DESIGN OF A HVDC-BASED CONTROLLER FOR LOAD CHANGE COMPENSATION AND STABILIZATION OF INTER-AREA OSCILLATIONS

I. Ngamroo

Electrical Power Engineering Program,
Sirindhorn International Institute of Technology,
Thammasat University, Pathumthani, 12121 Thailand
E-mail: ngamroo@siit.tu.ac.th

Received 12 November 2002, Accepted 26 March 2003

ABSTRACT

As an interconnected power system via a High-Voltage Direct Current (HVDC) link is subjected to a rapid load change with the frequency of inter-area oscillation mode, system frequency and tie line power may be severely disturbed and oscillate. To compensate for the rapid load change and stabilize both frequency and tie line power oscillations due to the inter-area mode, the dynamic power flow control via a HVDC link can be exploited. To implement this concept, a new design method of HVDC-based controller is proposed. To grasp a physical characteristic of the inter-area oscillation frequency, the technique of overlapping decompositions is employed to achieve the subsystem embedded with the inter-area mode. Consequently, the second-order lead/lag controller of HVDC link can be designed in this subsystem. To acquire the desired overshoot of frequency oscillations, the parameters of the controller are automatically optimized by the Tabu Search (TS) algorithm. The effectiveness of the designed controller is investigated in a three-area longitudinal interconnected power system which represents the interconnection between the south of Thailand and Malaysia power systems.

Keywords : *High-Voltage Direct Current (HVDC) Link, Load Change Compensation, Inter-Area Oscillations, Power System Stabilization, Overlapping Decompositions, Tabu Search*

1. INTRODUCTION

At present, a significant growth of electric energy demand, in combination with financial and regulatory constraints, has forced power utilities to operate systems near stability limits. Thus, a great 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. Under this circumstance, a High-Voltage Direct Current (HVDC) link offers major advantages in meeting these requirements^{1,2}, e.g., a long distance overhead bulk power transmission, an enhancement of damping in AC power system, a back-to-back asynchronous interconnection etc. Even in Thailand, the Electricity Generating Authority of Thailand (EGAT) has already implemented the

300 MW, 300 kV, 100 km HVDC Interconnection project to receive additional 300 MW from the Malaysian power system. In addition, a HVDC link can be applied as an energy transfer device from one power system to compensate for rapid load changes in other systems. Subject to large loads with sudden change such as a magnetic levitation transporter, a testing plant for nuclear fusion or even an ordinary scale factory like a steel manufacturer etc., the frequency of AC power system and the power flow in a tie line may be considerably perturbed from the normal operating values. This may lead to severe problems of frequency and tie line power oscillations due to an insufficient compensation of load change. The deviations of frequency and tie line power oscillations that exceed the normal limit, directly interrupt the operation of power system. Moreover, if the frequency of changing load is in the vicinity of the inter-area oscillation mode, system frequency and tie line power oscillations may experience a serious stability problem due to an inadequate system damping³. Under this situation, the conventional frequency control, i.e. a governor, may no longer be able to compensate for rapid load change due to its slow response. In addition, since the governor has no any stabilizing effects on the inter-area oscillation mode, the alleviation of frequency and tie line power oscillations can not be expected⁴.

To overcome this crux, this paper takes the advantage of the fast control offered by a HVDC link not only to compensate for the fast load change but also to stabilize the frequency and tie line power oscillations due to the inter-area mode. To implement this concept, a new design method of HVDC-based controller is presented. In the proposed design, the technique of overlapping decompositions⁵ is used to obtain the subsystem where the physical characteristic of inter-area oscillation mode is embedded. As a result, a HVDC-based controller can be designed to serve two purposes in this subsystem. In this study, a HVDC-based controller is practically in form of a second-order conventional lead/lag compensator. The control parameters are automatically optimized by the tabu search (TS) algorithm⁶. The effectiveness of the designed controller is evaluated in a three-area longitudinal interconnected power system which representing the interconnected power systems between Thailand and Malaysia.

