Modelling to stability analysis of brushless excitation systems on synchronous generator

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Abstract — The synchronous generators have an important role in current electric power systems. They are present in most power plants and are used to produce electric energy. These generators have an excitation system, used in its operation, which has an important impact on the transient stability of the system. This paper will study and characterize an unknown excitation system of an electric generator, which is not standardized, followed by the study of the transient stability of the generator connected to its load. Firstly, the paper will study excitation system without brushes. Then, taking into account the standard models of the IEEE, the best fitting model to the system in study will be chosen. After the modulation of the global system (excitation system, synchronous generator and its load), the parameters of the generator and its excitation system based on field-tests were estimated. This was done using an estimation tool available in Simulink from Matlab.

Sideways, was also seen the impact of the variations on the parameters in the response of the system, that is, in terminal voltage of the generator.

Index Terms — brushless excitation system, synchronous generator, AC1A, parameters estimation, transient stability

I. INTRODUCTION

Nowadays, in order to do transient stability studies there is an increasingly higher need to modulate and correctly represent the excitation system of the synchronous generators.

The level of precision of a stability study depends on the accuracy of its parameters and the dynamic models that describe the generator groups and its respective excitations systems. Often, the models used in the planning and operation studies aren't suited because the parameters of the real system are not known [1].

The purpose of this paper is to answer this need that can be seen in facilities, both in the country and worldwide. This paper uses the work [2] as a starting point, where it is explained how some of the parameters of an excitation system can be identified taking into account the field tests (bump test). In the case in question the tests were done regarding load rejection which is different from the previously mentioned in [2], where the standard model for describing the excitation system in the facility was also known. Taking into account some of the information regarding the system in study, in section II the system is fully described and characterized.

In section III we modulate the global system in the Simulink, which consists in the excitation system, synchronous generator and respective load. In this section an estimation of the generator and excitation system is made using the estimation tool from the Simulink and the measured response obtained from the fields tests.

II. CASE STUDY

In this section is presented the excitation system, of an electric generator, in study. In this description are shown the particularities of this system, when compared with the typical scheme of a brushless exciter. Followed are mentioned the parameters and the characteristics of the synchronous generator.

A. Excitation system description

The excitation system in study is of AC type, rotative and brushless. As is possible to see in the Fig. 1, the feed of the pilot exciter was origin in an auxiliary permanent magnet generator (PMG). The exciter is coupled and driven by the rotor of main generator. The system intended to study in this paper, there’s no auxiliary PMG.

![Fig. 1 – Typical scheme of a brushless exciter with a PM generator](image)

In the generator in study, the pilot exciter's power supply comes directly from the terminals of the main generator. This way we can combine in one system...
characteristics from both typical systems: brushless excitation system and the so called static systems (ST).

In the case of the brushless excitation system, it is usual to have a thyristors AC-DC electric converter, present in the stator, which feed the circuit present in the rotor of the generator. In the system in study, the AC-DC converter is changed by an AC-AC converter. This converter will be present in detail bellow.

The system in analysis is composed by an excitation machine, which normally is a three-phase induction machine with a cylindrical rotor coupled in the shaft of the main generator. This induction machine supply energy to the AC-AC converter. There’s also a diode rectifier connected to the excitation winding of main generator.

The mains components of the system are outlined in Fig. 2.

The AC-AC converter, supplied by the generator terminals, is compose by three anti-parallels pairs of thyristors, Fig. 3.

The converter present in the pilot exciter, works as a current regulator. According with the firing angle of the thyristors and the pulse with modulation (PWM) control, the current wave forms can be controlled, as shown in Fig. 4.

In the Fig. 2, from the left to the right, is possible so see an excitation machine (three-phase induction machine). This machine allows to supply a current excitation which permitt to do black start of the generator.

Additionally, there’s no need to appeal to transient batteries with field flashing during the few seconds before the black-start.

In the rotor there is a three-phase diode bridge rectifier is therefore an uncontrolled rectifier (Fig. 5). This is responsible for converting the AC current obtained from the excitation machine in DC current in order to deliver it to the excitation winding of the main generator.

