IMPROVED STABILITY WITH LOW TIME CONSTANT ROTATING EXCITER

H. R. Perry J. F. Luini J.C. Coulter
Pacific Gas and Electric Company
San Francisco, California

Abstract—This paper discusses the improved stability performance offered by a low rise time, high response excitation system to be installed on Unit No. 1 at the Diablo Canyon Site. Such an excitation system is provided by a low time constant rotating exciter with minor loop current feedback.

INTRODUCTION

In the early 1960's several factors were present in the northern and central California area that led to the decision by the Pacific Gas and Electric Company to install an extensive 500 kV transmission system that would overlay the 230 kV system in the area. The principal factors were (1) the economics of higher voltage transmission for a system that would soon reach a 10-million kilowatt peak and the increasing difficulty of acquiring transmission line rights-of-way, (2) the economics of going to 750 megawatt and larger generator size, and (3) the participation in the construction of the Pacific Northwest-Pacific Southwest Interconnection.

This decision brought with it the need to give more study to the problem of system stability. This was not surprising since the growth of the 230 kV system over the recent decades had resulted in a general improvement in stability. Long 230 kV transmission lines were being drastically shortened by the construction of intermediate substations with less of the remote hydro generation being transmitted long distances to the San Francisco Bay Area load center. Also, the newer and larger thermal units were being located nearer load and there was general improvement in breaker clearing times. As a result of these developments, periodic stability studies made during the 1950's and early 1960's showed the system becoming more stable with time.

These pre-EHV stability investigations were made on an AC Network Calculator and later by digital computer using the "classical" solution method. These studies were run only for the first swing duration. The excitation system on most of the post-World War II machines was an 0.5 ASA response rotating d.c. generator controlled by a continuous acting voltage regulator. The primary objective at that time was to maintain desired steady-state voltage levels with little emphasis placed on the dynamic performance of the excitation system.

Early EHV stability studies, including the new large generators and the Pacific Intertie, were made using the classical method. Subsequent studies, as early as 1965, represented generator saliency and crude approximations of load characteristics, excitation and governor systems. The results of studies run for more than the first swing gave reasons for concern over the proper representation of the system dynamics—particularly the load behavior and excitation system. The overall results of these and more refined studies are outside the scope of this paper.

This paper will discuss the reasons for selecting a high response excitation system for Unit No. 1 at the Diablo Canyon Site. This is a nuclear unit scheduled for operation in 1973. The generator is rated 1300 MVA, .90 PF, 25 kV. A second unit of similar size is planned at the site for 1974 operation.

The paper illustrates that the low time constant rotating exciter with minor loop current feedback is a practical way of providing fast rise times. We further demonstrate that conventional rate feedback combined with a power system stabilizer is very successful in damping oscillations while maintaining high regulator gain in the feed forward loop.

Paper 71 TP 16-PWR, recommended and approved by the Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE Winter Power Meeting, New York, N. Y., January 31-February 5, 1971. Manuscript submitted September 24, 1970; made available for printing October 30, 1970.

REGULATOR-EXCITER DESIGN REQUIREMENTS

With the construction of the Pacific Intertie, large centers of rotating mass were connected producing an interconnected system with a natural oscillation frequency of 1/3 Hertz, often modulated by higher local frequencies. This low frequency of oscillation required that studies be run for a longer time which disclosed the inadequacies of the then-current excitation system design. Not only were ceiling voltages too low, but field voltage corrections lagged 90° to 130° behind the desired corrections. This resulted in negative damping causing an increase in the magnitude of subsequent system oscillations. Subsequent simulation, design, and installation of power system stabilizers (supplementary excitation control) with frequency or shaft speed deviation input provided the necessary phase advance at a nominal investment[1]. In order to obtain the desired higher ceiling voltages, it would only be practical to purchase 2.0 ASA response exciters on generators ordered after the 1965 studies.

It is easily understood that maximum damping requires maximum volt-seconds at the right time to control generator field flux. The power system stabilizer provides the right time, and an exciter with a one or two-cycle ceiling voltage rise time will produce more volt-seconds. Others in the western United States have demonstrated that an SCR excitation system is also a very practical way of meeting the above rise times[2].

