USE OF INDUCTION GENERATORS EQUIPPED WITH SPEED GOVERNORS IN BRAZILIAN INDUSTRIAL SYSTEMS TO EXPLORE ALTERNATIVE SOURCES OF ENERGY

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Abstract **-This article shows the viability of using induction generator in power systems to supply part of the active power demand (co-generation), exploring alternative energy sources derived from industrial productive process surpluses. Firstly, it is presented a mathematical representation of the induction generator. Secondly, it is developed and analyzed a model for its speed governor, aiming to improve its steady and transient state operation. Finally, some simulations are run to compare the performance of a typical electrical system with and without the presence of induction generators.**

KEYWORDS
Electrical power systems, co-generation, induction generator, speed governor, alternative sources of energy.

1. INTRODUCTION

Nowdays, due to uncertainty in the level of the Brazilian hydraulic reserves, in function of the climatic changes which regulate the rate of occurence of rains, it becomes necessary to take advantage of all available energy resources. For example, it is pointed the Brazilian industrial surpluses resulted from productive process of the sugar cane in alcohol plants, and also the garbage and sewer processing for biogas production, can be used as alternative sources of energy to feed part of the loads of the electric system. To explore these energy sources, an efficient device is the induction generator [1,2], as shown in this work. This machine overcomes the synchronous generator in several aspects, such as: robustness, smaller volume, smaller induction generators, where most of the active power is supplied by synchronous machines. It is supposed that the induction generators belong to an alcohol plant which uses the industrial processing surpluses as the primary power source to drive such machines.

2. USE OF ALTERNATIVE SOURCES FOR ELECTRIC POWER GENERATION

Brazil has faced a serious electric power crisis. This is mainly caused by two factors: the decrease in water level in the reservoirs due to draught in some regions of the country, and the lack of investments in the electrical energy industry, mainly in the generation and transmission sectors. This crisis has represented a difficult phase in our history which, undoubtedly, demands to seek of mecanisms to soften its effects. One of the possible found solutions would be the use, for the government as well as for the entrepreneurs, of alternative sources of electrical energy generation [3]. The country possesses an enormous potential of these sources, mentioning among them those originating from biomass, such as: the burning of cane pulp for steam generation, and the processing of the garbage and sewer for biogas production [4]. The main advantages of the use of these energy resources for electric power generation consist of the following aspects: the energy is produced in the amount necessary for provision balance, the production cost is compatible with the benefits that it provides, and the risks for the environment are inexistent.

Thus these energy resources can be used as important sources for the electric power production, through thermoelectric plants, mainly in industrial systems. In the latter, the use of induction generators is considered a viable alternative for electric power production, due the characteristics presented by these machines.

3. INDUCTION GENERATOR MATHEMATICAL MODELLING

The models more used for the modelling of the induction machine take into account certain suppositions to simplify the equations. In this work, the single squirrel cage induction generator is used, considering only the electrical and mechanical rotor transients, since the much faster stator transients are neglected. This procedure, which is usually adopted for induction motor representation in electric system analysis programs [5,6], is also used for the generators. Therefore, the machine is represented by a transient voltage behind a transient reactance and the stator resistance. The single phase equivalent circuit of the transient model is shown in figure 1.

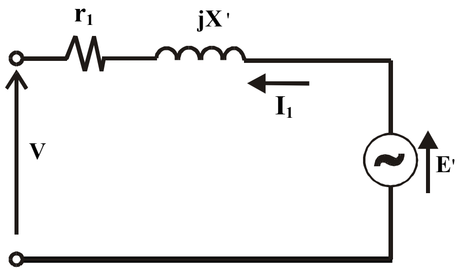

Figure 1 – Equivalent circuit for induction generator transient state

The differential equations for this modelling are:

$$\frac{d\dot{E}'}{dt} = \frac{1}{T_o}\left[j(X_o - X')\dot{I}_1 - \dot{E}'\right] - j2\pi fs\dot{E}' \qquad (3.1)$$

$$\frac{ds}{dt} = \frac{1}{2H}\left(T_m - T_e\right) \qquad (3.2)$$

To complete these equations, it is obtained the algebraic voltage equation corresponding to the electric circuit of figure 1.

