Grid Integration of Renewable Sources in the Distribution Network: An Analysis Through ATP-EMTP

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Abstract—The main objective of this work is to present the analysis of the behavior of synchronous generators of an electrical energy independent power producer, with their respective automatic voltage regulators (AVRs) and speed governors, in parallel with a power authority distribution system, for the distributed generation studies. It is highlighted that this generator is driven by a steam turbine with regulators and governors modeled in “ATP-Alternative Transients Program”, through the use of TACS subroutines. Among the analysis to be made are, the monitoring of voltage levels at the Common Coupling Point (CCP), before and after the Independent Producer (IP) entry point, as well as the analysis of the opening of the interconnection breaker and balanced three-phase fault. Moreover, the analysis of responses for the synchronous machines controls, voltage regulator and speed governor, are also the subject of analysis in this paper. The impacts of such generators in distribution networks are determined and compared through the use of a model of a distribution network, also modeled in ATP. This work presents, clearly and in a well defined manner, the main modifications in the power electrical system, more specifically in distribution networks, due to the presence of an independent power producer with two synchronous machines.

Keywords—distributed generation, synchronous generator, voltage profile, voltage regulator, speed regulator.

I. NOMENCLATURE

\( V_i \) - voltage at the independent generator bus bar (pu),
\( V_{ref} \) - reference voltage (pu),
\( K_a \) - regulator gain,
\( K_e \) - exciter constant related to self-excited field,
\( K_f \) - time gain for the regulator stabilizer circuit,
\( T_a \) - regulator amplified time constant (s),
\( T_f \) - regulator input filter time constant,
\( T_e \) - exciter time constant,

\( E_{max} \) - maximum exciter output voltage (applied to generator field),
\( E_{min} \) - minimum exciter output voltage (applied to generator field),
\( T_f \) - time constant for the regulator stabilizer circuit (s),
\( V_c \) = \( f(E_f) \) - saturation function,
\( V_{max} \) - maximum limit for the regulator output voltage (pu),
\( V_{min} \) - minimum limit for the regulator output voltage (pu),
\( E_f \) - field voltage (pu),
\( S_n \) - rated apparent power,
\( U_n \) - rated voltage,
\( L \) - length,
\( R_A \) - armature resistance (pu),
\( X_L \) - armature leakage reactance (pu),
\( X_Q \) - quadrature axis reactance (pu),
\( X_{dc} \) - direct axis reactance (pu),
\( X_{dq} \) - quadrature axis transient reactance (pu),
\( X_{d} \) - direct axis transient reactance (pu),
\( X_{q} \) - quadrature axis transient reactance (pu),
\( X_{dc} \) - direct axis sub transient reactance (pu),
\( X_{q} \) - quadrature axis sub transient reactance (pu),
\( X_{0} \) - zero sequence reactance (pu),
\( T_{d	heta} \) - direct axis transient short-circuit time constant (s),
\( T_{q	heta} \) - quadrature axis transient short-circuit time constant (s),
\( T_{d	heta} \) - direct axis sub transient short-circuit time constant (s),
\( T_{q	heta} \) - quadrature axis sub transient short-circuit time constant (s),
\( H \) - inertia moment (s),
\( P_e \) - electrical power (pu),
\( P_m \) - mechanical power (pu),
\( P_a \) - accelerating power (pu),
\( f \) - frequency (Hz),
\( \delta \) - load angle (degree),
\( \omega_s \) - synchronous speed (rad/s),
\( \omega_h \) - rotor speed (rad/s).

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II. INTRODUCTION

The interest for distributed generation has increased considerably over the years due to the restructuring in the Brazilian energy sector.

With the increasing demand for bio-fuels it has become common the ethanol production in sugar mill production plants, the electrical energy generation in such plants gained focus in the national energy scene. Such plants are increasing their production and are building larger installations all over the country. Consequently, an increase exists in the number of synchronous generators owned by sugar mill plants. Some of them are connected to the local power authority’s medium level voltage. This fact added to the current need to benefit from different forms of primary energy, technological advances and the awareness on environment conservation, is the way to induce and contribute to the dissemination of independent electrical power production.

Therefore, it is an emerging force the need to understand the influence of such aspects in the operation and design of electrical energy distribution networks. Among the analysis to be made, the monitoring of voltage levels in the Common Coupling Point (CCP), before and after the presence of the Independent Power Producer (IPP), as well as the analysis of loss of generation, the opening of interconnection breaker and distribution lines are made necessary. Moreover, the response of the synchronous machine controls, such as the speed regulator and voltage regulator are the subject of the studies in this paper.

III. SYSTEM MODELING

1. Voltage Regulator

A synchronous generator is used to represent the independent power producer, it is the type SM 59 with eight controls in the ATP model databank [1]. The voltage regulator is based in one of the models that are the basis for excitation regulators [2], [3] and [4].

According to the data input, this model can be reduced to four basic forms. The model used in this work for the voltage regulator can be seen in Figure 1, it is the type I model, one of the most complete designs recommended by the IEEE.

