Model Development and Validation of Brushless Exciters

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Abstract—**This paper describes the process of performing site tests and model development of brushless exciters. Brushless exciters are often a source for model inaccuracy when studying synchronous machines and excitation system, which may lead to incorrect stabiliser design and poor performance. The process described here involves on site testing of the excitation system both with the generating unit operating open circuit and synchronised to the network which will enable the extraction of parameters to fit a model for the brushless exciter based on the IEEE Std 421.5. Two case studies shall be presented to contrast the difference in approach given the different limitations faced at each site.**

Keywords—Brushless exciter, model validation, excitation system, AVR, synchronous machine, stability, field testing.

I. INTRODUCTION

Excitation systems play an important part in determining power system stability when analysing the performance of a power station or a meshed network. Accurate models of the excitation system are required for power system planning, optimal tuning of control systems such as power system stabilisers (PSS), and stability analysis.

Block diagrams, when supplied, often are based on typical or default values, and do not represent the behaviour of the exciter machine which is essentially an inside-out three phase synchronous machine.

The excitation system consists of the following elements:

- Automatic voltage regulator (AVR);

- PSS (often equipped with the AVR particularly in digital systems);

- Voltage and current sensing;

- Exciter (static or rotating); and

- Protection and monitoring.

For a number of years, manufacturers of AVR's often provided IEEE models for use in power stability studies. However there has been a gradual movement towards detailed models for each type of AVR that is on the market. This has largely been assisted by the improvement of control system implementation in digital based hardware which enables greater transparency of how the regulator is programmed and behaves under various conditions.

Unfortunately this is not the case with exciter machines. The inaccuracies of exciter models are often amplified during a refurbishment project. For example, a generator (asset owner) may wish to upgrade an analogue AVR control system to a new digital based system, but the rotating exciter remains unaltered. The model for the AVR supplied by the manufacturer may be well documented, but the exciter model is likely to be inaccurate. Data for the exciter machine is often carried over from its original installation (often 20 to 30 years old) and its validity not questioned, nor has the data ever been verified.

Therefore when the connection study of a new AVR is performed, the interaction of the new AVR model with an existing exciter model that is likely to be incorrect is interesting and frequently yields conflicting results in practice leading to repeat tests, repeat PSS design and downtime of the generator (both physically and commercially).

II. THE BRUSHLESS EXCITER

By definition, a brushless exciter is an alternator-rectifier exciter employing rotating rectifiers with a direct connection to the synchronous machine field, thus eliminating the need for brushes [2]. It is essentially an inside-out three-phase synchronous generator, the field winding of which is mounted on the stator housing, the three-phase windings being attached to the rotor. The three phase output voltage is rectified by diodes most commonly mounted on the rotating shaft and applied directly to the main generator field winding. Note that it is also possible to have an ac exciter with stationary diodes. In this case, slip rings are rings are required and it becomes possible to directly measure the main field quantities.

Figure 1 shows the commonly adopted simplified representation of an ac rotating exciter system as published by the IEEE [1]. The voltage applied to the field winding of the exciter is represented by e_{FD} whereas e'_{FD} is the voltage applied to the main generator field winding on the right of the model [5].
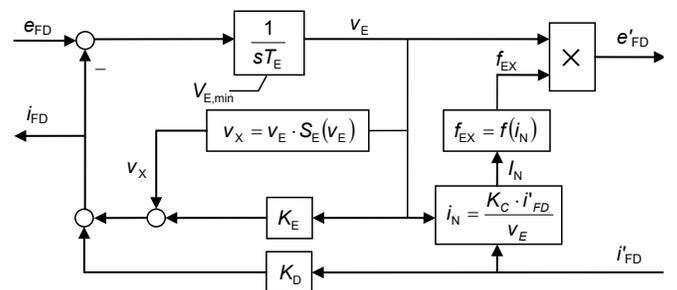

Figure 1. AC exciter model based on the IEEE Standard 421.5

Exciter models are typically assumed to be represented by a first order model. This philosophy is adopted from the IEEE Standard 421.5 [1]. This is an initial assumption made in this paper but is tested later in both the time and frequency domain. The assumption that a first order model is adequate as opposed to second order or higher models has been tested in many studies. Industry experience shows that in the vast majority of cases the compromise between complexity and accuracy provides acceptable results.

As with the synchronous generator, the exciter is also affected by saturation. As the exciter has an output voltage designed to allow 'field forcing', the effects of saturation at normal loading (steady state) are quite modest. The saturation effect is represented from the output voltage of the exciter, VE, and the saturation function SE(e_{FD}).

A. Exciter Field Current

The exciter model provided in Figure 1 does not provide an accurate signal for exciter field current. In most cases, the signal i_{FD} (also called Vfe) which is the negative input to the summing junction before the exciter integrator, is assumed to be exciter field current. This signal tends to show a slower response as it includes the armature reaction demagnetizing effect (KD) [4].

