IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 30, 2019, accepted May 21, 2019, date of publication May 29, 2019, date of current version June 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2919298

A Study of the Impacts Caused by Unbalanced Voltage (2%) in Isolated Synchronous Generators

WAGNER E. VANÇO[1], **FERNANDO B. SILVA**[2],
AND JOSÉ ROBERTO B. A. MONTEIRO[1], **(Member, IEEE)**
[1]São Carlos School of Engineering, University of São Paulo (USP), São Carlos 13566-590, Brazil
[2]Institute of Exact and Applied Sciences, Federal University of Ouro Preto, João Monlevade 35931-008, Brazil

Corresponding author: Wagner E. Vanço (vanco@usp.br)

This work was supported by the Brazilian National Council of Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPq).

ABSTRACT This paper presents an analysis of the oscillations caused by unbalanced loads in salient pole synchronous generators that operate in isolation under steady state. The oscillatory disturbances, arising from the second-order harmonics, may have or have the potential to cause electromechanical damage to the salient pole synchronous generator. In this paper, the goal is to identify and quantify the magnitude of the electromagnetic torque, which assumes an oscillatory form due to the current component from the negative sequence, caused by unbalanced currents. The self-same analysis was included for second-harmonic voltage oscillations in the qd0 domain, the currents induced on the damper windings together with the oscillation of the load angle and on the field current. These oscillations situated on the synchronous generator are analyzed for a degree of voltage unbalance close to 2% which is an acceptable value according to international regulations for power supply from distribution networks, and this same degree of tolerated voltage unbalance will be used herein for isolated synchronous generators.

INDEX TERMS Electrical losses, isolated synchronous generator, oscillating torque, oscillation, salient poles, second harmonic, unbalanced loads.

I. INTRODUCTION

The study of synchronous generators operating under unbalanced steady state has had little investigation made to it, and as a result, there is a shortage of publications concerning this subject. In the bibliography, one notes [1]–[3], where a generator connected to an infinite bus is studied, and which has an unbalanced energy network that is subject to a number of eventualities, such as short circuit analysis for study in transient and dynamic regime.

However, in [4], the analysis of an induction generator for wind generation is highlighted, where the problems caused by an unbalanced electric network are covered. Control by means of an isolated sliding mode control for a wound rotor synchronous generator, connected to an unbalanced load is given in [5], [6], the control results in a positive sequence voltage regulation from the stator, independent of the voltage and load value.

A study of the synchronous generator under a non-sinusoidal and asymmetric regime is presented in [7]. However, no mention is made as to the electromagnetic torque oscillations caused by unbalanced loads, not even how to quantify these oscillations.

In [8], the effects caused by unbalanced loads are presented in the dynamics of an energy system, which can be modeled as the only machine (synchronous generation) connected to an infinite bus, in the form of an analysis. However, the aforementioned analysis does not provide a study of the electromagnetic torque oscillations neither of the unbalanced loads in isolated generation, where the degree of unbalance is more accentuated than in a synchronous generator connected to an infinite bus.

In [9] a study is made of the characteristics of triple harmonic currents produced by salient pole synchronous generators. The analysis is made for a machine supplied with resistive and inductive balanced or unbalanced loads, different ground resistance values for the generator neutral and various configurations of transformer winding.

In another publication that dynamically analyses the electric variables of a synchronous generator connected to the network under unbalanced loads is given in [10].

A study that demonstrates a strong proximity to the present study is given in [11], the analysis however is made for induction motors under voltage unbalance, together with voltage

The associate editor coordinating the review of this manuscript and approving it for publication was Yuh-Shyan Hwang.

2169-3536 © 2019 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

harmonic distortion. The aforementioned study presents the case that such anomalies cause changes to voltage, torque and vibrations, the study also presents also the torque oscillations caused by an unbalanced and non-sinusoidal regime. Further still, other studies [12]–[15] investigate the doubly-fed induction generator (DFIG) through an approach that looks into voltage and load unbalance.

Thus, in relation to other studies cited [1]–[15], the study presented herein brings forward an investigation into the impacts caused by unbalanced loads in the running of salient pole synchronous generators operating in an isolated manner. A point of interest to highlight here is the identification and quantification of the oscillations that arise due to voltage unbalance.

Therefore, the aim of this study is to analyze the effects caused by unbalanced loads on small-scale synchronous generators, which operate in isolation and do not possess adequate protection. Examples of such are those generators used in emergency systems, shopping centers and commercial establishments that aim at reducing their peak time energy costs. The loads on these generators are distributed in a random fashion and are not concerned with the degree of unbalance caused through the inappropriate distribution of power across the phases.

The electric variables begin to suffer the influence of the second order component; the effect is felt through the electromagnetic torque, the voltage on the domain dq0, in the induced currents on the damper windings and field and in the machine power angle. Therefore, all these variables are computationally analyzed through a survey of the harmonic spectrum, along with a mathematical presentation of its behavior using Fourier series decomposition.

II. DEFINITION OF UNBALANCE

The unbalance of a power system is defined as being the deviation in the voltage or current magnitude of any one or two of the three phases of the three-phase system. When the voltages of a three-phase system are not identical in magnitude and/or the phase difference between these is not exactly 120 degrees, voltage unbalance thus occurs. Therefore, the unbalance of a power system can be expressed as the percentage of variation in currents and line or phase voltages on the rated current and voltage values [16]. The current and voltage unbalance are expressed by equation (1), being,

$$\left.\begin{array}{l}\left(\dfrac{I-i}{I}\right)\times 100\% \\[2ex] \left(\dfrac{V-v}{V}\right)\times 100\%\end{array}\right\} \tag{1}$$

where,

I - Rated current,

i - Real current,

V - Rated voltage,

v - Real voltage.

