A ROBUST DAMPING CONTROLLER DESIGN FOR A UNIFIED POWER FLOW CONTROLLER

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ABSTRACT

The unified power flow controller (UPFC) is a FACTS device, which can be used to control the power flow on a transmission line. This is achieved by regulating the controllable parameters of the system: the line impedance, the magnitude and phase of the bus voltage. In addition to control of real and reactive power flow, the UPFC can be employed to enhance power system damping by modulating the converter voltages. This article presents design of a robust damping control strategy for the series converter voltage magnitude. A relatively new 'loop-shaping' graphical strategy has been used to implement the H-∞ based robust performance and stability measures. The control designed has been tested on a single machine infinite bus system for different disturbance conditions. Test results indicate that the proposed robust controller damps the system transient very effectively over a good range of operation.

Keywords: UPFC, power system damping, robust control, loop-shaping method.

INTRODUCTION

The unified power flow controller (UPFC) is a multi-function FACTS device. The usual form of the device consists of two voltage source converters, which are connected through a common DC link capacitor. The first voltage source converter known as static synchronous compensator (STATCOM) injects an almost sinusoidal current of variable magnitude at the point of connection. The second voltage source converter known as static synchronous series compensator (SSSC) injects a sinusoidal voltage of variable magnitude in series with the transmission line. The real power exchange between the converters is affected through the common DC link capacitor. In the UPFC, the STATCOM and the SSSC are simply connected at their terminals so that each can act as the appropriate real power source or the sink for the other. The concept is that the SSSC will act independently to regulate power flow on the line, and the STATCOM will satisfy the real power requirements of the SSSC while regulating the local bus voltage [1, 2].

UPFC can be used for power flow control, loop flow control, load sharing among parallel corridors, providing voltage support, enhancement of transient stability, mitigation of system oscillations, etc. [3,4]. It can control all three basic power transfer parameters – line impedance, voltage magnitude and phase angle independently or simultaneously in any appropriate combinations. The stability and damping control aspect of an UPFC has been investigated by a number of researchers. The additional damping control circuits can be installed along with the normal power flow controllers. The signals employed are the magnitudes and phase angles of line voltages of the shunt and series converters [5,6]. Most of the control studies are based on linearized models of the nonlinear power system dynamics. Seo, *et al,* examined the robust controller design for small signal stability [7]. One of the important control objectives is to design a controller, retaining the system nonlinearities, which will provide satisfactory response over a wide range of operation.

This article presents a robust damping controller for the series voltage magnitude using a relatively new graphical method called 'loop-shaping'. The fixed parameter series voltage controller designed satisfying the robust stability and performance measures. The controller was tested on a single machine infinite bus system and was observed to provide excellent damping characteristics for a very good range of operation.

THE SYSTEM MODEL

Fig. 1 shows a single machine system connected to a large power system bus through a transmission line installed with UPFC. The UPFC is composed of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSC), and a DC link capacitor [3, 7]. In the figure, m and α refer to amplitude modulation index and phase angle of the control signal of the two VSCs (E and B), respectively.

The d-q components of the three phase currents of the input circuit (E) are written as,

$$\frac{d}{dt}\begin{bmatrix} I_{Ed} \\ I_{Eq} \end{bmatrix} = \frac{\omega_o}{L_s}\begin{bmatrix} -R_s & \omega L_s \\ -\omega L_s & -R_s \end{bmatrix}\begin{bmatrix} I_{Ed} \\ I_{Eq} \end{bmatrix} + \frac{\omega_o}{L_s}\begin{bmatrix} V_E - e_{Ed} \\ -e_{Eq} \end{bmatrix} \qquad (1)$$

V_E is the AC voltage at the sending end of the transmission line. Neglecting the input converter harmonics, the following equations can be written relating the amplitudes of the voltage vector components at the input converter (E) to the capacitor voltage on the common DC link:

$e_{Ed} = m_E V_c \cos\alpha_E$ (2)

$e_{Eq} = m_E V_c \sin\alpha_E$ (3)