Dynamically, the exciter field current is affected by the time constant of the exciter, TE, and the saturation effect from the path (SE + KE). In steady state, this result allows for exciter field voltage and current to be at the same level in per unit. The saturation can affect the overall exciter time constant, as when saturation occurs the inductance in the exciter reduces, and the time constant abides by the L/R relationship. Therefore, an accurate model of saturation is required for this method.

For the purposes of this paper, an alternative derivation was assumed. The signal required for exciter field current was exciter field voltage (denoted e_{FD}), and with this signal, a parallel transfer function is created as follows:

$$i_{FD} = e_{FD} * \frac{1}{1 + s . \frac{TE}{KE + SE}} \qquad (1)$$

Where i_{FD} is the exciter field current (i'_{FD} is the main machine field current).

B. Rectifier Model

The rectifier conduction introduces non-linear effects, depending on the field current (i'_{FD}) and the applied voltage, VE. These non-linear effects have been calculated and represented in a three step linearised function, F_{EX}. This function is a simplification of a non-linear response but experience with the widely used approximation has been such that it is seldom modelled to a higher level of complexity. It is also not uncommon to have KC set to zero, which introduces further approximations into the model.

All ac sources that supply rectifier circuits have an internal impedance that is predominately inductive. This impedance has an effect in the commutation process and produces a non linear characteristic as the rectifier load current and voltage varies.

Parameter KC is set appropriately to represent this behaviour. The IEEE recommended transfer function for F_{EX} is defined in Figure 2.
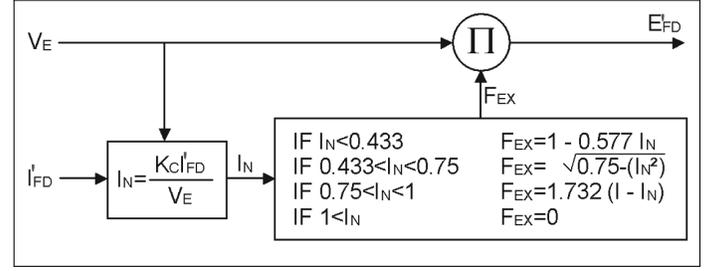

Figure 2. Characteristics of the non linear transfer function F_{EX}

C. Comparison of Exciters

The two most common types of excitation methods are (a) the brushless exciter (also referred to as a "rotating exciter"), and (b) the static exciter. The two excitation methods are shown graphically in Figure 3.
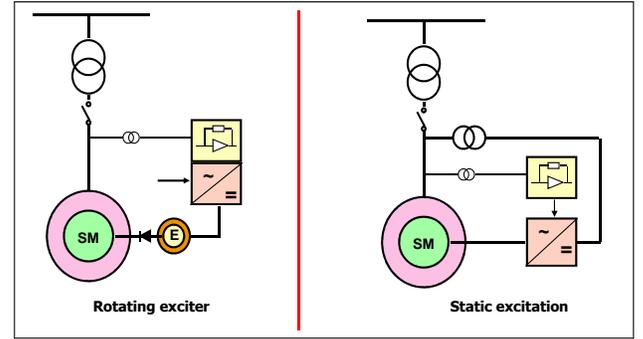

Figure 3. Comparison of the two main exciter types (a) the brushless exciter, and (b) the static exciter

Table I provides a brief comparison of the two main excitation system types. Performance aside, the choice of excitation system type often depends on economic factors (maintenance and cost of equipment).

Table I.   COMPARISON OF EXCITATION SYSTEM TYPES

Brushless Excitation	Static Excitation
Positive field forcing capability only	Positive and negative field forcing capability
Excitation response limited by exciter time constant TE	Fast excitation response time
No slip rings required (less maintenance)	Slip rings required (maintenance required)
Direct measurement of rotor quantities not possible (unless special instrumentation provided	Direct measurement of rotor quantities possible
Excitation of 1 to 200A	Excitation of 100 to 10,000A
Additional modelling required	Cost of converter bridge quite high

From a power system stability viewpoint, the brushless exciter is often considered more complicated for control and PSS design. For example, when analysing the transfer function from speed to torque through the PSS control path, the exciter adds considerable amount of phase lag that needs to be compensated for. This transfer function, shown in Figure 4, reflects the phase and gain relationship between the component

of torque produced by the action of the PSS and the generator speed oscillations, with no PSS phase compensation.
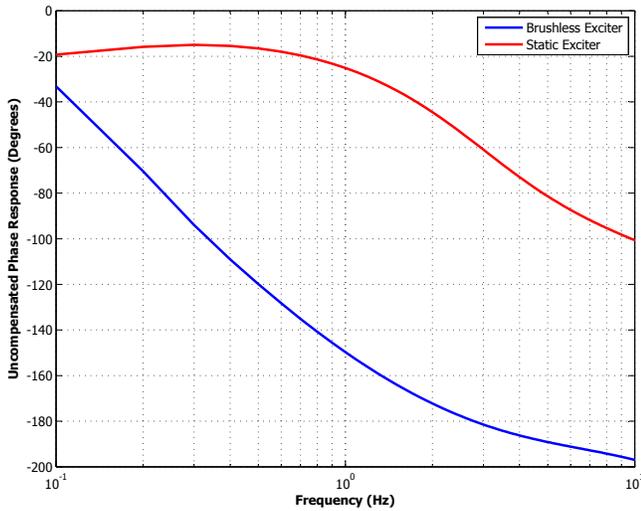