Based on the results of stability studies previously mentioned, the excitation system for Unit No. 1 at the Diablo Canyon Site was specified as a 2.0 ASA response with a rise time of one to two cycles.

The manufacturer provided preliminary design data that showed the maximum time constants for the regulator and exciter would be .02 and .015 seconds respectively. The ceiling voltage was estimated to be 4.45 p.u. and the nominal regulator gain to be 400. It was determined that the above four parameters would provide an excitation system that would satisfy the specified requirements. The selected exciter was to be an a.c. alternator with rotating rectifiers. Rate feedback would be taken from the alternator field current. Figure 1 shows in block diagram form the design data for the regulator-exciter system.

REGULATOR-EXCITER TESTS

Prior to shipping, extensive frequency response tests were performed by manufacturer's engineers on all excitation system components. Since most components are of solid state design, the frequency response corner frequencies are greater than 100 radians/sec. and therefore have a negligible effect on the dynamic performance. Consequently, regulator sensing filter, voltage error detector,

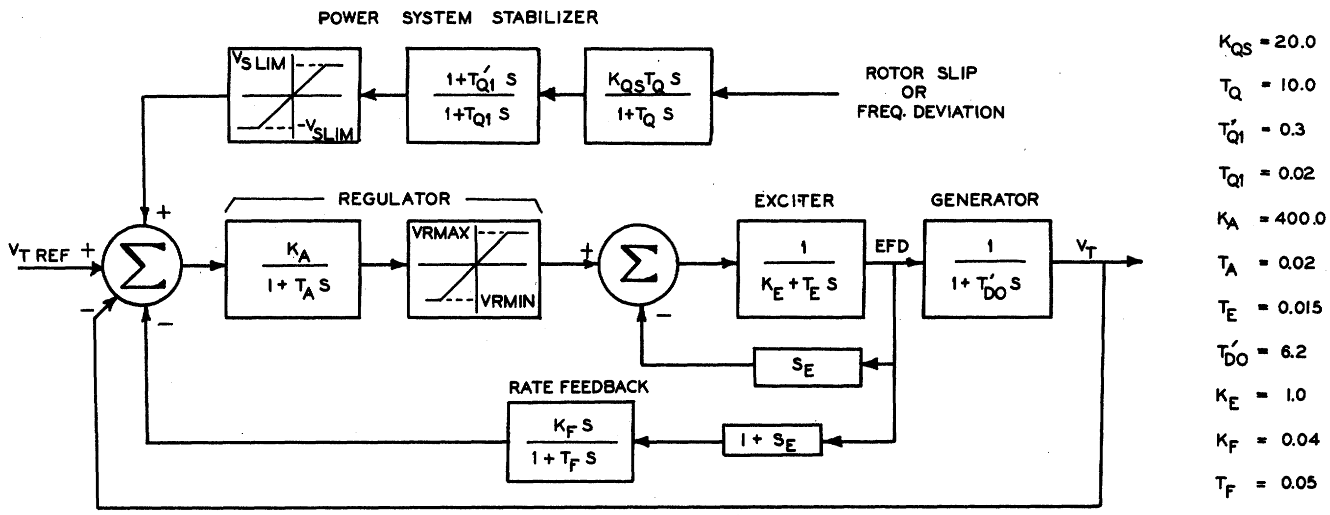

Fig. 1. Excitation and power system stabilizer block diagram with tabulation of design values.

power amplifier and exciter test results will be emphasized over other components.

Figure 2 lists the ratings for the PMG, brushless rotating rectifier exciter, and the a.c. generator. The solid state regulator provides the firing pulse information to modulate the PMG output to the a.c. alternator field. The alternator a.c. output is rectified by diodes mounted on the shaft and fed directly to the generator field.