α_E is the phase angle difference between the input converter AC voltage e_E and the line voltage V_E. The factor m_E is the modulation index of the input converter. The instantaneous powers at the AC and DC terminals of the input and output converters are equal if the converters are assumed to be lossless. This gives two power balance equations in per unit:

$V_c I_i = e_{Ed} I_{Ed} + e_{Eq} I_{Eq}$ (4)

$V_c I_o = e_{Bd} I_{Ld} + e_{Bq} I_{Lq}$. (5)

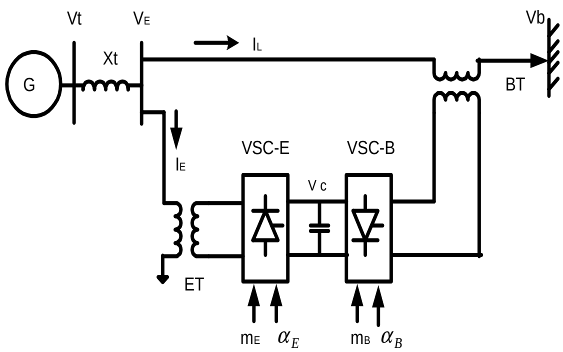

Fig.1 A single machine system with UPFC in one of the transmission lines

Since the net current to the capacitor is zero, the DC link circuit can be described by the equation as,

$$C \frac{dV_c}{dt} = (I_i + I_o) \quad (6)$$

The d-q components of the series injected voltage relating with the DC link voltage can be expressed as,

$e_{Bd} = m_B V_c \cos\alpha_B$ (7)

$e_{Bq} = m_B V_c \sin\alpha_B$ (8)

α_B is the angle between e_B and V_E, and m_B is the modulation index of the output converter. The transmission circuit equations including the series transformer of the UPFC can be expressed in d-q axes as,

$$\frac{d}{dt}\begin{bmatrix} I_{Ld} \\ I_{Lq} \end{bmatrix} = \frac{\omega_o}{L_L}\begin{bmatrix} -R_L & \omega L_L \\ -\omega L_L & -R_L \end{bmatrix}\begin{bmatrix} I_{Ld} \\ I_{Lq} \end{bmatrix} + \frac{\omega_o}{L_L}\begin{bmatrix} V_E - V_{bd} - e_{Bd} \\ -V_{bq} - e_{Bq} \end{bmatrix} \quad (9)$$

The voltages and the currents are indicated in Fig.1. Recognizing that,

$$\begin{bmatrix} I_{id} \\ I_{iq} \end{bmatrix} = \begin{bmatrix} I_{Ed} \\ I_{Eq} \end{bmatrix}; \begin{bmatrix} I_{od} \\ I_{oq} \end{bmatrix} = \begin{bmatrix} I_{Ld} \\ I_{Lq} \end{bmatrix} \quad (10)$$

and substituting equations (4-5) and (7-8), (6) can be rewritten as,

$$\frac{dV_c}{dt} = \frac{1}{C}[m_E \cos\alpha_E I_{Ed} + m_E \sin\alpha_E I_{Eq} + m_B \cos\alpha_B I_{Ld} + m_B \sin\alpha_B I_{Lq}] \quad (11)$$

The synchronous generator-exciter system is represented through the 4th order dynamic model,

$$\begin{aligned} \dot{\delta} &= \omega_o \omega \\ \dot{\omega} &= \frac{1}{2H}[P_m - P_e - D\omega] \\ \dot{e}_q' &= \frac{1}{T_{do}'}[E_{fd} - e_{qo}' - (x_d - x_d')I_d] \\ \Delta\dot{E}_{fd} &= \frac{K_A}{T_A}[V_{to} - V_t] - \frac{1}{T_A}\Delta E_{fd} \end{aligned} \quad (12)$$

Expressing the generator power output and the terminal voltages in terms of d-q components of shunt and series currents (I_E, I_L), the composite synchronous generator-UPFC system can be expressed through the 9th order dynamic equation,

$$\dot{x} = f[x, u] \quad (13)$$

Here the state vector comprises of [I_{Ed} I_{Eq} I_{Ld} I_{Lq} V_c δ ω e_q' E_{fd}] and the 4 controls are [m_E α_E m_B α_B].