The unbalance is generally presented as voltage unbalance by international standards. The voltage unbalance is also known as the line voltage unbalance rate (LVUR), and is given by (2). According to the National Electrical Manufacturers Association (NEMA) [17], it can be given as,

$$LVUR = \frac{\Delta V_{line}}{V_{med_{line}}} \times 100 \tag{2}$$

where,

ΔV_{line} - Maximum deviation of line voltages in relation to mean value,

$V_{med_{line}}$ - Arithmetic mean of the modules for the three-phase voltages (phase-to-phase voltages).

The IEEE uses equation (3) for the definition of voltage unbalance [18], the only difference between NEMA is the use of phase voltages and not line. Here, once again, the information concerning phase angle is lost, since only the voltage modules are considered. This is also known as the phase voltage unbalance rate (PVUR), which is given by,

$$PVUR = \frac{\Delta V_{phase}}{V_{med_{phase}}} \times 100 \tag{3}$$

where,

ΔV_{phase} - Maximum phase voltage deviation in relation to the mean value,

$V_{med_{phase}}$ - Arithmetic mean of the modules for the phase voltages.

Another index used by European standards to indicate the degree of unbalance [16], [19]–[21] is the voltage unbalance factor (VUF), based on the Fortescue transform, given in equation (4).

$$VUF = \frac{V_-}{V_+} \times 100 \tag{4}$$

where,

V_- - Negative sequence voltage module,

V_+ - Negative sequence voltage module.

In similar fashion, the currents can also be decomposed. The current unbalance or current unbalance factor (CUF) is calculated by,

$$CUF = \frac{I_-}{I_+} \times 100 \tag{5}$$

The CIGRÉ method provides the same results as those from the symmetrical components method (VUF), using a series of algebraic manipulations to express the unbalance from the line voltage modules [22], as shown in equations (6) and (7).

$$\beta = \frac{V_{AB}^4 + V_{BC}^4 + V_{CA}^4}{\left(V_{AB}^2 + V_{BC}^2 + V_{CA}^2\right)^2} \tag{6}$$

$$UB = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \times 100 \tag{7}$$

where,

V_{AB}, V_{BC}, V_{CA} - Three-phase voltage modules.

UB - Unbalance, given in (%).

III. UNBALANCE IN SYNCHRONOUS MACHINES

On many occasions, isolated synchronous generators operate with unbalanced three-phase loads, due to typical single-phase and biphase loads that are not applied uniformly across all three phases [4]. The stator currents on the three phases have different amplitudes and different phases with a value of 120°. For a synchronous generator with isolated balanced loads, one has $I_1 = I_2 = I_3$ and $\gamma_1 = \gamma_2 = \gamma_3$ [23].

$$\left.\begin{aligned} I_A(t) &= I_1 \cos(\omega_1 t - \gamma_1) \\ I_B(t) &= I_2 \cos(\omega_1 t - \frac{2\pi}{3} - \gamma_2) \\ I_C(t) &= I_3 \cos(\omega_1 t + \frac{2\pi}{3} - \gamma_3) \end{aligned}\right\} \tag{8}$$

When a three-phase synchronous machine operates with an unbalanced load, the positive sequence currents will create, in the air gap, a magnetomotive force (m.m.f), which rotates at synchronous speed. The zero sequence components (homopolar components), due to their spatial displacement of 120° electric between the three-phase stator windings, which themselves possess the same angular displacement in time, cancel out and do not produce an m.m.f result, hence there is no effect on the synchronous machine. However, the negative phase sequence currents will produce, in the air gap, an m.m.f that is moved at the opposite speed to the rotor, with an angular velocity of $(-\omega)$. By considering the magnetomotive force of the fundamental component between the stator and the rotor, [24]–[26] is able to mathematically describe this effect:

$$\left.\begin{aligned} mmf &= \sum KI_1 \begin{bmatrix} \cos(\theta)\cos(\omega t)+ \\ \cos(\theta - \frac{2\pi}{3})\cos[(\omega t - \frac{2\pi}{3})]+ \\ \cos(\theta + \frac{2\pi}{3})\cos[(\omega t + \frac{2\pi}{3})] \end{bmatrix} \\ mmf &= \frac{3}{2}KI_1 \cos(\theta - \omega t) \end{aligned}\right\} \tag{9}$$

where:

mmf Magnetomotive force (A.t);

K Project constant for the machine winding;

I_1 Maximum value of the fundamental component for the stator current (A);

θ Spatial angle with origin in one of the stator phases (degrees);

ω Synchronous speed (rad/s).

By performing the decomposition of the fundamental current through the theory of the symmetric components, one obtains:

$$mmf_+ = \frac{3}{2}KI_1 + \cos(\theta - \omega t),\ \text{sequence}(+) \tag{10}$$

$$mmf_- = \frac{3}{2}KI_1 - \cos(\theta + \omega t),\ \text{sequence}(-) \tag{11}$$

$$mmf_0 = 0,\ \text{sequence}(0) \tag{12}$$

The angular velocity of the negative sequence magnetomotive force is $(-\omega)$ as seen in equation (11), in this manner, the angular velocity relative to synchronous velocity on the rotor (ω) will cause oscillations of (2ω). The unbalance of synchronous generator loads on the machine rotor windings cause an effect similar to those which occur in asynchronous machines, however, with slip equal to 2, as noted in equation (13). This would be equal to the power supply on the synchronous generator field winding accepting an alternate supply with an induced current of double frequency, in addition to this current induced on the damper winding. However, this consideration does not take into account the difference of the non-symmetric windings on the rotor and the non-uniformity of the air gap [23], [27].

$$S_- = \frac{-\omega_r - \omega_r}{-\omega_r} = 2 \tag{13}$$

By including the harmonic components $h = 2$, the equation for electrical variables (V_e), can be represented mathematically by,

$$\dot{V}_e = V_{cc} + \dot{V}_{2\omega} \tag{14}$$

In other words, the relative speed between this wave and the rotor speed will create a situation where double frequency voltages and currents are induced (2ω). These are second orders components in the rotor windings (field winding and damper winding), as presented in Fig. 1.

