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EXPERIMENTAL INVESTIGATION OF THE ROLE OF STABILIZERS IN THE ENHANCEMENT OF AUTOMATIC VOLTAGE REGULATORS PERFORMANCE

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ABSTRACT

In electrical power systems, dynamic stability problems may be solved through the application of power system stabilizers (PSS), which improve the performance of the main automatic voltage regulators (AVR's) of the synchronous generators (DeMello, Concordia), (Anderson, Fouad). This paper offers a simple and practical approach to design such power system stabilizers. A prototype PSS has been designed, built and tested in laboratory for a model synchronous generator. The circuits used in monitoring speed changes of the generator, their manipulation until they are mixed up with the input signals to the AVR are detailed. These circuits are composed of a sequence of stages for filtering and amplification of the monitored signals in addition to lead-lag compensation networks. The system has been put together and tested for different system disturbances. Three system indices; the power angle, speed, and terminal voltage are recorded at different operating conditions. These results show the effective damping effect of the PSS on variations in power angle, speed, and other system dynamics. The system has been tested for both small and large changes in operating condition.

INTRODUCTION

In electrical power systems, each synchronous generator is equipped with an automatic excitation control unit, generally known as the automatic voltage regulator (AVR). The excitation controller is introduced to maintain the generator terminal voltage constant (within specified limits) under normal operating condition, and to control the magnitude and direction of reactive power flow; into or from the generating unit. Ever developing exciters with fast response and efficient AVR's, as well as the increasing complexity of large interconnected power systems have made oscillations which occur in the generator speed, and related output quantities after system disturbances a serious source of trouble in those systems (Elgard). In practice, it has been found useful to superimpose a finite number of stabilizing signals derived from speed, terminal frequency, output power, ... etc. on the main feedback signal (the error in the terminal voltage), normally fed to the voltage regulator. The superposition of the stabilizing signals provides the AVR with additional damping to these oscillations (Badr *et al.*) (El-Kharashi *et al.*).

Additional damping can be provided if the net influence of the stabilizer is to produce a component of electrical torque on the rotor which is in phase with speed variations (DeMello, Concordia). However, for any signal which may be employed as input to the stabilizer the transfer function of the stabilizer must compensate for the gain and phase characteristics of the exciter, generator, and the power system, which collectively determine the transfer function from the stabilizer output to the component of electrical torque which can be modulated via excitation control. Fig. 1 shows the main components and signals of the experimental system in block diagram representation.

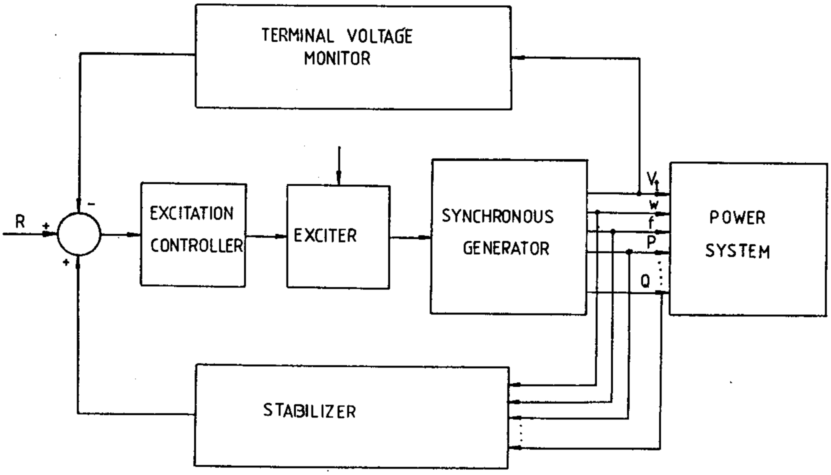

Fig. 1: Power system, AVR, and stabilizer configuration.

