost all Norms. This method presents reliable results, however it does not correspond to the physical reality since neither machine works on the air gap line nor does the correction obtained by the sum of \( \Delta F_f \) correspond to the physical reality.

Another way to consider the saturation effect is to suppose linear MC in \( E_R \). Correction is made with \( K = E'_{fns}/E_R \).

\[ x_{q} \] at point \( E_R \) is calculated by dividing \( x_{dns} \) by \( K \), excluding \( x_t \). The reactance \( x_q \) is not corrected because the larger part of quadrature flux passes through the air. If \( E'_{fns} \) is the voltage in the (fictitious) Linear New Magnetic Circuit, expression (6) could be written like expression (4) but with \( x_{dns} \) in the place of \( x_{dns} \).

The analysis of figure 3 confirms the above explanation.

2.2.2 The Graph Method using Poitier (corresponding to the ASA Method)

IEEE 115 describes this method but limits it to SG non-salient poles. ABNT NBR 5052 describes it as the ASA Method but not as limited to non-salient poles.

This method adds the corresponding mmf value to the nominal voltage in the air gap line \( (F_{fns}) \) with mmf to keep the SG in short circuit with the nominal current \( (F_A + F_x) \). If \( F_{fns} \) is the reference, the angle of \( (F_A + F_x) \) is \( (90 + \varphi) \). In order to obtain \( F_{fns} \), \( \Delta F_f \) value must add in \( (F_{fns} + (F_A + F_x)) \). That value is the difference between mmf corresponding to \( E_R \) on the saturation curve and the air gap line. The \( E_R \) value is calculated from the graph as shown in Figure 4.

The values obtained by this method are reliable. However, there is no theoretical basis for the method because it neither
corresponds to physical reality nor to any mathematical model.

### 2.2.3 – General Method

#### a- Non Salient Poles

In this method, \( F_f \) and \( F_A \) act in the same MC; the sum of both is the resulting \( F_R \); thus \( E_R \) and \( V \) may be found. \( F_A \) is calculated by the design or determined experimentally by the Poitier method.

To calculate the necessary \( F_f \) to maintain SG in nominal conditions, the first step is to obtain \( F_R \). So it is necessary to know \( E_R \), which can be found from equation (5) or graphically as showed in Figure 5. \( F_f \) is obtained from the expression

\[
F_f = F_R - F_A \quad (7)
\]

\( F_f \) allows \( E_f \) to be found from a no load voltage curve.

#### b- General Method: Salient Poles

With a salient SG pole it is not possible to undertake the direct composition of \( F_f \) and \( F_A \) because they act in MCs with different permeances. Decomposition on two axes: direct and quadrature, always allows offering different but constant permeance to each if saturation is not considered.

\( F_d \) is a component of \( F_A \) on a direct axis, and it can be calculated as follows:

\[
F_d = F_A \text{sen}(\delta + \varphi) \quad (9)
\]

and it can be added to \( F_f \) because both are on the same axis. Meantime it is necessary to observe: \( F_f \) has a rectangular spatial distribution, but spatial harmonics are not taken into consideration because of the pole design, which has variable value and increases from the center to the extremity, so permeance decreases, and it is possible to obtain a sinusoidal flux. But \( F_A \) and consequently \( F_d \) are practically sinusoidal, and when they are applied to a variable permeance the resultant flux will contain harmonics. Only the fundamental one is taken into consideration in this study. However, it is necessary to consider a correction for the \( F_d \) value, as proposed by J. A. Shouten.

