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EFFECTS OF FEEDBACK SIGNALS ON THE TRANSIENT RESPONSE OF A POWER SYSTEM USING A SOLID STATE EXCITATION SYSTEM

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INTRODUCTION

Transient stability study of a power system with classical methods as well as modern control approaches are adequately covered in standard texts and literature[1, 2, 3]. Most of these studies consider conventional relatively slow response excitation systems. Modern, fast-response, high gain, solid state excitation systems, though desirable in many respects, have the disadvantage that they introduce slowly-growing oscillations when the generator is on load. Such exciters, in addition to normal voltage regulator action, need additional stabilizing signals for satisfactory transient performance. In the teaching of transient stability in final year undergraduate power courses, it will be of benefit to students if an extra lecture is devoted to this important aspect of solid state excitation systems.

In this study a simple S.C.R. exciter was tested with different stabilizing signals on a small power system. It was observed that a combination of speed deviation and torque angle deviation signals reduces the transients most effectively.

SYSTEM REPRESENTATION

The power system considered consists of a 1.5 kW, 230 V alternator fed from a solid state exciter connected to an infinite bus through a transmission line.

A block diagram of the excitation system is shown in Fig. 1. A set of three controlled and three uncontrolled rectifiers rectify the three phase a.c. voltage and feed the field coil of the generator. By changing the firing angle of the controlled rectifiers, the excitation voltage may be varied from almost zero to a maximum value. The firing control circuit consists of a set of three comparators. The comparator compares a sawtooth voltage with a d.c. signal which is the summation of a reference signal, terminal voltage and other feedback signals. When these two voltages are exactly equal and opposite, the output voltage of the comparator switches its polarity. The output of the comparator is inverted and is used to fire the S.C.R.'s. The adder was used to add the terminal voltage and other feedback signals with the reference signal which

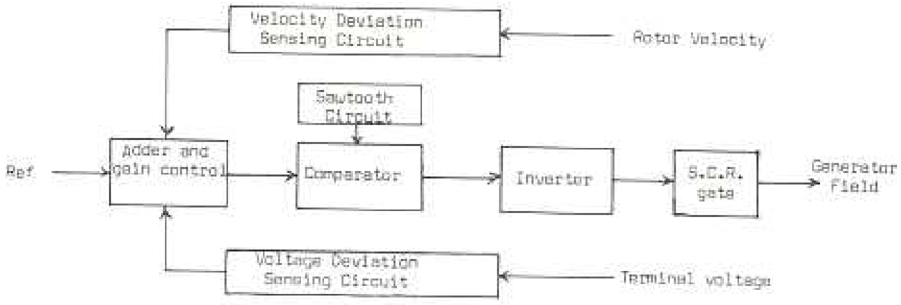

FIG. 1 Block diagram of excitation system.

produces a controlling d.c. signal for the comparator. The circuit also served the purpose of gain control for the individual feedback signals. Nominal excitation was obtained with the reference signal.

A simplified block diagram is given in Fig. 2. The input and output of the exciter can be related by the following two first-order differential equations.

$$pE_{fd} = \frac{K_r}{Tr} e_{t1} - \frac{1}{Tr} E_{fd} + (E_0 - K_r e_{tr})/T_r - \frac{K_r}{Tr} U_s(t) \tag{1}$$

$$pe_{t1} = (e_t - e_{t1})/T_V \tag{2}$$

Using Park's transformation, the equations relating flux, voltage and current of a synchronous machine feeding an infinite bus of voltage V through a transmission line having resistances and reactances r_e and x_e respectively under balanced condition can be written as

$$p\psi_{fd} = E_{fd} \frac{W_0 r_{fd}}{X_{afd}} - W_0 r_{fd} i_{fd} \tag{3}$$

$$p\psi_d = W_0 \left[\frac{x_e}{W_0} pi_d + r_e i_d - \frac{W}{W_0} X_e i_q + V \sin \delta \right] + W_0 r_a i_d + W \psi_q \tag{4}$$