In the present paper, an attempt is made to compensate for this phase lag by using a lead-lag network while the gain is adjusted by using a preamplifier stage of a variable gain. Owing to the complex nature of the problem and the difficulty which is incorporated in deriving an analytical form of the transfer function of the system including the stabilizer, the tuning of the stabilizer phase and gain has been performed by trail and error on the laboratory model. The response of the system including the stabilizer for different types of disturbance are recorded on the oscilloscope. The stabilizer parameters for best phase and gain compensation are thus recognized as those which provide the system with well damped performance at a wide range of operating conditions. A fast decay of the transient, which takes between 3 and 5 cycles is the criterion.

CALCULATION OF PHASE AND GAIN

The block diagram representation of a synchronous generator, connected to an infinite busbar through a transmission line as described in reference (DeMello, Concordia) is shown in Fig. 2 in addition to the proposed stabilizer. This stabilizer receives its input from the speed changes. The output from the stabilizer is introduced to the summation point, and thus manipulates the reference voltage setting of the AVR. In Fig. 2, the flow of the stabilizing signal is indicated by the dotted line, and the transfer function from the input reference to the torque component produced in the machine by the stabilizing signal can be written as:

$$\frac{\Delta T_{SIG}}{\Delta e_{REF}} = \frac{K_{EX}}{1 + s\, T_{EX}} \cdot \frac{K_3}{1 + s\, K_3\, T'_{do}} \cdot K_2 \, .$$

Since T_{EX}, the exciter time constant, is small for thyristor-type converters, the only time lag in the way of this signal is found to be $K_3 T'_{do}$, where K_3 is a constant which depends on the transmission line reactances, machine direct-axis synchronous reactance, and direct-axis transient reactance.

The required lead time T_1 of the stabilizing function will be approximately equal to this time lag of the power system under consideration, i.e.

$$T_1 \cong K_3\, T'_{do}$$

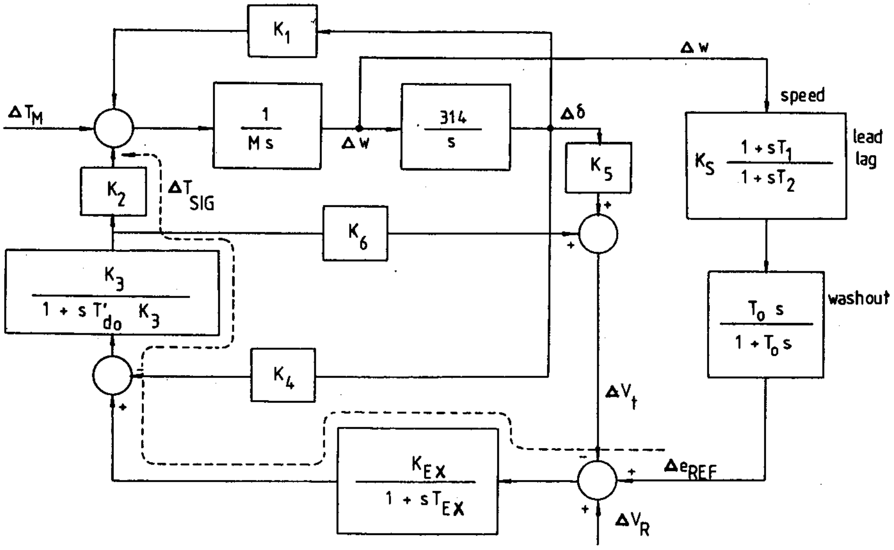

Fig. 2: Block diagram of the power system

The mechanical equation of the machine is written as:

$$\Delta T_M = \Delta T_E + (M/314).(d^2\delta/dt^2).$$

The electrical torque ΔT_E can be described in terms of two components which are the synchronizing and damping torque components as follows:

$$\Delta T_E = \Delta T_{SYN} + \Delta T_{DAMP},$$

where, ΔT_{SYN} is the torque component in time phase with the angle, and ΔT_{DAMP} is that component in quadrature to, i.e. in phase with, the speed. Therefore, the problem is reduced to making this electrical torque as damping as possible. In other words, it is required to obtain a pure damping torque making use of the stabilizing signal. In order to satisfy this requirement, the time lag is balanced by an equal time lead. Under these specified conditions, and using the block diagram representation of Fig. 2 the torque component due to the stabilizing signal at the torque summing point is pure damping, and can be expressed as:

