Sensitivity Analysis of the Synchronous Generation Repowering System in parallel with Induction Generator

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***Abstract*—In this work, it is proposed to calculate the sensitivity of parameters, based on analytical calculation, of repowered system between two electric generators, an induction generator and a synchronous generator, connected to a common bus in permanent regime, subject to a non-linear load. It is proposed a repowered system with simulated data where, based on percentage variations in the base values of the parameters, measurements are made for the analytical calculation that expresses the impact at the output caused by variations in the input. The experimental tests confirmed quantitatively the most sensitive variables for the system for the interval of interest. The results show that the generators and the nonlinear load are the input parameters with the highest sensitivity in the active power output and that the synchronous generator is responsible for the greater sensitivity in the reactive power output.**

***Keywords*—Sensitivity, Repowering, Induction Generator, Synchronous Generator**

I. INTRODUCTION

Repowering hydroelectric power plants has been increasing the power generated. Since there is spare capacity turbine power and that is not being exploited by the generator already installed, it can be repowering. Second [1] there are three possible ways to repotentializing: i) replacing the synchronous generator for a greater; ii) adding a second synchronous generator through double coupling on the turbine shaft; iii) adding a second generator coupled to the turbine shaft, but in this case an induction generator [2], [3]. [4] presents the technical requirements for connection of synchronous and induction generators in the distribution network.

The induction generator is viable technical and economically option to power generation [5]. The induction generator is used in electrical power plants repowering therefore has a low cost, more robust, simple construction, lower cost and less maintenance when compared with a synchronous machine. As disadvantage, external resources are required to compensate reactive power. On repowering, smaller induction generator is connected on a common bus to a larger synchronous generator and thus induction generator may have its reactive compensated by synchronous generator, without power factor losses in the coupling point between them and can be dispensed the control voltage, as this will be determined by system [6].

Another advantage that can be cited is related to the breaker, because for micro is most feasible using thermomagnetic circuit breakers. However, when there are two or more machines in parallel, it is interesting the use of motorized thermomagnetic circuit-breakers to facilitate synchronous operation between the machines. As the induction generator does not need synchronization, the cost can be further reduced, since the breaker motorization system is expensive. The induction generator does not require DC excitation and synchronization and has low maintenance costs [7].

The impact of induction generators connecting to the distribution system is studied in [8]. System losses and voltage drops are affected when the system supplies the reactive power required by the induction generator. No Canada in the Hydro-Quebec system, the demand for small generators connection, has been constantly increased [9]. The results indicate as a solution the correction of the power factor for the relation between losses due to changes in the voltage profile.

In [10] was held voltage and frequency control of parallel operation synchronous and induction generators. The synchronous generator has the exciter which provides variable excitation under different load conditions. The induction generator does not have either excitation control or speed control and it can provide constant power. The results show that any change in consumers reactive load is responded by the synchronous generator to keep the voltage nearly constant to 1 pu. The induction generator does not respond to the change in consumer's load and it always operates at its full rating.

Sensitivity analysis is the method to determine the most influential factors in the system [11]. The sensitivity analysis

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evaluates the response variation of a given output variable due to the changes made to the input parameters. The greater the variation in the output response, the greater the sensitivity. For [12], the sensitivity analysis measures the effect of a given input on a given output and verifies the uncertainty in the system response, caused by the uncertainties of the parameters.

[11] says that some authors consider models sensitive to input parameters in two ways: (i) the variability, or uncertainty, associated with the sensitivity of the input parameter to contribute to the output variability; (ii) the results of the models may have a high correlation with the input parameters, so that small changes in the input value will imply significant changes in the output. It is important to distinguish between uncertainty analysis for parameter importance and sensitivity analysis for parameter sensitivity. The author also classifies the main methods of sensitivity analysis in three categories: i) those that operate on only one variable at a time, ii) those that depend on the input matrix generation and associated output vector and iii) those that require particular input vector partitioning based on the resulting output vector. Most of these methods are intended for highly complex systems and require high computational effort.

