RESEARCH ARTICLE

A Stabilization of Frequency Oscillations in a Parallel AC-DC Interconnected Power System via an HVDC Link

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ABSTRACT This paper presents a new application of High Voltage Direct Current (HVDC) link to stabilization of frequency oscillations in a parallel AC-DC interconnected power system. When an interconnected AC power system is subjected to a large load with rapid change, system frequency may be considerably disturbed and becomes oscillatory. By utilizing the system interconnections as the control channels of HVDC link, the tie-line power modulation of HVDC link through interconnections is applicable for stabilizing the frequency oscillations of AC systems. In the design of power modulation controller, the technique of overlapping decompositions and the eigenvalue assignment are applied to establish the state feedback control scheme. To evaluate control effects, a linearized model of a parallel AC-DC interconnected system, including a power modulation controller of HVDC link, is investigated by simulation study. Simulation results show that the proposed controller is not only effective in damping out frequency oscillations, but also capable of alleviating the transient frequency swing caused by a large load disturbance.

KEYWORDS: High-Voltage Direct Current (HVDC) Link, AC-DC Interconnected Power System, Stabilization of Frequency Oscillations, Overlapping Decompositions, Eigenvalue Assignment Method.

INTRODUCTION

Nowadays, significant growth of electric energy demand, in combination with financial and regulatory constraints, has forced power utilities to operate systems nearly at stability limits. Thus, greater reliance is being placed on the use of special control aids to enhance system security, facilitate economic design, and provide greater flexibility of system operation. In addition, deregulation in the power industry and opening of the market for delivery of cheaper energy to customer are creating additional requirements for the operation of power systems.[1, 2] High qualities of ancillary services[3, 4] in power system such as frequency control and voltage control are also attractive options for power companies to offer their customers. In anticipation of these circumstances, advanced control strategies are much needed.[5, 6]

Recently, applications of power electronics devices in AC power systems provide attractive benefits of economics and innovative technologies.[7,8] In particular, High-Voltage Direct Current transmission link (HVDC link) offers major advantages in meeting these requirements,[8, 9] including long distance overhead bulk power transmission, transmission between unsynchronized AC systems, and marine cable transmission. Currently, the Electricity Generating Authority of Thailand (EGAT) is implementing the 300 MW, 300 kV, 100 km HVDC Interconnection project[10] to receive additional 300 MW power capacity from the Malaysian power system. In addition, one sophisticated advantage of HVDC link is the enhanced damping of AC transmission using power modulation via an HVDC link in a parallel AC-DC interconnected power system.[8, 9] When an AC power system is subjected to load disturbance, the system frequency may be considerably perturbed from the operating frequency. This may cause severe problems in system frequency oscillations. The deviation of frequency oscillations, that exceed the normal limit, directly interrupts the operation of power system. Moreover, the frequency oscillations may experience serious stability problems usually in the form of low frequency oscillations due to insufficient system damping.[11] To overcome this problem, this paper not only takes the advantage of power modulation control offered by HVDC link to enhance the system damping, but also extends to stabilize frequency oscillations in an AC power system. By utilizing the interconnections between AC power systems as control channels of power modulation of HVDC link, this creates a new application of the HVDC link to stabilize frequency oscillations. The proposed control can also be coordinated with conventional governor control for greater efficiency.

For the organization of this paper, first, problem formulation and practical motivation of proposed control will be explained. Then systematic design of the power modulation controller of HVDC link is described. Subsequently, the designed controller is evaluated in a linearized model of the power system by simulation study.

Problem Formulation and Practical Motivation of Proposed Control

Fig 1 shows the two-area interconnected system via parallel AC-DC links. This study system is used to explain the practical motivation of the proposed control. The HVDC link consists mainly of a rectifier at the area 2 side, an inverter at the area 1 side and a DC transmission line.

