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Control Loop Selection Methods for Damping Oscillations in Power System

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***Abstract--* Low frequency oscillations have received the greater source of concern with the evolution of new technologies in power system and growing inter-connections. These are resulting in complex stability problems. The stability of these low frequency oscillations is of vital concern and a prerequisite for secure operation of the system.In this paper a survey made on different methods involved while designing of the wide area damping controller and effectiveness of each method. Numerous researches have been done in this field with different approaches.**

Keywords- Control Loop Selection, Damping Controller, Inter-Area Oscillations, Wide-Area Control.

I. INTRODUCTION

Electromechanical oscillations are caused due to presence of insufficient damping torque in the system resulting the instability of the system. Today, the low-frequency oscillations damping is achieved with the devices such as static VAR compensators, Power system stabilizers(PSS), FACTS , static synchronous compensator(SSSC) and many more. Numerous methods are involved to select the input control signal for these controller so that they can effectively damp the oscillations.Several paper are present that deals with the different approaches for selecting the feedback control signal. Generally, there are two approaches that have been applied by most of the researchers to determine simultaneously the location and control signal for the damping controller namely geometric and residue approach. However, there are other techniques that also take the effect of control on the other eigenvalues in to consideration. Wide area measurement for control of low frequency oscillations are broadly categorised in 3 categories: Decentralized, centralized and multi-agent controller discussed in detail in [8].These controller involves different approaches which will be discussed in this paper. The main objective of the wide area control loop selectionare:

- Choose signal pairs that maximises the controllability/observability of the concern inter-area mode.
- The control loop must have a minimal effect on the other modes and minimum interaction with other global or local loops.

The paper is organized as follows: section II describes the methodologies for selecting the control signal in a decentralized or a centralized controller. Section III critically reviews the role of FACTS device in damping and techniques for the FACTS devices. Section IV discusses the procedure for the selection of stabilizing signal(s) for FACTS devices. Finally section V presents the main conclusion.

II. SIGNAL SELECTION METHODOLOGIES

A. Geometric approach

The geometric measure for controllability m_{ci} and observability m_{oi} associated with mode 'i' is given by:

$$m_{ci}(k) = \cos(\theta(f_i, b_k)) = \frac{|b_k^t f_i|}{\|b_k^t\| \|f_i\|} \quad (1)$$

$$m_{oi}(l) = \cos\big(\theta(c_l^t, e_i)\big) = \frac{|c_l e_i|}{\|b_k^t\| \|f_i\|} \quad (2)$$

In (1) and (2), b_k is the *kth* column of B matrix and c_l is the *lth* row of the C matrix, $\theta(f_i, b_k)$ *is* the acute angle between the input vector b_k and the left eigenvector f_i , $\theta(c_l^t, e_i)$is the acute angle between the output vector $c_l$and the right eigenvector e_i and are, respectively,$|z|$ *and* $\|z\|$ are the modulus and the Euclidean norm of z respectively. Using (1) and (2), the joint controllability/observability measure is given by:

$$m_{coi}(k, l) = m_{ci}(k)\, m_{oi}(l) \quad (3)$$

A large value of m_{coi} indicates that control loop is effective in controlling *ith* mode.

In paper[5], the two approaches(residue and geometric) have been applied on a Hydro-Quebec network where the comparison of the effectiveness is performed. The results show that the better robustness and performance is achieved by geometric measure. The simulation results show that wide area control is more effective in control than local control.

B. Residue approach

The residue indicate the movement of the eigenvalues (poles) corresponding to small gain whereas for the large gain, it is determined by the location of the zeroes. This method uses a combination of A, B, C matrix and left and right eigenvector as well. The residue of the signal can be calculated using eq.(9). The transfer function associated with system (3) is as follows:

$$G(S) = \frac{Y(S)}{U(S)} = C(sI - A)^{-1}B \quad (4)$$

The above equation can be rewritten as using the orthogonality between the left and right eigenvector as

$$G(S) = \sum_{i=1}^{n} \frac{R_i}{s-\lambda_i} \quad (5)$$

Where, R_i is the residue matrix associated with mode 'i' which is given by:

$$R_i = Ce_i f_i^H B \quad (6)$$

Where, $R_i$is Residue matrix for eigenvalue *i*;
C is Output matrix of the system;
B is Input matrix of the system;
$e_i$is Right eigenvector corresponding to eigenvalue *i*;
f_i^H *is* complex conjugate of the left eigenvector corresponding to eigenvalue *i.*

The maximum value obtained for the residue corresponding to u_k and $y_l$associated with mode 'i' are the most efficient signal for damping the low frequency oscillations.