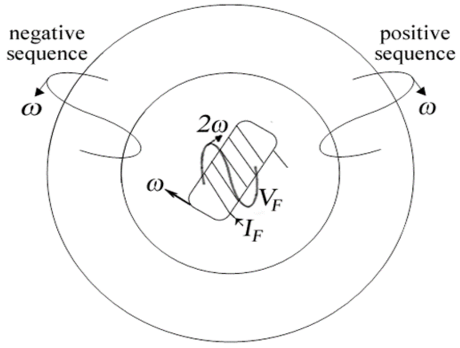


FIGURE 1. **Distribution and interaction of m.m.f due to positive and negative sequence components.**

In such an unbalance situation, the uneven heating of the rotor and the torque oscillations can become significant, where they also cause the reduction in machine efficiency. In a non-grounded system, the unbalance causes displacement on the neutral point, hindering the necessary relay and circuit breaker operation [16].

Negative phase sequence currents cause serious overheating on the rotor windings. It is therefore necessary to limit the admissible value of the negative phase sequence current, arising from unbalanced loads on a synchronous generator [28]. Table 1 presents the maximum unbalance current values for salient pole synchronous generators, as established by [29].

IV. MATHEMATICAL MODELLING: SYNCHRONOUS MACHINE

Reference [30] presents the equations for the synchronous machine with salient poles. The equations for the electrics

TABLE 1. Unbalanced operating conditions for synchronous machines.

Item	Machine type	Maximum I_2/I_N* value for continuous operation
	Salient pole machines	
1	Indirect cooled windings	
	motor	0.1
	generators	0.08
	synchronous condensers	0.1
2	Direct cooled (inner cooled) stator and/or field windings	
	motors	0.08
	generators	0.05
	synchronous condensers	0.08

*I_2/I_N is the negative sequence current over the rated current value of the generator.

of the synchronous machine are given by,

$$\left.\begin{aligned}
v_{qs}^{r} &= r_s i_{qs}^{r} + \frac{\omega_r}{\omega_b}\psi_{ds}^{r} + \frac{p}{\omega_b}\psi_{qs}^{r} \\
v_{ds}^{r} &= r_s i_{ds}^{r} - \frac{\omega_r}{\omega_b}\psi_{ds}^{r} + \frac{p}{\omega_b}\psi_{ds}^{r} \\
v_{0s} &= r_s i_{0s} + \frac{p}{\omega_b}\psi_{0s} \\
v_{kq}^{r'} &= r'_{kq} i_{kq}^{r'} + \frac{p}{\omega_b}\psi_{kq}^{r'} \\
v_{kd}^{r'} &= r'_{kd} i_{kd}^{r'} + \frac{p}{\omega_b}\psi_{kd}^{r'} \\
v_{fd}^{r'} &= r'_{fd} i_{fd}^{r'} + \frac{p}{\omega_b}\psi_{kd}^{r'}
\end{aligned}\right\} \qquad (15\text{-}20)$$

$$\left.\begin{aligned}
\psi_{qs}^{r} &= X_{ls} i_{qs}^{r} + X_{mq}\left(i_{qs}^{r} + i_{kq}^{r'}\right) \\
\psi_{ds}^{r} &= X_{ls} i_{ds}^{r} + X_{md}\left(i_{ds}^{r} + i_{fd}^{r'} + i_{kd}^{r'}\right) \\
\psi_{0s} &= X_{ls} i_{0s} \\
\psi_{kq}^{r'} &= X'_{lkq} i_{kq}^{r'} + X_{mq}\left(i_{qs}^{r} + i_{kq}^{r'}\right) \\
\psi_{kd}^{r'} &= X'_{lkd} i_{kd}^{r'} + X_{md}\left(i_{ds}^{r} + i_{fd}^{r'} + i_{kd}^{r'}\right) \\
\psi_{fd}^{r'} &= X'_{lfd} i_{fd}^{r'} + X_{md}\left(i_{ds}^{r} + i_{fd}^{r'} + i_{kd}^{r'}\right)
\end{aligned}\right\} \qquad (21\text{-}26)$$

where:

$v_{qs}^{r}, i_{qs}^{r}, \psi_{qs}^{r}$ Voltage, current and flux linkage stator for the quadrature axis (pu),

$v_{ds}^{r}, i_{ds}^{r}, \psi_{ds}^{r}$ Voltage, current and flux linkage stator for the direct axis (pu),

$v_{0s}, i_{0s}, \psi_{0s}$ Voltage, current and flux linkage for the zero sequence (pu),

$v_{kq}^{r'}, i_{kq}^{r'}, \psi_{kq}^{r'}$ Voltage, current and flux linkage for the quadrature axis damper winding (pu),

$v_{kd}^{r'}, i_{kd}^{r'}, \psi_{kd}^{r'}$ Voltage, current and flux linkage for the damper winding direct axis (pu),

$v_{fd}^{r'}, i_{fd}^{r'}, \psi_{fd}^{r'}$ Voltage, current and flux linkage for the field winding (pu),

r_s, X_{ls} Resistance and leakage reactance for the armature windings (pu),

r'_{kq}, X'_{lkq} Resistance and leakage reactance for the quadrature axis damper winding (pu),

r'_{kd}, X'_{lkd} Resistance and leakage reactance for the damper winding direct axis (pu),

r'_{fd}, X'_{lfd} Resistance and leakage reactance for the field winding (pu),

X_{mq}, X_{md} Magnetizing reactance, quadrature axis and the direct axis (pu),

ω_r Electrical angular velocity of the rotor (electrical radians per second)

ω_b Corresponds to rated or base frequency of the machine (electrical radians per second), and

p Differential operator $\left(\frac{d}{dt}\right)$.