The known expression:

\[
F_d = 0.9K_e.N_s.I / \text{polos.}\cos(\delta + \varphi) \quad (8)
\]

must be replaced by:

\[
F_d = 0.765K_e.N_s.I / \text{polos.}\cos(\delta + \varphi) \quad (9)
\]

\( F_q \) is a component of \( F_A \) on the quadrature axis, and it can be calculated from:

\[
F_q = F_A \cos(\delta + \varphi) \quad (10)
\]

Applied in inter-polar space, which has a small and irregular permeance, it results in a flux with strong harmonics prevailing third and multiples one (impossible to understand!). To make a composition of \( F_q \) with other mmf it would be necessary to replace it by a corresponding value that considered MC homogenous. This value depends on the width of the face pole referred to as the pitch pole. It can prove:

- Pole arch/Pole pitch = 0.6: \( F_q = 0.44F_A\cos\gamma \)
- Pole arch/Pole pitch = 0.7: \( F_q = 0.53F_A\cos\gamma \)

Not to take harmonics into consideration implies a 12% error in \( F_q \) but it is reflected in a lower value than 1% in the terminal voltage. However, in this MC the air part prevails so \( F_q \) affects \( E_{Aq} \) - reaction armatures emf, can be calculated with \( x_{Aq} \) reactance where \( x_{Aq} = x_q - x_l \).

\[
E_{Aq} = jx_{Aq}I_q \quad (11)
\]

### Method of Calculation
To determine field current $I_f$ and corresponding $E_f$, that makes it possible to work with nominal voltage and current as well as a determined power factor, the necessary steps are (not considered): a) The voltage in the $E_R$ air gap can be determined either by expression (5) or graphically as presented in Figure 5.

b) Value on direct axis is:

$$E_R = V + jx_i I_a + j(x_q - x_i) I_q$$  \(13\)

It is possible to prove $E_R$ is on the quadrature axis, and $F_R$ is on the direct axis, and this value can be determined from a load curve.

c) $F_{Ad}$ and $F_R$ (direct axis) composition permits the calculation of $F_f$ or $I_f$.

d) $F_f$ or $I_f$ on a no-load curve allows the determination of $E_f$.

3- Results

Two successful cases are presented that justify repowering:

- Case 1 emphasizes which parameters change and which do not.
- Case 2 discusses three methods by which the field current in the load may be determined, and compares it with the real value.

3.1- Case 1: CEMIG SG repowered

| Table 3: Data before and after repowering |
|-----------------------------------------|
| Power kVA                             | Before | After |
| 28241                                  | 36948  |
| Nominal Voltage                       | 13800/7 977V | 13800/7977V |
| Nominal current                       | 1182 A | 1547 A |
| Frequency/rpm                         | 60Hz/30 rpm | 60Hz/300rpm |
| Power factor                          | 0.95 | 0.95 |
| Class/Elevation (stator)              | B/60° | B/60° |
| Channels-Total                         | 288  | 288  |
| Channel per pole/pitch                 | 12/1-11 | 12/1-11 |
| Channel size                           | 23x118 mm² | 23x118 mm² |
| Class/Elevation (rotor)                | B/60° | F/ 80° |

3.1.1 – Considerations related to stator and rotor manufacture and insulation

Thick layers of cotton with asphalt were replaced by others with isolated bars including fine polyester or fiber glass layers with a material such as Nomex in the stator windings. Field winding conductors were also replaced by others isolated for $F$.

Current density increase based on the rise in temperature and/or an increase in conductor section allowed a 31% enhancement of SG capacity.

The SG changed its parameters as had been expected: all reactances increased about 30%, as presented in table 4. Time constant values behaved as expected.

| Table 4: SG parameters before / after |
|--------------------------------------|
| Before | After |
| Sat | Saturated/ Not Sat | Saturated/ Not Sat |
| Xd     | 0.71/0.76 | 0.9192/0.9955 |
| Xq     | 0.43/0.46 | 0.5604/0.604 |
| Xo     | 0.05/0.05 | 0.07/0.07 |
| X2     | 0.15/0.16 | 0.2/0.2 |
| X’d    | 0.171/0.173 | 0.2241/0.2269 |
| X’q    | 0.162/0.164 | 0.2117/0.2146 |
| X’’d   | 0.145/0.148 | 0.1901/0.1938 |
| Td’    | 0.7291/0.7337 | 0.8046/0.8101 |
| Tdo’   | 3.0354/3.2506 | 3.3255/3.5816 |
| Td’’   | 0.0511/0.0606 | 0.0504/0.0606 |
| Tdo’’  | 0.0615/0.0635 | 0.0613/0.0635 |
| Ta     | 0.1616/0.1641 | 0.1614/0.1641 |

