RECTIFIER CHOICES FOR SYNCHRONOUS GENERATOR EXCITERS

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Abstract - In synchronous generator exciters there exist rectifiers both in the actuator and in the AVR (automatic voltage regulator) feedback sensors. This paper discusses some of the choices available in each of these sub-systems, taking into account the overall dynamic performance of the AVR loop. This dynamic perfomance enables a fast reactive power dispatch.

KEYWORDS

Rectifier circuits, Synchronous generator control, AVR, Excitation system, Reactive power dispatch.

I. INTRODUCTION

A fast dispatch of reactive power contributes to the dynamic stability of the electric energy system's Q/V loop, avoiding its collapse.

In 1999, on March 11 there was a black out in the Brazilian electric energy system because of Q/V loop collapse. Many national and international experts in this matter (including A. Rocco that was systems operation manager of Eletropaulo S.A.) studied what to do to improve the operational security stability margins. One of the suggestions was to improve the AVR dynamics of the generators located near the energy comsumption centers, specifically Henry Borden, L.C.Barreto, and Porto Colômbia power stations.

Similar voltage collapse events also occurred in Japan, France, Sweden, USA and other times in Brazil in the last fifteen years.

These events were caused by local reactive power deficits. The electrical system was unable to supply, in the required time, the amount of reactive power necessary to keep the voltage levels within operational margins. The critical condition usually happened in the period immediately before the peak of demand, when the highest demand rate occurs.

This paper discusses some technical details related to the rectifiers that are used within the synchronous generator exciters, which affect the AVR dynamic response.

II. AUTOMATIC VOLTAGE REGULATOR MODEL

This paper will discuss only models AC4A (Alternator supplied controlled-rectifier exciter) and ST1A (Potential source controlled rectifier exciter) of IEEE standard 421 [1]. The only difference between both models is the energy source used for feeding the controlled rectifier. An independent electric network in used in the AC4A model while the synchronous generator terminals feeds its own rectifier (usually by means of a step-down excitation transformer) in the ST1A arrangement. The ST1A unifilar diagram is shown in Fig. 1.

Usually the automatic control operates as a terminal voltage controller (AVR-Automatic voltage regulator) although other operating modes may exist such as a power factor regulator or even as a VAR regulator. But these other operating modes usually work around the AVR, which acts as a subordinate loop inside the exciter system.

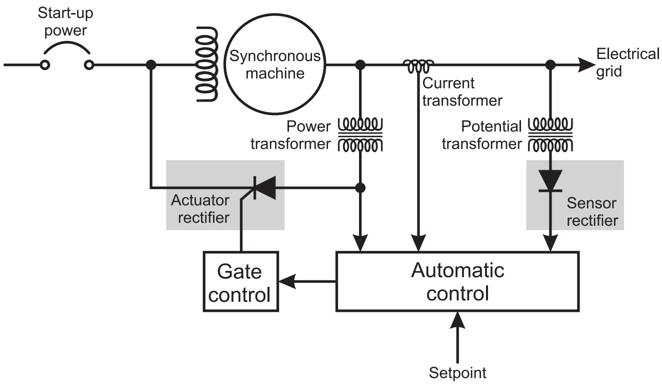

Fig. 1 Excitation system unifilar diagram for a ST1A excitation system - Potential source rectifier employing controlled rectifiers (adapted from IEEE Std. 421).

II.1 Actuator rectifier

The actuator rectifier is fed by the synchronous machine through a power transformer (except for low power, low voltage generators). High power exciter systems usually use a fully controlled three phase bridge although this is not required explicitely by the IEEE Std. 421. In some small generators it is possible to use single phase rectifiers. These two arrangements for the actuator rectifier are shown in Figs. 2 and 3.

Different ripple levels exist at the machine field terminals and produce side-effects, even considering that the field circuit has a large time constant. These ripple components depend on the excitation transfomer turns ratio (or in other words, of the ceiling voltage of the excitation system).

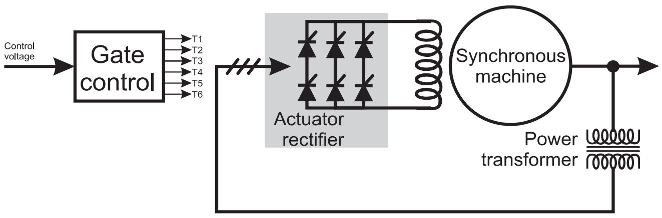

Fig. 2 Three phase full bridge rectifier, used for high power generators.