The mechanical equations are described by (27-29).

where,

T_e, T_L Electromagnetic torque and the load torque (pu),

H Inertia constant (seconds),

δ Rotor angle (radian), and

P Number of poles.

$$\left.\begin{aligned}
T_e &= \psi_{ds}^{r} i_{qs}^{r} - \psi_{qs}^{r} i_{ds}^{r} \\
p\frac{\omega_r}{\omega_b} &= \frac{1}{2H}(T_e - T_L) \\
p^2\delta &= \frac{\omega_b}{2H}(T_e - T_L)
\end{aligned}\right\} \qquad (27\text{-}29)$$

V. RESULTS AND DISCUSSION

The electric diagram of the isolated system is represented in Fig. 2.

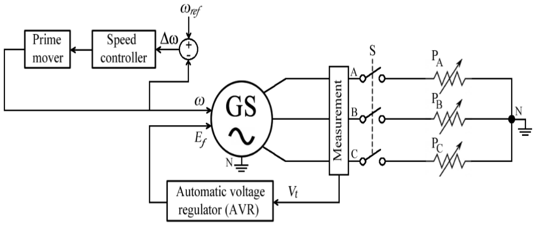


FIGURE 2. Synchronous generator operating in isolation.

The study of the oscillations caused by the voltage unbalance in a synchronous generator is carried out by means of computer simulation, through such it is possible to obtain the results that allow to analyze and quantify the intensity of the oscillations in the electric variables of the synchronous generator in the dq0 domain.

In order to obtain an idea of the imbalance that can occur in synchronous generators operating on a distribution system, the value of the voltage unbalance is recommended at 2% [31], [32], not exceeding the voltage unbalance above 3% in reference [33], and predicted by the ANSI standard C84.1-1995.

As stipulated by international norms, this study takes into account the analysis of disturbances caused in synchronous generators of protruding poles at a 2% degree of imbalance. This value can be considered low, compared to the voltage unbalance from unbalanced loads when operating alone.

In small or low power generators, the protection design may not be adequate, as such small isolated plants may operate without current unbalance protection, with the aim of producing design savings. Therefore, this study is set up without current unbalance protection for small salient pole synchronous generators operating in isolation.

The input parameters for the generator on the simulation were derived from the laboratory trials.

Table 2 shows the data and parameters of the synchronous generator. The data and parameters are necessary in order to perform the simulation in domain dq0, also reactances and their respective times are added for the transient and subtransient regime.

TABLE 2. **Nameplate data and the parameters for the electrics and mechanics of the synchronous generator.**

Parameter	Value
Nominal power	2 [kVA]
Nominal voltage	380 [V rms]
Nominal (full-load) current	3,0 [A rms]
Frequency	60 [Hz]
Nominal frequency	377 [rad/s]
Synchronous mechanical speed	1800 [rpm]
Nominal power factor	0,80
Nominal efficiency	0,85
Moment of inertia	0,0494 [kg.m^2]
Constant of inertia	0,438 [s]
Direct axis reactance, X_d	1,850 pu
Saturated direct axis reactance, X_{ds}	0,945 pu
Quadrature axis reactance, X_q	1,436 pu
Direct axis transient reactance, X'_d	0,370 pu
Direct axis subtransient reactance, X''_d	0,220 pu
Quadrature axis subtransient reactance, X''_q	0,200 pu
Direct axis short circuit transient time constant, T'_d	2,40 [s]
Direct axis short circuit subtransient time constant, T''_d	0,02 [s]
Quadrature axis short circuit subtransient time constant, T''_q	0,02 [s]
Leakage reactance, X_l	0,077 pu
Stator dc resistance, R_s	0,056 pu

The loads distributed on the phases A, B and C are respectively of 630 W, 500 W and 400 W. This load distribution on the phases causes a VUF of approximately 2%.

In order to simulate the synchronous generator under an unbalanced condition on the qd0 variables, firstly the powers are distributed on the abc phases (abc domain). By transforming the phase voltages and currents that are input variables with unbalance on the abc domain to qd0, the derivatives are calculated on the time domain. In this way, the unbalance is simulated for the voltages and currents on the qd0 domain. This imposed unbalance causes the appearance of a pulsating second harmonic component on the variables, due to the effect of the voltage and current of negative sequence caused by the unbalanced load to a voltage unbalance of 2%, according to the abovementioned tolerance levels.

In order to identify and quantify the components of the second order (2ω), the Fast Fourier Transform (FFT) was used. This allows for the analysis and quantification of values of the oscillations induced on the synchronous generator rotor windings, which cause oscillations on the electromagnetic torque and the remaining electrical variables.

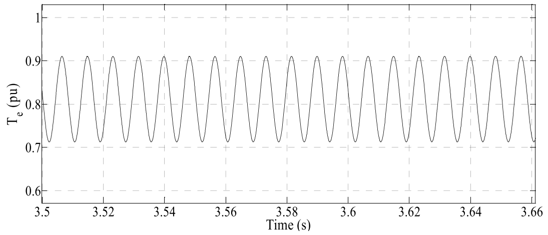


FIGURE 3. **Oscillating electromagnetic torque due to unbalance.**

Fig. 3, presents the behavior of the oscillating electromagnetic torque, due to unbalanced loads. An approximation for oscillation of torque is noted as between the values of 0.9 to 0.7 pu.