The methodology is tested on 16-machine interconnected system with multiple wind farm in paper[2]. The signal selection that can retain the electromechanical dynamics under varying operating conditions. An effective control signal must meet the following criteria:

1. The best pair is the one having highest |*R*| for all operating conditions which is a good indicator for effectiveness in control.
2. The variation in |*R*| and ∠*R*should be minimum in order to have a uniform damping contribution which ensure robust performance.
3. The sensitivity of the controller should beappreciably small for closely situated modes.

C. Hankel singular method:

It basically focuses on minimizing the interaction between the local control loops and the global control loops at the inter-area natural frequency. The system can be transformed into a balanced realization. Let (A,B,C,D) be a realization of the transfer function G(s), then (A,B,C,D) is called balanced if it gives solution for the following equations:

$$AP+PA^T+BB^T=0$$
$$A^TQ+QA+C^TC=0 \quad (7)$$

$$\sigma_i = \sqrt{\lambda_i(PQ)} \quad (8)$$

Such that P=Q=diag$(\sigma_1, \sigma_2, ... \sigma_n)$ where $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_n$. P and Q are controllability and observabilityGramians.σ is the hankel singular value(HSV).

This measure is best for determining the interaction between the control loop and specific mode. The signal with the high value of HSV is generally considered as it has a good observability/controllability to the states of the system. After the calculation of the Hankel singular values, the total contribution for a specific mode to that particular loop can be found by :

$$C_k = \sum_{i-1}^{n} \sigma_i^2 p_i(\lambda_i) \quad (9)$$

where
$\sigma_i$is the Hankel value calculated for the state variable *i* for a specific single input single output system.
$p_i$is the participation factor of the state variable *i*.
$\lambda_i$is the desired mode *k*.

The signal with highest value is chosen as the feedback control signal. This measure is used in paper[4] consisting of nine areas and 23 generators. In this paper, high controllability/ observability is achieved along with minimization of the interaction between the control loops. Selecting control loops to achieve two objectives is considered in this paper only. The author has selected the feedback signal using the graphically oriented heuristic criterion which based on this HSV total interaction method.

The modal interaction measure of the mode λ_k is given by:

$$I_k = \frac{C_k}{\sum_{\lambda_j \epsilon \Lambda} C_j} \frac{\sum_{i-1}^{N} \sigma_i^2 p_i(\lambda_i)}{\sum_{\lambda_j \epsilon \Lambda} \sum_{i-1}^{n} \sigma_i^2 p_i(\lambda_i)} \quad (10)$$

Where $\Lambda$is the set of all modes of the system.

Eq. (10) determines how the other modes will be affected if one controls the mode $\lambda_k$from the current loop. The modes are considered irrelevant and can be ignored during this analysis if

- Mode has small controllability/observability
- Mode of very low or high frequency as their effect is filtered with the washout filters present in the damping controllers. Therefore, they can be ignored.

In paper[7], considering differentcases, the best control loop signal has always good modal interactionmeasure . This paper also suggest the usage of lead-lag controller which can solve the conflict of the phase mismatch considered as the important measure for controlling the inter-area mode effectively. This problem is complicated if the communication delay is also considered.

D. Phase compensation conflict

For each electromechanical oscillations modes, to achieve the pure damping effect, phase compensation is required to achieve this.

A simple is lead-lag structure is considered for the controller. The transfer function is given by:

$$\frac{T_W s}{1+T_W s} \left(\frac{T_1 s+1}{T_2 s+1}\right)^m \quad (11)$$

Where
$T_w$is the washout filter time constant.
$T_1, T_2$are the time constants for controller.
m is the number of lead-lag blocks.
For achieving pure damping effect for the mode with the desired phase lead φ, the time constant $T_1$and T_2 can be calculated using:

$$\alpha = \frac{1-\sin(\frac{\varphi}{m})}{1+\sin(\frac{\varphi}{m})} \quad (12)$$

$$T_1 = \frac{1}{\omega\sqrt{\alpha}} \qquad (13)$$

$$T_2 = \alpha T_1 \qquad (14)$$

It should be noted that phase compensation conflict can be resolved using high order control structure[7],[8]. However, a control loop with little phase conflict would facilitate the design of the low order robust controller.

IV. ROLE OF FACTS DEVICES IN DAMPING

The placement of most of the controllable devices such as high voltage DC (HVDC) links and flexible ac transmission system (FACTS) is not related to the oscillatory stability. For instance, a static VAR compensator(SVC) is used for improving voltage of transmission system, thereby enhances the maximum power transfer capacity. There is an additional benefit for FACTS devices is the capability of improving the damping which requires proper selection of stabilizing signals and effective tuning of such controllers.