Figure 4. Uncompensated phase response of the transfer function $\Delta Te/\Delta\omega$ of a generating unit with (a) brushless excitation system, and (b) static excitation system

We can see that from the phase response shown in Figure 4, the difference in the area of interest (1-3Hz) is over 100 degrees, primarily due to the inductance of the exciter machine (TE). The objective of selecting the PSS phase compensation is to introduce the necessary phase shift in the PSS control path to compensate this transfer function to have a phase of nearly zero degrees throughout the range of frequencies of interest (0.1 to 3Hz) [3].

In addition, the time domain response is also significantly slower when a rotating exciter is present, meaning it is often difficult to achieve settling times compliant with the Rules of the local Grid Authority. Figure 5 shows the time domain response of terminal voltage to an unsynchronised voltage step comparing a generator with (a) brushless excitation and (b) a static excitation.
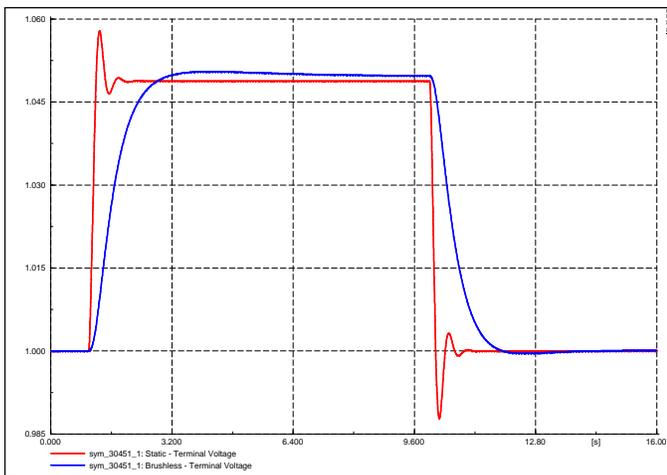

Figure 5. Unsynchronised voltage step response of a generating unit with (a) brushless excitation system, and (b) static excitation system

III. CASE STUDY A - GAS TURBINE GENERATOR

The first case study involves a 79.4 MVA aero derivative gas turbine. Initially, DIgSILENT performed routine testing of the excitation system in 2011 to evaluate compliance with the National Electricity Rules (NER) and the Generator's Performance Standard (GPS). Tests showed non-compliance with the unsynchronised and synchronised settling time requirement, and the registered model did not adequately represent the actual plant response.

In order to rectify the non-compliance issues, the AVR and PSS would need to be re-designed to improve the performance of the excitation system. However, to achieve a new design, an accurate model of the excitation system would be required. For this reason, DIgSILENT performed Parameter Identification tests to optimise the existing exciter model that accurately represents the plant.

Figure 6 shows an example of a voltage step response, with the actual plant response compared to the model prior to the model validation.
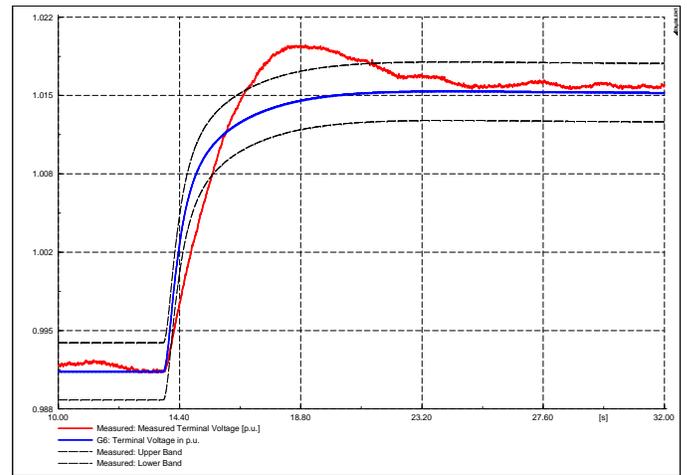

Figure 6. Synchronised terminal voltage response to a 2.5% step applied to the AVR of gas turbine, overlayed with the initial registered model

A. Field Testing

At this particular installation, the excitation system comprised of:

- A dual channel ABB UNITROL F digital AVR;
- A dual input channel PSS conforming to the IEEE PSS2B type;
- Potential source rectifier (shunt supply);
- A brushless ac exciter supplied by Brush Electric.