In this system, it is assumed that, originally, area 2 has supplied power P_{AC} via only an AC line to an area 1. Next, there are installations of large loads with sudden change, for example a magnetic levitation transportation, large steel mills or arc-furnace factories in area 1. Therefore, the demand for electric power in area 1 increases. Furthermore, these large load changes also cause a serious problem of frequency oscillations in area 1. In addition, many Independent Power Producers, (IPPs) that do not have sufficient frequency control abilities, have also been concentrated in area 1. This implies that the capabilities of frequency control of governors in area 1 are not enough. Accordingly, the governors in area 1 are not capable of stabilizing the frequency oscillations. On the other hand, area 2 has enough frequency control capability to compensate for area 1. Therefore, area 2 has an HVDC link installed in parallel with an AC tie-line in order to supply more power to area 1. In addition, area 2 offers stabilization of frequency oscillations to area 1 via an HVDC link. By regarding the interconnections between both areas as control channels of HVDC link, the DC tie-line power modulation is capable of stabilizing frequency oscillations of area 1 by complimentarily utilizing the control capability of area 2. According to the proposed control, the power system that has a large capability of frequency control is able to offer the service of frequency stabilization for other interconnected areas that do not have sufficient capabilities. The proposed control strategy can also be expected as a new ancillary service for stabilizing frequency oscillations in future deregulated power systems. To implement the proposed control in this study system, the design of the power modulation controller of HVDC link will be explained in the following section.

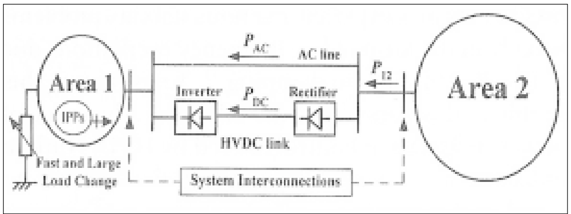

Fig 1. An HVDC link in a Parallel AC-DC Interconnected Power System.

Design of Power Modulation Controller by HVDC Link

Coordinated Control of HVDC Link and Governors

To simplify the control design of the power modulation controller, the concept of coordinated control of HVDC link and governors will be explained. The HVDC link is superior to the governor which is a conventional frequency control system in terms of high-speed performance. Based on this different speed performance, a coordinated control of HVDC link and governors is as follows. When some sudden load disturbances occur in an area, an HVDC link quickly starts the control system to suppress the peak value of transient frequency deviation. Subsequently, governors eliminate the steady state error of the frequency deviation. Another advantage in considering the different speed performance is that the dynamics of governors in both areas can be neglected in the control design of HVDC link for simplicity.

Control Design

The linearized model of a two-area interconnected system[12] including the dynamic of power modulation controller of HVDC link is delineated in Fig 2 where the dynamics of governors in both areas are eliminated. The power modulation controller is modeled as a proportional controller of active power.[13] It should be noted that the power modulation output of HVDC link (ΔP_{DC}), acting positively on an area, reacts negatively on another area in an interconnected system. ΔP_{DC}, therefore, flows into both areas with different sign (+, -), simultaneously. The time constant T_{DC} of proportional controller is set appropriately at 0.05 [sec][13] in the simulation study. Here, to simplify the control design, the state equation of the system in Fig 2 where the time constant T_{DC} is ignored, can be expressed as

$$S\ :\ \begin{bmatrix}\Delta\dot{f}_1\\ \Delta\dot{P}_{AC}\\ \Delta\dot{f}_2\end{bmatrix}=\begin{bmatrix}-D_1/M_1 & -1/M_1 & 0\\ 2\pi T_{12} & 0 & -2\pi T_{12}\\ 0 & A_{12}/M_2 & -D_2/M_2\end{bmatrix}\begin{bmatrix}\Delta f_1\\ \Delta P_{AC}\\ \Delta f_2\end{bmatrix}+\begin{bmatrix}-1/M_1\\ 0\\ A_{12}/M_2\end{bmatrix}\Delta P_{DC} \qquad (1)$$

Note that (1) is referred to as system "*S*". The variables and parameters of in Fig 2 are defined as follows. Δf_1, Δf_2 are frequency deviations of areas 1 and 2 respectively. ΔP_{AC} is an AC tie line power deviation between areas 1 and 2. ΔP_{DC} is a power modulation by HVDC link. ΔP_{12} is the total tie line power deviations ($\Delta P_{AC} + \Delta P_{DC}$). M_1, M_2 are inertia constants of areas 1 and 2. D_1, D_2 are damping coefficients of areas 1 and 2. A_{12} is an area capacity ratio between areas 1 and 2.