DESIGN OF ROBUST CONTROLLER

The damping control problem for the nonlinear power system model is stated as: given the system represented by the 9th order nonlinear set of equations (13), design a controller whose output u will stabilize the system following a perturbation in the system. Since there is no general method of designing a stabilizing controller for the nonlinear system, one way would be perform the control design for a linearized system, the linearization being carried out around a nominal operating condition. If the controller designed is 'robust' enough to perform satisfactorily for the other operating conditions in the vicinity of the nominal point, the design objectives are met. The linearized system of state equations are written as,

$$\begin{aligned} \dot{X} &= AX + Bu \\ Y &= CX \end{aligned} \quad (14)$$

The changes in operating points of the nonlinear system (13) can be considered as changes in the elements of the system matrices in (14). These perturbations are modeled as uncertainties and robust design procedure is applied to the perturbed linear systems. The design is carried out using a graphical construction procedure called 'loop-shaping' satisfying the robust stability and performance measures. A brief theory of the uncertainty model, the robust stability criterion, and the graphical design technique are presented in the following.

A. The Uncertainty Modeling

Suppose that the linearized plant having a nominal transfer function P belongs to a bounded set of transfer functions **P**. Consider that the perturbed transfer function resulting from the variations in operating conditions can be expressed in the form

$$\tilde{P} = (1 + \Omega W_2)P \qquad (15)$$

Here, W_2 is a fixed stable transfer function, also called the weight, and Ω is a variable transfer function satisfying $\|\Omega\|_\infty < 1$. The infinity norm (∞-norm) of a function is the least upper bound of its absolute value, also written as $\|\Omega\|_\infty = \sup_\omega |\Omega(j\omega)|$, and is the largest value of gain on a Bode magnitude plot. In the multiplicative uncertainty model (15), ΩW_2 is the normalized plant perturbation away from unity. If $\|\Omega\|_\infty < 1$, then,

$$|\tilde{P}(j\omega)/P(j\omega) - 1 \leq |W_2(j\omega)|, \forall\, \omega \qquad (16)$$

So, $|W_2(j\omega)|$ provides the uncertainty profile and is the upper boundary of all the normalized plant transfer functions away from unity in the frequency plane [8].

B. Robust Stability and Performance

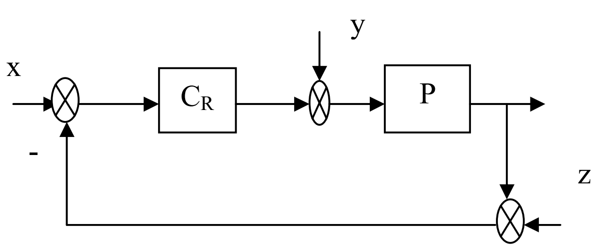

Fig.2 The plant-controller configuration for robust design

Consider a multi-input control system given in Fig.2. A controller C_R provides robust stability if it provides internal stability for every plant in the uncertainty set **P**. If L denotes the open-loop transfer function ($L=PC_R$), then the sensitivity function S is written as,

$$S = \frac{1}{1 + L} \qquad (17)$$

For a multiplicative perturbation model, robust stability condition is met if and only if $\|W_2 T\|_\infty < 1$ [7,8]. This implies that,

$$|\tilde{P}(j\omega)/P_{nom}(j\omega) - 1| < 1, \text{ for all } \omega \qquad (18)$$

T is the complement of S, and is the input-output transfer function. The maximum loop gain, $\|-W_2 T\|_\infty$ is less than 1 for all allowable Ω, if and only if the small gain condition $\|W_2 T\|_\infty < 1$ holds. The nominal performance condition for an internally stable system is given as $\|W_1 S\|_\infty < 1$, where W_1 is a real-rational, stable, minimum phase transfer function, also called a weighting function. The robust performance condition is,

$$\|W_2 T\|_\infty < 1, \quad \left\| \frac{W_1 S}{1 + \Omega W_2 T} \right\| < 1, \quad \forall \|\Omega\| < 1. \qquad (19)$$

Combining all the above, it can be shown that a necessary and a sufficient condition for robust performance is [8],

$$\| |W_1 S| + |W_2 T| \|_\infty < 1 \qquad (20)$$

C. The Loop-Shaping Technique

Loop-shaping is a graphical procedure to design a proper controller C_R satisfying the robust stability and performance criteria given above. The basic idea of the method is to construct the loop transfer function L to satisfy the robust performance criterion approximately, and then to obtain the controller from the relationship $C_R = L/P$. Internal stability of the plants and properness of C_R constitute the constraints of the method. Condition on L is such that PC_R should not have any pole zero cancellation.