$$\Delta T_{SIG} = K \,.\, \Delta w,$$

where K is the product of gains of the sub-blocks in the path of the stabilizing signal in the lower loop, i.e.:

$$K = K_{EX} \,.\, K_3 \,.\, K_2 \,.$$

The gain of this torque component will determine the damping ratio of the mechanical system. For a well damped system the gain should be chosen to obtain a specified damping ratio. Damping ratio of 0.5 is acceptable for this application.

THE SYSTEM UNDER CONSIDERATION

The stabilizer has been designed to operate in junction with the AVR of a synchronous generator connected to a large power system through a short transmission line. This limited-size power system has been simulated in laboratory by an experimental model. The experimental model consists of a 5 kVA synchronous generator connected to a large system busbar through a model short transmission line as shown in Fig. 3. The generator field current is supplied from a thyristorized excitation system. This exciter is a single-phase full-wave half-controlled thyristor bridge. The firing circuit of the thyristor bridge has been adjusted such that the overall gain of the bridge is constant, hence making its input-output characteristic linear. The control voltage of the exciter is obtained from the output signal of the AVR as shown in Fig. 3. A proportional-plus-integral (PI) controller has been chosen to achieve a high performance voltage regulator. The main signal input to the AVR is proportional to the terminal voltage of the synchronous machine. The stabilizing signal fed to the AVR is issued by the PSS.

This signal is proportional to the speed. It is derived from the shaft speed by means of the speed transducer and other electronic circuits, which constitute the PSS.

The speed transducer is an AC tachogenerator directly coupled to the shaft of the machine. The output of the tachogenerator is rectified and filtered to eliminate the 2000-Hz ripple, found to be superimposed on the detected waveform. This ripple is five times the frequency of the AC tachogenerator. The rectifier and filter stages, in addition to the following signal manipulation stages are incorporated in the PSS block of Fig. 3.

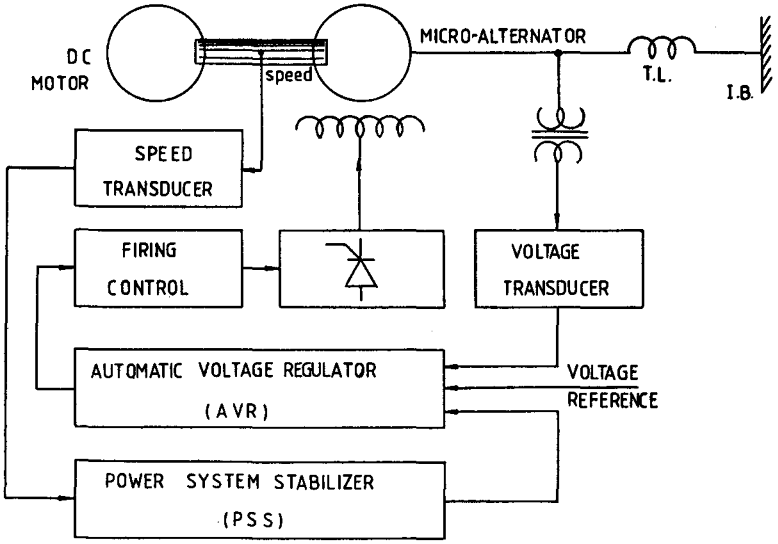

Fig. 3: The experimental system layout

THE POWER SYSTEM STABILIZER

The output from the 2000-Hz filter is subtracted from a constant DC voltage which is supplied by a separate battery source. This voltage level represents the synchronous speed of the system. The difference represents the changes in speed. The level of this signal is very small. Therefore, further amplification is necessary to boost the signal to a voltage level which allows for further shaping and manipulation. A difference amplifier stage with amplification factor of 100 is applied for this purpose. The signal is then re-shaped by means of a single-stage lead-lag network. From practice, it has been found that this stage must be preceded by a 50-Hz filter. The function of this filter is to get rid of any pickups of the power frequency. Finally, the output signal from the lead-lag stage is fed to a washout filter stage to eliminate the DC offset due to the operational amplifiers used in the implementation of the different stages of the PSS. The output signal from this stage is then fed into the comparator stage of the AVR with the same positive sign as that of the voltage reference. The influence of this signal is significant on the AVR operation during periods which follow system transients. The complete circuit of the PSS is shown in Fig. 4.

