ABSTRACT:
A new 'Gain Scheduling Stabilizer' for interconnected power systems has been described in this paper. The design of the PSS is based on a priori information about readily available machine and excitation system parameters and 'Observation' for a certain duration of time of the network from the bus of the machine concerned to ascertain the electrodynamic coupling of the machine to rest of the network.

The computational complexity of this PSS requires the use of relatively sophisticated computing system. Though, such computers are now available, they are not in common use in actual power plants. With this in view, the PSS design has been modified so that the adaptive gains are selected in real time based on the operating conditions and worst case network parameters. The modified PSS can be implemented using on-line computers having capabilities similar to those of ordinary PCs or even up systems with moderate memory and computational capabilities.

KEYWORDS:
Power System Stabilizers, Adaptive Control

INTRODUCTION:
The excitation systems of almost all modern synchronous generators, operating in an interconnected power system are equipped with high gain, low time constant automatic voltage regulators (AVR). The use of such AVRs, along with increasing utilization of long transmission lines for bulk power transfer have resulted in an overall lowering of dynamic stability margin of the system. This is manifested in the form of poorly damped low frequency oscillations of individual units with respect to the rest of the system; or worse still, of one group of coherent units with respect to another coherent group.

The stability of the system, in principle, can be considerably improved by the application of close-loop feedback control. Over the years, a considerable amount of research has been directed towards designing suitable Power System Stabilizers (PSS). Designing and tuning stabilizers are complex processes. A majority of stabilizers in use are of 'fixed gain' type, which are tuned by a combination of off-line mathematical modeling and field trials. Due to non-linear nature of the plant and continually changing loading pattern, network element values and topology of the network, the performance of these stabilizers can be considerably degraded. In recent years, a number of methods for designing 'Adaptive or Self Tuning Stabilizers' have been proposed. These include PSS based on model identification techniques, Gain scheduling PSS with precomputed gains stored in look-up tables, and PSS to cancel the negative damping contribution of the AVR.

Most of these stabilizers are computationally complex and often impossible to implement in real time with the moderate computational facilities available in modern power plants. The gain scheduling PSS described in this paper takes advantage of the a priori knowledge available about the system and combined with a simple on-line identification of the external reactance \( X_e \), enables gain scheduling most appropriate to the then system and operating conditions.

THE PSS DESIGN PHILOSOPHY:
A particular generating unit, operating in a multimachine environment, is modelled as a single machine connected to an infinite bus (SMIB) through a transmission line. However, unlike in an actual SMIB case, the changing network element values, the loading pattern of the other machines and the topology of the network beyond the machine concerned are made to reflect as a variable transmission line impedance (as opposed to the fixed impedance in SMIB case). As the machine and excitation parameters are known and the terminal quantities can be measured easily, the PSS gains could be selected to reflect the variable line impedance as known. It is for the estimation of this variable impedance, the network has to be observed from the terminals of the concerned generator.

The PSS chosen has the form \( k_p \Delta P + k_q A V \). The adaptive gains \( k_p \) and \( k_q \) are determined by instantaneous operating conditions and the transmission line impedance 'seen' by the machine and are obtained by local real time measurements at each machine. This is a truly adaptive PSS with excellent performance. However, since most of the on-line parameter identification techniques used in implementing gain scheduling PSS including the proposed new PSS require observation of the system after the disturbance has been initiated, there may be a considerable time delay between the disturbance initiation and the actual control action. To eliminate this delay, in the practical implementation of the proposed PSS, the on-line \( Z_e \) estimation has been replaced by an off-line estimation of the worst case \( Z_e \). This \( Z_e \) estimation process can be run as often as desired or even as a background process on the computer.

The PSS thus operates in the 'adaptive mode' with the gains now determined by the instantaneous operating conditions and the worst case transmission line impedance. The \( k_p \) and \( k_q \) values are obtained by detailed machine models to generate \( k_p \) and \( k_q \) surfaces in F-Q plane for worst case impedances \( Z_e \). Finally, only the polynomial coefficients are regenerates these surfaces are stored in an on-line computer so that the gains \( k_p \) and \( k_q \) at any particular operating point can be easily computed vector-matrix multiplications. Use of off-line computations to estimate the polynomial coeffi-
... clients have also helped to reduce the on-line memory requirement otherwise needed for storing a huge number of gain values in a look-up table. However, this involves additional computational burden on the real-time computer.