A necessary condition for robustness is that either or both $|W_1|$, $|W_2|$ must be less than 1[9]. If we select a monotonically decreasing W_1 satisfying the other constraints on it, it can be shown that at low frequency the open-loop transfer function L should satisfy,

$$|L| > \frac{|W_1|}{1 - |W_2|} \qquad (21)$$

while, for high frequency,

$$|L| < \frac{1 - |W_1|}{|W_2|} \approx \frac{1}{|W_2|} \qquad (22)$$

At high frequency |L| should roll-off at least as quickly as |P| does. This ensures properness of C_R. The general features of the open loop transfer function is that the gain at low frequency should be large enough for the steady state error, and |L| should not drop-off too quickly near the crossover frequency resulting in internal instability.

IMPLEMENTATION OF ROBUST CONTROL

Of the four controls identified for a UPFC, m_B and α_E have been found to provide damping to the system, effect of m_B being more predominant. In the collapsed plant-controller configuration of Fig.2, P is constructed such that voltage modulation index of the series converter (m_B) is the input and the generator speed deviation ($\Delta\omega$) is the plant output. The nominal loading of the generator is 1.01 pu at 0.94 power factor lagging. The nominal plant transfer is obtained as,

$$P = \frac{135.539s(s + z)(s + z_2)\ldots\ldots\ldots(s + z_6)}{(s + p_1)(s + p_2)\ldots\ldots\ldots\ldots\ldots\ldots(s + p_9)} \qquad (23)$$

where, the non-zero zeroes and poles of the system are [-3098.4,-19.58, -27±j364.15, -0.22±0.743], [-19.72,-

28.08 ± 2790.3, -9.4 ± 377.506, -0.212 ± 4.15, -0.25 ± 0.75], respectively.

Off-nominal power output between the range of 0.3-1.4 pu and power factor greater than 0.8 which gave steady state stable situations were considered in the robust design. The quantity $|\tilde{P}(j\omega)/P_{nom}(j\omega)-1|$ is constructed for each perturbed plant $\tilde{P}(j\omega)$ and the upper envelope in the frequency plane is fitted to the function,

$$W_2(s) = \frac{0.48s^2 + 3.2s + 0.64}{s^2 + 1.6s + 16} \quad (24)$$

A Butterworth filter satisfying the properties of $W_1(s)$ is selected as,

$$W_1(s) = \frac{K_c f_c^2}{s^3 + 2s^2 f_c + 2sf_c^2 + f_c^3} \quad (25)$$

Values of K_c=0.01 and f_c=0.1 were observed to be satisfy the requirement on the open loop transfer function L. For W_1 and W_2 selected above, the open-loop function L and the frequency response boundaries are plotted in Fig.3. The controller transfer function then obtained through the relation C_R=L/P is,

$$C_R(s) = \frac{-100(s + 0.1)(s + 0.5)}{s(s + 0.01)} \quad (26)$$

The robust and nominal performance measures given in (19) and (20) are shown in Fig.4. It can be observed that the nominal performance measure is very small relative to 0 db. The robust stability measure is marginally violated at the corner frequency. This is for a worst-case design in the absence of damping term in the electromechanical swing equation.