Here, the control scheme for power modulation of HVDC link (ΔP_{DC}) is designed by the eigenvalue assignment method, so that the dynamic aspect of the inter-area oscillation mode between areas 1 and 2 is specified. This mode can be explicitly expressed after applying the variable transformation[14]

$$Y = WX \qquad (2)$$

where, W is a transformation matrix, Y is the transformed state vector, and X is the state vector in (1). Therefore, the transformed system can be expressed as

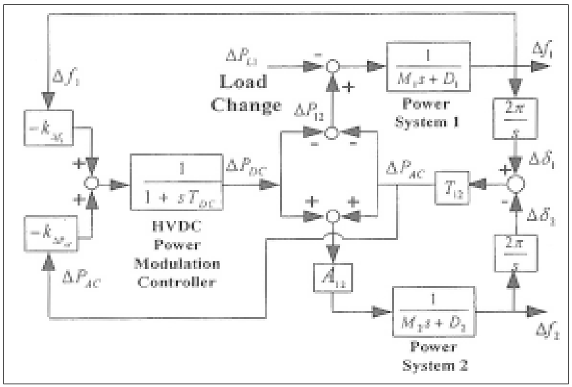

Fig 2. Linearized Model of Two-area System without Governors for Control Design of Power Modulation Controller of HVDC Link.

$$\begin{bmatrix}\Delta\dot{y}_1\\ \Delta\dot{y}_2\\ \Delta\dot{y}_3\end{bmatrix}=\begin{bmatrix}\alpha & \beta & 0\\ -\beta & \alpha & 0\\ 0 & 0 & \lambda\end{bmatrix}\begin{bmatrix}\Delta y_1\\ \Delta y_2\\ \Delta y_3\end{bmatrix}+\begin{bmatrix}\gamma_1\\ \gamma_2\\ 0\end{bmatrix}\Delta P_{DC} \qquad (3)$$

The transformed coefficient matrix of (3) consists of two diagonal blocks with complex eigenvalues $\alpha \pm j\beta$ and real eigenvalue λ. The complex eigenvalues physically correspond to the inter-area oscillation mode, while the real eigenvalue represents the system inertia center mode. From the physical view point, it should be noticed that the HVDC link between two areas is effective to stabilize the inter-area mode only, and therefore the input term of (3) corresponding to Δy_3 is zero. This means that the HVDC link cannot control the inertia center mode. To solve this crux, it is expected that the governors in both areas are responsible for suppressing the frequency deviation due to the inertia mode. Therefore, the power modulation controller of HVDC link is designed based on stabilizing the inter-area mode.

In order to extract the subsystem where the inter-area oscillation mode between areas 1 and 2 is preserved, from the system *S*, the technique of overlapping decompositions[15] is applied. First, the state variables of the original system *S* are classified into three groups, ie $x_1 = [\Delta f_1]$, $x_2 = [\Delta P_{AC}]$ and $x_3 = [\Delta f_2]$. According to the process of overlapping decompositions, the system *S* can be expanded as

$$\tilde{S}\ :\ \begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12} & 0 & a_{13}\\ a_{21} & a_{22} & 0 & a_{23}\\ a_{31} & 0 & a_{22} & a_{23}\\ a_{31} & 0 & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix}+\begin{bmatrix}b_{11}\\ b_{21}\\ b_{21}\\ b_{31}\end{bmatrix}\Delta P_{DC} \qquad (4)$$