![Fig. 1. Voltage regulator model.](image)

2. Speed Regulator

The speed regulator was implemented based in one of the simplest IEEE models, and often used in transient stability studies programs.

Figure 2 presents the block diagram for the speed regulator associated to the steam turbine (if $T_4 = 0$) or to the hydro turbine (if $T_4 \neq 0$).

![Fig. 2. Model for the speed regulator for a thermal/hydro turbine.](image)

**Fig. 3. Single line diagram for the electrical system in the case considered**
### TABLE I
**SYNCHRONOUS MACHINE PARAMETERS FOR THE INDEPENDENT GENERATOR**

<table>
<thead>
<tr>
<th>S_n (MVA)</th>
<th>x_o (pu)</th>
<th>T'_{\omega} (s)</th>
<th>x_d (pu)</th>
<th>T''_{\omega} (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.046</td>
<td>1.754</td>
<td>1.8</td>
<td>0.164</td>
</tr>
<tr>
<td>6.6</td>
<td></td>
<td>0.019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.004</td>
<td></td>
<td>0.164</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.793</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.166</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.119</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.17</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

3. **Electrical System**

The independent power producer generators become part of the electrical system of a power authority distribution network, as illustrated in Figure 3. Such system is connected to the independent power producer through an interconnecting circuit breaker, following instructions established in [5]. Data depicted in Figure 3 refer to the system rated values, however, particularly for the independent power producer generator does not operate with a 0.8 lagging power factor, after performing a load flow.

The source type representing the power authority was defined as a three-phase ideal source, being considered, therefore, as an infinite bus bar. To use such controllable model in ATP, it will be necessary to define the data listed in Table I.

The rated parameters obtained for the machine voltage and speed regulators, as well as data referred to the independent power producer synchronous generator, were obtained directly from manufacturers.

4. **Power Flow**

The energy independent generation provides a total power of 4 MVA to the interconnection with the power authority electrical system, through the coupling transformer, T2.

Furthermore, the independent power producer provides energy to its internal demand, rated in 2.8 MVA.

Active and reactive power produced by the power authority (G) and the Independent Producer (G1 and G2) can be seen in Table II.

### TABLE II
**ACTIVE AND REACTIVE POWER GENERATED BY THE SYSTEM POWER SOURCES**

<table>
<thead>
<tr>
<th>Source</th>
<th>P_r [MW]</th>
<th>Q_r [MVAr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>21.182</td>
<td>4.087</td>
</tr>
<tr>
<td>G1 = G2</td>
<td>3.302</td>
<td>0.385</td>
</tr>
</tbody>
</table>

Before the presentation of the studied cases, it is necessary to highlight that depending upon the “penetration”, for the distributed generation, the obtained results will be affected differently.

IV. **CASE STUDIES**

Beforehand must be emphasized that similar studies, with different software, were made in [6]. Reference [7] shows the use of ATP for the modeling of a synchronous generator voltage regulator that is driven by a hydraulic turbine.

I. **Three-phase short-circuit at the CCP.**

Studies are made according reference [11], concerning the fault clearing time. This reference advises that under the event of a fault in the network, the independent power producer generator must be taken out of the system in a maximum time of 6 cycles and the rearward relay must trip in 18 cycles (300 ms).

Therefore, our goal in this case is to watch the behavior of the connection in the frame of the 6 cycles with the system under fault.

Figure 4 illustrate the voltage behavior at the CCP with the assumption of this contingency.

![Figure 4: Voltage at busbar 3 in the event of a fault.](image1)

It can be observed a voltage interruption at the CCP, however this interruption lasts for only 6 cycles, corresponding to the period of time allowed for the fault in the system.

After the fault removal, voltage comes back to 1.0 pu.

![Figure 5: Voltage at the IPP generation busbar.](image2)

With the independent generation bus bar close to the CCP, it will experience a voltage dip. In this case the voltage regulator of both machines at the IPP will act to increase their field excitation, the aim being the increase in voltage level at the generation bus bar 4. Figures 4 and 5 illustrate the behavior of voltage at bus bars 3 and 4 respectively; bus bar 4 is at the IPP premises and portray the...
voltage regulator response for such machines. The voltage regulator responses of machines at the IPP are identical, so it is depicted in Figure 6 only the regulator response for one of the machines.

From the information in Figure 5, can be verified that the IPP generation bus bar experiences a voltage dip of approximately 55%, consequently, if the automation electronic equipment at the IPP plant, including computers are not suited to endure such kind of Short-Duration Voltage Variation (SDVV), all those equipment will be restarted.

Due to the short-circuit application, the IPP synchronous machines present a damped oscillating transient in their speed variation.

Figure 7 illustrates how the speed of machines G1 and G2 behave in the presence of the applied disturbance. Immediately after the fault application, synchronous machines have the tendency to increase their speed. Furthermore, it is evident that generator G1 that has lower inertia than G2, presents higher oscillation damping.

At Figure 7 can be observed that the machines didn’t oscillate for a long time span, the applied short-circuit lasted for only 6 cycles. Therefore the under or over frequency protection doesn’t have enough time to act.