3.2 – Case 2
SG n° 1 at Henry Borden Power Plant

A 33 MVA SG repowering permitted an increase of 30% of power as shown in Table 5.

| Table 5: Before and after repowering |
|--------------------------------------|
| Before | After |
| Power   | 33 MVA | 43MVA |
| Nominal Voltage | 11000 V | 11000 V |
| Nominal Current | 1734 A | 2260 A |
| Frequency/Rotation | 60Hz/300rpm | 60Hz/300rpm |
| Power Factor | 0.95 | 0.95 |
| Excitation | 200KW 300V | 200KW 300V |
| x_d | 1.386 |
| x_q | 0.8316 |

3.2.1 – Considerations about Electrical Project

Repowered project analysis leads to interesting conclusions:
a) In the stator, the conductor section was increased by 15%, from 822.31 mm$^2$ to 946.37 mm$^2$, and current density from 2.10 A/mm$^2$ to 2.38 A/mm$^2$ (13.3%). Bars were also replaced by the Robell type. Repowering was brought about by increases in the conductor section and density. The data analysis allows us to conclude that the increase in the density of the current (13.3%) is perfectly acceptable to the new temperature class.

b) In the previous rotor, the conductor cross section was of 4.064x50.8=206.45 mm$^2$. After repowering, the conductor cross section changed to 5x50=250 mm$^2$ representing an increase of 21% but the number of turns was reduced from 62.5 to 50. The reduction in the number of turns of field winding was necessary to limit the field voltage, because the excitation voltage must be limited to its earlier power.

In order to assess the impact on the rotor it is necessary to calculate the projected current value at the new power. Tests are made with the ASA method adopted by NBR 5052. Before repowering the field current was calculated by the indirect method and confirmed by a load test, as shown in Table 6.

| V (Line V) | I (Line A) | P (MW) | Q (MVAR) | If (A) | Vf (A) |
|-----------|-----------|--------|----------|--------|--------|
| 10900     | 1750      | 28.7   | 15.76    | 410    | 215    |

The value of the current found by the ASA method (indirect) was 398 A, representing a level 3% lower than the experimental results. The load test results after repowering are shown in Table 7.

| V (Line V) | I (Line A) | P (MW) | Q (MVAR) | If (A) | Vf (A) | Dt (1) | Dt (2) |
|-----------|-----------|--------|----------|--------|--------|--------|--------|
| 11029     | 1810      | 29.6   | 18       | 510    | 175    | 65     | 69     |
| 11192     | 2434      | 40     | 24       | 646    | 240    | 90     | 93     |

The current value found by the indirect method with a load of 34.6 MVA was 520 A and with 46.8 MVA was 630 A, that represents a level 2.5% lower than the experimental results. The experimental results confirm the ASA method with reasonable precision, thus justifying its use by ABNT, as also for salient pole machines. However, in spite of the fact that this method presents reliable results, it has no theoretical support.

The calculations are repeated using the: “Phasor diagram analysis salient polo machine corrected” method from IEEE 115-95. The values are:

a) For 34.6 MVA – If = 515 A
b) For 46.8 MVA – If = 635 A

These values are very close to those determined by the respective load tests as well as by the ASA method.

Finally, we present the solution given by the General Method with the following results:

a) For 34.6 MVA – If = 510 A
b) For 46.8 MVA – If = 630 A

The determination of the temperature rise in the generator field with no load and short circuit tests presents reliable values.

In this study the theoretical methods of support discussed lead to the conclusion that the only correspondence close to physical reality is that obtained by the General Method.