Figure 3 is the plotted frequency response test data for the regulator sensing filter. The corner frequency indicates a time constant of .0067 seconds. Although the frequency response curves for the error detector amplifier are not shown, they indicate time constants of .0005 seconds at a minimum gain of .32 volt/volt, and .005 seconds at a maximum gain of 36 volt/volt. In addition, the time constant for the power amplifier is .0007 seconds with a gain of 112 volts/volt. If the regulator time constant can be approximated by the simple sum of the above components, it has a minumum value of .0079 seconds and a maximum value of .0124 seconds. These values are well within the estimated regulator time constant of .02 seconds of Figure 1.

The exciter design is unique because it employs current feedback to reduce the effective time constant of the alternator. Since the a.c. alternator output voltage is inaccessible (rotating rectifier is directly connected to the generator field) its field current is used as an approximation of its output. The field current signal is obtained from a current shunt. This current signal is conditioned by the time constant compensator and then fed back into the power amplifier. This compensation is equivalent to negative feedback around the alternator with a gain setting of about 10. The net effect is to produce an effective exciter time constant which is 10 percent of the actual time constant.

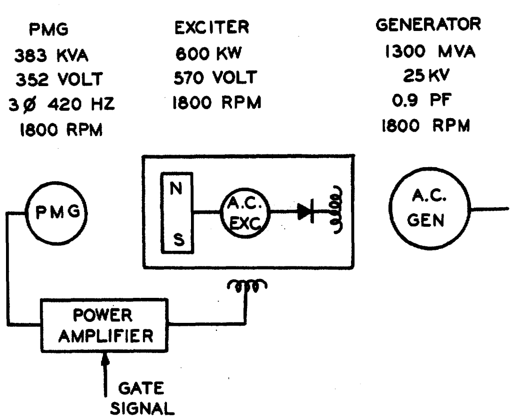

Fig. 2. Schematic of rotating exciter, PMG, generator, and regulator.

Figure 4 compares exciter frequency response tests with and without the time constant compensator. As desired, the compensated time constant is less than 10 percent of the uncompensated value of .125 seconds. Figure 5 illustrates the exciter response to a step input. As shown, the desired rise time of less than two cycles has been accomplished. The actual ASA response was calculated from Figure 5 to be 2.23 and the ceiling voltage was 5.0 p.u. (base voltage = 153 volts).

DISCUSSION

Presently, there are three conventional means of damping an excitation system. They are power system stabilizer, regulator gain reduction, and rate feedback[4]. A very effective damping approach is to maintain higher regulator gain, substantial rate feedback, and a power system stabilizer.

The high regulator gain provides high initial response. The rate feedback provides damping at the cost of closed loop gain and phase lag, and the stabilizer settings make up the lost gain and phase lag.

The lost gain and phase can be explained by considering the block diagram of Figure 1. If rate feedback is not used, the closed loop portion represented by V_T/V_{TREF} can be expressed as

$$\frac{K_A}{(1+T_AS)(1+T_ES)(1+T'_{do}S)+K_A} \qquad \text{Eq. (1)}$$

where S is the Laplacian operator. If rate feedback is used,

$$V_T/V_{TREF} = \frac{K_A(1+T_FS)}{K_A(1+T_FS)+[K_AK_FS+(1+T_ES)(1+T_AS)(1+T_FS)](1+T'_{do}S)} \qquad \text{Eq. (2)}$$

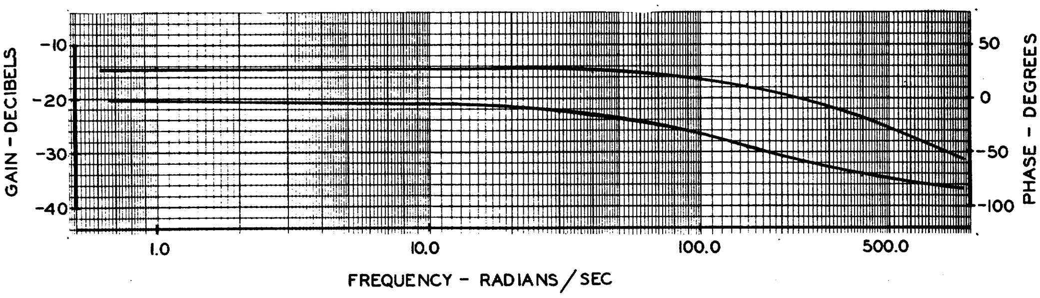

Fig. 3. Frequency response of the regulator error sensing filter.