where $z_1 = \left[x_1^T, x_1^T\right]^T$ and $z_2 = \left[x_2^T, x_2^T\right]^T$. The element a_{ij}, b_{i1} (i, j = 1, 2, 3) correspond to each element in the coefficient matrix in (1). The system $\tilde{S}$ in (4) can be decomposed into two interconnected overlapping subsystems,

$$\tilde{S}_1\ :\ \dot{z}_1=\left(\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}z_1+\begin{bmatrix}b_{11}\\ b_{21}\end{bmatrix}\Delta P_{DC}\right)+\begin{bmatrix}0 & a_{13}\\ 0 & a_{23}\end{bmatrix}z_2 \qquad (5)$$

$$\tilde{S}_2\ :\ \dot{z}_2=\left(\begin{bmatrix}a_{22} & a_{23}\\ a_{32} & a_{33}\end{bmatrix}z_2\right)+\begin{bmatrix}a_{21} & 0\\ a_{31} & 0\end{bmatrix}z_1+\begin{bmatrix}b_{21}\\ b_{31}\end{bmatrix}\Delta P_{DC} \qquad (6)$$

The state variable x_2, ie the AC tie line power deviation (ΔP_{DC}) between both areas, is repeatedly included in both subsystems, which implies "*Overlapping Decompositions*".

For system stabilization, consider two interconnected subsystems $\tilde{S}_1$ and $\tilde{S}_2$. The terms in the right hand sides of (5) and (6) can be separated into the decoupled subsystems (as indicated in the parenthesis in (5) and (6)) and the interconnected subsystems. As mentioned in Ikeda et al[15], if each decoupled subsystem can be stabilized by its own input, the asymptotic stability of the interconnected overlapping subsystems $\tilde{S}_1$ and $\tilde{S}_2$ are maintained. Moreover, the asymptotic stability of the original system S is also guaranteed. Consequently, the interactions with the interconnected subsystems in (5) and (6) are regarded as perturbations and are neglected during control design. As a result, the decoupled subsystems of $\tilde{S}_1$ and $\tilde{S}_2$ can be expressed as

$$\tilde{S}_{D1} \quad : \quad \dot{z}_1 = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} z_1 + \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix} \Delta P_{DC} \qquad (7)$$

$$\tilde{S}_{D2} \quad : \quad \dot{z}_2 = \begin{bmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{bmatrix} z_2 \qquad (8)$$

In (7) and (8), there is a control input ΔP_{DC} appearing only in subsystem $\tilde{S}_{D1}$. Here, the decoupled subsystem $\tilde{S}_{D1}$ is regarded as the designed system, which can be expressed as

$$\begin{bmatrix} \Delta \dot{f}_1 \\ \Delta \dot{P}_{AC} \end{bmatrix} = \begin{bmatrix} -D_1/M_1 & -1/M_1 \\ 2\pi T_{12} & 0 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{AC} \end{bmatrix} + \begin{bmatrix} -1/M_1 \\ 0 \end{bmatrix} \Delta P_{DC} \quad (9)$$

It can be verified that the eigenvalues of (9) are $\alpha \pm j\beta$, ie the inter-area oscillation mode in the system S. It should be noticed that by virtue of overlapping decompositions, the physical characteristic of the original system is still preserved after the process.

Here, the control purpose of HVDC link is to damp the peak value of frequency deviation after sudden load disturbance. Since the system (9) is the second-order oscillatory system, the percent overshoot $M_{P(new)}$ is available for the control specification. When the new value of percent overshoot is given, the new damping ratio ζ_{new} is calculated by

$$M_{P(new)} = \exp(-\zeta_{new}\pi / \sqrt{1-\zeta_{new}^2}) \qquad (10)$$

Next, to assign the new eigenvalues $\alpha_{new} \pm j\beta_{new}$, the new imaginary part (β_{new}) is specified at β. Thus, the new undamped natural frequency $\omega_{n(new)}$ can be determined by

$$\omega_{n(new)} = \beta_{new} / \sqrt{1-\zeta_{new}^2} \qquad (11)$$

As a result, the new real part α_{new} can be calculated by

$$\alpha_{new} = \zeta_{new}\omega_{n(new)} \qquad (12)$$

By eigenvalue assignment method, the feedback control scheme of ΔP_{DC} can be expressed as

$$\Delta P_{DC} = -k_{\Delta f_1}\Delta f_1 - k_{\Delta P_{AC}}\Delta P_{AC} \qquad (13)$$

Note that, the state feedback scheme is constructed by two measurable signals, ie a frequency deviation of area 1 and an AC tie-line power deviation. In this paper, even the control design is developed in a two-area interconnected system, the proposed design is applicable to a general multi-area interconnected system with any configuration.