\( Z_e \) IN MULTI-MACHINE ENVIRONMENT:

The actual system is represented in Fig. 1A and the modelled system in Fig. 1B. It may be noted that it is impossible to compute the model transmission line impedance \( Z_e \) solely from measurements made at the generator bus unless some assumptions are made about the remote fictitious bus. Assuming that the voltage of the fictitious bus is 1.0 pu and \( Z_e \) has a given \( X/R \) ratio, it is possible to obtain a quadratic expression for \( X_e \) (imaginary part of \( Z_e \)). Appendix 1 in terms of the operating point \( P_{to}, Q_{to} \) and \( v_{to} \) at the generator terminal. By monitoring these quantities at the generator terminal over a wide range of operating conditions, it is possible to estimate the range of \( Z_e \) values as 'seen' by the particular unit concerned.

For an SMIB model with the machine operating with \( P_{to}, Q_{to} \) at the generator terminal, it is well known that the transmission line reactance \( X_e \), poorer is the electro-dynamical coupling between the machine and the infinite bus. In other words, a higher transmission line impedance in an SMIB model is detrimental from dynamic stability point of view. Therefore, out of the entire range of \( Z_e \) values as observed from the machine terminal over a period of time, the maximum value of \( Z_e \) (hence maximum \( X_e \)) is chosen to represent the electro-dynamical coupling of the machine to the fictitious bus, since it can be expected to represent the 'worst case' situation of dynamic stability of the particular unit.

THE \( k_p \) AND \( k_w \) SURFACES:

With the 'worst case' \( Z_e \) available from the system data observed over a certain duration of time, it is now possible to model the system as a linearized SMIB model for any particular operating point \( P_{to}, Q_{to} \). For a realistic operating range of a generating unit given by, 0.10 \( \leq P_{to} \leq 1.10 \) and -0.20 \( \leq Q_{to} \leq 0.80 \) ...(1)

we can have \((n+1)(n+1)\) operating points, about each of which the SMIB model can be linearized, where n denotes the number of small incremental steps into which the \( P_{to} \) and \( Q_{to} \) ranges have been divided. For each of these \((n+1)(n+1)\) operating points, the eigenvalues of the SMIB model are checked with \((k_p \Delta P)\) and \((k_w \Delta w)\) stabilizers with \( k_p \) decreased in small steps from zero and \( k_w \) increased in small steps from zero, till the rightmost eigenvalue of the linear system stop moving towards the left. The corresponding values of \( k_p \) and \( k_w \) are the chosen gains of the PSS at that particular operating point. This off-line exhaustive method of searching for \( k_p \) and \( k_w \) for each operating point, results in gain-surfaces represented by \((n+1)(n+1)\) points in the \( P_{to}, Q_{to} \) and \( P_{to}-Q_{to} \) spaces.

The fundamental aspect of 'tuning' by this method is that the decay rate, i.e., the negative of the real part of the eigenvalue of the least damped mode, is maximized. This technique has long been recognized as one of the methods of tuning a PSS. A major advantage of tuning by this method is that since attention is always focused on the 'least damped' mode, it prevents the exciter or any other modes from becoming unstable while trying to stabilize the rotor mode.
The expanded version of eqn. (4a), for example, looks like,
\[
\begin{align*}
N_1 - \frac{1}{v_0}\left[\text{f}_p(u_0, v_0) + \text{f}_p(u_{N_1-1}, v_0) + \ldots + \text{f}_p(u_{N_1-1}, v_{N_2-2})\right] = \frac{1}{v_0}\left[\frac{1}{a_{00}} + \ldots + \frac{1}{a_{00}}\right] \\
N_2 - \frac{1}{v_0}\left[\text{f}_p(u_0, v_0) + \text{f}_p(u_{N_1-1}, v_0) + \ldots + \text{f}_p(u_{N_1-1}, v_{N_2-2})\right] = \frac{1}{v_0}\left[\frac{1}{a_{00}} + \ldots + \frac{1}{a_{00}}\right] \\
\end{align*}
\]

The values of \(f_p(u_i, v_j)\) and \(f_w(u_i, v_j)\) are either the actual gains computed by the tuning algorithm already described (when \(N_1, N_2 = n+1\)) or interpolated values from best-fit curves (when \(N_1, N_2 < n+1\)).