In the literature, sensitivity analysis can be performed using mathematical, statistical and graphical methods. Graphically, the impact caused by the output of the system expresses the variations of the input parameters. For k system parameters, $k-1$ variables are kept fixed at their base value, while a parameter is changed. In the base case, the values for the input parameters and the output are defined, which is the base solution, defines a central point given by the union of the sensitivity curves of the parameters. Because of the ramifications from the center point, this type of chart is called a spider diagram or spider graph [13].

This work aims to present the relationship of influence between the inputs and outputs of the repowering system. The proposed electric power system consists of a synchronous generator that operates in parallel with the induction generator on the common bus subjected to the non-linear load. The sensitivity analysis based on the analytical method will present quantitative results for the sensitivity index of each parameter.

II. Mathematical Modeling

A. Three-Phase Induction Generator under Sinusoidal Steady State

Fig. 1, presents the equivalent electric circuit that models the steady-state induction machine represented by phase and referred to the stator. Where R_s is stator resistance, X_s is stator leakage reactance, R_r is rotor resistance referred to the stator, X_r is rotor leakage reactance referred to the stator, R_m is magnetization resistance and X_m is magnetization reactance [4].

B. Three-phase Synchronous Generator under sinusoidal steady state

Fig. 2 and Fig. 3 present the equivalent electrical circuit that models the steady synchronous machine represented in the reference system for the dq0 transformation with fixed reference in the rotor, for direct and quadrature axes, respectively [4].

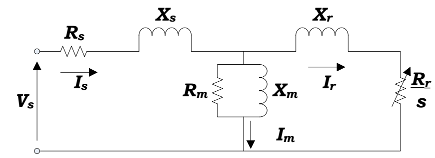

Fig. 1. Induction machine equivalent circuit.

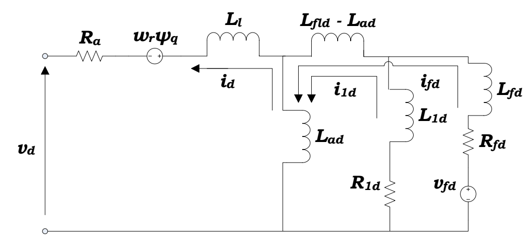

Fig. 2. d-axis synchronous machine equivalent circuit.

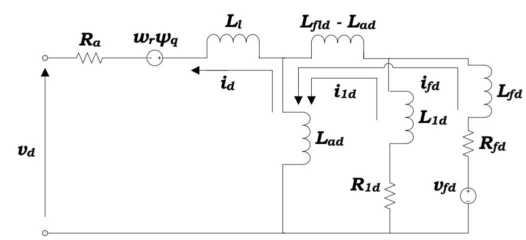

Fig. 3. q-axis synchronous machine equivalent circuit.

Where e_d is direct axis stator phase voltage, e_q is quadrature axis stator phase voltage, e_{fd} is field voltage, i_d is direct axis stator phase current, i_{1d} is direct axis winding amortisseur current, i_{fd} is field current, i_q is quadrature axis stator phase current, i_{1q} is quadrature axis winding amortisseur current, i_{2q} is quadrature axis second winding amortisseur current, w_r is electric angular velocity of the rotor, ψ_d is direct axis flux linkage, ψ_q is quadrature axis flux linkage, R_a is armature resistance, R_{fd} is field resistance, R_{1d} is direct axis winding amortisseur resistance, R_{1q} is quadrature axis winding amortisseur resistance, R_{2q} is quadrature axis second winding amortisseur resistance, L_{ad} is direct axis mutual inductance between the stator and rotor windings, L_{aq} is quadrature axis mutual inductance between the stator and rotor windings, L_l is the leakage inductance, L_{fd} is the field leakage inductance,

L_{ld} is direct axis winding amortisseur leakage inductance, L_{lq} is quadrature axis winding amortisseur leakage inductance the L_{2q} is quadrature axis second winding amortisseur leakage inductance and L_{fld} - L_{ad} is linking flux both field winding and the amortisseur.