Simulation Results and Discussion

In this paper, a two-area interconnected system (400 MW : 2,000 MW) with reheat steam turbine[12] is used to design and evaluate the effects of the power modulation controller of HVDC link. System data are given in an appendix. The simulation study is carried out by software Matlab[16], Simulink[17] and Control System Toolbox.[18]

Based on the minimum requirement of the North American Power Systems Interconnection Committee[19], the transient frequency swings should not exceed ± 0.02 Hz. To satisfy this requirement, after experimentally designing and testing the effects of controller, the desired percent overshoot $M_{P(new)}$ of the inter-area mode is appropriately selected at 1 %. The design results of power modulation controller are given in Table 1.

First, the effect of designed controller is evaluated in a system in Fig 2. Note that governors in both areas are not included in this system. It is assumed that for a step-load, such as a large steel mill and an arc-furnace factory[20], an increase of 4 MW (0.01 [p.u.MW]) occurs in an area 1 at $t = 1.0$ [sec]. Fig 3 indicates that the frequency oscillations (dotted line), which are composed of the inter-area mode and the inertia center mode, are very large and undamped. After an HVDC link is incorporated with an AC link, the magnitude of the first overshoot of frequency deviation is suppressed until less than 0.02 Hz, as expected by the design specification.

Although the oscillatory part representing the inter-area mode is stabilized completely, the frequency deviation corresponding to the influence of inertia mode continuously decreases and finally reaches a stead-state value. This is due to the difference between the load disturbance and the generation power that is still zero. In this case, governors are expected to solve this problem.

Next, to investigate the concept of coordinated control of HVDC link and governors, the conventional controllers of governors in both areas are included in this system as shown in Fig 4. In the area 1, in addition to a large load with fast change, the Generation Rate Constraints (GRC)[21] are also equipped with the turbines of both areas as shown in Fig 4. The rate of change in turbine power output with respect to time ($d(\Delta P_{t1})/dt$) is restricted as $-0.1/60 \le d(\Delta P_{t1})/dt \le 0.1/60$ [p u MW/sec]. As clarified in Kothari[21], the turbine equipped with GRC experiences large overshoot of frequency oscillations with a long settling time. This is due to an inadequate generation power during the occurrence of abrupt load change. This situation may emerge in a real power system if many IPPs with insufficient frequency control capabilities have been concentrated in the area 1. Here, a step-load disturbance of 0.01

Table 1. Results of Control Design.

Design Steps	Numerical Results
1. Eigenvalues of Inter-Area Mode (Before Control)	$\lambda_{1,2} = \underline{-0.0208} \pm j\,0.5601$ Percent Overshoot = 89 %
2. Design Specification	Desired Percent Overshoot $M_{P(new)} = 1$ %
3. New Eigenvalues (After Control)	$\lambda_{1,2} = \underline{-0.8211} \pm j\,0.5601$
4. State Feedback Control Scheme	$[k_{\Delta f_1}, k_{\Delta P_{AC}}] =$ [-0.3201, -2.144]

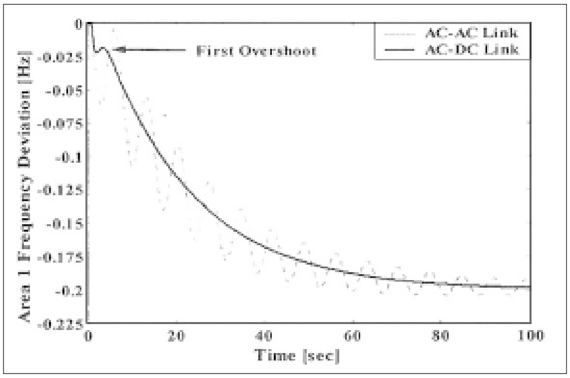

Fig 3. Frequency Deviation of Area 1 in case of no Governors.