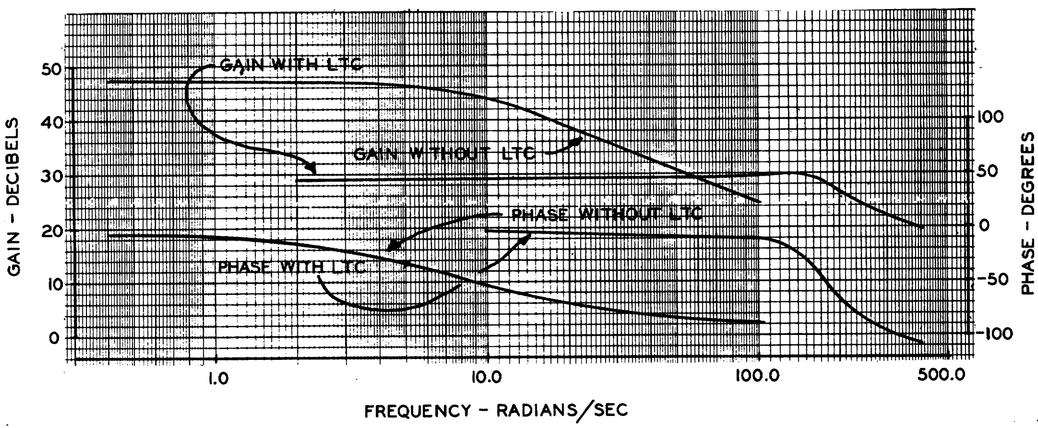

Fig. 4. Frequency response tests for exciter, with and without low time constant compensation.

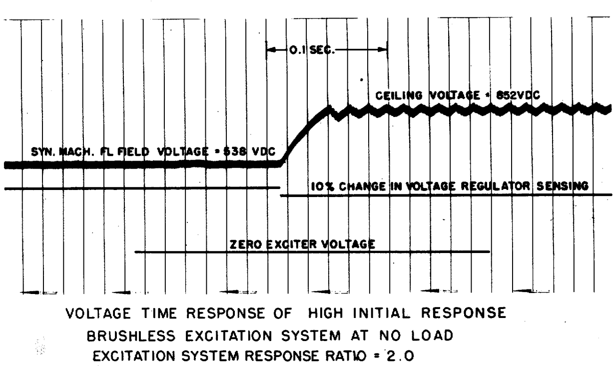

Fig. 5. Exciter ASA response.

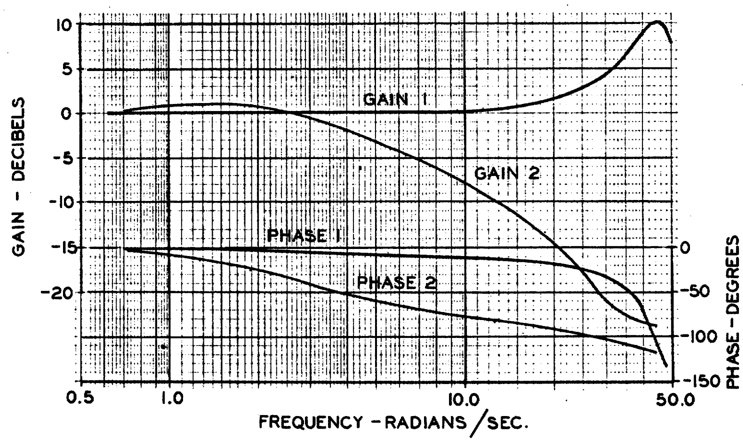

Fig. 6. Frequency response comparison of the excitation-generator closed loop with and without rate feedback.