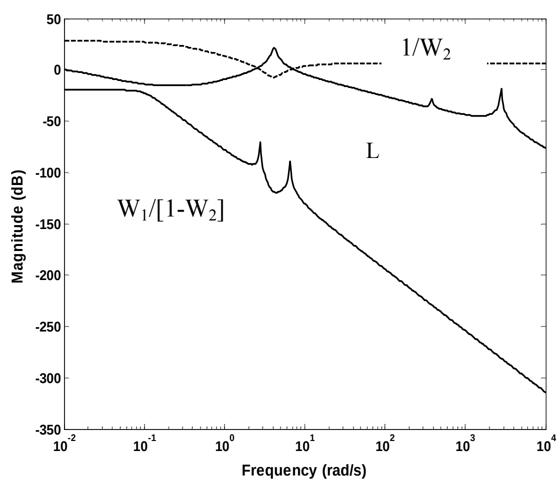

Fig.3 The open-loop function and the frequency boundaries

While selecting the open-loop transfer function, the internal stability of the plant in addition to the design criterion (19)-(22) had to be checked. A disturbance of 50% input torque pulse for 0.1 second on the generator shaft was simulated for this purpose. The rotor angle variations of the generator for the nominal operating point with and without the robust controller are plotted in Fig. 5. As can be observed, the robust controller provides extremely good damping to the rotor oscillations.

The robust controller was then tested for its damping characteristics for a number of loading conditions and for different disturbances. Figure 6 shows the rotor angle variations of the generator for 4 different loadings with a 50% toque pulse disturbance for 0.1s duration. The generator loadings considered are 1.01, 0.85, 0.67, and 0.45 pu, respectively.

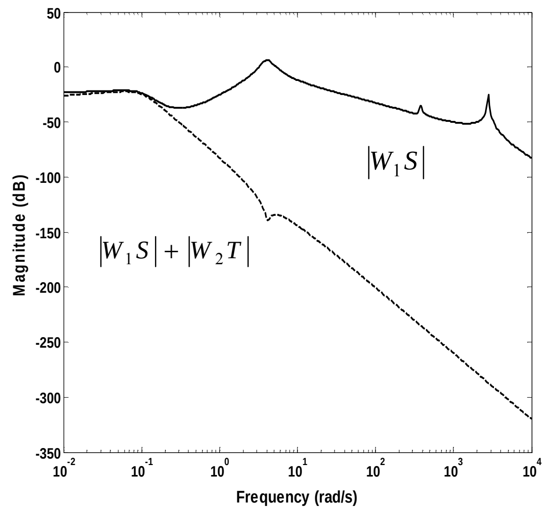

Fig.4 Convergence of robust performance and stability indices

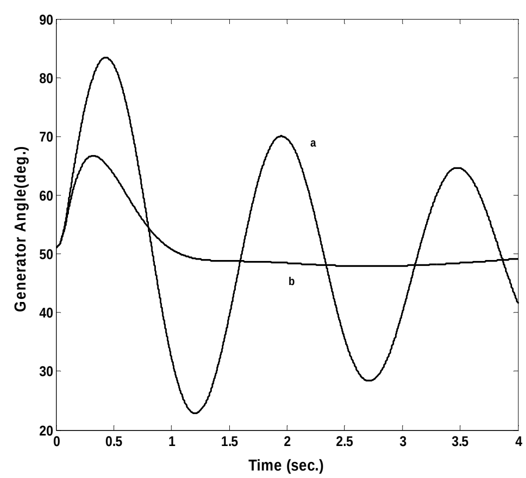

Fig.5 Rotor angle response of the generator at nominal operation with, (a) no extra UPFC control, (b) robust series voltage magnitude control.

Fig.7 shows the rotor angle variations for three-phase faults on the remote bus for 0.2 second. The different loading conditions considered are 1.3, 1.01, 0.85, 0.66, and 0.45, respectively. It can be observed that good damping properties are exhibited for all the loading conditions. While the controller could be designed to provide even more damping, this could result in significant steady state errors.

