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A Novel Algorithm to Minimize the Excitation of Undesirable Oscillations-State Space

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Abstract - A new state-space type stabilizer to minimize low frequency oscillation is proposed. The proposed Power System Stabilizer (PSS) design not only damps the oscillations by moving the Eigen-values to desired left hand plane locations but additionally reduces the excitation of the mode itself through optimization of the left eigenvector of the poorly damped electro-mechanical mode. The stabilizer is implemented as a State-Space (SS) type controller which is optimized using a constrained optimization procedure. Two possible inputs, speed and electrical power are considered as candidate inputs to the stabilizers. The state-space design is also compared with one based on traditional lead-lag compensation. The SS type stabilizer with electrical power input is shown to perform better compared to any other type of PSS by minimizing low frequency oscillations.

Keywords: Power system dynamic stability, Small signal analysis, Power System Stabilizer.

I. INTRODUCTION

Power system often exhibits poorly damped low frequency electro-mechanical oscillations when subjected to small disturbances; and Power System Stabilizers (PSS) are widely used to mitigate such oscillations. The idea of PSS design by means of introducing electrical torque in phase with speed by compensating phase *lag* due to excitation system and generator was first introduced in [1]; and procedures for tuning single input Power System Stabilizers were demonstrated in [2][3]. Since then, several other types of PSS structures and their design techniques have been proposed. The central idea of all the above designs is to selectively place the closed loop poles (eigenvalue assignment) in well damped locations. Certainly eigenvalues play a key role in dynamic performance as they decide the rate of decay (or rise) of the variable during disturbance; on the other hand eigenvectors are also equally important as they shape the response of the variable. Therefore if the closedloop system can be assigned a judicious eigenstructure (eigenvalues *and* associated eigenvectors) then it is possible to achieve even better transient response compared to that obtained by assigning only the eigenvalues of the closed-loop system [6]. Several applications of eigenstructure assignment technique have been reported in literature, for example in [7] it has been applied to design of an aircraft controller.

The PSS design problem can be formulated as a linear Multi-Input Multi-Output (MIMO) feedback controller design problem. In such a case there is a possibility for the existence of extra degrees of freedom which remain free after the assignation of eigenvalues. These degrees of freedom can then be used to further optimize the eigenvector.

The design problem formulated as a constrained optimization algorithm is discussed in Section II. The test system used in PSS design is presented in Sections III. The lead-lag type PSS and its design method is presented in Section IV; and SS type PSS is described in Section V. The results are presented and discussed in Section VI.

II. PSS DESIGN ALGORITHM

a. Linear output feedback control system and closed loop eigenvalue selection

The procedure starts by considering the linearized power system state space formulation (1) for the system without PSS, whose matrix has eigenvalues. Then a set of eigenvalues of interest is selected. This set typically includes the eigenvalues associated with the poorly damped electromechanical oscillation modes and any other modes deemed to be critical to the system's performance from prior knowledge. These eigenvalues are then assigned fixed desirable locations in the complex plane, which will be achieved when the feedback dynamic compensator is realized. The necessary dimension, , of the dynamic compensator state vector now follows using the middle equation in (4), and is essentially the difference between the original number of inputs to the system and the number of eigenvalues to be assigned. Note that in order to get a realizable controller requires , which is not a limitation because additional eigenvalues can always be assigned to satisfy this condition. The new power system with the dynamic compensator has an equivalent linearized model of the form shown in (3)-(4). This state formulation is used for controller design using the partial left eigenstructure assignment technique described in Section II.b.

b. *Procedure for selecting left eigenvectors*

The proposed method, in contrast to eigenvalue assignment methods, not only assigns the eigenvalues to suitable well damped complex plane locations, but also ensures that their excitation itself is minimized through additional left eigenvector assignment. Selection of the partially assignable left eigenvectors requires selection of suitable values for the elements of the parametric vectors as in (6). This is achieved through the use of a non-linear optimization algorithm. The requirement of minimizing mode excitation can be mathematically quantified using an objective function as in (9).

Where is left eigenvector associated with calculated using (6) and free parametric vector and are vectors of weight and if else if . The justification for the above objective function can be given by observing that the elements of the left eigenvector corresponding to a given mode represent the relative contributions of states into that mode. Reducing the eigenvector elements is achieved through the reduction of the weighted objective function (9), thus reduces the excitation of that particular mode. The weights can be selected to give more importance to certain states as desired.