### B. Generator Characterization

This section defines the characteristics and presents the data for the synchronous generator under study, in particular its nominal conditions (voltage, power and frequency), its reactance’s, time constants, among other features.

<table>
<thead>
<tr>
<th>Characteristics of the Synchronous Generator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal conditions</td>
<td></td>
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<tr>
<td>$V_n$ [kV]</td>
<td>11</td>
</tr>
<tr>
<td>$S_n$ [MVAr]</td>
<td>12.153</td>
</tr>
<tr>
<td>$f_n$ [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>Reactances [pu]</td>
<td></td>
</tr>
<tr>
<td>$X_d$</td>
<td>1.7</td>
</tr>
<tr>
<td>$X'_d$</td>
<td>0.14</td>
</tr>
<tr>
<td>$X''_d$</td>
<td>0.12</td>
</tr>
</tbody>
</table>
### III. MODELLING OF THE GLOBAL SYSTEM

This chapter describes the considerations and simplifications made in the global system modeling. For system modeling was done using the Simulink, which is an integrated simulation tool in Matlab.

#### A. Synchronous generator representation

For the modeling of the overall system was begun by choosing a block that will represent the generator. The choice was based on the parameters which are necessary for its characterization. In addition, it was opted for the block shown in the Fig. 6 because their parameters largely coincide with those provided by the manufacturer.

The block that represents the behavior of the synchronous machine has an entrance $V_f$ (field voltage), that allows to adjust the reactive power, and $P_m$ (mechanical power), that defines the active power of the system.

For the case study concerns the synchronous machine operates as a generator, so $P_m$ will always be positive.

The output labeled "m" allows access to various electrical quantities of the machine. In this particular case the quantities of interest are: the field current ($I_{FD}$) and terminal voltage ($V_T$). The latter can be obtained through the components d-axis and q-axis stator voltage by using the expression (1).

$$V_T = \sqrt{V_d^2 + V_q^2} \quad (1)$$

#### B. Load representation

The system load is modeled by the block denoted "Three-Phase Parallel RLC Load" shown in Fig. 7. This block is a balanced three-phase load such as a combination of RLC elements. For a constant frequency, in this case 50 Hz, the load presents a constant impedance. The powers P and Q load varies proportionally with the square of the voltage thus providing an elasticity in relation to the voltage equal to 2. This block is characterized by the phase to phase voltage of the load (11 kV), and rated frequency (50 Hz), active power (P), reactive ($Q_L$) and capacitive ($Q_C$).

#### C. Excitation System representation

The modeling of the excitation system under study was based on models provided by the IEEE. However, according to [6], this does not match any of the IEEE standard model, as indicated in Table II.

It is noted that reference [6] mentioned in the below table refers to the international standard IEEE Std. 421.5, confirming that the excitation system and respective control model of Ansaldo Energy is not represented by any internationally standardized format.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Excitation system or controller</th>
<th>Submitted for qualification consisting of:</th>
<th>Qualified consisting of:</th>
<th>Settings were changed in the course of testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ansaldo-Energia</td>
<td>EAA</td>
<td>Structure doesn’t fully correspond to [6]</td>
<td>Russian structure of the controller is implemented</td>
<td>Yes</td>
</tr>
</tbody>
</table>

In Table III, [3], we can see the available models according to IEEE considering the category, type of exciter and power source.

#### TABLE II

RESULTS OF QUALIFICATION OF THE EXCITATION CONTROLLERS OF ANSALDO ENERGIA

#### TABLE III

EXCITATION SYSTEM CHARACTERISTICS

According to Table III, there's no available standard model that fully comprises all the characteristics described in section II.A. In the studied system, the exciter from the generator rotor has a rotating three-
phase rectifier bridge, that uses diodes, which means it’s not controlled. From the reference [7], we can see a simplified model for all excitation system where we have the two main blocks: Automatic Voltage Regulator (AVR) and the Exciter seen in Fig. 8. In this model the complexity of entire system is represented by a simple block that corresponds to a lead-lag compensator.