$$\dot{E}' = \dot{V} - (r_1 + jX')\dot{I}_1 \qquad (3.3)$$

where:

$$X_o = X_1 + X_m \qquad (3.4)$$

$$X' = X_1 + \frac{X_m X_2}{X_m + X_2} \qquad (3.5)$$

$$T_o = \frac{X_2 + X_m}{2\pi f r_1} \qquad (3.6)$$

In figure 1 and in equations (3.1) to (3.6), it was adopted the following notation:

$\dot{E}'$ - transient voltage phasor proportional to rotor linked flux
$\dot{V}$ - terminal voltage phasor
$\dot{I}_1$ - terminal current phasor
r_1 - stator resistance
s - induction machine slip
f - system frequency
X' - transient reactance seen from machine terminals
X_o - open circuit reactance
X_1 - stator reactance (steady state)
X_2 - rotor reactance (steady state)
X_m - magnetizing reactance (steady state)
T_o - open circuit time constant
T_e - electrical torque
T_m - mechanical torque
H - inertia constant of turbine-generator set

All the terms whose units were omitted are expressed in pu (per-unit system) using the generator ratings as reference or base values. Notice that the time constants are expressed in seconds (s), the system frequency in Hertz (Hz) and the inertia constant in seconds (s or W.s/VA or J/VA).

4. SPEED GOVERNOR MATHEMATICAL MODELLING

4.1 Importance of Speed Governors

After an unbalance between generation and load, the electric system shows a tendency of self-regulating and to reach a new equilibrium state which cannot be satisfactory for its operation. This happens because the system usually possesses several loads that work within a narrow frequency range. In this sense, the speed governors are normally employed in synchronous generators aiming to bring the system frequency back to its normal operation condition.

As to the induction generators operating in an electric system, it is also interesting to have them equipped with speed governor devices. Thus, these controls will allow to adjust the portion of generated active power supplied to the power system, whenever it is required. As the speed of an induction generator varies, due to a disturbance in the electric system, its governor acts so as to reestablish the normal operation speed. In this sense, this speed governor only operates in the form referred as "primary regulation”, since the maintenance of a constant frequency in the network (“secondary regulation”) is a function of a group of synchronous generators connected to the control center of system operation.

4.2 Speed Governor Modeling

The block diagram of the induction generator speed governor implemented in the transient stability program is shown in figure 2. This was developed by analogy with speed governor models of synchronous machines, taking into account that the induction generator operation speed is above the synchronous speed, whose value depends on the constructive characteristics of each machine and its electrical load.

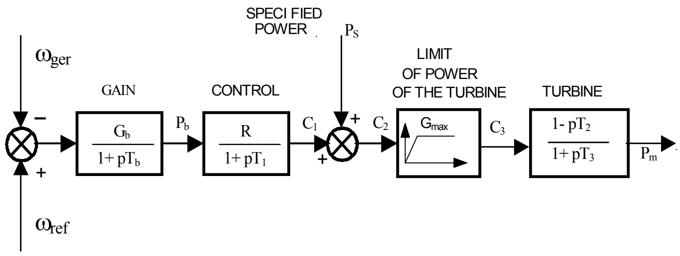

Figure 2 – Block diagram of an induction generator speed governor

The diagram shown in figure 2 presents several transfer functions which permit to write the relationship between the input and output variable of each block. The difference between the initial speed, taken as reference (ω_{ref}), and the actual speed (ω_{ger}) of the induction generator produces an error which is dependent to the disturbance occurred in the system. The values of "G_b" and "T_b ", represent, respectively, the gain and the "flyball" time constant, in the same way "R" and "T_1", represent, the regulation factor and the time constant of the control valve. The sign "C_1" is added to the specified power " P_S " results in a value "C_2", which is compared with the maximum active power limit it activates "G_{max}" resulting in "C_3". This value is taken to the transfer function of the prime mover or turbine resulting in the input mechanical power to the induction generator "P_m ". The terms "T_2" and "T_3" are the time constants of the turbine. The mechanical power "P_m" produces the mechanical torque "T_m" of equation (3.2).

5. TEST SYSTEM AND GENERAL DATA

To analyze the behavior of induction generators operating in an electric system, the test system shown in the online diagram of figure 3 was built. Notice that there are three synchronous generators and two induction generators supplying three load regions. The regions A and B represent two great consumers and the region C represents an alcohol plant with its load and generation working in parallel (co-generation) with the electric power utility (represented by the synchronous generators). The network active losses were neglected.