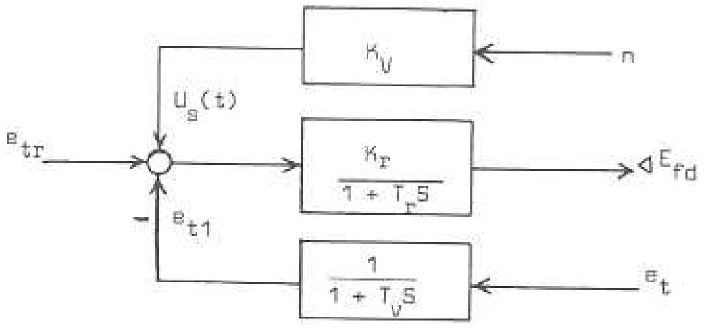

FIG. 2 Simplified block diagram for excitation system.

$$p\psi_q = W_0\left[\frac{x_e}{W_0}pi_q + r_e i_q + \frac{W}{W_0}X_e i_d + V\cos\delta\right] \qquad (5)$$

$$+ W_0 r_a i_q - W\psi_d$$

Where the currents and fluxes are related by the equations

$$\psi_{fd} = X_{ffd}\, i_{fd} - X_{afd} - i_d \qquad (6)$$

$$\psi_d = X_{afd}\, i_{fd} - x_d\, i_d \qquad (7)$$

$$\psi_q = -X_q\, i_q \qquad (8)$$

The basic swing equations describing the electromechanical oscillation of the synchronous generator can be broken up into two first-order equations given by

$$p\delta = W_0 n \qquad (9)$$

$$pn = \frac{1}{2H}\left[P_{in} - \frac{E_{fd}V}{X_d + X_e}\sin\delta - \frac{V^2(X_d - X_q)\sin 2\delta}{2(X_d + X_e)(X_q + X_e)}\right] \qquad (10)$$

Combining equations (1) through (10), the synchronous generator exciter system in the absence of damping, amortisseur circuits and governor action can be represented by 7 first-order nonlinear state equations.

$$\dot{\underline{X}} = f[\underline{X}, U_s(t)] \qquad (11)$$

Where $\underline{X}$ is a state vector of i_{fd}, i_d, i_q, n, δ, E_{fd}, e_{t1}.
Details of the method of solution can be found in reference (9).

Computational results

The generator and exciter system was simulated on a digital computer. The set of nonlinear equations (11) was solved with a fourth-order Runge Kutta integration technique for different stabilizing signals $U_s(t)$. The results have been grouped into the following two major sections.

(i) *Effects of exciter parameters:* In order to investigate the effect of regulator gain on system stability, a symmetrical 3 phase fault at the machine terminals for 6 cycles duration was considered. The operating torque and torque angles of the under-excited machine were 0.315 p.u. and 60° respectively (the maximum torque which can be delivered at this excitation being 0.37 p.u.). At this operating point, the machine in absence of automatic voltage regulator cannot survive a three phase fault. For low values of regulator gain (greater than 2.0) the first swing stability improves, but damping is poor. Too large a regulator gain again deteriorates system stability and for gains of 200 and over the machine falls out of step. The system can be operated at a much higher gain when a signal derived from the rotor shaft speed deviation is fed to the exciter in addition to the normal terminal voltage feedback. The results are shown in Fig. 3. It was observed that the first peak was minimum for a regulator gain of 40 while the minimum settling time was obtained for a gain of 20 at the cost of