3.2.2 – Considerations on stator rotor manufacture and insulation

The impregnation during coil manufacture has to be performed under vacuum pressure in order to guarantee the absence of air, combining synthetic epoxy- and polyester-base resin with solid mica-base material insulation.

The insulating tape is the essential part of the MICADUR technique, which consists of the application of a fine fiber glass layer that serves as a base for the mica paper. The two materials are joined with epoxy base resin.

Anti-corona painting and application of low resistivity epoxy base varnish, allows a suitable basis for the insulation of the nucleus. At the extremities of the bars a high resistivity cover is used to reduce the superficial voltage gradient of the winding.

3.2.3 – Considerations on the Mechanical Project

The increase in power from 33 to 43 MVA requires a corresponding mechanical increase in demand. The main concern is presented below:

3.2.3.1 – Axle

A horizontal axle unit engaged by two Pelton turbines is submitted to two combined torsion (resulting from binary pair application) and flexion (caused by the massive action of rotating parts, magnetic thrust of rotor in relation to stator and radial hydraulic thrust of turbine) efforts.
The maximum axle effort and fatigue resistance were calculated with satisfactory results. Also, the analysis of the parameters obtained guarantee that the key is able to transmit new power.

3.2.3.2 – Calculation of stator nucleus buckle

The calculation of stator nucleus buckle was undertaken with software whose data input into the program consist of the component stator nucleus and supporting structure geometry.

Other necessary data are: nucleus temperatures, the heat of the air in the air gap, and elasticity of support. Simulation results have indicated some possibility of buckling inside the nucleus plates after repowering. The same happened before repowering.

3.2.3.3 – Calculation of structural efforts provoked by thermal expansion.

The results obtained by using the computer program indicate some admissible mechanical tension due to thermal expansion.

The values calculated by the program are too conservative for split structures such as occur in the case presented, and the effect of the expansion due to heating is better absorbed in this case by the flexibility of the existing elements.

4-Conclusion

4.1 - New Power Guarantee

All the methods for confirming the new power are well known but the main focus is on the indirect tests for the calculation of the field current.

ASA, Flux superposition (Phasor Analysis) and the General Method all present excellent results. It must be emphasized that calculations made in a similar way on other machines of the Henry Borden Power Plant – Cubatão/SP consistently confirmed that the results are more reliable than the values presented by loading tests.

4.2- Insulation Guarantee

The new insulation has presented a lifetime at least equal to that of the original equipment by using stable materials, when applied with techniques that guarantee the absence of contamination.

4.3- Mechanical Guarantee

Certain critical points due to the increased effort provoked by the increase in power were verified. It is important to take special care with: Key, Axis, and Stator Buckle. Computational simulations showed that SG can work with the new power.

4.4- Payback Guarantee

Finally, a comparison between the cost of repowering and that of the acquisition of a new machine is important. The following values have been updated to 2007: cost of repowering a 33MVA SG , 360 rpm, and 20 pole machine for 43 MVA is: U$ 2,400,000.00. The value of a new generator of the same characteristics is U$ 4,500,000.00. This comparison confirms that financial repowering is financially feasible.

4.5 Sustainability guarantee

In times of environmental awareness it is necessary to make every effort to recycle raw materials.

References:

1. Fitzgerald, A. E. & Kingsley Jr, C. & Umans S. D (2006). Electrical Machines, 6th Edition: Bookman.
2. IEEE 115-95 – IEEE Guide: Test Procedures for Synchronous Machines.
3. Kundur, P (1994). Power System Stability and Control. New York: MacGraw-Hill.
4. Langsdorf A. S. (1967). Alternating Current Machines Theory-MacGraw-Hill Book Company Translation: Rafael Gomez de Ureta of original Alternating Machines Theory.
5. Data-Book of Henry Borden Power Plant – Cubatão/SP consistently confirmed that the results are more reliable than the values presented by loading tests.
6. ABNT - NBR 5052 (1984). Synchronous Machines - Tests –.
7. NBR 5117- Synchronous Machines Specifications.