The synchronous machine field circuit doesn't filter completely all high frequency components that are present in the field voltage. It may happen that some of these high frequency components may still appear at the stator terminal voltage. Anyway, these high frequency components may induce higher losses in the machine ferromagnetic circuit. Although these are important issues, this will not be further discussed in this paper since we are mainly interested in the dynamic performance issues.

The half-wave arrangement shown in Fig. 3 is frequently used in low power generators, where cost considerations are important.

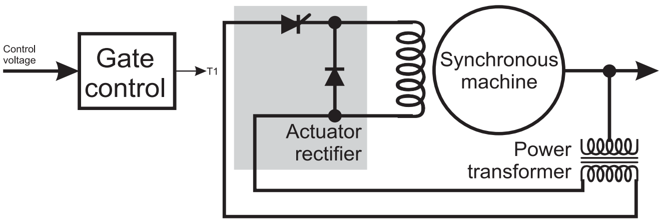

Fig. 3 Half wave, single phase actuator rectifier, that can be used for low-power generators.

The actuator structures introduce different control delays in the loop dynamics, smaller when a full bridge actuator is used.

II.2 Feedback circuits and their associated rectifiers

The automatic control requires a feedback signal that is given by the potential transformers (at least one). There are several arrangements for producing this feedback signal, which are shown in Figs. 4 to 6. Other possibilities exist and were studied but, due to the lack of space, will not be presented.

Figure 4 shows the simplest arrangement where just one potential transformer and one diode are used. Figure 6 shows a sophisticated arrangement where 3 potential transformers are used associated with an intermediary transformer (a low power and voltage transformer) which produces 6 output phases whose signals feed a 12 pulse diode rectifier.

Obviously, cost and sizing are important considerations in an actual exciter system but in this paper we will concentrate on the technical aspects. Each one of these feedback arrangements has different output ripple levels and require different output filters to bring the feeback ripple level to acceptable values. When the sensor rectifier generates less ripple in its output voltage, a smaller time constant can be used in the filter, contributing to the higher AVR response speed.

The filter structures shown in Figs. 4-6 are all single pole low pass filters but other choices are possible which would reduce the undesirable ripple components to lower levels.

Each one of these feedback circuits produce different DC levels for the same AC input. For this reason we included a gain ajustment circuit with each one of the feedback circuits that would normalize all the feedback signals to the same level.

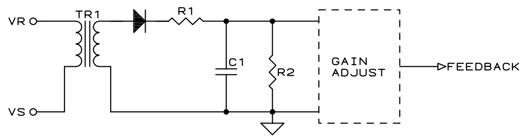

Fig. 4 Half wave, single phase rectifier with filter.

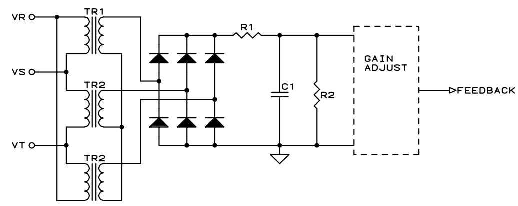

Fig. 5 Full wave, three phase rectifier with filter.

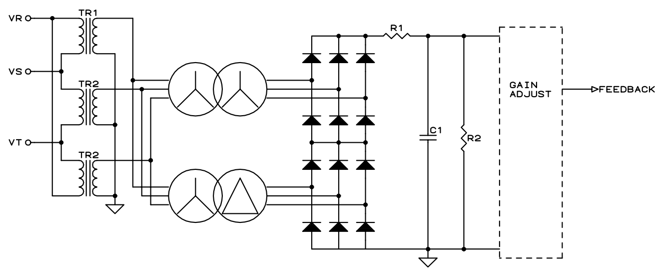

Fig. 6 Twelve pulse rectifier circuit with filter.

One other possibility for producing a feedback signal would be to use directly the voltage samples taken **simultaneously** at the outputs of the 3 potential transformers. From these samples (taken at high frequency, several times per cycle) it would be possible to produce a feedback signal using the Park transformation. The hardware circuit associated with this feedback circuit certainly includes several A/D converters and also a dedicated CPU but this is not the main problem. This possibility seems attractive because it would produce a signal proportional to the instantaneous voltage at the generator terminals. But, due to noise considerations an actual implementation would require filtering and so this "ideal digital transducer" would also be associated to a time constant and will not be further discussed in this paper.