The organizations of this paper are as follows. Section 2 describes the problem statement. Next, the design methodology is presented in section 3. Subsequently, the TS algorithm is given in section 4. The experimental results are discussed in section 5. Finally, the main outcome from this study is summarized.

2. PROBLEM STATEMENT

Figure 1 : A HVDC System in a Three-area Longitudinal Interconnected Power System.

The three-area interconnected power system with longitudinal configuration is shown in Fig. 1. This study system emulates the interconnected power systems between Thailand and Malaysia. Area 1 represents the greater Bangkok power system network including the northern and northeastern parts of Thailand. The south of Thailand denoted by the area 2 is connected to the Malaysian power system (area 3) via a HVDC link. In a real situation, an area 2 is connected to an area 1 via a weak and long tie line. In addition, large loads with rapid change, which are considered as system disturbances, frequently occur in area 2. However, a power generation in area 2 is not enough to compensate for changing loads. Thus, the bulk power transfer from an area 1 is required during the peak load period. Nevertheless, the power transfer in a tie line 1-2 is inevitably constrained by thermal and stability limits. Power transmission from other sources is significant required. Due to insufficient load compensation, a severe frequency oscillation becomes a serious stability problem in area 2. Especially, if the frequency of the changing load is in the vicinity of the inter-area mode between areas 1 and 2, this may drastically cause both frequency and tie line power oscillations.

On the other hand, an area 3 has sufficiently the frequency control capability. During the occurrence of load disturbances, a HVDC link is used as the energy transfer device from area 3 to area 2. The tie line power flow control of HVDC link via the area interconnections can be applied to compensate for the fast load change as well as stabilize the frequency and tie line power oscillations due to the inter-area mode. Therefore, a HVDC-based controller is designed to solve this problem.

3. DESIGN OF HVDC-BASED CONTROLLER

Figure 2 : A Linearized AC-DC Interconnected Power System Model without Governors.

The linearized model of a three-area interconnected power system³ around the normal operating condition for design of HVDC-based controller is shown in Fig. 2. The HVDC link is represented by the active power controller with a time constant $T_{DC} = 0.05 \text{ sec}$ ⁷. Since the response of HVDC link is much faster than that of governor, the dynamics of governors are ignored in this model. For simplicity, the linearized state equation with neglecting T_{DC} can be expressed as

$$S : \begin{bmatrix} \Delta \dot{f}_1 \\ \Delta \dot{P}_{T12} \\ \Delta \dot{f}_2 \\ \Delta \dot{f}_3 \end{bmatrix} = \begin{bmatrix} -D_1/M_1 & -a_{12}/M_1 & 0 & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} & 0 \\ 0 & 1/M_2 & -D_2/M_2 & 0 \\ 0 & 0 & 0 & -D_3/M_3 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \\ \Delta f_2 \\ \Delta f_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ a_{23}/M_2 \\ -1/M_3 \end{bmatrix} \Delta P_{DC} \quad (1)$$

where $\Delta f_1, \Delta f_2, \Delta f_3$ are frequency deviations in areas 1, 2 and 3, respectively. ΔP_{T12} is a tie line power deviation. ΔP_{DC} is a power flow controlled by a HVDC link. Δu_{DC} is a control signal from a HVDC-based controller. System parameters are given in part 5.

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 decompositions⁵ is applied. First, the state variables of S , are classified into three groups, i.e., $\chi_1 = [\Delta f_1]$, $\chi_2 = [\Delta P_{T12}]$ and $\chi_3 = [\Delta f_2, \Delta f_3]^T$. Therefore, the system S can be expressed in compact form as

$$S : \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \end{bmatrix} \Delta P_{DC} \quad (2)$$

where $z_1 = [x_1^T, x_2^T]^T$ and $z_2 = [x_2^T, x_3^T]^T$. The sub-matrices A_{ij} and B_{il} , ($i, j = 1, 2, 3$) have appropriate dimensions identical to the corresponding state and input vectors. According to the process of overlapping decompositions, the system S can be expanded as

$$\tilde{S} : \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & A_{13} \\ A_{21} & A_{22} & 0 & A_{23} \\ A_{21} & 0 & A_{22} & A_{23} \\ A_{31} & 0 & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \\ B_{21} \\ B_{31} \end{bmatrix} \Delta P_{DC} \quad (3)$$