Curve 1 – without rate feedback
Curve 2 – with rate feedback

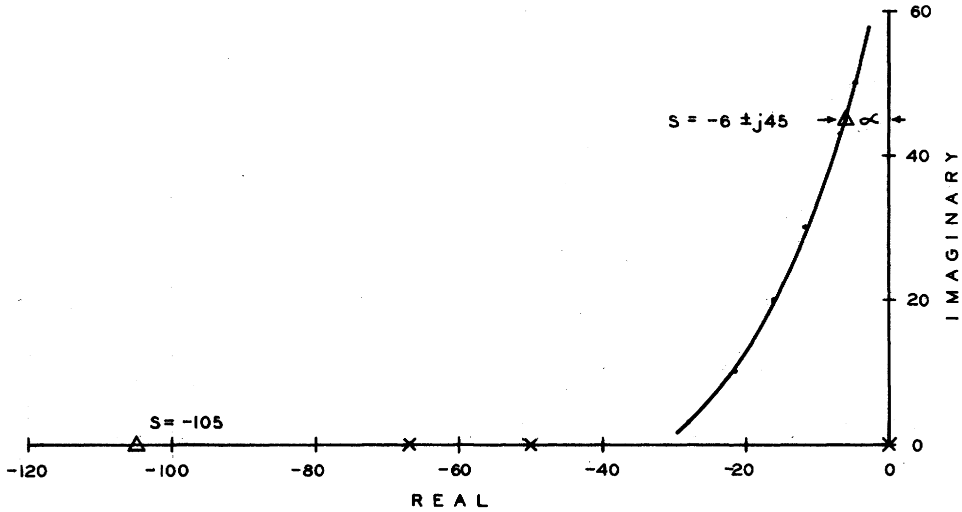

Fig. 7A. Root locus plot for excitation system and generator closed loop without rate feedback.

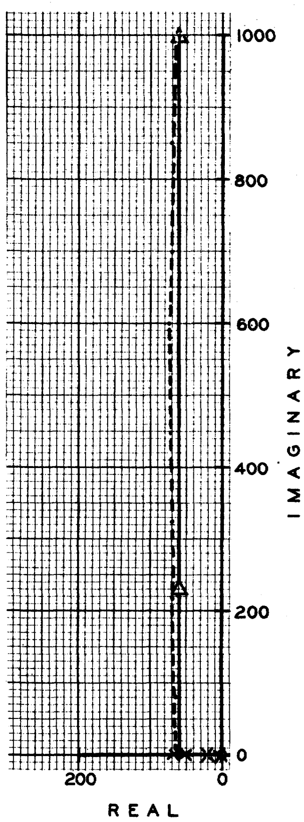

Fig. 7B. Root locus plot for excitation system with rate feedback.

Figure 6 shows the lost gain and phase by comparing the frequency response of Eq. (1) and Eq. (2).

Additional explanation of rate feedback damping can be obtained by plotting the root locus of Eq. (1) and (2) in the S plane.

Figure 7A is the root locus plot for Eq. (1). The magnitude of α determines the exponential damping.

To demonstrate the significance of rate feedback in Eq. (2) of the excitation system E_{FD}/V_{TREF} is considered first.

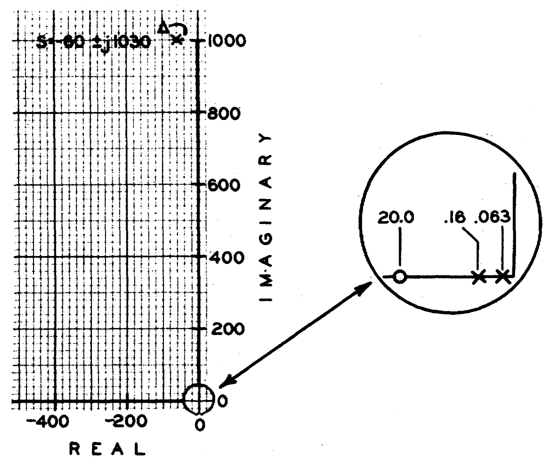

Fig. 7C. Root locus plot for excitation system and generator closed loop with rate feedback.

$$E_{FD}/V_{TREF} = \frac{K_A(1 + T_F S)}{K_F K_A S + (1 + T_A S)(1 + T_E S)(1 + T_F S)} \quad \text{Eq. (3)}$$

Figure 7B is the root locus plot for Eq. (3) for a rate feedback time constant $T_F = 1.0$. Notice here that α has a value of 58.5. If T_F takes on a smaller value the root locus will be pushed to the left. In particular, if $T_F = .05$ (see dotted lines on Figure 7B) α takes on a value of 68.3 which is not much different from 58.5.