Access to the main generator field was not possible, and as such signals such as main generator field voltage and current, and rotor angle were not able to be recorded during on site tests. Due to the limited access of these signals, testing was limited to:

- Voltage step responses (existing data from 2011 re-used);

- Transfer function measurement of the AVR; and

- A load rejection to derive the generator's d-axis parameters.

As the interactions between the AVR, exciter and generator are meshed and complicated, there was a need to isolate the source of error between the AVR and the exciter and generator. Note that because the output of the exciter could not be recorded, the error of any potential exciter model developed is coupled with that of the generator. This is highlighted in Figure 7.
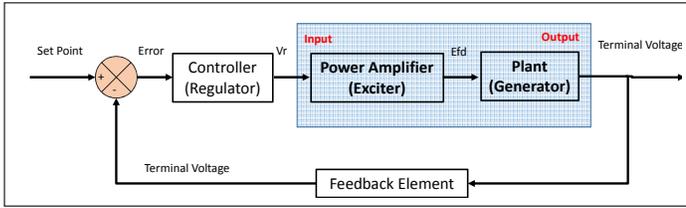

Figure 7.   Overview of the model for the excitation system for Case A

The frequency response of the voltage regulator alone at standstill (summing junction input to AVR output) was measured to confirm the model of the AVR. Figure 8 shows the measured transfer function of the regulator compared with the model. The alignment is such that it demonstrates the source of error is within the exciter and/or synchronous machine.
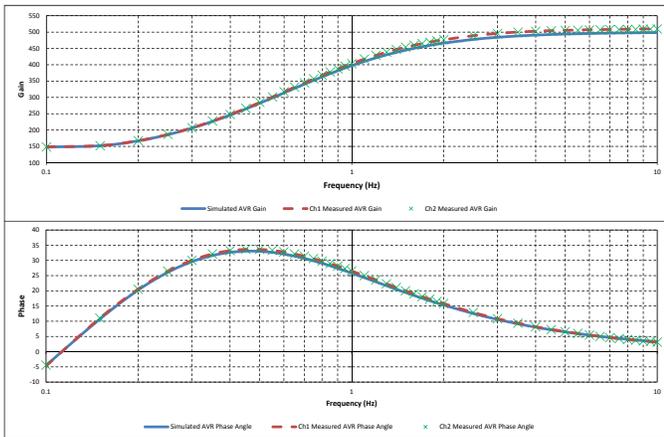

Figure 8.   Measured transfer function of the voltage regulator compared with the model

B. Exciter saturation

The exciter saturation function $SE(e'_{FD})$ is defined as a multiplier of pu exciter output voltage to represent the increase in exciter excitation requirements due to saturation. To accurately derive the exciter saturation, the exciter output voltage needs to be measured and plotted against exciter field current. Unfortunately, the exciter output voltage could not be measured and the exciter saturation could not be derived from site testing. Typical data has been assumed from similar sized Brush machines that allows for a small amount of saturation when the exciter is loaded.

C. PowerFactory Parameter Identification

As tests were limited due to lack of available primary signals for validating the exciter, a series of Parameter Identification simulations were performed using the existing data recorded during the compliance tests. Model Parameter Identification is a tool in PowerFactory that optimises parameters of power system elements when compared to input and output measurement signals. Figure 9 shows the process of identification.
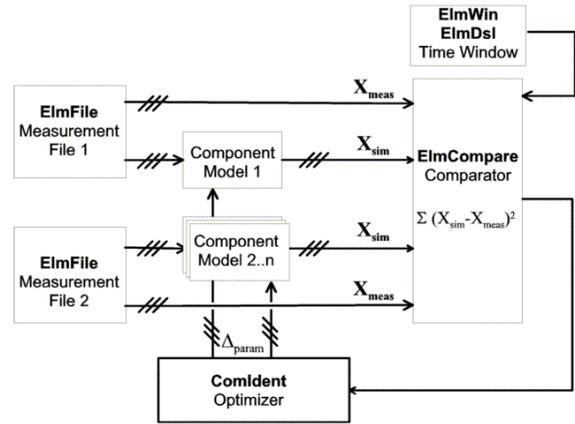

Figure 9.   The PowerFactory Parameter Identification process

Figure 10 shows the composite model used for the Parameter Identification simulations. A window function was used to ensure the Parameter Identification calculation commenced only when a transient event occurs.
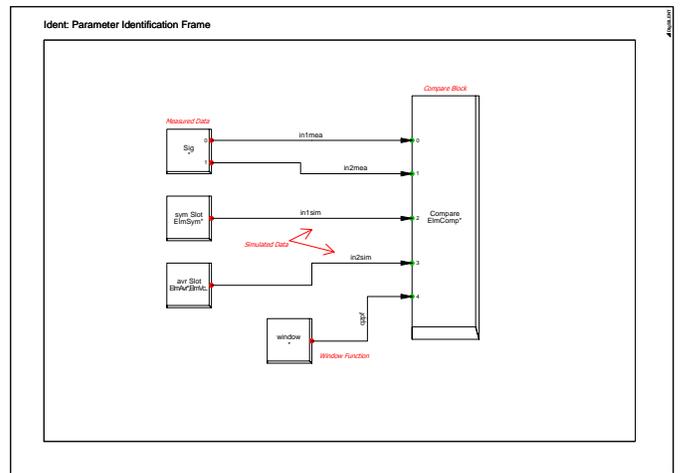