II.3 Automatic controller considerations

Concerning the AVR loop controller where there are three different aspects to discuss.

a) The controller can be implemented digitally or by analog circuits although nowadays a digital implementation would be more usual. The point to be considered is the sampling rate adopted within this controller which certainly affects the overall loop performance. This sampling rate adds a time delay T_{Sample} that, in a first approximation (Eq. 3), adds other time constants of the AVR loop.

b) There exist several types of loop controllers that can be adopted. The most common are:

- PID controllers
- PI controller
- "lead-lag" controllers with a field voltage compensation (following Gabriel Kron 1954 patent)

c) Each one of the controllers can accept different tuning procedures, which affect the system overall performance.

These aspects are fully detailed in [2]. There exist several papers and books about this subject [3,4,5,6,7,8,9,10,11]. Our main interest in this paper is to discuss the effects of the sensor and actuator rectifiers in the overall performance of the exciter system. One central idea of this paper is that overall performance doesn't depend only on the controller choice, so we adopt a simple PI controller for making comparisons.

III. MATHEMATICAL MODEL

This paper considers two possibilities for the mathematical model of the exciter system:

- in the first approach all rectifier bridges (actuator and sensor) are replaced by linear equivalent models;
- the second approach takes into account all details of the rectifier bridges.

When making the preliminary controller tuning procedures it is much more convenient to use the simplified approach. Later on, this controller setup is checked using the detailed model.

The block diagram of the exciter system given in Fig. 7 deserves some explanations:

a) The AVR loop controller is given directly by its PI transfer function. Its output is a "firing command signal" also called $V_{Command}$;
b) The firing pulses are produced by a "gate controller";
c) The synchronous generator is replaced by a single pole transfer function (with a time constant given by T'_{do}). This modelling approach is valid when the machine in open circuit conditions. Under loaded conditions this modelling is approximate. The machine gain is unitary since we are using a PU system with appropriate bases. The base adopted for the terminal voltage is the machine nominal voltage and so the terminal voltage would be 1 [PU] at nominal conditions. The field base adopted is the "field voltage at no-load conditions" that corresponds to 1 [PU] terminal voltage.
d) The actuator rectifier is still kept "unmodelled";
e) The feedback circuit, which includes the potential transformers, rectifier circuits and filters is also kept "unmodelled".

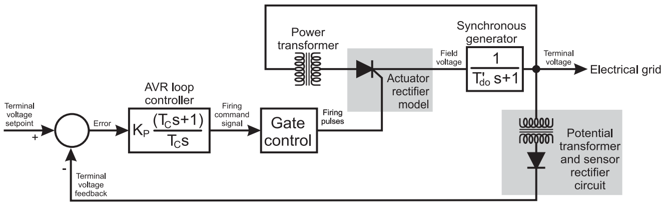

Fig. 7 Mathematical model for the excitation system.

The first simplification to be made in order to obtain a linear model is to consider that the terminal voltage is always around 1 [PU]. Then, exciter system model would be given by Fig. 8, where we eliminated the power transformer which feeds the actuator rectifier.

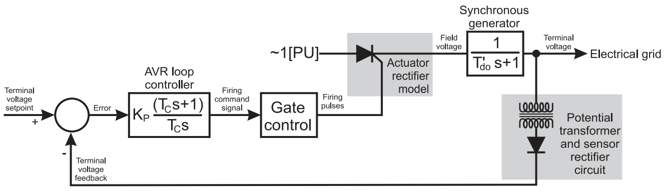

Fig. 8 Mathematical model for the excitation system considering that terminal voltage is always near 1 [PU].

As a final step we have Fig. 9, where both the actuator rectifiers and feedback rectifiers are replaced by their representing blocks.

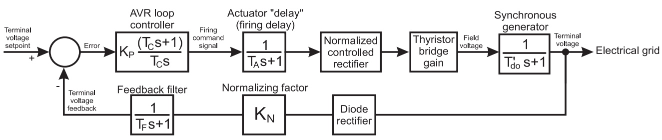

Fig. 9 Mathematical model for the excitation system considering that terminal voltage is always near 1 [PU].