Although the algorithm used here ensures that the new poles of the system with feedback compensation are located at the specified design values, additional measures must be taken in order to ensure only the problematic open-loop poles move to these locations, i.e., it should not be the case that some other pole has moved to these locations, and the problematic is still posing a threat. This is achieved through an additional objective function. The approximate change in in the open loop eigenvalues , when the controller is implemented can be calculated by using the sensitivity of the eigenvalue to the controller as [9].

Where and are left and right eigenvectors associated with .The minimization of the additional objective function (11) ensures that the selected eigenvalue (but not any other one) is moved to the desired location.

Where is a weight associated .

The two objective functions (9) and (11) can be combined to form a single objective function . Additional terms are also added to objective function as shown below to account for other constraints.

III. TEST SYSTEM

The application of the proposed control design method is demonstrated using the two-area four-generator system. The system, transmission line data and the power flow are shown in Fig. 2. All the generators are equipped with IEEE type AC4A exciters; and each generator is represented by a two axis model which has four state variables, viz. rotor angle , rotor speed , field winding flux linkage , and quadrature axis flux linkage . The dynamic data for the generators and exciters are given in Appendix. Loads are modelled as constant impedances .Fig.

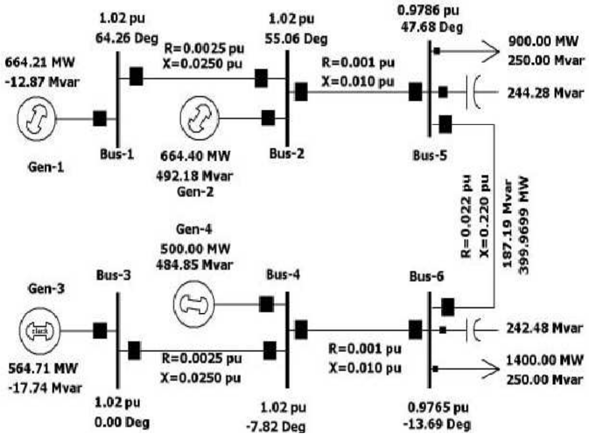

Fig.2 Two-Area Four-Generator power system

Table I lists details of the three least damped modes of the system. The analysis of the participation factors and mode shapes reveals that the first mode is an inter-area mode; and the other two are plant modes. The inter area mode is poorly damped while the plant modes are well damped. The objective of the controller design is to improve the damping ratio of the inter-area mode to at least 5% by moving the associated complex conjugate pair of eigenvalues to further left in the complex plane. This is achieved by installing a PSS on the generator that has the most influence on that mode which can be determined by identifying the input-output pair that has the largest residue for that mode.

TABLE I

SYSTEM EIGEN ANALYSIS -WITHOUT PSS

No.	Eigenvalue	Freq. (Hz)	Damping Ratio(%)	Dominant State *	Mode Type
1	-0.059±j2.1062	0.3352	2.80		Inter-area
2	-1.2633±j7.7302	1.2303	16.13		Area-1 Plant
3	-1.4643±j7.5345	1.1992	19.08		Area-2 plant

The residues between candidate input-output pairs and eigenvalues associated with a mode of interest (the inter-area oscillation mode) can be calculated using (12)

…….. 12

where and are the right and left eigenvectors associated with the eigenvalues of mode of interest; and and are the input and output vectors of the system.

The generator speed and power are considered as candidate input signals to the PSS; and the output of the PSS is used to modulate the of the exciter of the chosen generator. The values of residues are shown in Table II. It can be seen that for both the speed and power signals the largest residue is for Gen-4 and therefore it is selected as the most suitable generator to install a PSS with.

TABLE II

SYSTEM EIGEN VALUES –WITHOUT PSS

PSS Location	Input	
	Speed	Power
Gen-1		
Gen-2		
Gen-3		
Gen-4		

IV. CONVENTIONAL PSS DESIGN PROCEDURE

The single-input lead-lag type PSS shown in Fig. 3, is used as the benchmark to evaluate the proposed SS type stabilizer. The conventional PSS is designed using the phase compensation technique briefly outlined below.