Figure 10.   Composite frame for Parameter Identification simulations

This identification is principally performed in the following way:

1) A measurement file object is created which maps the raw measured data onto one or more signals.
2) The measurement signals are used as inputs by the signals which are used as inputs by the models of

the power system elements for which one or more parameters have to be identified.

3) The output signals of the power system elements are fed into a comparator, just as the corresponding measured signals. The comparator is thus given the measured response on the excitation and the simulated response of the element models.

4) The comparator calculates an objective function, which is the weighted sum of the differences between the measured and the simulated response, raised to a power.

5) The identification command will collect all objective functions from all comparator objects in the currently active study case and will minimize the resulting overall objective function.

Five primary scenarios were considered for Parameter Identification simulations. These were:

1) Full load, under excited;
2) Full load, over excited;
3) Medium load, unity power factor;
4) Low load, under excited; and
5) Low load, over excited.

By considering the chosen range of operating scenarios, the Parameter Identification simulation optimises the model to reflect the variation in generator dynamics. The variation in dynamics is affected by loading and temperature. The operating point at medium load and unity power factor was chosen with the exciter in mind. When the machine is operated at its MCR, an excitation current is present which is called the nominal excitation current Ifn. If a vector is drawn from this point to the $-Ug^2/Xd$ point expressed in per unit on the reactive power axis (assume terminal voltage is at 1 per unit), the magnitude of this vector is proportional to field current. The load of the exciter is increased or decreased with operation on this vector. Therefore, points 3, 4, and 5 cover the loading of the exciter.

Figure 11 shows the measured terminal voltage response to a 2.5% step applied to the AVR, overlayed with the validated model response.
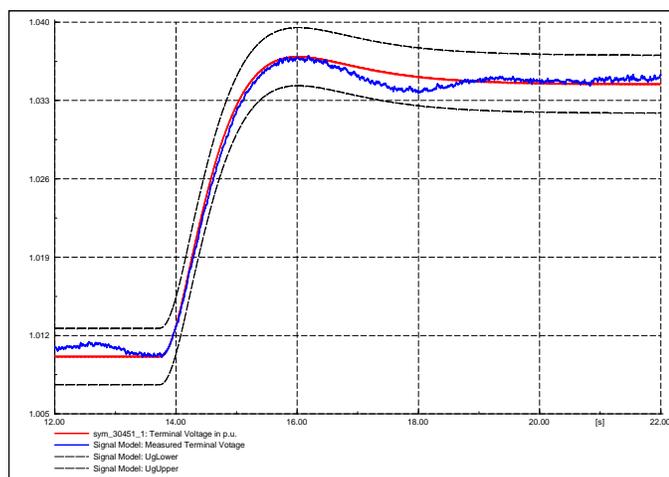

Figure 11. Synchronised terminal voltage response to a 2.5% step applied to the AVR of gas turbine, overlayed with validated exciter model

IV. CASE STUDY B - HYDRO GENERATING UNIT

The second case study involves a 100 MVA hydroelectric generating unit. The asset owner is intending to upgrade the excitation system controller. This will trigger a requirement under the NER to provide a validated model of the excitation system, including the exciter. The determination of settings for the excitation controller and PSS is dependent on the characteristics of the rotating exciter. DIgSILENT and the asset owner considered it prudent to first develop and validate the exciter model before undertaking the analysis to set the controller.

As opposed to Case A, there was no existing model of the exciter and therefore DIgSILENT's role was to propose a model for the rotating exciter.

The excitation system comprised of:

- A single channel ABB UNITROL M analogue AVR;
- A dual input channel PSS;
- Potential source rectifier (shunt supply);
- An ASEA brushless ac exciter.

A. Field Testing and Model Development

Unlike in Case A, access to the rotor was available, and therefore the main generator field voltage was able to be measured. Direct measurement of the generator field current was not possible due to the rotating rectifiers, and a signal for rotor angle was not available. The test methodology was therefore extensive, and included:

- Resistance measurements of the generator stator, rotor and exciter field;
- Transfer function measurement of the exciter and synchronous generator;
- Transfer function measurement of the AVR;
- Measurement of the generator's open circuit and short circuit characteristics;
- Voltage step responses;
- Load rejection tests for d-axis parameters and unit's inertia.