III. Sensibility Analysis

The analytical method used to verify the impact on the output caused by variations in the input parameters is independent of the size of the range of the parameters. The method is based on one-at-a-time measurements and performs the calculation of the difference between the output values and the base solution to define the impact caused by each parameter in the system. The method analytic is the generalization of the method of the sum of differences [13].

A. Analytical Method

For k input variables, the output of the system is given by the function $y = f(x_1, x_2, ..., x_k)$, where $\beta = y$ when y is the base solution.

The analytical method comprises the following steps: i) obtain system output values according to one-at-a-time measures and ii) perform linear normalization transformation. The proposed method dispenses with graphical analysis, requiring only the one-at-a-time measures. The sensitivity index $S(x_i)$ is given by the relation between the sum of the differences between the output values and the base solution β, that results in the impact of the parameter that was varied, and the resulting impact of each input variable, given by (1).

$$S(x_i) = \frac{\frac{1}{n} \cdot \sum_{j=1}^{n} |y_{ij} - \beta|}{\sum_{i=1}^{k} \left(\frac{1}{n} \cdot \sum_{j=1}^{n} |y_{ij} - \beta| \right)} \tag{1}$$

where i is the parameter index, n is the number of parameter one-at-a-time measures, y_{ij} is the system output for j-th measure of x_i, k is the parameters number and β is the base solution.

IV. Methodology

The methodology for the proposed sensibility analysis was developed in the following steps:

- i All keys on of Fig. 4 with the characteristics of Tab. I.
- ii Vary the excitation voltage of the field of the synchronous generator;
- iii Vary the mechanical power of the primary machine of the synchronous generator;
- iv Vary the speed of the induction generator;
- v Vary the trigger angle of the non-linear load rectifier.

The sensitivity analysis of the proposed model is performed through the simulated data in M_1 for each variation of the input parameters.

A. Model

The simulation is performed for the computational model for *IEPS* shown in Fig. 4, where M_1, M_2, M_3 e M_4 are points for quantities measurements.

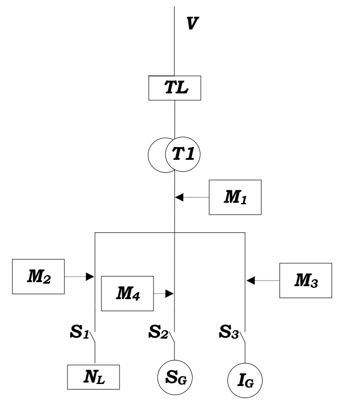

Fig. 4. Interconnected electrical power system - IEPS.

Computational tests of this work will be performed with system composed of two generating units, a synchronous and another induction. Both units will be in parallel by feeding nonlinear load N_L consisting of triac rectifier feeding sets of lamps. Two phases with total power of $5kW$ and the third phase with $4kW$. To regulate generators speed, S_G and I_G, were used diesel engine and induction motor with frequency inverter, respectively.

V. Computational Tests

Components and values of *IEPS* of Fig. 4 are reported in the Tab. I, along with their values.

TABLE I
Acronyms and values of the components from *IEPS*.

Variables	Components	Components Values of Used
S_G	Synchronous Generator (main generator)	37kVA, 380V three-phase, salient 4poles, 60Hz
I_G	Induction Generator	7.5kVA, 380V three-phase, cage rotor 4poles, 60Hz
N_L	Nonlinear Load	14kW three-phase 380V, 60Hz
S_1, S_2, S_3	Interrupter	

The main purpose of the computational tests of the *SEPI* of Fig. 4 is to present influence relation of the input parameters and the repowering system outputs.

VI. Results

The sensitivity analysis of the real system is performed through the data collected in the meter M_1, for each variation of the input parameters. The input parameters are: i) non-linear load rectifier trigger angle, θ, ii) mechanical power of the synchronous generator primary machine, P_{MEC}, iii) induction generator speed, ω_{IG} and iv) synchronous generator field voltage, $V_{f_{CAP}}$ for the capacitive synchronous generator and $V_{f_{IND}}$ for the inductive synchronous generator. The output parameters are: i) active power, ii) reactive power, iii) total power, iv) power factor, v) total voltage harmonic distortion and vi) total current harmonic distortion.