For a realistic SMIB machine-excitation system model, it was found that \(N_1 = N_2 = 7\) as also \(M_1 = M_2 = 7\), results in polynomial fittings with acceptable errors. Therefore, for a given worst case \(Z_e\), only 49 algebraic coefficients for each \(k_p\) and \(k_w\) gains need to be computed and stored in the real-time computer. For any operating point within the range of operation specified in (1), the gains \(k_p\) and \(k_w\) can be simply computed by,
\[
k_p = [u][AKP][v]^T \quad k_w = [u][AKW][v]^T \quad \text{...(5)}
\]
where \([AKP]\) and \([AKW]\) are the 7x7 matrices containing the algebraic coefficients
\[
AKP_{ij} = a_{7-i,7-j} \quad AKW_{ij} = b_{7-i,7-j}, \quad i=1,2,..,7
\]
and,
\[
[u] = [u^6 u^5 u^4 u^3 u^2 u^1] \quad [v] = [v^6 v^5 v^4 v^3 v^2 v^1] \quad \text{...(6)}
\]

RESULTS:
A dynamic flux-linkage multimachine model is used for the purpose of studies. The configuration is shown in Fig.2 and the machine and system parameters are given in Appendix-2. Widely different machine ratings were intentionally chosen so as to highlight the performance of the PSS on both small and very large machines. Each unit is represented by a 10th order dynamical model consisting of a 7th order synchronous generator, 1st order AVR, 1st order turbine and 1st order governor.

For the purpose of PSS design, the possible operating range of each machine is chosen as given in eqn (1), and the ranges of \(P_t\) and \(Q_t\) were divided into 10 steps each. Thus for each machine, \(k_p\) and \(k_w\) were computed for 121 different points in the \(P_t - Q_t\) plane. The tuning was carried out with incremental steps of 0.02 and 1.0 for \(k_p\) and \(k_w\) respectively. The computed \(k_p\) and \(k_w\) surfaces (top) and the corresponding synthesized surfaces (bottom) at same resolution are shown in Fig.3.

The multimachine model was subjected to a wide range of operating conditions by changing the machine loadings as well as the loads on bus 4 and 5, and for each of those operating points, \(Z_e\) estimations were done from bus 1, 2 and 3. A sample of those results are given in Table 1. As evident from the table, for any particular unit the worst case \(Z_e\) occurs when..
it is supplying a high active power \((P)\), but with a negative reactive power \((Q)\) generation. This is expected, since under these circumstances a unit is known to be most weakly coupled to the rest of the network.

With the knowledge of worst case \(Z_e\) and the machine parameters for each unit, stabilizers were designed for each of the three units. Sample time response plots of change in active power following pulse disturbances at \(V_{ref}\) points of each of the three machines, with and without PSS, are shown in Fig.4.

Table 2 \((A, B \text{ and } C)\) shows the eigenvalues of each of the three machines with and without the proposed PSS for some typical operating points. The identification of the rotor and exciter modes was done using the 'Participation Matrix technique'. It is obvious from the eigenvalue tables, that with the proposed PSS in action, the damping of each machine has considerably improved, while, in general, there is hardly any detrimental effect on the synchronizing torques.

<table>
<thead>
<tr>
<th>Machine #1 ((pu))</th>
<th>Machine #2 ((pu))</th>
<th>Machine #3 ((pu))</th>
<th>(X_{e1}) ((pu))</th>
<th>(X_{e2}) ((pu))</th>
<th>(X_{e3}) ((pu))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 -0.15 0.80 0.30 0.80 0.30</td>
<td>0.30 +0.70 0.80 0.30 0.80 0.30</td>
<td>0.80 -0.10 0.80 0.30 0.80 0.30</td>
<td>0.80 -0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
</tr>
<tr>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
<td>0.80 0.30 0.80 0.30 0.80 0.30</td>
</tr>
</tbody>
</table>