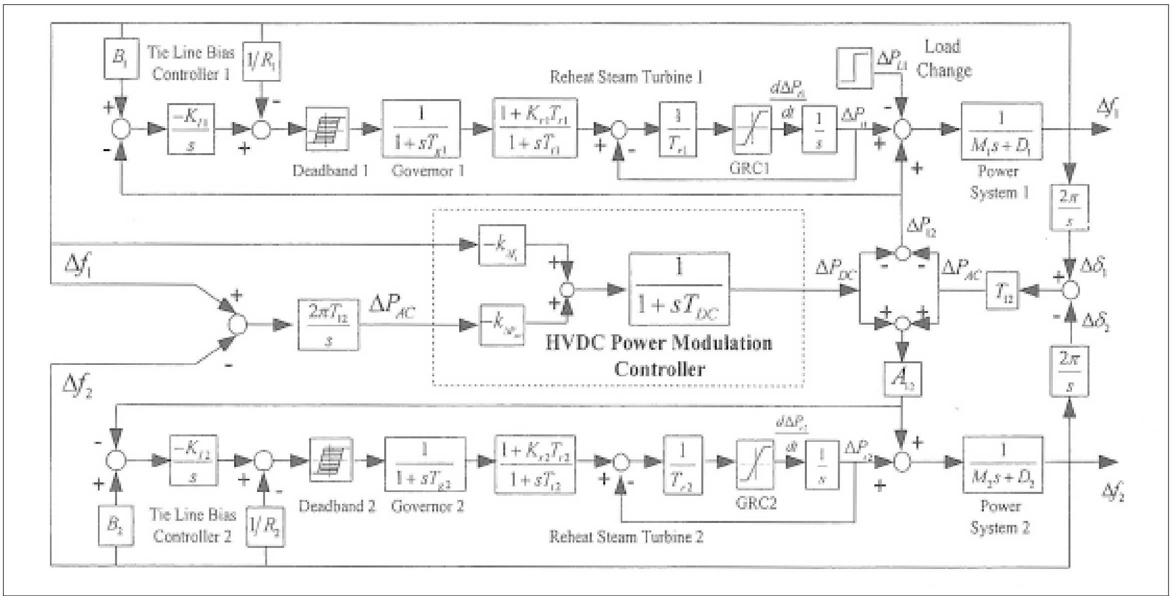

Fig 4. A Power Modulation Controller of HVDC link in a Linearized Model of Two-area System including Governors.

[p.u.MW] is applied to an area 1. As shown in Fig 5, after the suppression of peak frequency deviations of both areas by HVDC link, governors in both areas continue to eliminate the steady state error of frequency deviations slowly, as expected.

It is envisaged that the magnitude of the peak value of frequency deviation of area 1 is reduced from about 0.05 Hz to less than 0.02 Hz. These results clearly confirm the coordinated control of HVDC link and governors. Moreover, the tie-line power deviation is improved considerably by an HVDC link as depicted in Fig 6 (left). For the required MW capacity of power modulation controller, it is evaluated from the peak value of power output deviation of HVDC link, ΔP_{DC}. As shown in Fig 6 (right), the necessary MW capacity of power modulation controller is about 0.008 [p.u.MW], which is less than the size of load change.