Table 1 shows the input data of the test system for the transient stability program. Tables 2, 3 and 4 show, respectively, the parameters of the synchronous machines, the induction generators and the induction generator speed governors.

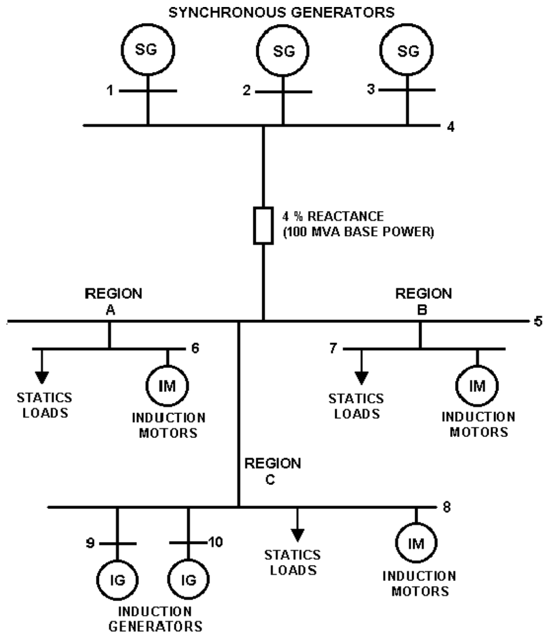

Figure 3 - Schematic diagram of 10-bus test system (4% reactance between buses 4 and 5, 100 MVA base)

Table 1 – Initial input data of the test system.

Bus No.	Generated Power		Consumed Power		Terminal Voltage	
	MW	MVAr	MW	MVAr	pu	degree
1	24,000	12,990	0,000	0,000	1,000	0,000
2	16,000	12,981	0,000	0,000	1,000	-0,000
3	20,000	12,981	0,000	0,000	1,000	-0,000
4	0,000	0,000	0,000	0,000	1,000	-0,000
5	0,000	0,000	0,000	0,000	0,984	-1,430
6	0,000	0,000	27,00	14,00	0,984	-1,430
7	0,000	0,000	27,00	14,00	0,984	-1,430
8	0,000	0,000	12,00	6,00	0,984	-1,430
9	3,000	-1,414	0,000	0,000	0,984	-1,430
10	3,000	-1,414	0,000	0,000	0,984	-1,430

Table 2 –Synchronous machine parameters

Bus No.	Power (MVA)	H (s)	X'd (pu)	X'q (pu)	Xd (pu)	Xq (pu)	X"d (pu)	X"q (pu)
1	30,0	3,0	0,26	0,62	1,00	0,620	0,26	0,310
2	30,0	3,0	0,26	0,62	1,00	0,620	0,26	0,310
3	30,0	3,0	0,26	0,62	1,00	0,620	0,26	0,310

Table 3 –Induction generator parameters

Bus No.	Power (MW)	H (s)	Rs (pu)	Rr (pu)	Xs (pu)	Xr (pu)	Xm (pu)
9	3,0	1,0	0,01	0,009	0,098	0,098	3,9
10	3,0	1,0	0,01	0,009	0,098	0,098	3,9

Table 4 – Speed governors parameters

Bus No.	Gain (pu)	Tb (s)	R (pu)	T_1 (s)	T_2 (s)	T_3 (s)	Power (MW)
9	1,0	1,0	0,05	0,5	0,0	0,05	5,0
10	1,0	1,0	0,05	0,5	0,0	0,05	5,0

The data from table 1 show the use of induction generators in the system of figure 1, in such condition that they were responsible to supply a small portion of the total load demand (10%, approximately).

6. SIMULATIONS

Two types of simulations are made: the first one to test the speed governor model of the induction generator implemented in the transient stability program; and the second one to verify the dynamic behavior of an electric system when induction generators are connected to the system, working in parallel with synchronous generators (co-generation).

In all the studies, a loss of 33% of the total synchronous generation is simulated, which is represented by disconnecting the third synchronous machine (20 MW unit) from the system.