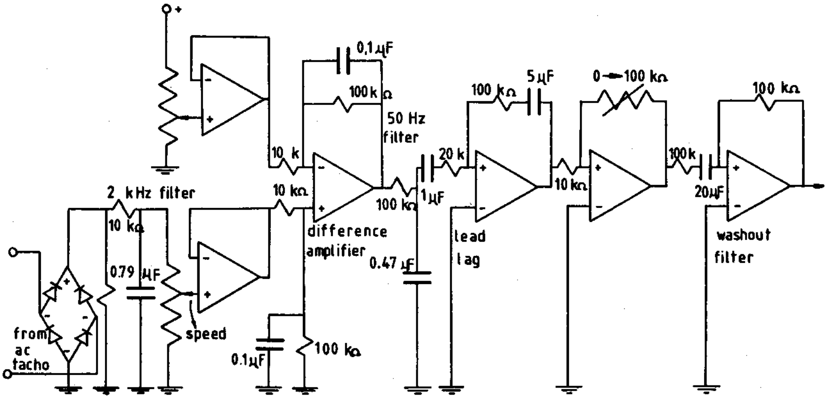

Fig. 4: The PSS Circuitry

Comments on the Measurement of Speed Deviations

Measurement of speed deviations, from the synchronous speed of a generating unit, is rather difficult. The difficulty stems from that these deviations are very small under dynamic operating conditions. Moreover, these changes are embodied in the large dc voltage output of the speed transducer. Two important measures must be taken to obtain satisfactory feedback control signal proportional to the speed deviation. The first one is to use effective filtering stages at different points in the circuit to trap the undesired harmonics completely. The second measure is to apply a circuit which is capable of extracting the required to measure small changes from the associated large dc level signals.

The second requirement can be satisfied by using an instrumental difference amplifier as shown in Fig. 4. The output from the difference amplifier is the required amplified signal proportional to deviations in the speed.

The Lead-Lag Network

The transfer function of the lead-lag network can be written as:

$$\frac{\Delta V_{s\,s}}{\Delta w} = K_s \frac{1 + T_1S}{1 + T_2S},$$

where, T_1 is the lead time- and T_2 is the lag time-constant. The lag time T_2 has been chosen less than 0.05 seconds, while the lead time T_1 is calculated to eliminate the lag angle introduced by the machine field and the excitation system (Ogata). The gain K_s may be chosen such tha the mechanical system is well damped.

The tuning of T_1 and K_s has been made such that the compensation can cover a wide range of operating conditions and variations of system parameters. In the present paper the PSS has been tuned, i.e. T_1 and K_s have been adjusted, in the laboratory on-line while the experimental system was operating with the machine delivering both active- and reactive power to the infinite bus through the model transmission line. For different settings of T_1 and K_s the system response to dynamic changes under different operating conditions, transmission line reactances, and stabilizer parameters has been observed using a storage oscilloscope.

TEST PROCEDURES AND RESULTS

Procedures

The experimental system has been tested for step changes in the mechanical torque T_M and the voltage V_R referencs, when the machine is initially loaded. The lead time T_1 is initially adjusted at its smallest value and the tests are carried out. T_1 is slightly increased in steps, tests are repeated, and the rotor angle and speed deviations are recorded on the oscilloscope simultaneously. If the change in T_1 produces a more damped response, then T_1 is set at this value and the gain K_s is varied. Many trials are made to change K_s to obtain the best damped response. Another useful signal which has been recorded on the oscilloscope was the output signal from the stabilizer. The criterion here is that the signal must be of sufficient magnitude, and phase lead with respect to the speed signal. The test results are shown in Figures 5, 6, 7.