Combining the results obtained for E_{FD}/V_{TREF} with the remaining generator term of Eq. (2) yields,

$$\frac{V_T}{V_{TREF}} = \frac{\dfrac{K_A(1 + T_F S)}{\left(1 + \dfrac{S}{\alpha_1}\right)\left(1 + \dfrac{2\alpha_2 S}{\alpha_2^2 + \omega_2^2} + \dfrac{S^2}{\alpha_2^2 + \omega_2^2}\right)\left(1 + T'_{do} S\right)}}{1 + \dfrac{K_A(1 + T_F S)}{\left(1 + \dfrac{S}{\alpha_1}\right)\left(1 + \dfrac{2\alpha_2 S}{\alpha_2^2 + \omega_2^2} + \dfrac{S^2}{\alpha_2^2 + \omega_2^2}\right)\left(1 + T'_{do} S\right)}} \quad \text{Eq. (4)}$$

which is equivalent to Eq. (2).

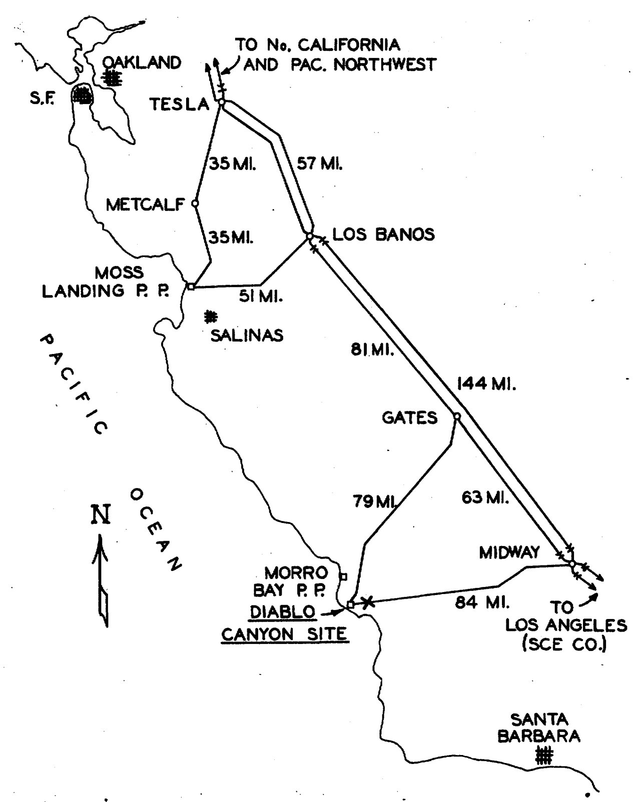

Fig.8. One line diagram of Diablo Canyon Site with fault location.

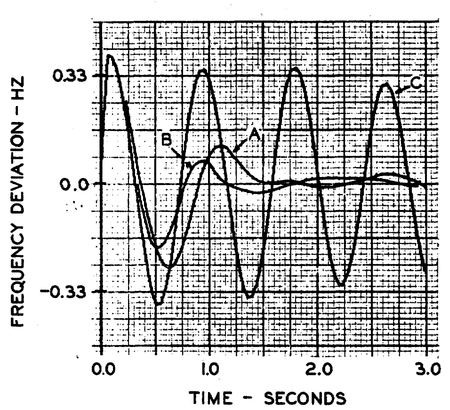

Fig. 9. Frequency deviation comparison for a 4-cycle fault on the Midway circuit adjacent to the 500 kV bus at the Diablo Canyon Site.

Curve A – 2.0 ASA conventional excitation system.
Curve B – low time constant excitation system with rate feedback.
Curve C – low time constant excitation system without rate feedback.