The following remarks can be made about Fig. 9:

a) The gate control is replaced by an "actuator delay" which represents the firing delay associated with the controlled rectifier.
b) The actuator rectifier relationship between the firing command signal and the actual field voltage is non-linear (normally depending on the $\cos\alpha$ where α is the firing

angle). In this case we have "linearized" the actuator characteristics, which is a normal feature when using digital controllers. Thus, the relationship between the firing angle α and the command voltage available at the controller output $V_{Command}$ is given by:

$$\alpha = \cos^{-1}\left(V_{Command}\right) \quad \mathbf{(1)}$$

Considering this equation, the rectifier mean output voltage is directly proportional to $V_{Command}$.

c) The controlled rectifier is replaced by a "normalized controlled rectifier" which has the same **waveform** of the correspondent rectifier (either Fig. 2 or 3). This normalization factor makes the output mean voltage always 1 [PU] for ideal firing angle $\alpha = 0$.

d) The normalized rectifier output is multiplied by thyristor bridge gain which is related to the ceiling voltage in PU.

e) The feedback circuit is represented by 3 different blocks. First of all, an equivalent diode rectifier which has the same **waveform** of the choosen circuit, given by one of the Figs. 4 to 6. This output is multiplied by a normalizing factor in order to produce always a 1 [PU] signal independently of the diode rectifier choice. Finally, the feedback filter is represented by a single pole transfer function.

These remarks are fully detailed in [2].

Taking Fig. 9 as the basis it is possible to simulate (using Simulink/Matlab) several situations combining different choices for the actuator and for the feedback rectifier circuit. Figure 10 presents the linear equivalent circuit used for tuning procedures and for simplified simulation purposes. In this case:

a) The actuator is replaced linear gain and an equivalent delay T_{Eq} which depends on which kind of actuator is being considered. For the 6 phase controlled rectifier shown in Fig. 3, this equivalent time delay would be:

$$T_{Eq} = \left(\frac{1}{60\ [Hz]}\right) \Big/ 12 \approx 1.4\,[ms] \quad \mathbf{(2)}$$

This first order delay can be derived from [12] considering:

$$G(s) = e^{-sT_{Eq}} \approx \frac{2 - T_{Eq}s}{2 + T_{Eq}s} \approx \frac{1}{T_{Eq}s + 1} \quad \mathbf{(3)}$$

b) The feedback circuit doesn't include any kind of rectifier and is represented by a simple low pass filter.

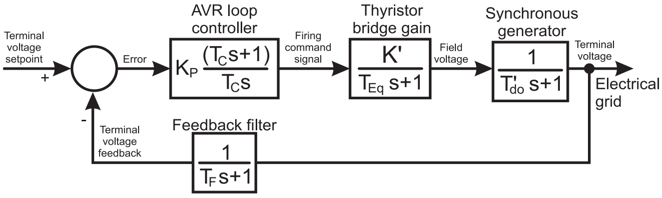

Fig. 10 Simplified linear mathematical model for the excitation system.

IV. SIMULATION CONDITIONS

Simulations will be made using several combinations of actuator (Figs. 2 and 3) and feedback circuits (Figs. 4 to 6). In this paper we only present the results using a full-bridge actuator. The reasons are twofold: this is the normal choice for high power generators and the firing circuit doesn't introduce a significant delay (which would exist in the Fig. 3 arrangement).

In order to simulate the excitation system it is necessary to establish numerical values:

a) The generator time constant $T'_{do} = 5\,[\sec]$ which is a typical value, that corresponds to a pole at -0.2 [rd/s];

b) The AVR controller time constant is adjusted in order to cancellate the synchronous generator pole. So $T_C = T'_{do} = 5\,[\sec]$;

c) The setpoint changes are very small (0.005 [PU]) in order to keep the linearity assumptions valid. Otherwise, the thyristor bridge would probably operate at "ceiling voltage conditions", with firing angle restrictions.

d) Ceiling voltage is 3 [PU]

e) Simulations will be made considering several adjustments for the feedback filter:

T_F = feedback filter time constant [ms]	Feedback filter pole location [rd/s]
4.17	240
16.7	60
66.7	15

f) The controller gain K_C is always adjusted in order to achieve critical damping and depends on the feedback filter used in each arrangement;

g) After adjusting the controller gain K_C it is possible to calculate the closed loop cutoff frequency, using the linearized model

K_C [PU of field voltage / PU of terminal voltage]	ω_C [rd/s] Closed loop cutoff frequency (from linearized model)
84.1	74.8
23.9	20.4
6.2	5.3

The results for the different feedback choices are presented below.