Results

Step change in the mechanical torque reference

This test has been carried out with the machine initially delivering 0.8 of its rated power at rated voltage to the power system through a relatively large reactance model transmission line. The change in the mechanical torque is performed by suddenly decreasing the voltage across the field of the driving dc motor (Fig. 3). These test results are shown in Fig. 5.

Fig. 5(a) shows the speed response of the system to a 0.2 p.u. step increase in the mechanical torque. The initial load on the generator is 0.8 p.u. at unity power factor. The machine is working without stabilizer. When the same test was carried out but with a stabilizer in operation the speed response gave the well damped form of Fig. 5(b).

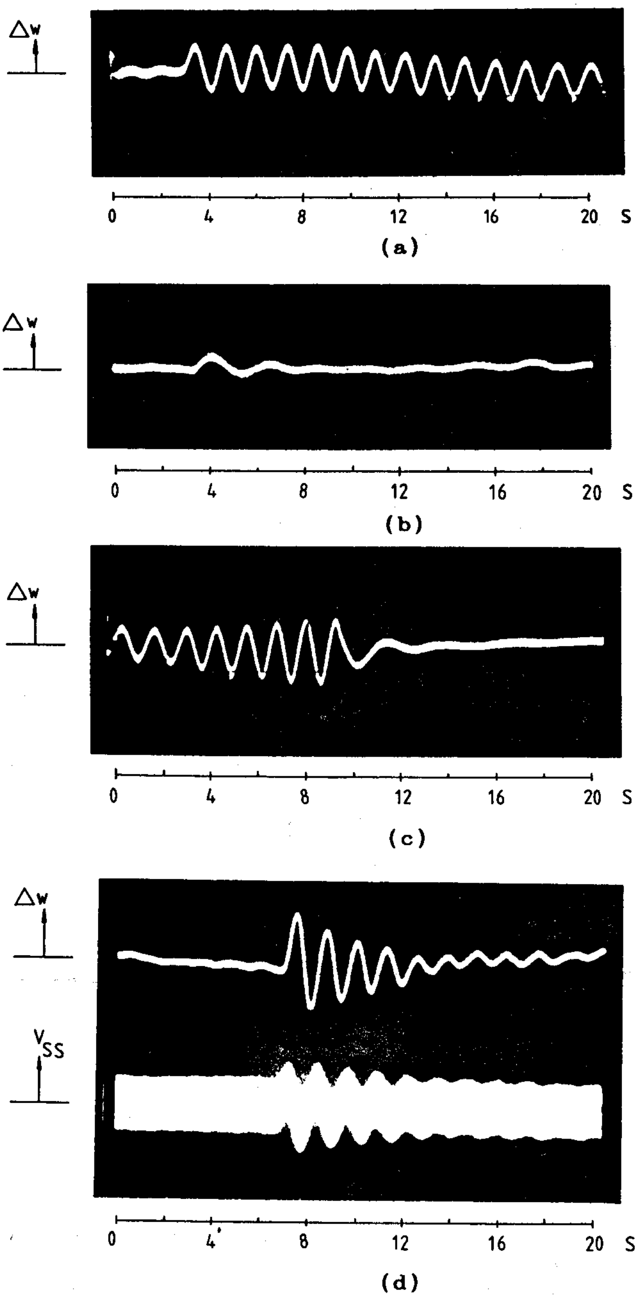

Fig. 5: System response to a step change in mechanical torque

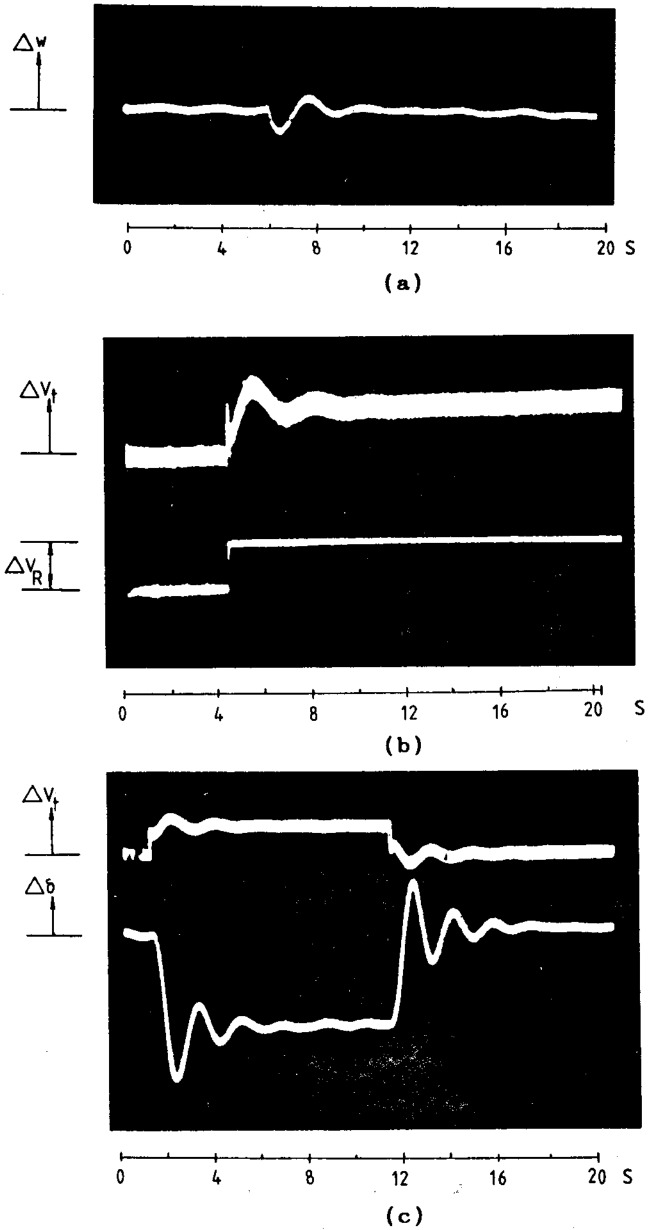

Fig. 6: System response to a step change in the reference voltage

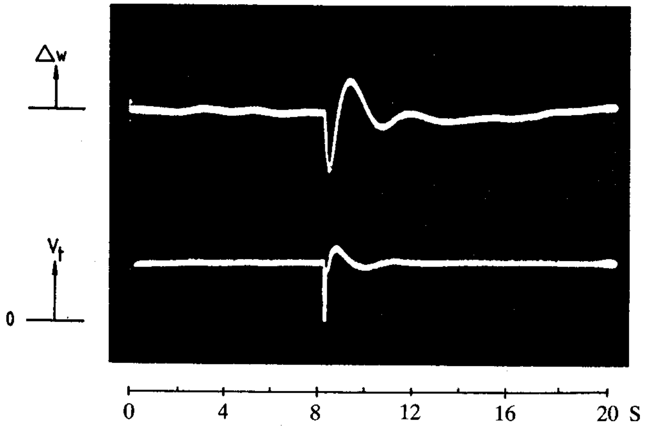

Fig. 7(a): Response to a short-duration 3-phase short-cirucit at the machine terminals.

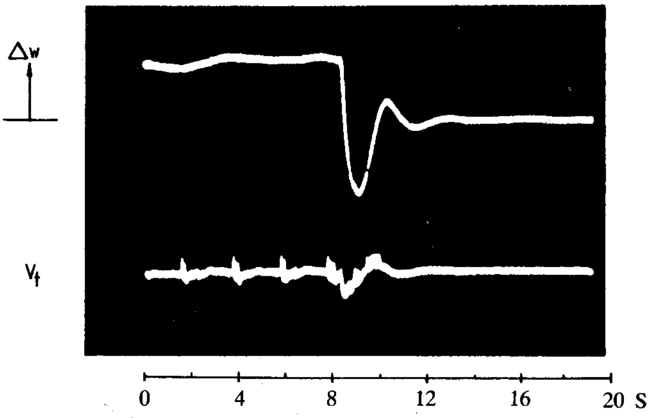

Fig. 7(b): Response to a rough synchronization to the large system bus bar.