Finally, the changing load in area 1 assumed here consists of three different components in the frequency domain[22], one of which has a frequency corresponding to the inter-area oscillation mode (0.56 rad/sec) as

$$\Delta P_{L1}(\omega t) = 0.005\sin(0.2t) + 0.003\sin(0.56t - \pi) - 0.004\sin(0.9t + \pi/4)\ \ [\text{p u MW}] \qquad (14)$$

The periodic load change starts at $t = 0$ [sec]. As depicted in Fig 7, the responses Δf_1 and Δf_2 severely fluctuate with an increase in amplitude in case of AC-AC link. On the contrary, after applying an HVDC link, the frequency oscillations are practically damped out. These frequency deviations are in ± 0.02 Hz. These results clearly confirm the proposed power modulation controller of HVDC link is very effective in damping out oscillations caused by load disturbances.

Conclusions

In this paper, a sophisticated method for stabilizing frequency oscillations in a parallel AC-DC

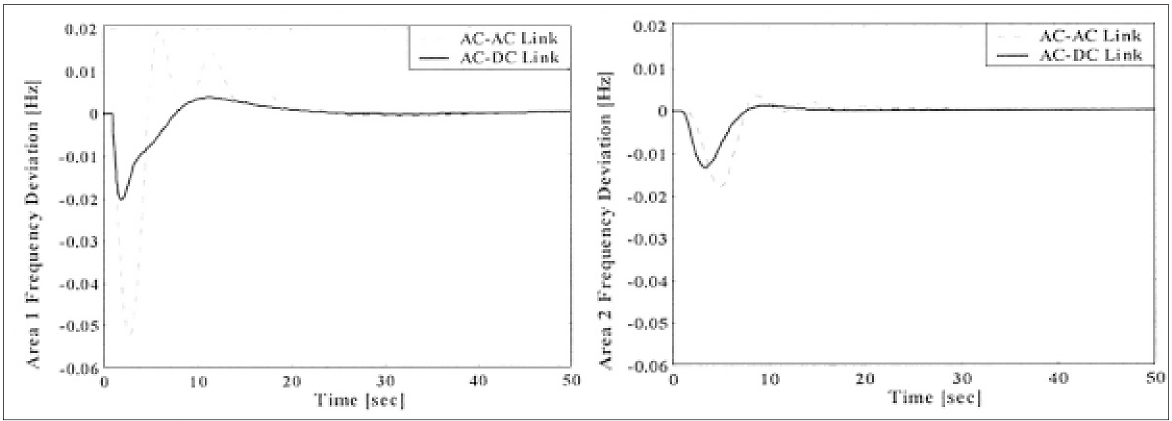

Fig 5. Frequency Deviations of Area 1 (left) and Area 2 (right) with governors (step load).

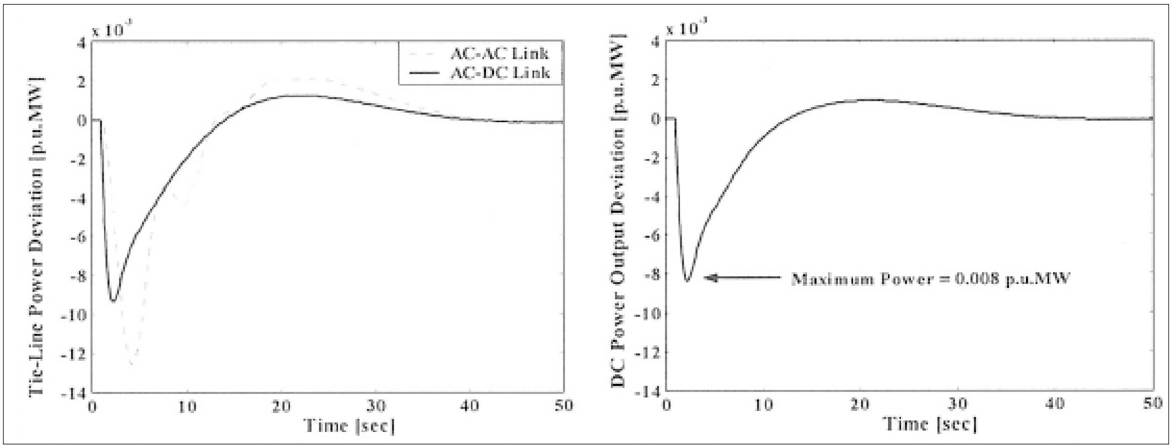

Fig 6. Tie-Line Power Deviations (left) and Power Output Deviation of HVDC link (right).

interconnected power system via an HVDC link has been proposed. The main outcomes from this paper can be summarized as follows.