From all the models seen in Table III, the one with more common characteristics with the case study is the AC1A model, from IEEE, which is why this is the chosen model to represent our system. These characteristics will be described in detail:

- the AC1A model describes brushless excitation systems, rotative type;
- in the AC1A model from IEEE the AVR is represented by a lead-lag compensator, as we can see in the simplified schematics provided by the supplier of the excitation system in study in Fig. 8;
- the exciter represented by the AC1A model, is composed of a rectifier diode bridge, therefore, non-controlled. The exciter is modulated through an integrator block with a time constant $T_F$ and a limiter, with the lowest possible null voltage, which can also be seen in the model for the system in study (MAT block).

Based on the former assumptions, the model for the excitation system was built, as illustrated in Fig. 21 of the Appendix.

D. Identification of the generator parameters and its excitation system parameters

Using the “Parameter Estimation” tool in the Matlab/Simulink, we can estimate the parameters for the generator and excitation system. Throughout this process several simulations were made by manually altering the parameters of the global system in order to foresee the impact of said parameters in the response system.

The records of a field test with the information regarding the terminal voltage were used to identify the system. In the case of the field test there is a total load rejection, in automatic mode of 0.5 MW 3 Mvar. The generator was initially under-excited, consuming reactive power (3 Mvar) and providing active power (0.5 MW). Using the Simulink, a load rejection event was created at $t = 6$ s, to mimic as much as possible the rejection of 0.5 MW 3 Mvar. Therefore, it was initially considered that the system had a 1 MW, 3 Mvar load and at $t = 6$ s, a rejection of load of 0.5 MW, 3 Mvar is created, which brings the system to a final load of 0.5 MW. Since the variation of the generator terminal voltage is almost only proportional to the reactive rejection power this is an acceptable approximation. Furthermore, since the active component of the power is a lot smaller than the reactive component and it is in quadrature regarding the later, the active component has little effect on the voltage variation.

The signal obtained in the field test (terminal voltage, $V_T$), that was used as a benchmark to estimate the parameters for the excitation system and the generator is the one in Fig. 9, below.

Using the global model built with the Simulink, seen in the Appendix, some simulations can now be created. However, as the study progressed, it was observed that there was no differential feedback loop, which is defined by a gain $K_F$ and a time constant $T_F$. According to the schematics for the system seen in Fig. 8, we can easily verify that the system has no that feedback path. Moreover, and taking into account that we are dealing with a brushless excitation system, the measurement for the excitation current in the rotor of the generator $I_{FD}$, which is used as an entry for this feedback loop, is not directly accessible.

This situation lead to the study of the effect of the parameter $K_F$ in the behaviour of the system. The 1rst simulation was based on the data collect from the IEEE [8] for the excitation, except for $T_R$, which was considered as 20 ms. As for the generator, the information can be seen in Table I.

By considering the alteration of only $K_F$, the results will be the ones represented in Fig. 10.
By decreasing the parameter $K_F$, designated as stabilizer gain, the system response becomes more and more oscillatory. By increasing $K_F$, the system reacts showing a smaller voltage sag, thus resulting in the lack of oscillations in the response after a given value.

The inexistance of this stability block in the system in study results in a totally unstable response, since its absence is the equivalent of a null $K_F$.

Consequently, it was necessary to individually change some of the system's parameters in order to achieve a stable system. $T_B$ and $T_C$, were altered, which lead to a later conclusion that the time constant associated with the exciter shown in the IEEE would be too high. From the information gathered in [9], in which the studied exciter was defined by a high dynamic, a smaller value, 0.2 s, as $T_E$ was adopted.

After several simulations it was concluded that the parameters should take the following values, $T_B = 27$ s and $T_C = 1$ s, values at which the system becomes stable, although there are still some small amplitude oscillations as it is demonstrated in Fig. 11.

Taking into account the parameters used up to this point, the system shows a slow response time (about 4 s), given the disturbance at which it was subjected.