The system $\tilde{S}$ in (3) can be decomposed into two interconnected overlapping subsystems,

$$\tilde{S}_1 : \dot{z}_1 = \left(\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} z_1 + \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} \Delta P_{DC} \right) + \begin{bmatrix} 0 & A_{13} \\ 0 & A_{23} \end{bmatrix} z_2 \quad (4)$$

$$\tilde{S}_2 : \dot{z}_2 = \left(\begin{bmatrix} A_{22} & A_{23} \\ A_{32} & A_{33} \end{bmatrix} z_2 + \begin{bmatrix} B_{21} \\ B_{31} \end{bmatrix} \Delta P_{DC} \right) + \begin{bmatrix} A_{21} & 0 \\ A_{31} & 0 \end{bmatrix} z_1 \quad (5)$$

The state variable x_2 , i.e. the tie line power deviation between areas 1 and 2 (ΔP_{T12}), 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 (4) and (5) can be separated into the decoupled subsystems (as indicated in the parenthesis in (4) and (5)) and the interconnection subsystems. As mentioned in a reference 5, if each decoupled subsystem can be stabilized by its own input, the asymptotic stability of the interconnected overlapping subsystems $\tilde{S}_1$ and $\tilde{S}_2$ and are maintained, moreover the asymptotic stability of the original system S is also guaranteed. Consequently, the interactions with the interconnection subsystems in (4) and (5) are regarded as perturbations and are neglected during control design. As a result, the decoupled subsystems of $\tilde{S}_1$ and $\tilde{S}_2$ and can be expressed as

$$\tilde{S}_{D1} : \begin{bmatrix} \Delta \dot{f}_1 \\ \Delta \dot{P}_{T12} \end{bmatrix} = \begin{bmatrix} -D_1/M_1 & -a_{12}/M_1 \\ 2\pi T_{12} & 0 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Delta P_{DC} \quad (6)$$

$$\tilde{S}_{D2} : \begin{bmatrix} \Delta \dot{P}_{T12} \\ \Delta \dot{f}_2 \\ \Delta \dot{f}_3 \end{bmatrix} = \begin{bmatrix} 0 & -2\pi T_{12} & 0 \\ 1/M_2 & -D_2/M_2 & 0 \\ 0 & 0 & -D_3/M_3 \end{bmatrix} \begin{bmatrix} \Delta P_{T12} \\ \Delta f_2 \\ \Delta f_3 \end{bmatrix} + \begin{bmatrix} 0 \\ a_{23}/M_2 \\ -1/M_3 \end{bmatrix} \Delta P_{DC} \quad (7)$$

Figure 3 : A HVDC-Based Controller.

In (6) and (7) there is a control input ΔP_{DC} appearing only in the subsystem $\tilde{S}_{D2}$. Here, the decoupled subsystem $\tilde{S}_{D2}$ is employed to design a HVDC-based controller. Note that the eigenvalues corresponding to the inter-area oscillation mode between areas 1 and 2 in (7) are almost identical to that of (1). This exhibits the merit of overlapping decompositions that the physical characteristic of the original system is still preserved in the decoupled subsystem.

In this study, the structure of HVDC-based controller is in form of a second-order lead/lag compensator as depicted in Fig.3. There are five parameters for the designed controller consisting of time constants T_1, T_2, T_3, T_4 and a stabilization gain K . The control purpose of the designed controller is to damp the peak value of frequency oscillation in area 2 after the load disturbance. Therefore, Δf_2 is selected as the input signal of the controller. To achieve this purpose, TS is employed for parameters optimization. The objective function (F) used here is based on the design specification that requires the maximum overshoot of Δf_2 against the step load to be. $M_{p, design}$. Therefore, the optimization problem can be formulated as follows.

$$\begin{aligned}
&\text{Minimize} && F = |M_{p,design} - M_{p,actual}| \\
&\text{Subject to} && K_{\min} \leq K \leq K_{\max} \\
&&& T_{i,\min} \leq T_i \leq T_{i,\max}
\end{aligned} \tag{8}$$

where $M_{p,actual}$ is the actual maximum overshoot of Δf_2 against the step load for each trial solution. $K_{\max}$ and $K_{\min}$ are maximum and minimum stabilization gains which are set to 50 and 0.1, respectively. $T_{i,\max}$ and $T_{i,\min}$ are maximum and minimum time constants which are set to 5 and 0.01, respectively.