Given equation (14), the resulting electromagnetic torque will be the sum of the continuous electromagnetic torque, plus the sum of the pulsating electromagnetic torque of 2 fundamental frequencies.

The electromagnetic torque presented in Fig. 3 can be decomposed into a Fourier series, where it can be written in the following manner,

$$T_e = 0.8117 + 0.099\sin(2\omega t + 168.4^\circ)\,(pu)$$

The pulsation of the electromagnetic torque in relation to its nominal value exceeds 12% oscillation, proving oscillations of mechanical torque, which results in mechanical vibrations and consequently audible noise.

The mechanical vibration resulting from the oscillating torque causes heating in the bearings of the synchronous generator, since the friction increases when the electromagnetic torque enters the pulsating permanent regime.

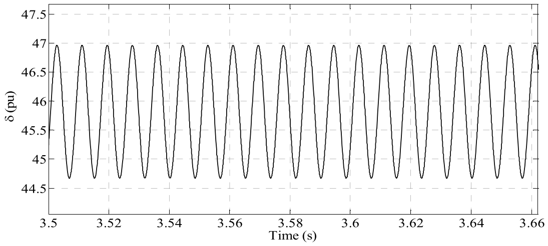


FIGURE 4. **Variation on the load angle, due to unbalance.**

Figure 4 presents the oscillation of the load angle on the synchronous generator, arising from an unbalanced three-phase load. Note that there is an oscillation on the load angle between the values of 46.96 and 44.67 degrees.

Given equation (14), the decomposed load angle in Fourier series, can be represented by the following expression,

$$\delta = 45.81 + 1.14\sin(2\omega t - 30.4^\circ) \quad \text{(deg)}$$

The power angle oscillates above 2.5%, which can lead to the synchronous generator losing stability, when up against sudden load switching, short-circuit, failures, among other eventualities in transitory state.

The current induced on the field winding of the synchronous generator is presented in Fig. 5.

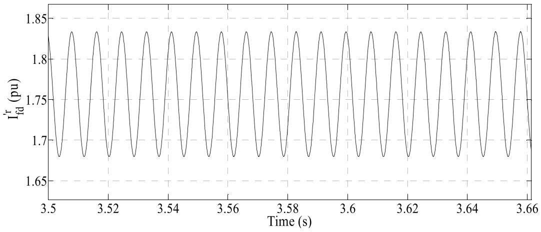


FIGURE 5. Oscillation on the field current, due to unbalance.

The field current for this condition can be represented by the following equation,

$$I'^{r}_{fd} = 1.757 + 0.0768 \sin(2\omega t + 112.3^\circ) \quad \text{(pu)}$$

The currents induced on the field and damper windings will go on to result in superficial losses on the rotor windings, which will then result in heating and thus the elevation in rotor structure.

The current induced on the quadrature axis damper winding and on the direct axis damper winding is presented in Fig. 6.

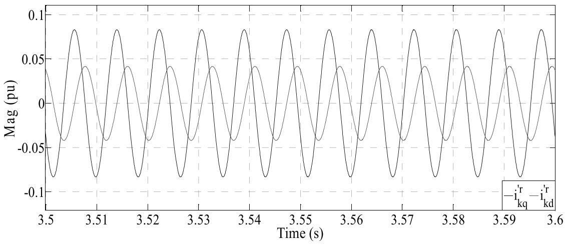


FIGURE 6. Induced current on the direct axis damper winding and on the direct axis damper winding.

The induced current on the damper quadrature axis winding and on the direct axis winding, is represented by the equations below,

$$\begin{aligned} i'^{r}_{kq} &= 0.0831 \sin(2\omega t + 206.9^\circ) \quad \text{(pu)} \\ i'^{r}_{kd} &= 0.0418 \sin(2\omega t + 116.4^\circ) \quad \text{(pu)} \end{aligned}$$

With the rise of induced currents on these damper windings, the synchronous generator goes on to experience a new portion of losses and reduction in efficiency.

Considering the variables d and q (voltage and current), and by employing these process variables, the appearance of the second order component in the dq electrical variables presented in this study was verified.

The direct and quadrature axis voltage oscillations, arising from voltage unbalance on the synchronous generator are presented in Fig. 7.

The oscillations on the direct axis and quadrature current are shown by Fig. 8.

The voltage for the direct and quadrature axis, decomposed in Fourier series are given by,

$$\begin{aligned} v^{r}_{ds} &= 0.7307 + 0.0231 \sin(2\omega t + 9.1^\circ) \quad \text{(pu)} \\ v^{r}_{qs} &= 0.7102 + 0.0181 \sin(2\omega t + 97.4^\circ) \quad \text{(pu)} \end{aligned}$$

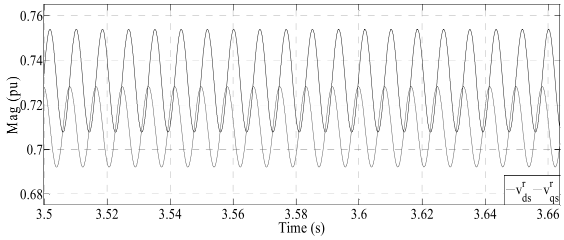


FIGURE 7. Voltage oscillation of the direct and quadrature axis.

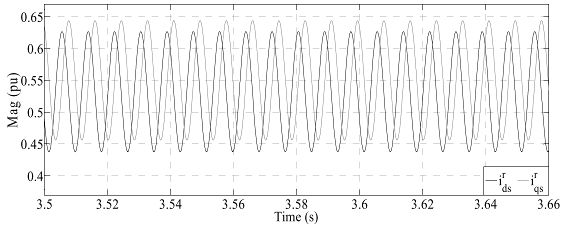


FIGURE 8. Current oscillation of the direct and quadrature axis.