This section focuses on selection of the most stabilizing signal for damping control rather than on proper placement of the FACTS devices. Generally, the two methodologies(geometric and residue) are used by the scholars to select most appropriate signal but other methods are also discussed in the section below.

The methods include minimum singular values(MSV), the right-half plane zeros(RHP-zeros), Hankel singular values(HSV) and the relative gain array(RGA) as indicators to find the appropriate signals in single-inputsingle-output and multiple-input multiple-output(MIMO) systems. In a SISO system, only the RHP-zeros criteria is used for limiting the performance of the closed loop system and HSV is for checking the controllability-observability when one FACTS device is present.The MSV and RGA are used for quantifying the degree of directionality and the interaction level in MIMO systems.

A. Minimum Singular Value(MSV)

The maximum and minimum singular values are used for quantifying the degree of directionality in the MIMO systems. Considering a MIMO system having transfer function G with m outputs and n inputs, G can be decomposed with the singular value decomposition as follows:

$$G = U \sum V^H \qquad (15)$$

Where $\sum = \begin{bmatrix} \sum_1 & 0 \\ 0 & 0 \end{bmatrix}$

$$\sum_1 = \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_k \end{bmatrix}$$

Where σ_i(i=1,2,…,n) ≥ 0 are singular values placed diagonally in descending order with k=min{m,n} and U and V input and output singular vectors respectively. U and V are used to check the strength and weakness of input-output directions. Thesmallest singular value is the indicator of controllability showing the smallest gain for any input direction[3]. It is desired to input-output signal with large minimum singular value to avoid ill-conditioning.

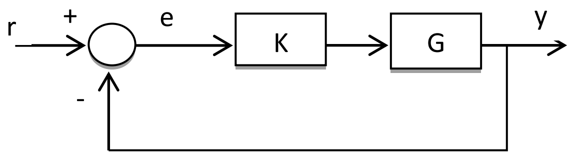

Fig. 1 Block diagram of Plant with feedback.

B. Right half plane zeros(RHP-zeros)

When different input-output for any plant is considered, different zeros also appear. Those I/O pairs that produce RHP zeros are undesirable because of their limiting performance. Consider a negative feedback system as shown in fig. 1 with a plant G=z/p along with a constant gain controller K=k, the closed loop transfer is given by

$$G_c = \frac{KG}{1+KG} = \frac{kz}{p+kz} = k\frac{z_{cl}}{p_{cl}} \qquad (16)$$

From the above transfer function, it can be seen that pole locations are changed by the feedback whereas location of zeros remain unchanged. When the feedback gain is increased, the closed-loop poles will be moved from open loop poles to open loop zeros and when the feedback gain is decreased, the closed-loop poles will be moved to open-loop poles, that leads to gain instability[3].

Thus, the selection of the input-output pair should be such that the closed loop plant will have a minimum number of the RHP-zeros which shouldn't lie within the closed-loop bandwidth.

C. Relative gain array(RGA)

It provides a measure of interaction caused by decentralized control. Assume u_j and y_i are an input and an output of a multivariable plant G respectively with m inputs and m outputs, and that y_i controlled by u_j. The RGA is a matrix of the relative gains, and a relative gain is the ratio of two gains in two extreme cases defined as follows:

First case: All other loops are open and all other input changes are zero and the gain is

$$\left(\frac{\Delta y_i}{\Delta u_j}\right)_{\Delta u_k=0,\forall\, k\neq j} = g_{ij} = [G]_{ij} \qquad (17)$$

Second case : All other are closed and all other input changes are zero and the gain is

$$\left(\frac{\Delta y_i}{\Delta u_j}\right)_{\Delta y_k=0,\forall\, k\neq j} = \hat{g}_{ij} = \frac{1}{[G^{-1}]_{ji}} \qquad (18)$$

Where

$[G]_{ij}$element of G on the *i*th row and *j*th column;

$[G^{-1}]_{ji}$element of $[G]^{-1}$on the *j*th row and *i*th column.

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The ratio of g_{ij} and $\hat{g}_{ij}$is known as the relative gain,which is defined as

$$\lambda_{ij} = \frac{g_{ij}}{\hat{g}_{ij}} = [G]_{ij}[G^{-1}]_{ji} \quad (19)$$

All of the relative gains λ_{ij}compose the RGA, which can beexpressed as

$$\Lambda = G \times (G^{-1})^T \quad (20)$$

Where × denotes an element by element multiplication known as the Hadamard or the Schur product and T represent the transpose of the matrix.

The RGA possesses the following properties:

- It is independent of output and input scaling.
- Each row and column sums upto 1.0,$\sum_{i=1}^{m} \lambda_{ij} = 1$.
- $RGA_{ij}$is independent of other pairing of loops.