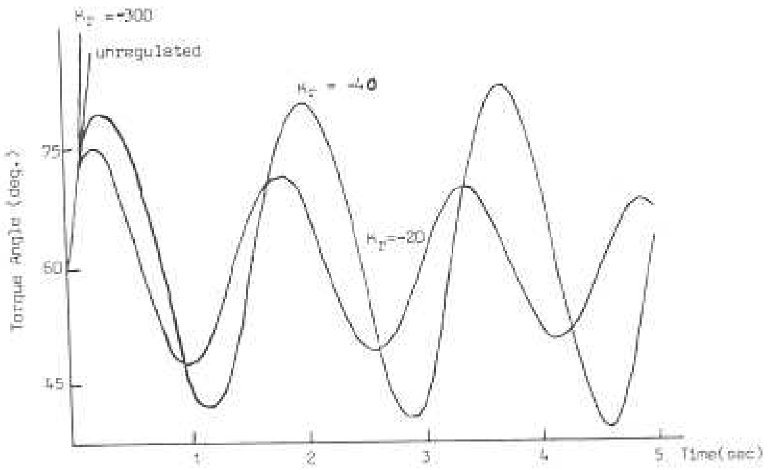

FIG. 3 Swing curves for three phase fault without stabilizing feedback signal.

some deterioration in peak overshoot. Considering both peak overshoot and settling time, a gain of 20 has been chosen for the rest of the study.

A large time constant in the excitation system deteriorates the transient response, and in the absence of adequate stabilizing signal the system may become unstable. An auxiliary stabilizing signal may offset this deterioration of response due to the introduction of large time constants in the exciter. A higher

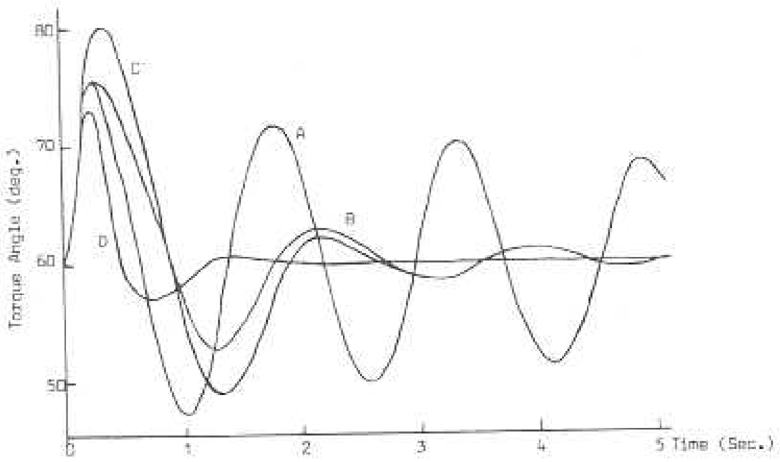

FIG. 4 Swing curve for a three phase fault (6 cycles) on generator terminal.
A: Terminal voltage feedback only.
B: With velocity feedback.
C: With velocity and field current feedback.
D: With velocity and torque angle feedback.

ceiling voltage of the exciter has been observed to give smaller overshoots and an improved damping.

(ii) *Effects of additional feedback signals:* Effects of various feedback signals derived from different states of the system were investigated for different types of transient disturbances such as 3 phase faults at different sections of the system, torque steps, torque pulses, line switchings, etc. Swing curves for a 3 phase fault with different stabilizing signals are given in Fig. 4, while a comparative study of settling time and peak overshoots are presented in Fig. 5.

Type of Feedback → Settling time (sec.) First rotor excursion (deg.) Type of Disturbance	e_t (only)	n	n, pn^2	$n, \Delta I_{fd}$	$n, \Delta I_a$	$n, \Delta\delta$
Three phase fault at generator terminal $\delta_o = 60^o$	10.5	3.35	3.3	2.4	Unstable	1.1
	75.0	75.1	74.5	79.8	-	73.0
Three phase fault at middle of transmission line $\delta_o = 60^o$	12.0	4.5	4.5	3.35	3.55	1.2
	109.3	95.1	95.4	81.7	86.5	77.8
Switching in a parallel transmission line $\delta_o = 60^o$	11.0	3.75	3.7	3.25	1.75	0.65
	8.1	19.5	19.4	15.6	8.2	45.6
15% torque pulse for 6 cycles $\delta_o = 60^o$	9.0	1.65	1.6	0.6	1.55	0.45
	64.9	63.4	63.4	61.6	61.8	61.6
50% torque pulse for 6 cycles $\delta_o = 60^o$	11.0	3.45	3.45	1.65	2.1	0.6
	77.9	72.1	71.8	65.4	66.0	65.7
100% torque pulse for 6 cycles $\delta_o = 60^o$	12.2	4.3	4.3	1.75	3.35	1.1
	99.0	85.1	83.7	71.6	69.8	71.2
Three phase fault on generator terminal $\delta_o = 45^o$	10.0	4.3	4.3	3.2	Unstable	1.3
	56.5	56.3	56.3	62.5	-	55.4
25% torque step $\delta_o = 45^o$	12.0	3.85	3.75	0.9	0.8	1.1
	71.3	66.1	66.0	55.6	52.4	51.4
40% torque step $\delta_o = 45^o$	12.8	3.15	3.1	1.15	0.9	0.65
	88.7	78.3	78.3	60.6	55.8	54.9