6.1 Studies of the speed governor model developed for the induction generator

Initially, the studies are accomplished to analyze and compare the results obtained with the induction generators, working in the system of figure 3, but in two different conditions: absence (curves SG-OUT) [7] and presence (curves SG-IN) of the speed governors of such machines.

For the analysis, just the results referring to one of the induction generators are shown, since both are identical and present the same behavior.

6.2 Studies of the electric system dynamics with the induction generators

In these studies, a transient stability program is used to analyze and compare the operation of the electric system of figure 3 in two different conditions: absence (curves IG-OUT) and presence (curves IG-IN) of induction generators equipped with speed governors.

The base or reference case is when the induction generators are out of the system (curves IG-OUT). Thus, the whole active power demanded by the system it supplied only by the synchronous generators because the induction generators of figure 3 are disconnected. Since the synchronous generators are identical, only one of them is chosen to show the impact of the disturbance.

When the induction generators are in the system (curves IG-IN), the two machines are each one working with 3 MW of active power specified, which altogether represent 10 % of the active power supplied by the three synchronous generators. To accomplish the analysis of the behavior of the system, besides the curves of the same synchronous machine of case 1, it is also presented some results related to one of the induction generators.

7. RESULTS

7.1 Study results of the speed governor model developed for the induction generator

The graphics of speed, mechanical power, active power and reactive power shown in figures 4, 5, 6 and 7, respectively, present the behavior of the induction generator connected to bus 9 of the test system of figure 3, for the absence (curves SG-OUT) and presence (curves SG-IN) of speed governor.