For this study, the varied parameters one-at-a-time were θ, P_{MEC}, ω_{IG}, $V_{f_{IND}}$ and $V_{f_{CAP}}$, in order to observe their sensitivity as a function of the active power, in watt (W), and of the reactive power, in Volt-Ampere-Reactive (VAr). The base values of the parameters and their respective ranges are shown in Tab. II.

TABLE II
BASE-VALUES AND RANGE ADOPTED FOR SIMULATED DATA COLLECTION

Parameter	Base-value	Range	Base-value variation [%]
θ	$90°$	[0 180]	$[-100\%\ \ 100\%]$
P_{MEC}	$20kVA$	$[3k\ \ 37k]$	$[-85\%\ \ 85\%]$
ω_{IG}	$1830rpm$	[1800 1860]	$[-1.64\%\ \ 1.64\%]$
$V_{f_{IND}}$	$0.999pu$	[0.998 1.000]	$[-0.1\%\ \ 0.1\%]$
$V_{f_{CAP}}$	$1.0005pu$	[1 1.001]	$[-0.05\%\ \ 0.05\%]$

The data collected in the simulation are shown graphically in Fig. 5 and Fig. 6, corresponding to the one-at-a-time measures for *active power* and *reactive power* for the inductive synchronous generator, respectively. It is observed that the mechanical power of the synchronous generator primary machine, P_{MEC}, is the most sensitive parameter, with the greatest impact on the two outputs. This observation was confirmed by the calculated sensitivity indices, which presented values above 43%, arranged in Tab. III.

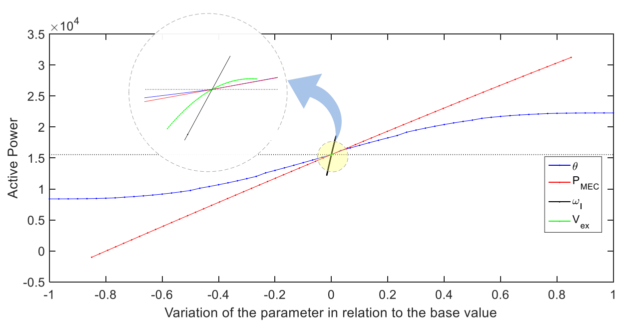

Fig. 5. Graph-spider of data simulated of power generation system for active power with the inductive synchronous generator.

The data collected in the simulation are shown graphically in Fig. 7 and Fig. 8, corresponding to the one-at-a-time measures for *active power* and *reactive power* for the capacitive synchronous generator, respectively. It is observed that the mechanical power of the synchronous generator primary machine, P_{MEC}, is the most sensitive parameter, with the greatest impact on the two outputs. This observation was confirmed by the calculated sensitivity indices, which presented values above 46%, arranged in Tab. III.

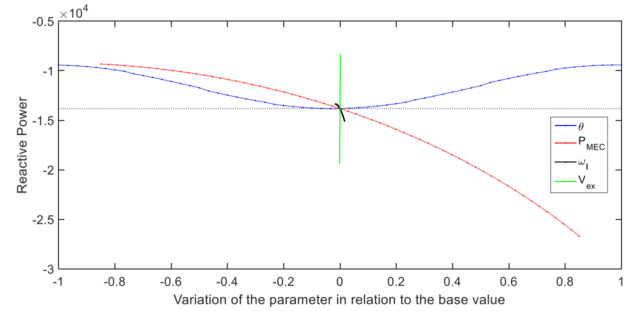

Fig. 6. Graph-spider of data simulated of power generation system for reactive power with the inductive synchronous generator.

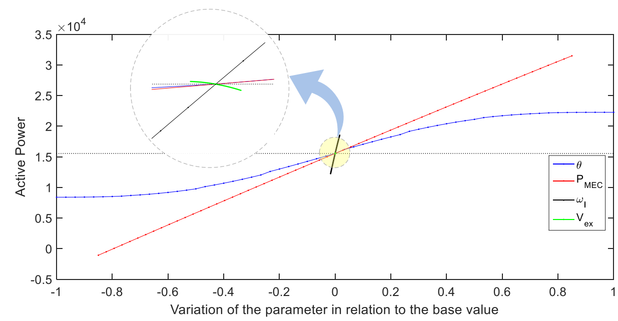

Fig. 7. Graph-spider of data simulated of power generation system for active power with the capacitive synchronous generator.