FIG. 5 Settling time and first rotor excursions with different feedback signals for different disturbances.

Normal terminal voltage feedback was present in all these studies.

(a) *Velocity feedback:* A signal derived from shaft speed deviation was found very effective in providing damping to system oscillations following a disturbance in a power system. Settling time is reduced to a great extent compared to that with a.v.r. only. A gain of 20 in the velocity feedback circuit has been found satisfactory. Too large a gain in the velocity feedback circuit causes an oscillatory response and the machine may even lose synchronism.

(b) *Field current feedback:* The field current deviation or combination of velocity and field current deviation when fed to the exciter were not found to show any improvement in transient stability. But, combination of 20 times speed deviation with 0.5 times absolute value of field current deviation $(|\Delta i_{fd}|)$ was found to reduce the settling time significantly, but with an increase in peak overshoot for three phase faults. Compared to velocity feedback alone, the velocity and field current combination was found to provide better damping for all types of disturbances.

(c) *Armature current feedback:* A combination of 20 times velocity and 0.6 times armature current deviation from nominal value was found to provide good damping following a 3 phase fault but were found to lead to unstable cases for other disturbances. Another combination gave stable cases for other types of disturbances but failed for 3 phase fault. In general, this type of signal is not to be recommended in a feedback scheme.

(d) *Torque angle feedback:* A signal derived from change of torque angle from the nominal value in combination with velocity signal was found to be very effective in reducing both the peak overshoot and settling time. Best results were obtained when 20 times speed deviation signal was combined with 1.0 times torque angle deviation signal.

A combination of velocity and acceleration signal was also tried but was not found to be as effective as scheme (d).

CONCLUSIONS

Stability of a synchronous generator depends to a very large extent on the gain of the excitation system. The generator can get unstable for too small as well as too large an exciter gain. Stabilising signals, in addition to the normal voltage regulator signal, enables the use of higher exciter gain.

A feedback signal proportional to shaft speed deviation improved the transient response following a disturbance. Further improvement can be obtained by combining this signal with the magnitude of field current deviation. A combination of velocity and rotor angle deviation signal has been found to be most effective.

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APPENDIX

System data

$X_{afd} = 1.0$ $X_{ffd} = 1.195$ $T_r = 0.02$ sec $X_d = 1.05$
$H = 2.4$ sec $K_r = -20.0$ $X_q = 0.558$ $r_a = 0.1134$
$X_e = 1.56$ $r_{fd} = 0.01542$ $r_e = 0.0425$ $f = 50$ Hz

ABSTRACTS–ENGLISH, FRENCH, GERMAN, SPANISH

Effects of feedback signals on the transient response of a power system using a solid state excitation system

This paper analyses the effects of feedback signals in a solid state excitation system, in addition to the normal voltage regulator signal, on the transient stability of a power system. It was observed that a suitable combination of speed deviation and torque angle deviation signal reduces the transients most effectively.