Clearly, it is desired to pair $u_j$and y_i so that is close to 1 because this means that the gain from u_j to y_i is unaffected by closing other loops. On the other hand, a pairing corresponding to is undesirable, because it means that the steady-state gain in a given loop changes sign when other loops are closed.

If a pairing of an output and an input corresponds to a negative steady-state relative gain, then the closed-loop system has at least one of the following properties.

- The overall closed-loop system is unstable.
- The loop with the negative relative gain is itself unstable.
- The loop with the negative relative gain is opened makes the closed-loop system unstable.

It is designed to pair inputs and outputs such that the diagonal elements of the RGA matrix are close to unity,which shows less interaction. Large RGA elements are undesirable for a plant.

In the decentralized control, the relative interaction can be represented by the matrix $E = (G - \widetilde{G})\widetilde{G}^{-1}$, where matrix $\widetilde{G} = diag(G_{ii})$denotes the matrix with the diagonal elements of G. An important relationship for decentralized control is given by

$$(I + GK) = (I + E\tilde{T})(I + \tilde{G}K) \quad (21)$$

where the complementary sensitivity function $\tilde{T} = GK(I + GK)^{-1}$ is the closed-loop transfer function of the diagonal system G At frequencies where the feedback is effective, $\tilde{T} \approx I$ and it can be shown that

$$(I + E\tilde{T})^{-1} \approx \tilde{G}G^{-1} = \Gamma \quad (22)$$

Where $\Gamma = \{\Upsilon_{ij}\}$ is the performance relative gain array (PRGA), known as an indicator for interaction. The PRGA elements larger than 1 imply that there are interactions.

IV. PROCEDURE OF SELECTION OF STABILIZING SIGNAL(S) FORFACTS DEVICES

The procedure to select stabilizing signals for supplementary controller of the FACTS devices using the RGA-number, the MSV, the HSV and the RHP-zeros can be described as follows:

For a SISO system, the RHP zeros and the HSV are used as indicators to select the most responsive signal, using only one FACTS device, to a mode of the inter-area oscillation[3]. The procedureto carry out the selection is summarized below:

1. After placing a FACTS device, choose the stabilizing signal candidates for supplementary control.
2. For each candidate, calculate the RHP-zeros. If any RHP-zeros is encountered in the frequency range of 0.1–2 Hz that is undesirable, then the corresponding candidate must be discarded.
3. Check the observability and controllability of the remaining candidates using the HSV. The candidate with the largest HSV is preferred, which shows that the corresponding signal is more responsive to the mode of oscillation and is the selected as the final choice.

For a MIMO system, in addition to using the HSV and the RHP-zeros, the MSV and the RGA-number are also used, with multiple FACTS devices, to find the most responsive signals to modes of the inter-area oscillation. The procedure is subscribedas below:

1. Place the FACTS devices in the system and choose the possible stabilizing signal candidate sets for supplementary control.
2. Calculate the MSV for the candidate sets in step 1. In the case of having a large number of candidate sets, a range of candidate sets with larger values of the MSV should be selected for a more detailed input-output controllability analysis.
3. Calculate the RHP-zeros for the selected candidate sets considered in step 2. Those candidate sets, which encounter the RHP-zeros, will be discarded.
4. Calculate the RGA-number for the remaining candidate sets from step 3. Candidate sets with smallerRGA-number are preferred. Few candidate sets with the RGA-number close to the achieved smallestRGA-number will be selected for the next step.
5. The observability and controllability of the selected candidate sets from step 4 will be checked usingthe HSV. The candidate set with the largest HSV is preferred and is the final choice for thestabilizing signals for the supplementary controllers.

In paper [3], the importance of selecting the most effective stabilizing signal is described. It is also noted that controllability/observability alone is not the adequate analytical tool to identify the most effective control signal. The final selection must be done in a more detailed way. In SISO systems, selection is done using RHP zeros and HSV indicators. For MIMO system, the MSV and the RGA-number are used in addition with RHP-zeros and the HSV. With the selected signal, controllers are designed and the result show that the selected signals are responsive.

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V. CONCLUSION

In this paper, a comprehensive survey is made on the selection of the most stabilizing feedback control signal used for the designing of the controller that ensures robustness of the controller. The paper critically analyses the different techniques used for selecting the control loop. In order to validate the feedback signal performance, different methods with their performance on the system is analysed with the help of research papersand presented in this paper and it is evident that from the results that the controllers provide improved and effective damping. It is also noted that controllability/observability alone is not the adequate analytical tool to identify the most effective control signal. Further, the choice of FACTS device control inputs are also analysed. The selection approach for selecting the feedback signal usingFACTS device in SISO and MIMO systems are discussed and using these signal supplementary controllers are designed.

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