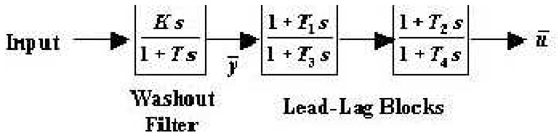

Fig.3 The single input lead-lag type PSS

The washout filter serves to block the dc component of the signal while allowing the oscillatory component to pass through. The time constant, *T*, of the washout filter is chosen to be 10 sec, which is a typical value for a practical system. If the open loop critical eigenvalue , is desired to be moved parallel to ***X***-axis to improve its damping the necessary phase compensation, , to be provided by the stabilizer for single input-output system can be calculated as [10].

where is the residue between input-output pair for calculated using (12).

The required phase lead is achieved with the aid of two lead-lag blocks; each providing half of the required phase lead. The gain is adjusted to achieve the necessary damping of 5% for the critical mode. Table XI shows the necessary phase compensation to be provided by the stabilizer; and the corresponding stabilizer parameters for two different input signals, generator speed and power.

V. SS TYPE PSS

The State Space (SS) type PSS shown in Fig. 4. The washout filter serves the same purpose as that in conventional PSS described above with the same time constant *T*=10 sec. The dynamic compensator part of the PSS is designed using the proposed algorithm. The first step in the design procedure is to derive the linearized power system model with the washout filter. The linearized system will have a single input and a single output

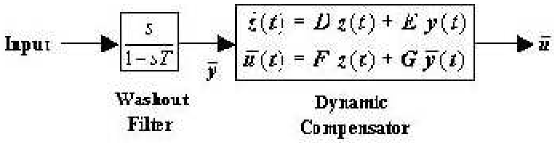

Fig.4 The State Space (SS) type PSS

The main objective of the design is to improve the damping ratio of the critical inter-area mode to *5%*. Additionally the participation factors shown in Table I reveals that the Gen-4 has a high participation in the Area-2 plant mode. Therefore it is important to ensure that the damping of this mode is not deteriorated. As explained in section II.C the assigned eigenvalues cannot be exactly the same as open-loop eigenvalues. Therefore, the new eigenvalues for Area-2 plant mode are chosen to be slightly left of its original location. Thus, during SS type stabilizer design the set of original eigenvalues will be assigned a new set of eigenvalues At least four inputs are required to assign the four eigenvalues (set of two complex conjugate pair of eigenvalues) to the closed loop system (Section II.C.) Using (4) the required dimension of dynamic compensator state vector is .

Now, the parameters of the dynamic controller can be designed as a linear output feedback controller using the algorithm presented in Section III. The parameters of SS type PSS obtained using the algorithm for speed and power input are listed in Table XII and Table XIII respectively.

VI. RESULTS

The conventional lead-lag type PSS and the SS type PSS designed as described above were incorporated into the power system model. The results of small signal analysis and nonlinear transient simulation are compared in following subsections.

A. *Speed Input Stabilizer*

Tables III and IV list the few least damped modes of the system obtained through small signal analysis when speed input lead-lag and SS type PSS are installed on Gen-4. Note for the case of SS type PSS the first and fourth pair of eigenvalues are the set of predetermined set of eigenvalues those were selected as a first step of controller design. In both the cases the damping of critical inter-area mode improved from 2.8% to 5.01% by moving them almost parallel to X-axis.

Fig. 5 shows the transient response of speed and electrical power of Gen-4 for 20 ms fault at Bus-1 and the responses are exactly identical for the two cases. This shows that the optimization algorithm could not achieve a better left eigenstructure than that obtained using the conventional design. Therefore, the option of using the electrical power as an input signal to the PSSs is investigated and the results are analyzed in the following Subsection.