Effet de signaux de réaction sur la réponse transitoire d'un réseau de puissance utilisant un système d'excitation statique

Cet article analyse, dans le cas d'un système d'excitation statique, l'effet de signaux de réaction complétant le signal normal du régulateur de tension, sur la stabilité transitoire d'un réseau de puissance. On a observé qu'un signal formé d'une combinaison convenable de l'écart de vitesse et de la variation de l'angle polaire réduit le plus efficacement les transitoires.

Einflüsse von Rückkopplungssignalen auf das Einschwingverhalten eines Starkstromsystems bei Benutzung eines Festkörpererregungssystems

Diese Arbeit untersucht die Einflüsse von Rückkopplungssignalen in einem Festkörpererregungssystem, zusätzlich zu dem normalen Spannungsreglersignal, auf das Einschwingverhalten eines

Starkstromsystems. Es wurde beobachtet, dass eine geeignete Kombination von Drehzahlabweichungs- und Drehmomentwinkelabweichungs-Signalen die Einschwingvorgänge am wirkungsvollsten verringert.

Efectos que las señales realimentadas ejercen sobre la respuesta transitoria de una red de potencia que utiliza un sistema de excitación de estado sólido

En este artículo se estudian los efectos que la realimentación de señales- añadidas a la señal normal de regulación de la tensión- ejercen sobre la estabilidad transitoria de una red de potencia que tiene un sistema de excitación de estado sólido. Se observa que una combinación determinada de señales de desviación del par y de la velocidad reduce el transitorio con mayor efectividad.

BOOK REVIEWS

Vibrations and Waves in Physics: IAIN G. MAIN

(Cambridge University Press, 1978, 336 pp., £17.50 hardback, £4.95 paperback)

Wave phenomena are commonplace in physics and electrical engineering, where the same basic mathematical model is used to describe a wide range of very different phenomena, ranging from simple mechanical vibrations to the propagation of electromagnetic radiation through space. This book attempts to provide an introduction to the subject at first-year undergraduate level, and to present a unified approach to the properties of vibrations and waves. In this way a springboard is provided from which the student can take off into any specialised branch of the subject or into any application of wave theory.

The book is very carefully planned, and is largely successful in its aims. It begins by treating simple vibrations and oscillations, and follows, in logical sequence, with forced and damped oscillations, anharmonic oscillations and two-coordinate systems. Non-dispersive waves, dispersive waves, electromagnetic waves and de Broglie waves then follow, and the list of topics ends with boundary conditions and diffraction. An important and interesting feature of the book is that after each new topic is introduced it is followed by a treatment of some of its applications to phenomena in physics and engineering. There are plenty of worked examples in the text, and at the end of each chapter some carefully-graded problems covering most aspects of the work. Answers and hints for solution are provided at the end of the book.

Students could learn much by working through this book, and would find the juxtaposition of the different aspects of vibrations and waves helpful in developing a genuine insight into the subject. Engineers may find the examples and applications biased more towards physics than they would like, but in spite of this the book provides a sound basis for a wide range of engineering topics. The book is well-illustrated and beautifully produced.

D. C. NORTHROP, *Department of Electrical Engineering and Electronics, U.M.I.S.T.*

Physics for Engineers and Scientists: D. ELWELL and A. J. POINTON

(Eliss Horwood, 1978, 356 pp., £15)

This revised version of the authors' earlier book Physics for Electrical Engineers promises to be very useful. It fills the gap between school text-books and the more profound works which are much too specialized for the student engineer. The subjects covered are limited to: heat and thermodynamics; wave theory; atomic and nuclear theory; solid state electronics, magnetism, including nuclear magnetic resonance, masers and lasers; dielectrics. However, in the reviewer's experience, these are all subjects which are rarely covered in such a concise and clear way in other texts. Worked examples, and problems with answers are given at the end of each chapter. A bibliography at the end of some of the chapters will be helpful for students who wish to go more deeply into certain topics. Although the price is high, and a paperback edition is not produced, this is a book which can be thoroughly recommended.

A. BUCKLEY, *Assistant Editor, I.J.E.E.E.*