IV.1 Simulation using 12 pulse feedback rectifier circuit

This feedback circuit is shown in Fig. 6 and produces the best feedback signal when considering the ripple amplitude.

Due to this low ripple content, the filter requirements can very low and the exciter system can produce a high dynamic performance. The adopted filter was 4.17 [ms] and would corresponds to a filter cut-off frequency of 240 [rd/s].

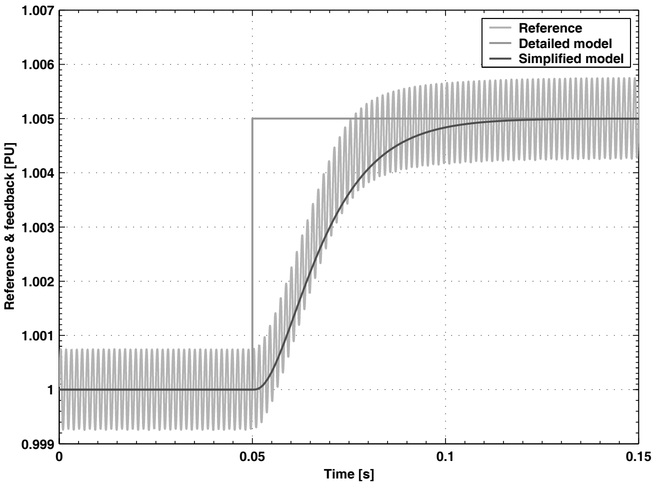

Fig. 11 AVR step response considering a full bridge actuator and a 12 pulse feedback circuit. Feedback signal is shown only after filtering.

The actuator bridge output voltage is shown in Fig. 12.

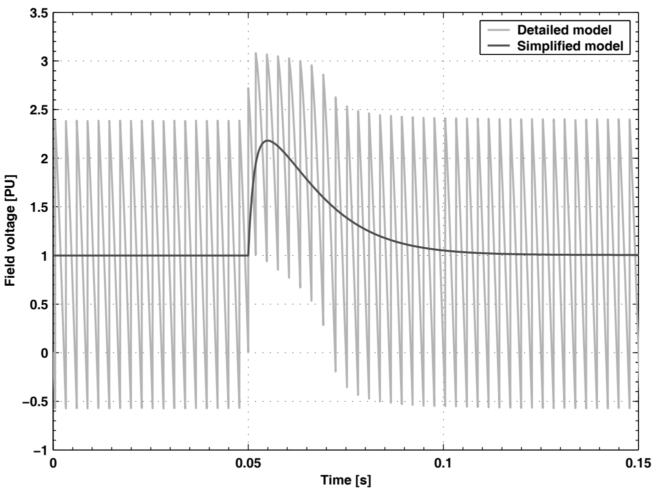

Fig. 12 Field voltage produced by the full bridge actuator. Results for both detailed and simplified bridge models are shown.

Results shown in Figs. 11 and 12 can justify the use of the simplified model when the actuator ceiling voltage is not reached, which can reproduce accurately the excitation system. Thus, standard linear control tools (frequency analysis and root locus) can be used for preliminary tuning procedures.

The application of the root-locus for the simplified model produces Fig. 13 where it can be seen that the critical gain for this configurations is 84.1 [PU/PU]. This would produce a settling time ≈ 50 [ms] as shown in Fig. 11 and corresponds to a closed-loop cutoff frequency ≈ 75 [rd/s] (Bode diagrams are not presented due to space limitations).