Due to the extensive testing, the process of model development did not rely on Parameter Identification, but rather on deriving values for the exciter parameters from first principles. The model was therefore developed and verified in the time and frequency domain using the results from site.

With the availability of the mentioned signals, each component of the excitation system could be theoretically be tested and verified independently. In this case, the AVR is planned to be replaced by a new digital based system and could be considered as a "black box" as a model for the existing AVR is not required to be submitted as part of the connection of the planned alteration. However, for closed loop simulations a reasonably accurate model is required. To verify the adequacy of the model for the regulator, a transfer function measurement was made. Figure 12 shows the frequency response of the AVR

model compared with the measured transfer function, prior to the gain introduced by the converter. The agreement is suitable to proceed with the model development of the exciter.
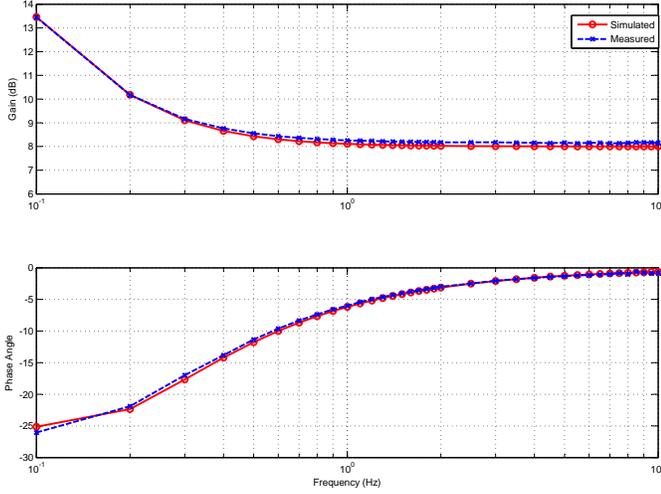

Figure 12. Measured transfer function of the analogue AVR compared with the model

B. Resistance measurements

The resistance measurements of the generator stator, rotor and exciter field winding provide valuable information to be able to assess the steady state performance of the model. As the measurements were taken at standstill, the temperature of the winding under test must be considered to be able to correct to rated temperature.

For all three tests, the resistance was measured three times, both in the forward and reverse direction. For the rotor resistance, R_{FD} the per unitisation occurs as follows:

$$Z_{FDbase} = \frac{3phVA_{base}}{i'^2_{FDbase}} \tag{2}$$

$$R_{FD} = \frac{MeasuredResistance}{Z_{FDbase}} \tag{3}$$

The rotor resistance is of particular importance particularly when deriving steady state generator field current from measurements of field voltage (from Ohm's law), and also understanding the affect it has on the generators (and exciters) time constant. It is also of significance when determining the saturation characteristic of the exciter and the synchronous generator.

C. Frequency response

The frequency response of the exciter was measured during unsynchronised operation. The unit was operated below 0.8 pu terminal voltage to minimize the effects of saturation in the exciter or in the main machine during the test. Figure 13 show the measured and corresponding simulated frequency response of the ac exciter. The simulated response was calculated using the validated settings, and corrected to test temperature.
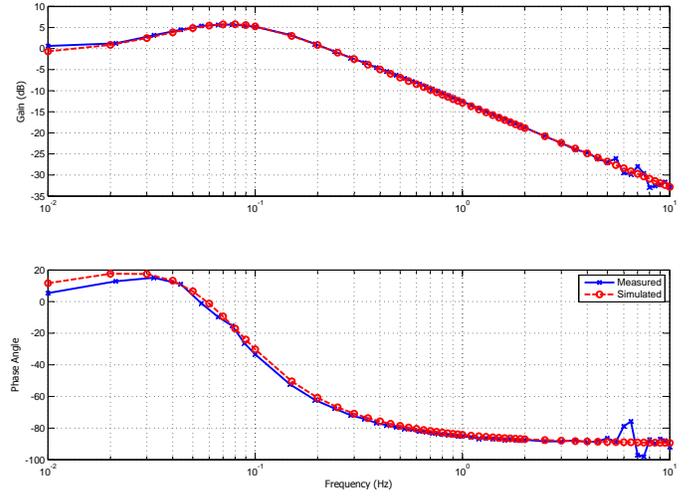

Figure 13. Measured transfer function of the exciter compared with the model

The frequency response of the model shows good agreement with the measured transfer function, which suggests that the developed model is suitable for use in large scale stability studies, including the design of a stabiliser.

D. Steady state performance

The basis of the per unit system of the exciter is to have the required excitation to produce 1 pu terminal voltage on the air gap line. This per unit system is universally used in power system stability studies as it offers considerable simplicity [4]. This is achieved by ensuring that parameters KE and KD are carefully selected to achieve this condition.

To evaluate the steady state performance of the exciter, it is of interest to identify the steady state error of the AC exciter alone. This has been done by injecting the measured generator field voltage to the steady state AC exciter model and finding the calculated value of exciter field current. The calculated exciter field current is then compared with the measured value (in amperes) and an error assigned to the value. This methodology also confirms the exciter field current base with the least error. The outcome is shown in Figure 14.