Hereupon, a new estimation is done, this time using 20 ms as $T_R$ and $T_A$. These two time constants are related with the type of equipment used in the real system and regarding which there is no information. After having the system modulated in the Simulink, the estimated tool can be accessed as follows: Analysis → Parameter Estimation → New Experiment.

The result for the 1rst estimation, in which $T_R = T_A = 20$ ms, can be examined in Fig. 12. The estimated parameters can also be consulted in Table IV, in the Appendix.

By analysing the results obtained through the simulation by estimating the system's parameters, it can be observed a higher static error than the response obtained through the field test. This correlates mainly with the value of $K_A$, which is 484.6 in the present case. Another difference between the simulation and the field test can be observed in the interval between the minimum value of the simulation curve and 6.5 s, showing a faster response in the simulation which is most likely linked with $T_A$.

Next, and in order to fully understand the impact of some of the parameters of the excitation system, namely $K_A$, $T_E$ e $T_A$ on the terminal voltage, it is time to conducted a few more simulations in which these parameters are manually altered one at a time.
• Variation of the $K_A$ (voltage regulator gain):

As expected, with an increase in $K_A$, the final value is more similar to the value seen before the disturbance, since the gain in the regulator is in inverse proportion to the steady-state error. Additionally, a boost in $K_A$ produces an increase in the way the voltage raises after the minimum value is attained. It is also possible to observe that as $K_A$ is raised, an increasingly lower minimum value depth of the voltage dip is obtained.

• Variation of the $T_A$ (voltage regulator time constant):

With this simulation it is possible to confirm that an increase in $T_A$ produces a slower response particularly in the interval from when the minimum is hit and roughly 6.5 s. Therefore, an increase in the time constant $T_A$ has the opposite affect of what is seen when $K_A$ is increased, regarding the minimum value obtained in the voltage sag, which means the higher $T_A$, the higher is the voltage sag.

• Variation of the $T_E$ (exciter time constant):

An analyses on the results obtained with the time constant $T_E$, demonstrate, as expected, that a smaller time constant produces a faster response. As for the voltage sag, $T_E$ has a similar effect to $T_A$ but opposite to $K_A$, which means the higher $T_E$ is, the higher the voltage sag will be.

After observing the results obtained by the individual alteration of each parameter, a new simulation is made by combining the appropriate values for each parameter, in order to achieve similar results to those seen on the test field. For this reason, in the next simulation $K_A = 820$ and $T_A = 0.06$ s while the rest of the parameters are estimated. The value chosen for $K_A$ is intended to mirror the late stage of the response, to the one seen in the field test, when steady state is reached. Although $T_A$ was originally considered as 0.02 s, it was later proven not this was not a realist number since the time constant represents in itself the sum of several times associate with the real system: the acquisition and processing time of $V_T$ (0.02-0.03 s), computation of the control algorithm and calculation of the respective shooting angle for the thyristors (0.02 s) and the broadcasting of the shooting signal for the thyristors (0.01 s) that results in the total of 0.05-0.06 s.

Moreover, it is possible to verify in Fig. 14 which $T_A$ value that leads to the system response (measured response vs simulation response) nearest between the minimum and the zone in which reaches approximately the steady state will be between 0.5 s and 0.8 s. The results of the estimated parameters after these considerations are shown in the following table.

| TABLE IV |
|---|---|---|---|---|
| RESULTS OF THE LAST ESTIMATION |
| $K_A$ | $T_A$ [s] | $K_C$ | $K_D$ | $K_E$ |
| $T_B$ [s] | $T_C$ [s] | $T_R$ [s] | $T_R$ [s] | $a$ |
| 20.13 | 2.14 | 0.1 | 0.014 | 0.001 |
In the Fig. 6, the response obtained with the new estimation parameters is shown.

The red curve shown in the previous figure corresponds to the best approximation that has been achieved, after taking into account several considerations between estimations.

In order to complement this analysis, it was performed several simulations for different values of $T_B$ and $T_C$, and combinations of these parameters, to verify its impact in the system response.