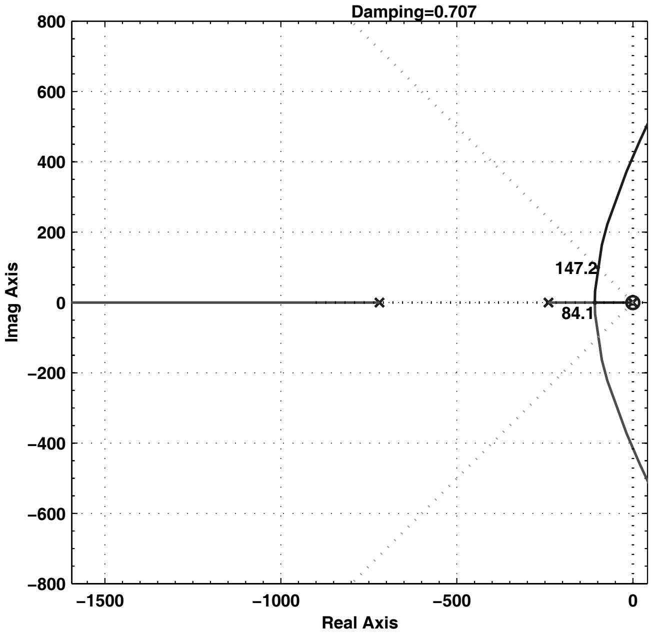

Fig. 13 Root locus for the simplified model. Critical gain is 84.1 [PU/PU].

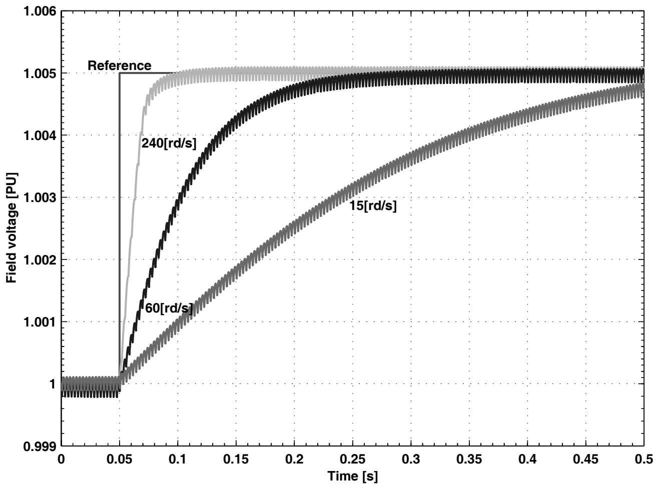

Fig. 14 AVR step response for a full bridge actuator and a 12 pulse feedback circuit. Different filter cutoff frequencies are considered and loop is always retuned to achieve critical damping. Only results from the detailed model are shown.

The 12 pulse feedback circuit can be used with other feedback filters. The overall responses are shown in Fig. 14 and are slower, as expected.

IV.2 Comparing different feedback rectifiers

When feedback rectifier circuits with lower number of pulses are used, the feedback filter of 240 [rd/s] can cause an erratic firing of the gating circuit. As an extreme condition, using the single pulse rectifier of Fig. 4 would force the feedback filter to be lower than 15 [rd/s].

In order to show this effect a six-pulse and twelve pulse sensor rectifiers are compared in Fig. 15.

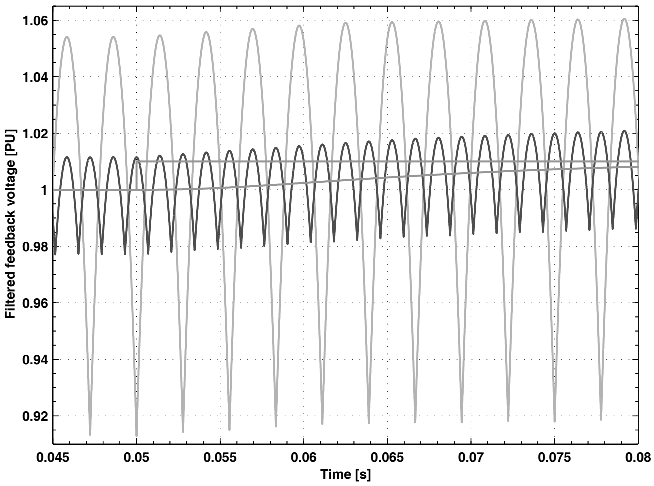

Fig. 15 Feedback after filtering, considering a six pulse and twelve pulse sensor rectifiers. Feedback filter is kept at 240 [rd/s] in both cases. The reference step and the output of the simplified linear models are also shown and are independent of the feedback rectifier sensor.

IV.4 Actuator saturation

Since the AVR controller is usually adjusted for achieving high performance, it is normal to have large proportional gains. Thus, the actuator bridge can be driven to ceiling voltage conditions when the AVR error is sufficiently large. This simulation is given in Fig. 16 and the simplified linear model cannot represent this situation in detail.