Figure 7C is the root locus plot for Eq. (4), which includes rate feedback. As can be seen, the dominant $|\alpha|$'s are much greater than those of Eq. (1) without rate feedback.

Damping can also be changed by varying the rate feedback gain K_F while leaving T_F fixed. Actually, a combination of both parameter changes would probably be more effective, as can be seen from the dotted line of Figure 7B.

Compensation for the detrimental effects of increased rate feedback can be obtained by appropriate power system stabilizer settings. Referring again to Figure 6, for T_F = .05 seconds the appropriate lead setting is at the 45° phase lag frequency, i.e., T'_{Q1}, (Figure 1) = 1/3.3 = .300 seconds. An acceptable lag setting, T_{Q1}, is

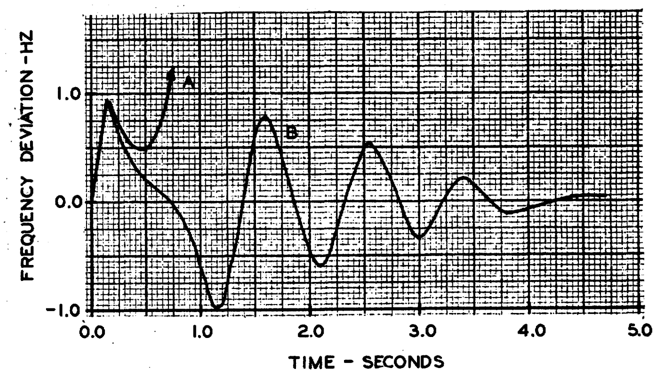

Fig. 10. Frequency deviation comparison for a 9.6-cycle fault on the Midway circuit adjacent to the 500 kV bus at the Diablo Canyon Site.
Curve A – 2.0 ASA conventional excitation system.
Curve B – low time constant excitation system with rate feedback.

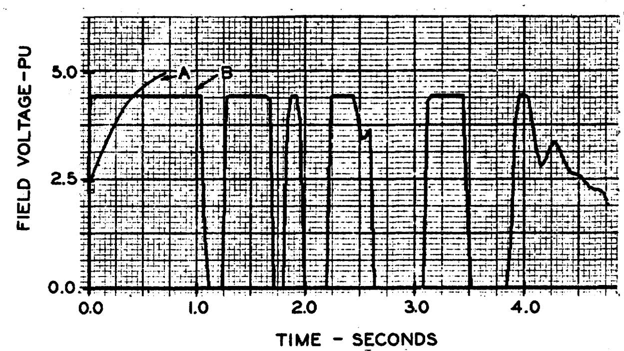

Fig. 11. Field voltage comparison for a 9.6-cycle fault on the Midway circuit adjacent to the 500 kV bus at the Diablo Canyon Site.
Curve A – 2.0 ASA conventional excitation system.
Curve B – low time constant excitation system with rate feedback.

.02 seconds. It should be emphasized that only one lead-lag stage is necessary with a high initial response exciter due to the low exciter time constant.

Of the many disturbances that could occur, a three-phase fault on the Midway circuit adjacent to the 500 kV bus at the Diablo Canyon Site was selected to demonstrate the results of the above concepts on system damping. Figure 8 shows a one-line diagram for the Diablo Canyon area with the fault location. Two fault conditions are compared; (1) normal 4-cycle fault clearing and line removal to Midway, (2) 9.6-cycle fault clearing and line removal to Midway. The 9.6-cycle fault represents backup fault clearing. For each fault condition a conventional 2.0 ASA excitation system is compared to the low time constant excitation system with rate feedback. Both systems include a power system stabilizer.

Figure 9 compares generator frequency deviation for the 4-cycle fault. Curve A is for the 2.0 conventional system, Curve B is for the low time constant system with rate feedback, and Curve C is for the low time constant system without rate feedback. Figures 10 and 11 compare generator frequency deviation and field voltage for the 9.6-cycle fault.

A comparison of Curves B and C on Figure 9 shows the importance of rate feedback and Curve B shows improved damping over Curve A. A more significant advantage of the low time constant–rate feedback system is shown in Figures 10 and 11. The difference amounts to a stable or unstable system and can be attributed to the fast rise time of the field voltage.