- **Variation of the $T_B$ (lag time constant):**

- **Variation of the $T_C$ (lead time constant):**

- **Combinations of the ($T_B$, $T_C$):**

The realization of previous simulations provided some conclusions about the impact of $T_B$ and $T_C$ in system response.

By decreasing the value of $T_C$, there is a delay in the signal and increases the signal overshoot. In respect to the $T_B$ parameter, it was verified that its increase leads to a delay signal, and consequently, an increase of the time response. Thus, this parameter has an impact contrary to the $T_C$.

With the results of these simulations, it was possible to conclude which the setting values in AVR (Automatic Voltage Regulator) ($T_B$ e $T_C$) in the real system will be close to those obtained in the last estimation. The $T_B$ and $T_C$ values estimated lead to a stable and without overshoot system response.

Finally, some simulations were also carried out for various combinations of ($T_B$, $T_C$), maintaining a ratio of 10 between these two parameters.
With these simulations it can be seen that keeping the ratio of $T_B = 10T_C$, and increasing the $T_C$, and consequently $T_B$, the steady-state error increases, such as with the decrease of the $K_A$.

IV. CONCLUSIONS

In this paper was presented a description and modelling in Simulink of a system composed by an excitation system, synchronous generator and its load in order to identify the parameters, that describe the real system, using for this a load test rejection data.

Initially, the simulation where $K_F$ was changed, it was concluded that this is critical for a stable response, since for $K_F = 0$, the system response has a totally unstable response.

Considering $K_F = 0$, the voltage stability control becomes heavily dependent of the three AVR parameters, that are adjustable: $K_A$, $T_B$ e $T_C$.

In addition, it was concluded which the exciter time constant, also has a great impact on the system response speed. By decreasing $T_E$, the response is considerably faster, with a smaller depth of the voltage dip.

For combinations of $T_B = 10T_C$, and within the possible range of $T_B$ and $T_C$, the system is stable, although the steady-state error increases with increasing the $T_C$, and consequently, $T_B$.

Regarding the estimation of the generator parameters and its excitation system it was verified that the Parameter Estimation tool, given the high number of parameters to identify, has as many local optima solution. Thus, the estimation of the global optima depends essentially of the initial conditions of the parameters considered for each estimation and also its range of variation (more or less narrow).

### APPENDIX

**TABLE IV**

RESULTS OF THE FIRST ESTIMATION

<table>
<thead>
<tr>
<th>$K_A$</th>
<th>$T_A$ [s]</th>
<th>$K_C$</th>
<th>$K_D$</th>
<th>$K_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>484.6</td>
<td>--</td>
<td>0.11</td>
<td>0.44</td>
<td>0.81</td>
</tr>
<tr>
<td>$T_B$ [s]</td>
<td>$T_C$ [s]</td>
<td>$T_E$ [s]</td>
<td>$T_R$ [s]</td>
<td>$X_d$ [pu]</td>
</tr>
<tr>
<td>20.7</td>
<td>1.81</td>
<td>0.11</td>
<td>--</td>
<td>0.001</td>
</tr>
<tr>
<td>$b$</td>
<td>$T_{d0}$ [pu]</td>
<td>$T_{q0}$ [pu]</td>
<td>$T_{q0}$ [pu]</td>
<td>$X_d$ [pu]</td>
</tr>
<tr>
<td>5.5</td>
<td>0.011</td>
<td>1.8</td>
<td>0.26</td>
<td>1.74</td>
</tr>
<tr>
<td>$X_d'$ [pu]</td>
<td>$X_q'$ [pu]</td>
<td>$X_d'$ [pu]</td>
<td>$X_q'$ [pu]</td>
<td>$X_q'$ [pu]</td>
</tr>
<tr>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
<td>1.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Fig. 21 – Excitation system model implemented in the Simulink.

Fig. 20 – Effect of some combinations ($T_B$, $T_C$) in the terminal voltage, keeping $T_B = 10T_C$. 

![Graph showing the effect of combinations on terminal voltage](image-url)
Fig. 22 – Global system model implemented in the Simulink

REFERENCES