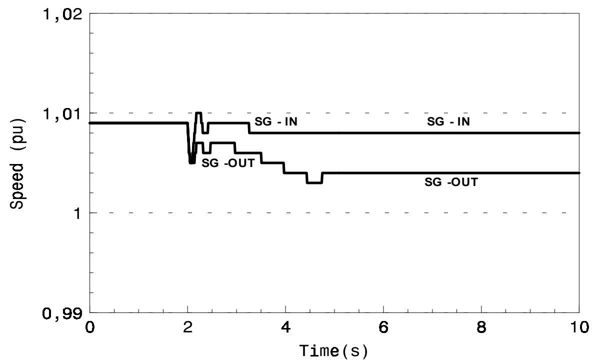

Figure 4 – Induction generator speed response

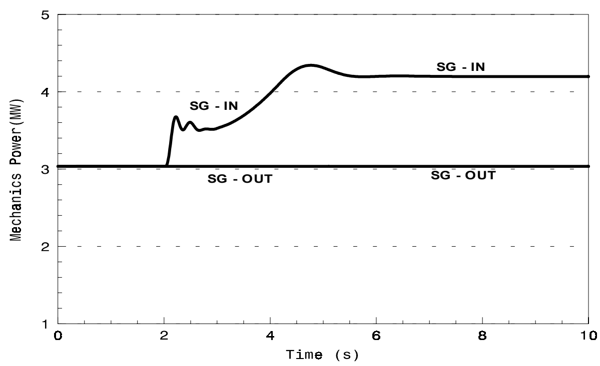

Figure 5 – Induction generator mechanical-power response

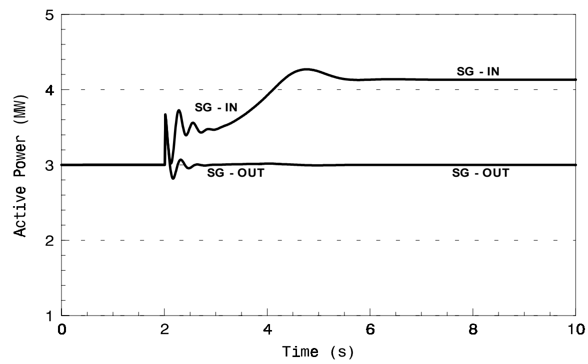

Figure 6 – Induction generator active power response

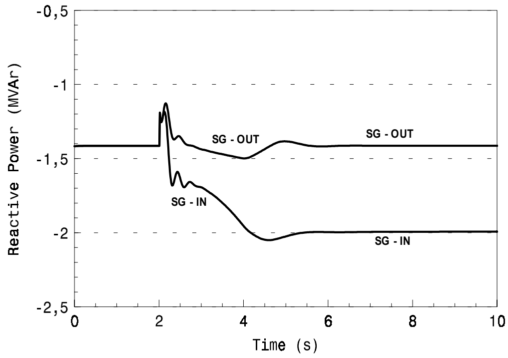

Figure 7 – Induction generator reactive power response

In the first situation, that is, when there is no speed governor (curves SG-OUT), it is observed that the induction generator active power, despite being requested to supply a value which is larger than the rated power in the beginning of the disturbance, comes back to its initial value of operation (see figure 6). This is because the mechanical power do not follow this variation, since, in the absence of an appropriate control, it is always constant (see figure 5) during the entire operation of the primary machine. The final speed of operation is, approximately, 0,5% below the pre-disturbance value (see figure 4) because the frequency of the bus, where is connected the generator, also suffers small decrease due to the disturbance. As the speed of the induction generator depends on the synchronous speed of the rotating field, if there is a decrease of this, that tends to suffer a reduction in the same proportion (see figure 4).

In the second situation, that is, when the speed governor are working (curves SG-IN), it is observed that the induction generator behaves so as to assist fully the new needs imposed by the system due to the disturbance. In the case of the active power (see figure 6), it can be concluded that the induction generator acts to attend the demand increment required by the system to face the overload imposed by the loss of a generator unit. This is now possible due to the appropriate action of the speed governor which acts in order to increase the available mechanical power for the induction generator (see figure 5). In the case of the reactive power, as there was a variation (increment) of the active power supplied by the induction generator, the reactives necessary for its excitation were also altered (increased), to adjust to the new operation needs (see figure 7). Finally, analyzing the speed behavior of the induction generator (see figure 4), a difference is observed in relation to the case without regulator. Now, the speed was adjusted by the action of the governor which made it goes back quickly to a value very close to that of the initial operation condition (reference).

7.2 Study results of the electric system dynamics with the induction generators

The graphics of frequency, active power, reactive power and terminal voltage shown in figures 8, 9, 10 and 11, respectively, present the behavior of one synchronous generator number 1, of the test system of figure 3, for the absence (curves IG-OUT) and presence (curves IG-IN) of induction generators.