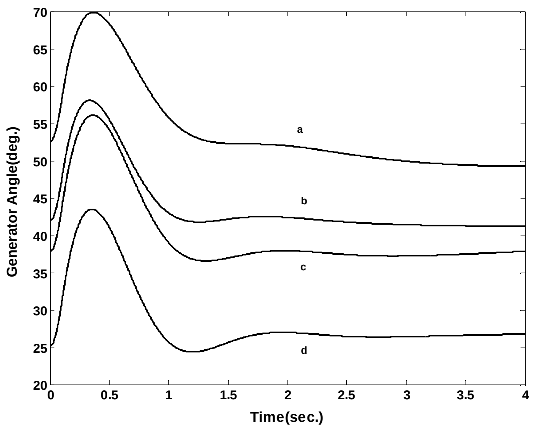

Fig.6 Generator rotor angle variation with robust damping control of series voltage magnitude for (a) P_e=1.01 pu, (b) P_e=0.85 pu, (c) P_e=0.67 pu, (d) P_e=0.45 pu. The disturbance is a 50% torque pulse for 0.1s.

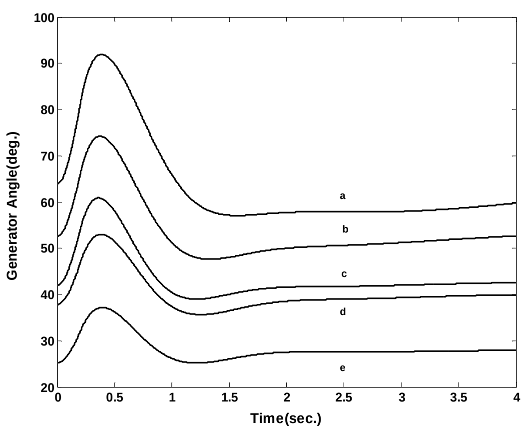

Fig.7 Generator angle variations following a three-phase fault for 0.2s duration with robust controller. The responses are for 1.3, 1.01, 0.85, 0.67, and 0.45 pu power outputs, respectively.

CONCLUSIONS

A robust design of a damping controller for the series voltage magnitude of a UPFC on a single machine system is proposed. A graphical loop-shaping technique has been employed to select the open loop transfer function subject to satisfaction of H-∞ based robust stability and performance measures. The controller designed was tested for a number of disturbance conditions including symmetrical three-phase faults. The robust design has been found to be very effective for damping control over a wide range of operating conditions of the power system. The graphical loop-shaping method utilized to determine the controller function is simple and is straightforward to implement.

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REFERENCES

[1] K.K.Sen and E.J.Stacey, "UPFC – Unified Power Flow Controller: Theory, Modeling and Applications", IEEE Trans. on Power Delivery, Vol. 1, No 4, October 1998, pp.1453-1460.

[2] A.S.Mehraban, A. Edris and C.D.Schauder, "Installation, Commissioning and Operation of the World's First UPFC on the AEP System", 1998 International Conference on Power System Technology, Aug. 1998, Vol. 1, pp.323-327.

[3] A. Nabavi-Niaki and M.R. Irvani, "Steady State and Dynamic Models of Unified Power Flow Controller (UPFC) for Power System Studies", IEEE Trans. on Power Systems, Vol. 11, No. 4, November 1996, pp.1937- 1943.

[4] L.Y.Dong, L. Zhang and M.L.Crow,"A New Control Strategy for Unified Power Flow Controller", IEEE PES Winter Meeting, 2002, Vol. 1, pp.562-566.

[5] H.F. Wang, "Damping Function of Unified Power Flow Controller", IEE Proc.-Gener. Transm. Distrib., Vol. 146, No.1, January 1999, pp.81-87.

[6] N.Tambey and M.L.Kothari, "Damping of Power System Oscillations with Unified Power Flow Controller (UPFC)", IEE Proc.-Gener. Transm. Distrib., Vol. 150, No.2, March 2003, pp.129-140.

[7] J. Seo, S.Moon, J.Park and J. Choe, "Design of a Robust UPFC Controller for Enhancing the Small Signal Stability in the Multi-machine Power Systems", IEEE Power Engineering Sciety Winter Meeting, 2001 IEEE, Vol 3, Jan/Feb 2001, pp.1197-1202.

[8] Doyle, J.C., Francis, B.A., and Tannenbaum, A.R., "Feedback Control Theory", MacMillan Publishing Co, New York, 1992.

[9] A. Chao and M. Athans, "Stability robustness to unstructured uncertainty for linear time invariant systems", The Control Handbook (Editor, W.S. Levine), CRC Press and IEEE Press, 1996.

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