TABLE 3. Analysis of the synchronous generator electric variables for the condition of VUF = 2%.

Electrical variables	Value		
	Average value	Second-order component (2ω)	Second-order component (2ω) (%)
T_e	0.8117 (pu)	0.099 (pu)	12.197
δ	45.81 (deg)	1.14 (deg)	2.488
i''^{r}_{fd}	1.757 (pu)	0.0768 (pu)	4.371
i''^{r}_{kq}	-	0.0831 (pu)*	-
i''^{r}_{kd}	-	0.0418 (pu)*	-
v'^{r}_{qs}	0.7307 (pu)	0.0231 (pu)	3.161
v'^{r}_{ds}	0.7102 (pu)	0.0181 (pu)	2.548
i'^{r}_{ds}	0.55 (pu)	0.0937 (pu)	17.04
i'^{r}_{qs}	0.53 (pu)	0.0944 (pu)	17.7

*Induced values on the damper winding

By analogy, the oscillations on the direct axis and quadrature current can also be represented by the decomposition in Fourier series,

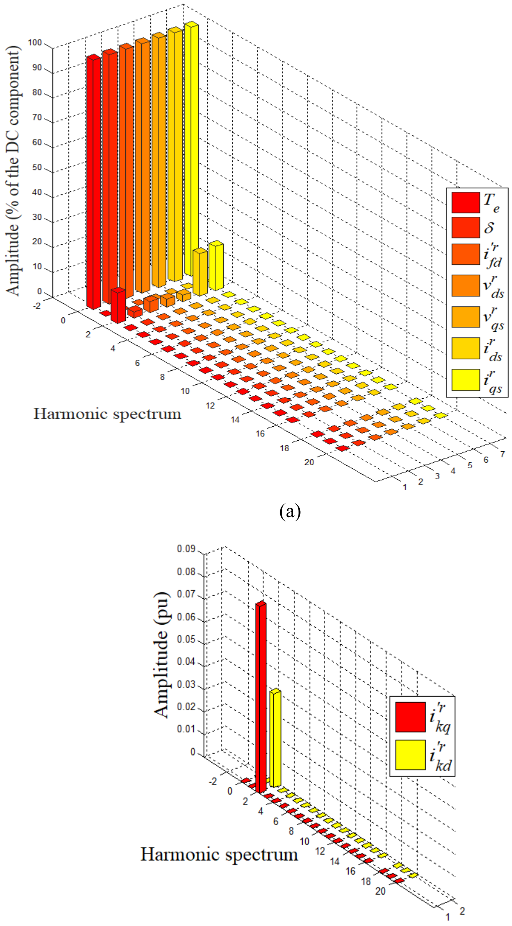
$$\begin{aligned} i^{r}_{ds} &= 0.55 + 0.0937 \sin(2\omega t + 114.1^\circ) \quad \text{(pu)} \\ i^{r}_{qs} &= 0.53 + 0.0944 \sin(2\omega t + 206.4^\circ) \quad \text{(pu)} \end{aligned}$$

By analyzing the results obtained in the computer simulations, Table 3 is produced, where the values for the electric variables are presented from the synchronous generator, concerning the condition of voltage unbalance at 2%.

Note that the synchronous generator goes on to suffer the influence of the second-order component across all variables. This produces a more expressive value on the electromagnetic torque, where it reaches 12.197% of the value of its continuous component, as seen on Table 3.

From the results on Table 3, one can to plot the graphs presented in Fig. 9.

Figure 9 (a) presents the harmonic spectrum showing the second-order component in percentage values for each variable in relation to its continuous component. While Fig. 9 (b)



(a)

(b)

FIGURE 9. Harmonic spectrum showing the rise of the second-order component on the analyzed electric variables.

presents the harmonic spectrum showing the second-order component that is induced on the damper windings, with its amplitude values being given in pu.

VI. CONCLUSION

The majority of isolated generators have their loads distributed in an inadequate form between the phases; such distribution is arranged without prior study or in a random fashion, which can imply in elevated unbalance. In addition, isolated synchronous generators tend to suffer from a greater degree of unbalance than synchronous generators that operate on a distributed system. The energy concessionaire, however, can perform allocation maneuvers of loads on the distribution system phases with the aim of reducing the unbalance over the electric network, which is different to an isolated generator, where the load distribution remains restricted to an isolated circuit.

The effect of the second-order component induced on the rotor of the synchronous machine brings as consequences, yield fall, higher temperatures, audible noise and alterations in the behavior of the machine in steady state.

From the results found in this study, it became apparent that voltage unbalance due to loads causes a series of changes in the behavior of the synchronous generator, with the rise of the second-order component on the rotor windings.

In this study, a VUF of 2% resulted in an electromagnetic torque oscillation, for which the portion of the second-order component passed the value of 12%. In addition, for the same analysis, it was noted that the current unbalance (I2/IN) reached a value of 13.43% on the synchronous generator, a value that surpasses the limits present on Table 1 (Item 1), and proposed in [29]. This provides an indication that higher unbalanced voltage values will result in a high level of current unbalance, causing damage to the synchronous generator.

Therefore, this study demonstrated that it is possible to identify and through the analysis of the Fourier transform, quantify the oscillations that appear in the electric variables of a synchronous generator, while supplying unbalanced loads. This brings to the fore, the importance that when dealing with isolated synchronous generators, it is essential to perform a study of the symmetrical distribution of loads. This is performed while constantly quantifying the degree of voltage and current unbalance to which a generator can be subjected, in order to prevent eventual damage (to the generator and the load) as well as avoid any reduction to the working life of the equipment.