**Table 2A**

<table>
<thead>
<tr>
<th>Network Loading</th>
<th>Machine #1 ((R: \text{Rotor Mode}, E: \text{Exciter Mode}))</th>
<th>Machine #2</th>
<th>Machine #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without PSS</td>
<td>(R: -1.129 + j8.172) (E: -4.327 + j0.399)</td>
<td>(R: -2.855 + j3.849) (E: -2.855 + j3.849)</td>
<td>(R: -2.981 + j5.041) (E: -3.574 + j7.354)</td>
</tr>
<tr>
<td>With PSS</td>
<td>(R: -0.989 + j7.750) (E: -4.375 + j0.350)</td>
<td>(R: -2.999 + j9.419) (E: -3.132 + j2.859)</td>
<td>(R: -2.873 + j3.845) (E: -2.873 + j3.845)</td>
</tr>
</tbody>
</table>

**Table 2B**

<table>
<thead>
<tr>
<th>Network Loading</th>
<th>Machine #2 ((R: \text{Rotor Mode}, E: \text{Exciter Mode}))</th>
<th>Machine #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without PSS</td>
<td>(R: -0.594 + j7.183) (E: -6.286 + j14.748)</td>
<td>(R: -1.167 + j5.685) (E: -4.490 + j17.838)</td>
</tr>
<tr>
<td>With PSS</td>
<td>(R: -0.902 + j7.408) (E: -6.301 + j14.758)</td>
<td>(R: -1.074 + j5.515) (E: -4.517 + j17.842)</td>
</tr>
</tbody>
</table>

**Fig. 4** AP response with and without the PSS.
TABLE - 2C

<table>
<thead>
<tr>
<th>Network Loading</th>
<th>Without PSS</th>
<th>With PSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R : Rotor Mode</td>
<td>E : Exciter Mode</td>
<td></td>
</tr>
<tr>
<td>1 R : -0.218 ± j1.952 E : 4.294 ±j20.514</td>
<td>R : -0.336 ± j2.061 E : -4.069 ± j27.316</td>
<td></td>
</tr>
<tr>
<td>2 R : -0.321 ± j1.956 E : -4.436 ± j30.524</td>
<td>R : -0.331 ± j2.061 E : -4.275 ± j27.091</td>
<td></td>
</tr>
<tr>
<td>3 R : -0.224 ± j1.961 E : -4.284 ± j20.740</td>
<td>R : -0.457 ± j2.106 E : -4.428 ± j29.927</td>
<td></td>
</tr>
<tr>
<td>MVA : 100</td>
<td>Rf : 0.000686</td>
<td>Ta (sec) : 0.09</td>
</tr>
<tr>
<td>MVA : 233</td>
<td>Xd : 1.180000</td>
<td>-</td>
</tr>
<tr>
<td>MVA : 453</td>
<td>Xq : 1.050000</td>
<td>-</td>
</tr>
<tr>
<td>MVA : 5.24640</td>
<td>Xad : 1.105000</td>
<td>-</td>
</tr>
<tr>
<td>MVA : 8.244790</td>
<td>Xq : 0.975000</td>
<td>-</td>
</tr>
<tr>
<td>MVA : 1.511000</td>
<td>M#2</td>
<td>250.00</td>
</tr>
<tr>
<td>MVA : 20.00</td>
<td>M#3</td>
<td>20.00</td>
</tr>
<tr>
<td>MVA : 30.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS:

This paper has described the designing technique of a simple gain scheduling PSS based on machine parameters and observations of the external network from the machine bus at various loading conditions. The PSS design essentially involves off-line tuning at different operating points using a linearized high order SMIB model and solving a system of linear equations. Therefore, the real-time computational load is reduced to simple vector matrix multiplications. The PSS has been tried out on a multimachine model for a wide range of operating conditions with machine ratings ranging from 100 MVA to 835 MVA and the results are quite encouraging.

REFERENCES

APPENDIX - 1

Let us suppose that the X/R ratio of the model transmission line of impedance $Z_e$ (R + jX) is k. Then it can be shown that, for a SMIB model with negligible local load at generator bus,

$$A \sigma^2 + 2B \sigma + C = 0, \text{ where } A = I_a^2(1 + 1/k^2)$$

$$B = 2V_t I_a \sin \phi_t - \cos \phi_t / k$$

$$C = (V_t^2 - V_n^2)$$

$$V_n = 1.0 \text{pu (assumed voltage of remote fictitious bus)}$$

For normal operating values of $P_r$, $Q_r$, and $V_n$ we get two real values of $A$ (i.e. $B^2 - 4AC > 0$), and the least positive value is selected since the other value of $A$ (if positive) is normally found to be very high (0.70pu or higher).