E. Exciter saturation

The saturation function in the developed PowerFactory model uses an exponential function to model the saturation characteristic. DIgSILENT have reviewed the ASEA exciter datasheet provided by the generator and have designed the saturation characteristic of the exciter model accordingly. The exciter saturation function has been modelled as an exponential function:

$$S(E_x) = A \cdot e^{B \cdot E_x} \tag{4}$$

The simulated open-circuit air gap line and the saturation characteristic of the revised exciter model are shown in Figure 15.
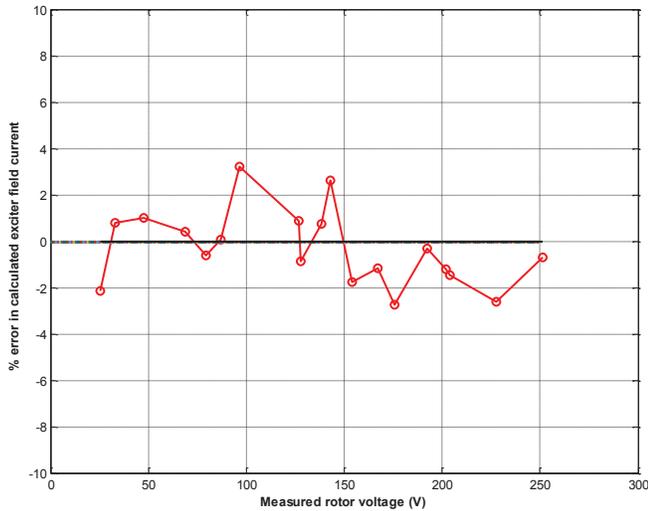
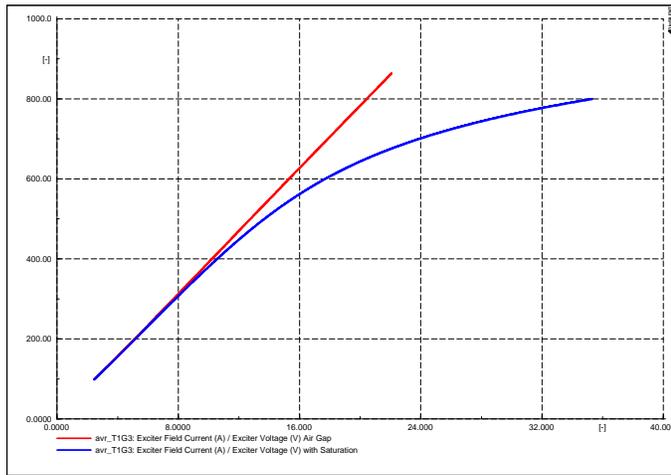Figure 14. Percentage error in steady exciter field current values against measured generator field voltage

Figure 15. PowerFactory model exciter saturation characteristic

F. Exciter time constant

The exciter time constant is represented by a simple fixed time constant TE with a minimum limit limiting the state variable and all negative values, as the ac exciter can not provide negative field current due to the rotating diodes.

The exciter time constant may be determined by a simple time domain test whereby the discharge resistor on the excitation system is bypassed and a diode is put in place such that the field of the exciter is allowed to discharge through itself. With the diode in place the excitation is suddenly removed and the field allowed to discharge. The time constant of the decaying waveform is then determined. This is taken to be the time constant of the exciter machine.

As the test is performed in the unsynchronised condition, the active component is the d-axis stator flux and flux in the exciter (as affected by the field winding and demagnetisation caused by the rotor current through KD) and hence terminal voltage of the synchronous machine responds to a change in

field voltage according to the d-axis time constants (Tdo' and Tdo") and the exciter time constant. Note that the unit was operating at 0.90 p.u. terminal voltage to minimize the effects of saturation.

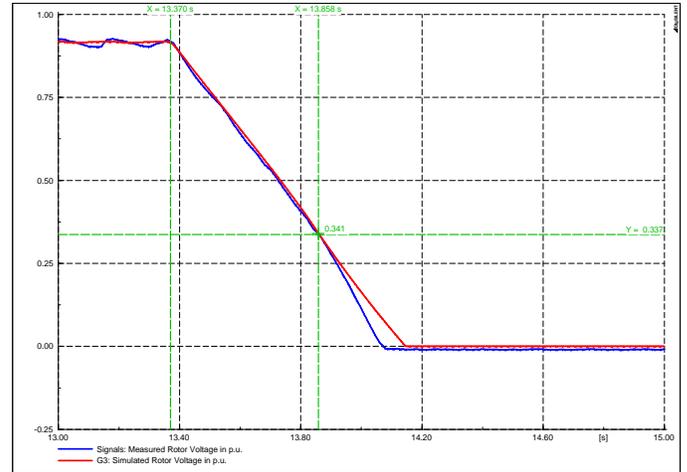The response of the rotor voltage to this sudden de-excitation and discharge is shown in Figure 16.