Through quantification, one is able to perform the 2ω oscillation analysis of the electrical variables on the synchronous generator, being that the main contribution of this paper is found in the analysis of the oscillations of the second order component in salient pole synchronous generators, which operate in isolation. These double frequency oscillations are caused by the negative sequence current. For the particular case under analysis, an unbalance voltage rate of 2% on the synchronous generator causes an increased unbalance and consequently high pulsation of electromagnetic torque on the remaining electrical variables, thus reflecting on the alteration of the behavior associated with the synchronous generator in island operation in steady state.

Through the obtained results, one notes that these oscillations are worrying and open a line of research toward projects of intelligent control and inexpensive for the mitigation of these oscillations in island mode synchronous generators.

REFERENCES

[1] V. O. Zambrano, E. B. Makram, and R. G. Harley, "Stability of a synchronous machine due to an unsymmetrical fault in unbalanced power systems," in *Proc. 20th Southeastern Symp. Syst. Theory*, Charlotte, NC, USA, Mar. 1988, pp. 231–235. doi: 10.1109/SSST.1988.17050.

[2] E. B. Makram, V. O. Zambrano, and R. G. Harley, "Synchronous generator stability due to multiple faults on unbalanced power systems," *Electr. Power Syst. Res.*, vol. 15, no. 1, pp. 31–39, 1988. doi: 10.1016/0378-7796(88)90037-5.

[3] D. D. Robb and P. C. Krause, "Dynamic simulation of generator faults using combined abc and 0dq variables," *IEEE Trans. Power App. Syst*, vol. PAS-94, no. 6, pp. 2084–2091, Nov. 1975. doi: 10.1109/T-PAS.1975.32058.

[4] E. Muljadi, D. Yildirim, T. Batan, and C. P. Butterfield, "Understanding the unbalanced-voltage problem in wind turbine generation," in *Proc. Ind. Appl. Conf. 34th IAS Annu. Meeting*, Phoenix, AZ, USA, vol. 2, Oct. 1999, pp. 1359–1365. doi: 10.1109/IAS.1999.801678.

[5] R.-S. Muñoz-Aguilar, P. Rodríguez, A. Dòria-Cerezo, I. Candela, and A. Luna, "A sensor-less sliding mode control scheme for a stand-alone wound rotor synchronous generator under unbalanced load conditions," *Int. J. Elect. Power Energy Syst.*, vol. 60, pp. 275–282, Sep. 2014. doi: 10.1016/j.ijepes.2014.03.003.

[6] R. S. Muñoz-Aguilar, P. Rodríguez, A. Dòria-Cerezo, I. Candela, and A. Luna, "Sensor-less sliding mode control of a stand-alone wound rotor synchronous generator with unbalanced load," in *Proc. 37th Annu. Conf. Ind. Electron. Soc.*, Melbourne, VIC, Australia, Nov. 2011, pp. 3982–3987. doi: 10.1109/IECON.2011.6119960.

[7] R. R. Oliveira, C. A. L. Rocha, A. C. Delaiba, J. C. Oliveira, and F. N. Belchior, "Three-phase synchronous generators performance with unbalanced and non-linear loading-analytical and experimental analysis," in *Proc. IEEE Int. Symp. Ind. Electron.*, Montreal, QC, Canada, Jul. 2006, pp. 1744–1749. doi: 10.1109/ISIE.2006.295834.

[8] R. H. Salim, R. A. Ramos, and N. G. Bretas, "Analysis of the small signal dynamic performance of synchronous generators under unbalanced operating conditions," in *Proc. IEEE PES Gen. Meeting*, Providence, RI, USA, Jul. 2010, pp. 1–6. doi: 10.1109/PES.2010.5589949.

[9] M. F. Abdullah, N. H. Hamid, Z. Baharudin, M. F. I. Khamis, and M. H. M. Nasir, "The study of triplen harmonics currents produced by salient pole synchronous generator," in *Proc. Int. Conf. Elect. Eng. Inform.*, Bandung, Indonesia, Jul. 2011, pp. 1–5. doi: 10.1109/ICEEI.2011.6021569.

[10] S. Kadiman, S. P. Hadi, Tumiran, and F. D. Wijaya, "Teaching the large synchronous generator dynamic model under unbalanced steady-state operation," in *Proc. Int. Conf. Inf. Technol. Elect. Eng. (ICITEE)*, Yogyakarta, Indonesia, Oct. 2013, pp. 409–413. doi: 10.1109/ICITEED.2013.6676277.

[11] P. Donolo, G. Bossio, C. De Angelo, G. García, and M. Donolo, "Voltage unbalance and harmonic distortion effects on induction motor power, torque and vibrations," *Electr. Power Syst. Res.*, vol. 140, pp. 866–873, Nov. 2016. doi: 10.1016/j.epsr.2016.04.018.

[12] J. Yao, M. Yu, W. Hu, Z. Chen, and T. Zhou, "Improved control strategies for a DFIG-based wind-power generation system with SGSC under unbalanced and distorted grid voltage conditions," *Int. J. Elect. Power Energy Syst.*, vol. 77, pp. 185–196, May 2016. doi: 10.1016/j.ijepes.2015.11.016.

[13] B. Jeong and S. Song, "Torque ripple compensation using negative sequence current control during unbalanced grid conditions in a DFIG system," in *Proc. 31st Int. Telecommun. Energy Conf.*, Incheon, South Korea, Oct. 2009, pp. 1–5. doi: 10.1109/INTLEC.2009.5351950.

[14] S. Hu, X. D. Zou, Y. Kang, and X. C. Lin, "An enhanced control scheme for unbalanced operation of doubly-fed induction generator," in *Proc. 7th Int. Power Electron. Motion Control Conf.*, Harbin, China, Jun. 2012, pp. 2134–2140. doi: 10.1109/IPEMC.2012.6259175.