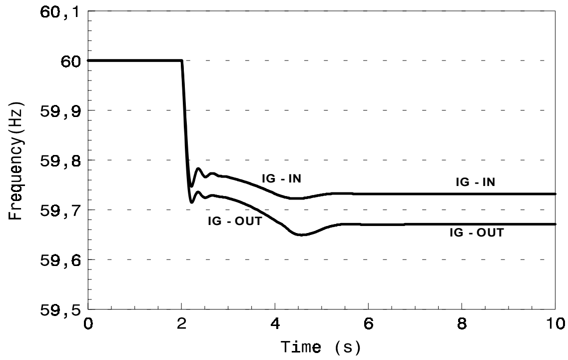

Figure 8 – Synchronous machine frequency response

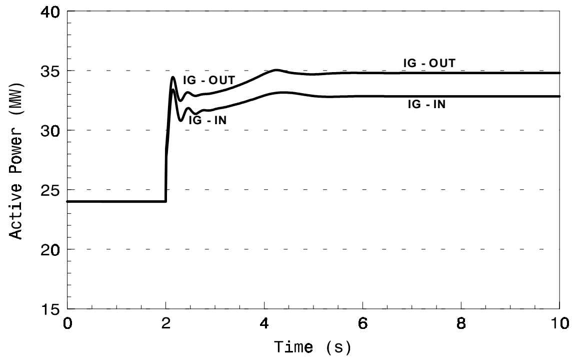

Figure 9 – Synchronous machine active power response

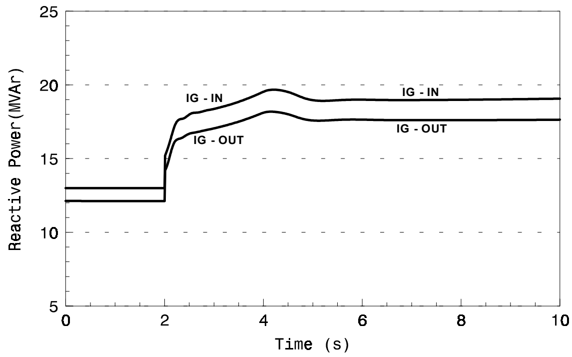

Figure 10 – Synchronous machine reactive power response

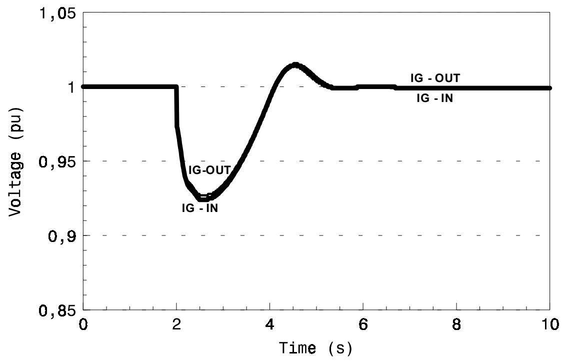

Figure 11 – Synchronous machine terminal voltage response

With regards to the frequency behavior of figure 8, it is verified that it has stabilized in different values for the two simulated situations (absence and presence of induction generators). Taking 60 Hz as the rated and reference frequency value, it can be observed that there was a frequency decrease in the two cases, but with more intensity with no induction generator (around 0,6% - curve IG-OUT) than with induction generators (around 0,44% - curve IG-IN). Thus, the reduction of system frequency oscillations is larger for the case when the induction generators are operating, that when these are inoperative.

The active power shown in figure 9 presented an increase for the two situations although it was less accentuated with induction generators (around 37.5% - curves IG-IN) than with no induction generators (around 56.0% - curves IG-OUT). This difference may be explained because when the induction generators are in operation they aid the synchronous generators remainders to supply the demand of active power of the system, since the system loads continue demanding approximately the same active power even after the loss of one synchronous generator.

With regards to the reactive power behavior of figure 10, it is verified that it tends to rise in the two situations, because the synchronous generators remainders tend to compensate for the synchronous unit that was lost. As expected, the operation with induction generators causes larger reactive power increase (around 58,2% - curve IG-IN) than without them (41,6% - curve IG-OUT). This difference may be explained because the total reactive power required to excite the induction generators must be attended by the synchronous generation, no matter how many are in operation.

The terminal voltage at the bus where the disturbance took place is illustrated in figure 11. It presents a sudden fall (around 8,0%) just after the synchronous generator loss, either for the absence or presence of induction generators. The reason is that the system felt the lack of such unit who was responsible for about one third of the total load demand. The induction generators had no influence on the voltage response, since these machines take no part on the voltage control.

8. CONCLUSIONS

This article showed that co-generation, using induction generator(s) instead of synchronous generator(s), is a very interesting and advantageous option, because it allows not only to benefit from the use of alternative energy sources existing in some industrial systems, but also helps to improve the global dynamics of the electric system.

Moreover, if the induction generators are equipped with speed governors, the participation of these units in the electric system dynamics is even more effective, because the governors make possible to accomplish speed adjustments through the control of the prime mover mechanical power.

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BIBLIOGRAPHICAL REFERENCES

[1] Parsons. Jr.,.R., 1984, “Cogeneration Application of Induction Generators”, IEEE Transactions on Industry Applications, Vol. 1A-20, No.3, My/June, pp 497-503.

[2] Souza, C.L., Neto, L.M., Guimarães, G.C. e Moraes, A. J., “O uso de geradores de indução na melhoria da estabilidade de um sistema elétrico”, Revista Eletricidade Moderna. Brasil, p.84 - 97, 2000.

[3] Neiva, J., 1987, “Fontes Alternativas de Energia”, Rio de Janeiro, Brasil, p.155.

[4] Carioca, J.O.B., “Biomassa – Fundamentos e Aplicações Tecnológicas”, Fortaleza, Brasil, p.644.

[5] Kundur, P., 1994, “Power System Stability and Control”, McGraw-Hill Inc., EPRI,USA.

[6] Souza, C.L., Moraes, A. J., Oliveira, J.C. e Guimarães, G.C., “Uma metodologia de agregação de cargas estáticas e motores de indução para análise da estabilidade transitória” ,VIII ERLAC, 1999.

[7] Souza, C.L., Neto, L.M., Guimarães, G.C. e Moraes, A. J., “Power System Transient Stability Analysis Including Synchronous and Induction Generators”, IEEE Porto Powertech, Porto, Portugal, September 2001.