To demonstrate the influence of the PSS in maintaining system stability a special test has been performed. The results of this test are recorded in the oscillogram of Fig. 5(c). In this test, the machine was operated with the PSS switched off, at the beginning. The machine was initially operated at its full-load power. A sudden increase in the mechanical torque has been applied. The magnitude of the torque increment was known in advance to be sufficient to drive the machine out of step through an increasing-oscillation mode. The machine started to oscillate. Oscillations of the speed were recorded. A growing oscillation amplitude was observed. Ultimately, the machine would have fallen out of step. At this stage of the test the PSS was switched on. The oscillation died away in a very short period, Fig. 5(c). It was also recognized that the insertion of the PSS was bumpless. Not only did the stabilizer improve the system damping but also its sudden insertion in the middle of transient did not add to the disturbance.

In Fig. 5(d) the upper trace represents the speed signal in response to a small step change in the mechanical torque while the lower trace represents the corresponding output signal from the PSS when its loop was open. The oscillogram shows that the PSS output signal leads the speed by an angle which has been obtained through the tuning process. The magnitude of the PSS signal is sufficient to modify the reference signal of the AVR. One constraint on the PSS output signal is that it must vanish as the speed becomes constant at the rated value. The PSS signal must not contain any dc offset. This test has been performed during the testing process of the final stage of design.

Step change in the terminal voltage reference

The effect of the PSS on the generator terminal voltage has been examined by applying a step change in the system voltage reference, while the PSS was in operation. The test was performed for different loading conditions of the machine. Test results are shown in Fig. 6.

The variations in speed in response to a step change in the reference voltage the synchronous machine, with the PSS loop closed is shown in Fig. 6(a). The damping effect of the stabilizer is obvious in this oscillogram. The effect of the stabilizer on the terminal voltage of the machine, while it is delivering 0.8 p.u. power, is shown in Fig. 6(b). The upper beam represents the terminal voltage in response to a step increase in the reference, which is represented by the lower beam. Fig. 6(c) shows the results of a similar test where a step increase in the voltage reference of the AVR was applied then, after the system has reached a new steady state, an opposite and equal step was introduced. In this figure the upper beam represents the generator terminal voltage while the lower beam represents the power angle. The damping effect of the PSS is clear from the fast settling of the power angle in both directions.

Transient tests

Under transient conditions, especially at severe short circuits AVR's have a defined job: forcing of excitation. After fault clearing, and during less-severe transients, when power oscillations take place the AVR plays a different role. It acts to improve the system stability and maintain the power network intact. In such conditions the PSS monitors speed variations and takes part in the damping of the system oscillations.

The ability of the designed PSS to provide the machine with the necessary damping torque under transient conditions has been checked by means of two tests.

The first one is a short-duration three-phase short-circuit test at the terminals of the generator. The short circuit was cleared almost as soon as it had been applied. The net effect of this short-duration fault is to disturb the steady state performance of the generator and introduce heavy oscillations superimposed on the rotor speed. Fig. 7(a) shows the damping effect of the stabilizer during and after the short circuit on the machine terminals; the upper beam represents the changes in speed, and the lower beam represents the terminal voltage.

The second transient test was a rough-synchronization test. In this test the machine had been connected to the system bus bar while the speed of the rotor was relatively far from the synchronous speed. Fig. 7(b) shows the speed and voltage variations following a rough synchronization condition of the machine to the infinite bus bar. The synchronization switch was closed to infinite bus while the rotor speed was larger than its synchronous value. The oscillogram shows the ability of the stabilizer to damp away the shock on the system caused by the faulty switching procedure.

CONCLUSION

A power system stabilizer has been designed and put to work with the AVR of the synchronous generator. The PSS secures effective damping for both cases of limited dynamic performance as well as transient conditions.

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