[15] A. B. Ataji, Y. Miura, T. Ise, and H. Tanaka, "Direct voltage control with slip angle estimation to extend the range of supported asymmetric loads for stand-alone DFIG," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1015–1025, Feb. 2016. doi: 10.1109/TPEL.2015.2414481.

[16] S. Chattopadhyay, M. Mitra, and S. Sengupta, *Electric Power Quality*, 1st ed. New Delhi, India: Springer, 2011, p. 182.

[17] *Motors and Generators*, Standard ANSI/NEMA MG1-1993, 2009.

[18] *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*, IEEE Standard 112-1191, 1991.

[19] C.-Y. Lee, "Effects of unbalanced voltage on the operation performance of a three-phase induction motor," *IEEE Trans. Energy Convers.*, vol. 14, no. 2, pp. 202–208, Jun. 1999. doi: 10.1109/60.766984.

[20] A. I. Maswood, G. Joos, P. D. Ziogas, and J. F. Lindsey, "Problems and solutions associated with the operation of phase-controlled rectifiers under unbalanced input voltage conditions," *IEEE Trans. Ind. Appl.*, vol. 27, no. 4, pp. 765–772, Jul. 1991. doi: 10.1109/28.85494.

[21] J. Reeve and P. C. S. Krishnayya, "Unusual current harmonics arising from high-voltage DC transmission," *IEEE Trans. Power App. Syst.*, vol. PAS-87, no. 3, pp. 883–893, Mar. 1968. doi: 10.1109/TPAS.1968.292205.

[22] G. Beaulieu, M. H. J. Bollen, S. Malgarotti, and R. Ball, "Power quality indices and objectives. Ongoing activities in CIGRE WG 36-07," in *Proc. Power Eng. Soc. Summer Meeting*, Chicago, IL, USA, vol. 2, Jul. 2002, pp. 789–794. doi: 10.1109/PESS.2002.1043433.

[23] I. Boldea, *Synchronous Generators* (The Electric Generators Handbook), 1st ed. Boca Raton, FL, USA: CRC Press, 2005.

[24] W. E. Vanço, F. B. Silva, J. R. B. A. Monteiro, J. M. M. de Oliveira, A. C. B. Alves, and C. A. B. Júnior, "Analysis of the oscillations caused by harmonic pollution in isolated synchronous generators," *Electr. Power Syst. Res.*, vol. 147, pp. 280–287, Jun. 2017. doi: 10.1016/j.epsr.2017.03.003.

[25] P. Kundur, *Power System Stability and Control*, 1st ed. Toronto, ON, Canada: McGraw-Hill, 1993.

[26] F. B. Silva, W. E. Vanço, F. A. da Silva Gonçalves, C. A. Bissochi, Jr., D. P. de Carvalho, and G. C. Guimarães, "A proposal for the study of voltage sag in isolated synchronous generators caused by induction motor start-up," *Electr. Power Syst. Res.*, vol. 140, pp. 776–785, Nov. 2016. doi: 10.1016/j.epsr.2016.05.008.

[27] I. Boldea and L. N. Tutelea, *Electric Machines: Steady State, Transients, and Design With MATLAB*, 1st ed. Boca Raton, FL, USA: CRC Press, 2019.

[28] L. J. Myatt and P. Hammond, *Symmetrical Components: The Commonwealth and International Library: Applied Electricity and Electronics Division*, 1st ed. London, U.K.: Pergamon, 1968.

[29] *Rotating Electrical Machines—Part 1: Rating and Performance*, Standard IEC 60034-1:2004, 11th ed., 2004.

[30] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. Pekarek, *Analysis of Electric Machinery and Drive Systems*, 3th ed. Hoboken, NJ, USA: Wiley, 2013.

[31] *Power Quality Indices and Objectives*, document CIGRE C4.07/CIRED, Joint Working Group, 2004.

[32] *Electricity Supply–Quality of Supply—Part 2: Voltage Characteristics, Compatibility Levels, Limits, and Assessment Methods*, document NRS 048-2:2003, Pretoria, South Africa, 2003.

[33] W. H. Kersting, *Distribution System Modeling and Analysis*, 3th ed. Boca Raton, FL, USA: CRC Press, 2012.

WAGNER E. VANÇO received the bachelor's degree, with a focus on electric power systems, and the master's degrees in electrical engineering from the Federal University of Uberlândia, in 2014 and 2016, respectively. He is currently pursuing the Ph.D. degree in electrical engineering with the University of São Paulo. He works essentially under the following themes: electric machines, electric grounding systems, generated power quality, magnetic saturation, and synchronous and asynchronous generation in isolated and distributed systems.

FERNANDO B. SILVA received the bachelor's degree in electrical engineering, with a focus on electric power systems, the master's degree in electrical machines, and the Ph.D. degree in electrical systems dynamics from the Federal University of Uberlândia, in 2010, 2015, and 2018, respectively. He is currently a Professor with the Electrical Engineering Department, Federal University of Ouro Preto, João Monlevade (ICEA) campus. His research interests include electrical machines (synchronous and induction machines), dynamics of electrical systems (development of static excitation systems for synchronous and induction generators, and modeling of active power filters), and hydroelectric plants (specification of electromechanical equipment).

JOSÉ ROBERTO B. A. MONTEIRO received the B.E., M.Sc., and Ph.D. degrees in electrical engineering from the School of Engineering of São Carlos (EESC), University of São Paulo (USP), São Carlos, Brazil, in 1994, 1997, and 2002, respectively, where he has been a Professor, since 2004. His research interests include power electronics, control, electric machines, and drives.

• • •