TABLE III
SYSTEM EIGEN ANALYSIS-WITH SPEED INPUT LEAD-LAG TYPE PSS

No.	Eigenvalue	Freq.(Hz)	Damping Ratio(%)	Dominant State*
1				
2				
3				

TABLE IV
SYSTEM EIGEN ANALYSIS-WITH SPEED INPUT SS PSS

No.	Eigenvalue	Freq (Hz)	Damping Ratio(%)	Dominant State*
1				
2				
3				
4				

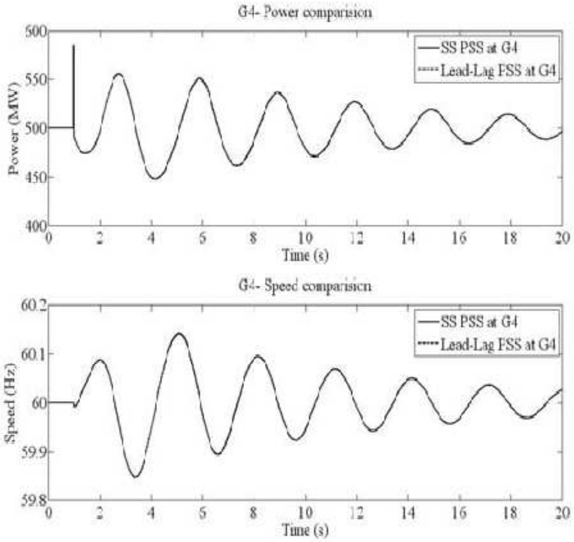

Fig. 5 Transient response comparison for 20ms 3-ph fault at Bus-1

B. *Power Input Stabilizer*

Tables V and VI list the few least damped modes of the system when power input lead-lag and SS type PSS are installed on Gen-4. The damping ratio of critical inter-area mode improved to 5% by moving them almost parallel to ***X***-axis. Fig. 6 shows the transient response of speed and electrical power of Gen-4 for 20 ms fault at Bus-1. These results clearly show that the responses of the system with SS type PSS are better compared to lead-lag type PSS. Unlike in the speed input case, the optimization algorithm has been able to achieve a smaller left eigenvector elements corresponding to the speed of the generators. This reduction in the left eigenvector entries has resulted in comparatively smaller excitation of low-frequency inter-area mode in the case of SS type PSS.

TABLE V
SYSTEM EIGEN ANALYSIS-WITH POWER INPUT LEAD-LAG PSS

No.	Eigenvalue	Freq. (Hz)	Damping Ratio(%)	Dominant State*
1				
2				
3				

TABLE VI
SYSTEM EIGEN ANALYSIS-WITH POWER INPUT SS PSS

No	Eigenvalue	Freq.(Hz)	Damping ratio(%)	Dominant State*
1				
2				
3				
4				

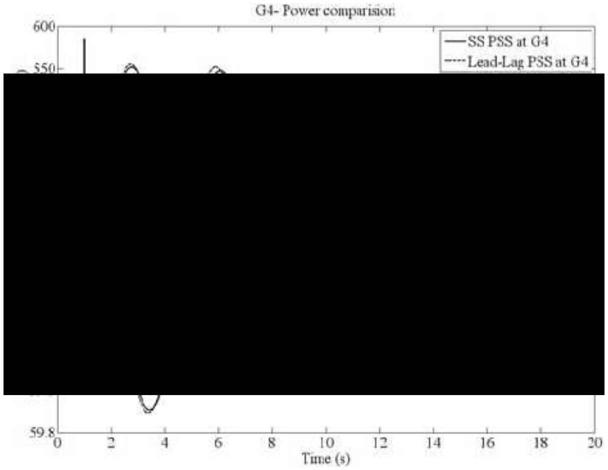
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Fig.6 Transient response comparison for 20ms 3-ph fault at Bus-1

VII. CONCLUSION

A new algorithm based on left eigenstructure assignment has been proposed to minimize the excitation of undesirable oscillations. Together with this algorithm a new State Space type PSS has been proposed to facilitate flexibility of controller design. The generator speed and electrical power have been evaluated as candidate input signals. For the power system considered in this paper it was not possible to improve the left eigenstructure with the speed input SS type PSS whereas a significantly better left eigenstructure was achieved with the electrical power input SS type PSS. This demonstrates the effect of the choice of input signal on the achievable left eigenstructure. With the right choice of input signal, the proposed eigenstructure assignment based SS type PSS can minimize the excitation of undesirable oscillations while achieving the required damping. The proposed controller has been able to reduce the magnitude of oscillations of the speed of synchronous generators.

VIII. APPENDIX

TABLE VII
LEAD LAG TYPE PSS PARAMETERS

Input	Phase Comp.(Degree)			K
Speed	50.73	0.7582	0.3114	7.05
Power	141.63	2.7495	0.0914	0.002

TABLE VIII

SPEED INPUT SS TYPE PSS PARAMETERS

- -

- - -

TABLE IX

POWER INPUT SS TYPE PSS PARAMETERS

Synchronous Generators: GENROU model data:

Damping constants, D:

Gen-1	Gen-2	Gen-3	Gen-4
10.0	1.0	6.5	1.2

Exciters: AC4A model data:

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