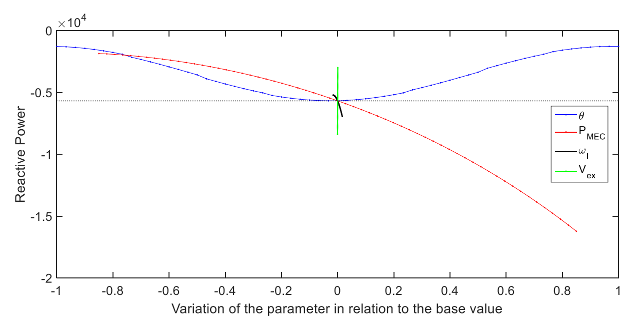

Fig. 8. Graph-spider of data simulated of power generation system for reactive power with the capacitive synchronous generator.

In analysis in Fig. 6 and Fig. 8, it is observed that the synchronous generator field voltage has a higher sensitivity in the reactive power output than in the active power output, that are shows in Fig. 5 e Fig. 7. In practice, when it is desired to change the synchronous machine reactive power, the machine field voltage is modified. The synchronous machine can then receive or supply reactive to the network. The excitation voltage curve of the synchronous generator is increasing for the inductive and decreasing for the capacitive for the active power.

The Table. III presents the sensitivity indexes S for the parameters θ, P_{MEC}, ω_{IG}, $V_{f_{IND}}$ and $V_{f_{CAP}}$ calculated by the analytical method.

TABLE III
SENSITIVITY INDICES CALCULATED BY THE ANALYTICAL METHOD FOR SIMULATED DATA

Output	$S(\theta)$	$S(P_{MEC})$	$S(\omega_{IG})$	$S(V_{f_{IND}})$
Power Active	33.26%	55.65%	10.89%	0.20%
Power Reactive	23.11%	43.60%	4.58%	28.71%

Output	$S(\theta)$	$S(P_{MEC})$	$S(\omega_{IG})$	$S(V_{f_{CAP}})$
Power Active	33.12%	55.96%	10.85%	0.07%
Power Reactive	29.46%	46.71%	5.83%	18.00%

In practice, to change the active power of the system, one can: i) increase the power generated by the synchronous generator, ii) increase the power generated by the induction generator and iii) change the load consumption, confirming the data presented in Table. III, for P_{MEC} of $55,65\%$, ω_{IG} of $10,89\%$ and θ of $33,26\%$ for the inductive and P_{MEC} of $55,96\%$, ω_{IG} of $10,85\%$ and θ of $33,12\%$ for the capacitive.

To change the reactive power output of the system the greatest impact is given by the parameters for P_{MEC} of $46,60\%$, θ of $23,11\%$ and $V_{f_{IND}}$ of $28,71\%$ for the inductive and P_{MEC} of $46,71\%$, θ of $29,46\%$ and $V_{f_{CAP}}$ of $18,00\%$ for the capacitive, according to Table. III,, thus confirming that the synchronous generator is most responsible for the system reactive variation, either by the mechanical power variation or by the excitation voltage variation.

The analytical method is notable by the adequacy of the indices of the impact generated for different range parameters. Note that even small-range parameters, such as ω_{IG}, had a considerable impact even at values close to their base value, within their small range.

VII. Conclusion

This work confirmed that the induction generator, the synchronous generator, and the nonlinear load are the most sensitive input parameters for the active power output of the electrical system. It was clear, from the results, that the excitation voltage of the synchronous generator is a parameter of greater sensitivity, independent of the synchronous machine producing or consuming reactive powers, for the reactive power output. The analytical method expresses coherent sensitivity index values for input data with different ranges, confirming practical knowledge.

Acknowledgment

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