Figure 16. De-excitation test of the field to determine the open loop time constant of the exciter

The time taken for the rotor voltage to fall by 63.2% is 0.488 seconds. This is the time it takes for the induced dc current (excitation current) maintaining the flux linkages to decay to zero. It is not the exciter open loop transient time constant as the exciter is connected to the rotor winding and there is a resulting feedback path through the demagnetising gain, KD. It is thus expected that the observed time constant in this test will be lower than the required time constant TE.

The decay of the rotor voltage is largely dependent on TE and KE and for simplification, KD was excluded from the calculation. The time constant TE is calculated to be 0.655 seconds. Using this time constant in the closed loop model produces a close match between the measured results and the simulated results, as shown in Figure 16.

G. Dynamic performance

The dynamic performance of the model in time domain was verified by performing unsynchronised and synchronised voltage step response simulations and comparing them to the actual plant response. Figure 17 compares the responses of the model and the actual plant response to a synchronised voltage step response. Good agreement is obtained between the simulated and measured terminal voltage.

In addition to the step response tests, the exciter model was further validated by open loop simulations. This involved injecting measured excitation voltage (treating the AVR as a black box) to the field of the exciter model and comparing the simulated rotor voltage with the measured data. Figure 18 compares the open loop response of the exciter model and the actual plant response to a synchronised voltage step response.
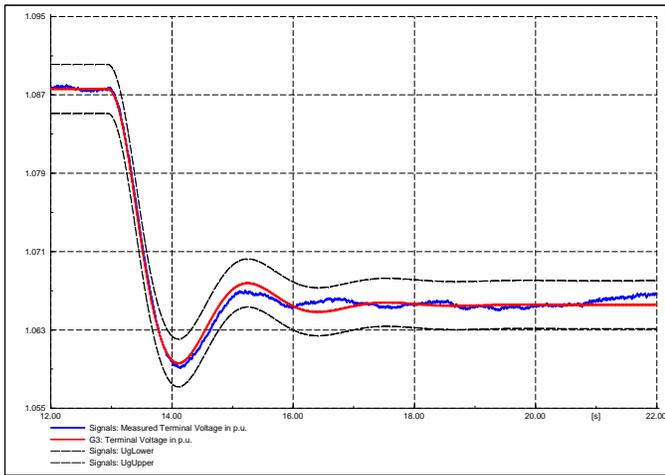
Figure 17. Synchronised voltage step response to a 2.5% step applied to the AVR of Hydro, overlayed with actual plant response
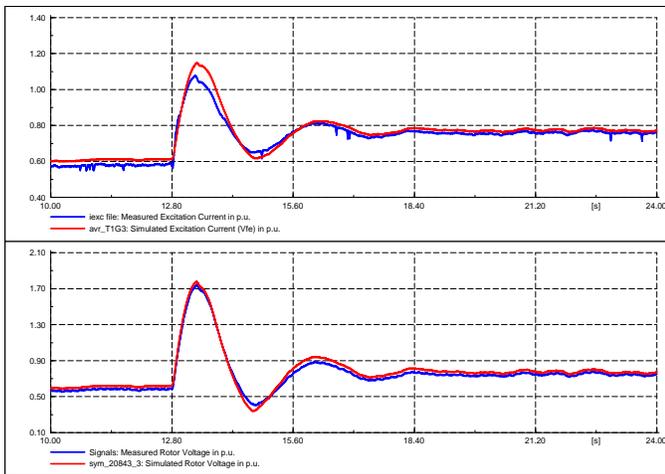

Figure 18. Open loop response to a 2.5% step applied to the AVR of Hydro, overlayed with actual plant response

V. CONCLUSION

DIgSILENT has approached two case studies differently based on the availability of key signals at each site. The simplified IEEE representation for the brushless ac exciter was used to represent the exciter at both sites, however the approach to develop and validate the model was quite different.

In case study A, minimum time was spent on site perform field tests. However, a considerable amount of time was required to perform Parameter Identification simulations to optimise the model to fit the actual plant response. As no access was available to the main field, the exciter model can not be verified in isolation, however the overall simulated response of the generating unit agrees well with the actual plant response.

In contrast, case study B required time on site and access to the generator to perform all the measurements at standstill, in the unsynchronised condition, and synchronised to the grid. The extensive tests and data collected reduced the time to derive model parameters and validate the model for the exciter. The exciter model was able to be verified in isolation both in

the time domain and frequency domain due to access to the main field. The simulated responses agree well with the actual plant response in both domains.

The results in both cases are quite good and show high level of agreement with the actual plant response. The validated models for both case studies confirms that the simplified IEEE ac exciter model is suitable for power system stability studies.

ACKNOWLEDGMENT

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