- By utilizing the system interconnections as the control channels of HVDC link, the tie-line power modulation of HVDC link creates a new application of HVDC link to stabilize frequency oscillations in AC power systems.
- By applying the technique of overlapping decompositions and the eigenvalue assignment method, a design method of power modulation controller of HVDC link can be systematically developed. Although the design method is developed in the two-area system, it can be directly applied to a general multi-area interconnected power system with any configuration.
- In a study of two-area interconnected system, the control scheme of power modulation controller is simply constructed by a state feedback of two measurable signals. Therefore, it is easy to implement in a real system.
- By simulation study, the designed controller is very effective in suppressing the frequency oscillations caused by rapid load disturbances. In addition, it can be coordinated with the conventional governors effectively.

For further study, the proposed control design of HVDC link will be extended to stabilization of frequency oscillations in a multi-area interconnected power system with any configuration, including longitudinal and radial loops.

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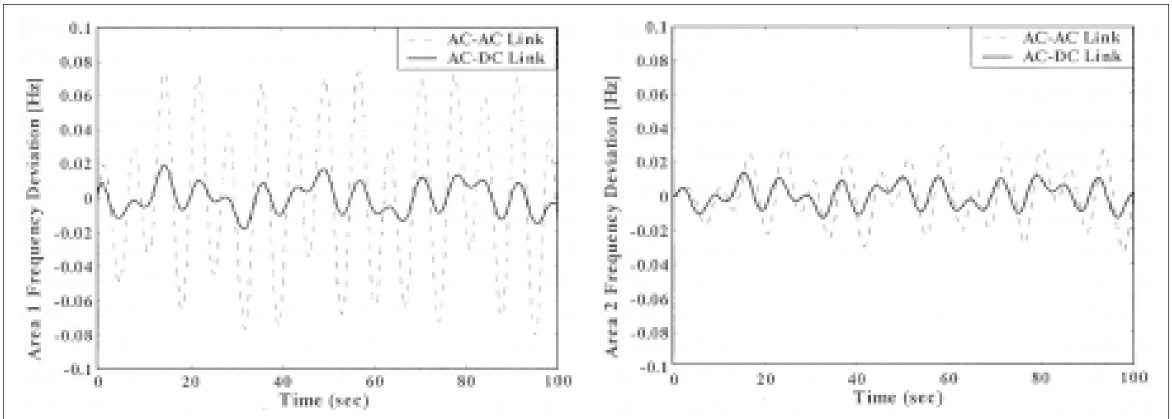

Fig 7. Frequency Deviations of Area 1 (left) and Area 2 (right) (periodic load changes).

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APPENDIX

System Data[12]

Inertia Constant	$M_1 = 0.2, M_2 = 0.167$	[p u MWs/Hz]
Damping Coefficient	$D_1 = D_2 = 0.00833$	[p u MW/Hz]
Turbine Gain	$K_{r1} = K_{r2} = 0.333$	
Reheat Turbine Time Constant	$T_{r1} = T_{r2} = 10$	[sec]
Turbine Time Constant	$T_{t1} = T_{t2} = 0.3$	[sec]
Governor Time Constant	$T_{g1} = T_{g2} = 0.2$	[sec]
Regulation Ratio	$R_1 = R_2 = 2.4$	[Hz/p u MW]
Bias Coefficient	$B_1 = B_2 = 0.2$	[p u MW/Hz]
Integral Controller Gain	$K_{I1} = K_{I2} = 0.4$	[1/sec]
Area Capacity Ratio	$A_{12} = 0.2$	
Synchronizing Power Coefficient (parallel AC-AC lines)	$T_{12AC} = 0.02$	[MW/rad]
Synchronizing Power Coefficient (parallel AC-DC lines)	$T_{12DC} = 0.01$	[MW/rad]