CONCLUSIONS

System studies for the installation of Unit No. 1 at the Diablo Canyon Site showed that a conventional high response excitation system would not result in stable operation for delayed fault clearing. Analytical studies enabled us to determine the characteristics needed for stable operation. These were a low rise time and high ASA response exciter. Subsequently a low time constant rotating exciter system with minor loop current feedback was designed and tested that met these requirements.

A low rise time exciter operating with rate feedback and a power system stabilizer significantly increases system damping for both normal and delayed fault clearing time.

REFERENCES

1. Gerhart, A. D., Hillesland, T., Luini, J. F., "Power System Stabilizer: Field Testing And Digital Simulation," to be presented at the Winter Power Meeting, February 1971.
2. Farmer, R. G., Kent, M. H., Hartley, R. H., Wheeler, L. M., "Four Corners Project Stability Studies," Conference Paper presented at 1968 ASME/IEEE Joint Power Generation Conference, San Francisco, Calif., September 15-19, 1968.
3. IEEE Committee Report, "Computer Representation Of Excitation Systems," IEEE Transactions Power Apparatus and Systems, Vol. 87/No. 6, pp. 1460-64, June 1968.
4. DeMello, F. P., Concordia, C., "Concepts of Synchronous Machine Stability As Affected By Excitation Control," IEEE Transactions Power Apparatus And Systems, Vol. 88/No. 4, pp. 316-29.

A HIGH INITIAL RESPONSE BRUSHLESS EXCITATION SYSTEM

T. L. Dillman, Member IEEE, J. W. Skooglund, Senior Member, IEEE
F. W. Keay, Senior Member, IEEE, W. H. South, Member IEEE, and
C. Raczkowski, Senior Member, IEEE
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

Abstract—A high initial response excitation system retaining the advantages of the absence of commutators, collectors and brushes while responding with the speed of an electronic exciter has been developed. Calculated performance of this system has been confirmed by factory tests. With the exciter loaded, the excitation system achieved 95% of ceiling voltage in 0.016 seconds following a 10% step change in the voltage regulator sensing signal. In addition to the high initial response capability, the excitation system also includes supplementary feedback control for improving the small signal dynamic performance characteristic of the exciter. With the addition of feedback, the effective exciter time constant is reduced by a factor of thirty compared to its value without feedback. The tests confirm that low time constants and high initial response can readily be attained in an excitation system which includes a brushless exciter with non-controlled rectifiers.

INTRODUCTION

Recent years have seen increased application of fast response, high performance excitation systems to improve the transient stability of synchronous machines. Many of these installations are at hydro plants where, typically, long transmission circuits connect the plant to the system and stability is an important design consideration. Electronic exciters have become nearly the standard for hydro installations. Today, solid-state, controlled rectifiers have replaced the mercury-arc rectifier for such applications.

The short time constants of electronic exciters have made it possible to apply very effective positive damping of machine oscillations with suitable supplemental signals. Such supplemental signals can provide positive damping with conventional rotating exciters, but more effective damping can be obtained with the faster responding, low time constant excitation systems.

The application of faster excitation systems to steam turbine generators has developed at a slower pace. Traditionally, steam turbine generators have derived excitation energy from the shaft with a direct-connected rotating exciter. The Westinghouse brushless excitation system employs a shaft driven alternator-rectifier exciter with rotating rectifiers directly connected to the generator field. This scheme retains the concept of a shaft power source, independent of power system disturbances, and provides improved reliability and reduced maintenance by eliminating all commutators and collector rings and associated brushes.

To provide faster response of this excitation system, an obvious approach is the replacement of the rotating diodes with controlled rectifiers. Such a system, although feasible, appears less desirable than the system described herein because of complexity and because an oversize alternator operating continuously at ceiling voltage would be required.

This paper describes an alternate scheme which retains the

Paper 71 TP 29-PWR, recommended and approved by the Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE Winter Power Meeting, New York, N. Y., January 31-February 5, 1971. Manuscript submitted September 14, 1970; made available for printing November 11, 1970.