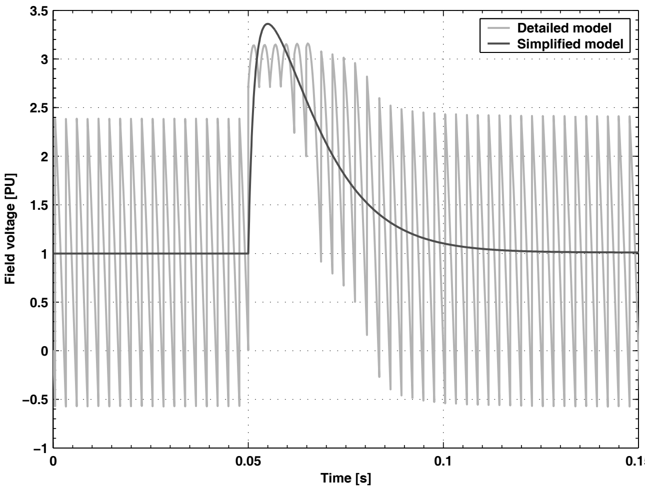

Fig. 16 Field voltage produced by the full bridge actuator. Results for both detailed and simplified bridge models are shown. A 0.01 [PU] step is applied at the reference. In this simulation a 12 pulse feedback sensor with a 240 [rd/s] filter is considered.

The actuator saturation shown in Fig. 16 should also be considered in the controller structure. There are different techniques available for avoiding windup effects [13] and these are particularly important during generator startup conditions, when the actuator will remain saturated for a long interval.

V. CONCLUSIONS

The AVR dynamics was discussed in this paper. Modeling and control techniques are presented. Simulation results are presented for different rectifiers used in both actuator and feedback sensor. A 12 pulse sensor rectifier produces a low ripple feedback signal and enables a faster dynamic performance, required for faster reactive power dispatch from generators connected to a grid system.

REFERENCES

[1] IEEE Std 421.5 – 1992, August 1992, "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies";

[2] H. S. Barbuy, "Regulador de tensão de gerador" – Master thesis, (advised by C. Goldemberg), São Paulo, EPUSP, 2001;

[3] R. J. Koessler, "Techniques for Tuning Excitation System Parameters", IEEE Transactions on Energy Conversion, Vol. 3 Nº 4 – 12/1988;

[4] A. Godhwani & M. J. Basler, "A Digital Excitation Control System for use on Brushless Excited Synchronous Generators", IEEE Trans. on Energy Conversion, Vol. 11 Nº 3 – 9/1996;

[5] A. Godhwani & M. J. Basler & K. Kim & T.M. Eberly, "Commissioning Experience with a Modern Excitation System", IEEE Trans. on Energy Conversion, Vol. 13 Nº 2 – 6/1998;

[6] IEEE Task Force on Digital Excitation Systems, "Digital Excitation Technology – A Review of Features, Function and Benefits", IEEE Summer Power Meeting; Panel Session on Digital Excitation System Application and Models, January 23, 1996, Baltimore, MD;

[7] IEEE Task Force on Digital Excitation Systems, "Computer Models for Representation of Digital-Based Excitation Systems", IEEE Transactions on Energy Conversion, Vol. 11 Nº 3 – 9/1996, pp 607-615;

[8] V. Arcidiacono & S. Corsi & C. Raffaelli & E.Rosa (ENEL) G. Ottaviani & S. Togno & G. Baroffio (ABB), "The ENEL´s Experience on the Evolution of Excitation Control Systems through Microprocessor Technology", IEEE Trans. on Energy Conversion, Vol. 13, Nº 3 – 9/1998;

[9] Richard C. Schaefer & Kiyong Kim, "Excitation control of the synchronous generator", IEEE Industry Applications Magazine – March/April 2001;

[10] P. M. Anderson & A. A. Fouad, Power System Control and Stability, IEEE PRESS, New Jersey, USA, 1993;

[11] P. Kundur, "Power System Stability and Control", McGraw – Hill, 1994;

[12] K. Ogata, Modern Control Engineering, Prentice-Hall, Inc. 1997;

[13] L. A. P. Fernandes, "Técnicas Anti-windup" – Master thesis, (advised by C. Goldemberg), São Paulo, EPUSP, 2001.