II. The sudden opening of the interconnection breaker (minimum power exported).

With the aim to evaluate the influence of independent system penetration in the power authorities’ network and its close relation with the generator inertia moment, with reference to the transient stability maintenance, a new power flow configuration was established, as can be seen in Table III.

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_c$ [MW]</th>
<th>$Q_c$ [MVAr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.7</td>
<td>0.25</td>
</tr>
<tr>
<td>G2</td>
<td>0.7</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The sudden opening of the interconnection breaker may be the origin of a large unbalance between electrical and mechanical power, according the balance equation (1), where the electrical power is lower than the mechanical power.

$$\frac{2Hd^2\sigma}{\omega_d dt^2} = P_m - P_e = P_o$$

(1)

Machines at the independent generation are supplying an inexpressive load (loads at the IPP) and present a low equivalent inertia, characteristic of sugar cane and ethanol production plants.

In face of the interconnection circuit breaker sudden opening, despite of lower independent system penetration in the power authorities’ network, there is a considerable oscillation in the electrical machine G2, as depicted in Figure 8.

Both IPP machines face a sudden load rejection. Thus, the operating speed increases smoothly to $\omega = 189.63$ rad/s, $f = 60.4$ Hz.

With G1 taken off the system, a new power system scenario is built. The machine G2 is now responsible by electrical loads at the IPP as a whole. Thus, the electrical power is larger than mechanical power in Equation (1), what takes to the generator deceleration, $\omega = 184.45$ rad/s, $f = 58.71$ Hz, as in Figure 8. However, the machine operation frequency oscillates in a slow damped transient behavior between $f_1 = 59.6$ Hz, $\omega = 187.15$ rad/s and $f_2 = 59.33$ Hz, $\omega = 186.42$ rad/s and tends to stabilize at $f = 59.4$ Hz, in other words, $\omega = 186.74$ Hz.
Concerning the speed regulator, Figure 9, it follows the oscillations present in the operating speed of machine G2, and tends to stabilize around 1.17 pu, in another words an increase in steam injection of 17% in the generator turbine to cater for the solicitation of an increase in active power.

With the purpose to mitigate the harmful effects from the sudden operation of the interconnecting breaker, it will be possible to use a flywheel (inertial disk), with the aim to increase the inertia of the set to make the independent system machine more robust with reference to transient oscillations.

From a simplified point of view, it is presented the analysis of a flywheel that can be represented by Figure 10.

\[
M = T_i(\theta, \dot{\theta}) - T_o(\theta_0, \dot{\theta}_0) - I\dot{\theta} = 0
\]  

(2)

In addition to the retrieval of generating unity G1, inside a cycle after the operation of the breaker, criterion adopted by technical recommendations referring to voltage oscillations [3,4], [11], the option was the insertion of a flywheel in the axis of generator G2 with the objective to elevate the equivalent inertia of this set.

From an extensive number of computer simulations and using the above mentioned equations, it was verified that for a moment of inertia \( I = 800 \ \text{kg m}^2 \) the machine G2 of the IPP is stabilized presenting better voltage at the generation bus bar (Figure 11), excitation (Figure 12) and operating speed (Figure 13).

Figure 11 shows the voltage at the IPP generation bus bar, figure 12 depicts the generator voltage regulator in action. Voltage magnitude remains inside acceptable limits and defined by legislation [10,11]. Has no noticeable oscillations, what contributes enormously for the electrical energy quality.

It is observed the correct and efficient action of machines’ excitation regulator, in the sense to grant the voltage at the generation bus bar around the value previously set, 1.0 pu. The new regimen is established with 20% of over excitation.

Concerning speed oscillations, as in Figure 13, the maximum obtained reaches the magnitude of \( \omega = 189.3 \ \text{rad/s}, f=60.3 \ \text{Hz} \) (tolerable operation zone). However, after the dumped transient, the machine reaches the new steady state and stabilizes in a speed \( \omega = 186.77 \ \text{rad/s} \ (f = 59.5 \ \text{Hz}) \) [4].
This work shows that dynamic studies must be made to mitigate harmful effects to IPP stability, especially in face of unexpected operation of the interconnection breaker. Such anomaly put some pressure on the electrical energy quality at the IPP installations, aside from engaging the steam turbine blades due to the cumulative effect of vibrations originated in frequency oscillations of the IPP synchronous generators.

The speed transient oscillation affects immediately the industrial frequency of the IPP generation system, putting at risk its power energy quality, mainly with reference to the efficiency and effectiveness of computerized equipment in the industry.

For short-circuit situations at the CCP, the IPP is subject to substantial voltage sag. Such dip lead to losses in their industrial process, with consequent waste of raw material depending on the process involved. Therefore, it is highlighted the need of a better specification of equipments concerning their voltage variation support ability. It must be highlighted that during short-circuit attention must be turned to the over voltage produced by the fault removal in the steady-state reestablishment. Therefore, it can be inferred that the quality of protection and machine controls can be a major influence in the system adequate operation.

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