4. TABU SEARCH ALGORITHM

As a promising tool, TS is an iterative improvement procedure, which can start from any feasible initial solution and attempt to find a better solution. TS is a heuristic method that is based on a local search method with the ability to escape from being trapped in local optima⁶. Following, the basic components of TS are briefly described. Subsequently, the procedure of TS is presented.

4.1 TS Components

Encoding and Decoding Scheme : The concatenated encoding method is employed as shown in Fig. 4. Each parameter is encoded in a binary string normalized over its range. This encoding method stacks each normalized string in series with each other to construct the string individual. The same number of n bits is used to represent each parameter string.

Figure 4 : Example of 30 bits concatenated encoding scheme.

On the other hand, the actual value of each parameter can be obtained by (9) for objective function evaluation.

$$P_i = P_{i,\min} + \frac{B_i \times (P_{i,\max} - P_{i,\min})}{2^n - 1} \tag{9}$$

where P_i is the actual value of the i -th parameter, $P_{i,\max}$ and $P_{i,\min}$ are the maximum and minimum value of the i -th parameter. B_i is the decimal integer value of binary string of the i -th parameter. In this paper, 10 bits are used to represent each parameter.

Trial Solution Generation : In practice, a trial solution is generated by flipping one bit of the binary string individual at a time. Figure 5 conceptually demonstrates the process. A neighborhood solution space (NS) is defined as the maximum number of trial solutions per iteration.

Initial Solution: 100101101011000110101110010011
 Trial Solution 1: 000101101011000110101110010011
 Trial Solution 2: 110101101011000110101110010011
 Trial Solution 3: 101101101011000110101110010011

Figure 5 : Concept of Trial Solution Generation.

In this paper, NS is set up to 95% of the total number of bits used ($\lfloor 0.95 \times n \times N \rfloor$) where N is a number of searched parameter.

Tabu List Restriction : As an adaptive memory, a tabu list (TL) is used to control the search process to avoid being trapped in local optima. Systematically, TL keeps attributes (bit positions) that created the best solution of past iterations for a certain period so that they are fixed and cannot be used to create new solution candidates. As the iteration proceeds, TL stores a new attribute as a fixed attribute and releases the oldest one as shown in Fig. 6.

Figure 6 : Mechanism of Tabu List.

As the only control parameter of TS⁶, the size of TL, or so-called the tabu length, is dependent to the application. However, observing the quality of the solution can identify the appropriate size of the tabu length. If the size of the tabu length is too small, the cycling of solution occurs in the search process. On the other hand, if the size is too large, the search process is too restricted and may deteriorate the quality of the solution. In this paper, the tabu length is set to $\lfloor 0.7 \times n \times N \rfloor$.

Termination criterion : This criterion is set to allow the search process to stop and return the best solution. In this paper, TS will stop if the maximum allowable number of iteration is reached.

4.2 TS Procedure

To apply TS for parameter optimization, the initial feasible solution is generated arbitrarily. A trial solution is created and examined if TL does not restrict it. The best solution is updated during the search process until the termination criterion is satisfied. The following notations are defined for the TS procedure:

- TL : the tabu list
 NS : the neighborhood solution space
 F(X) : the objective function of solution X
 F_b^k : the best objective function at iteration k
 X_o^k : the initial feasible solution at iteration k
 X_m^k : a trial m solution at iteration k
 X_{cb}^k : the current best trial solution of iteration k
 X_b : the best solution reached
 k_{max} : the maximum allowable number of iterations.

The TS procedure can be described as follows:

1. Read the constraints of searched parameters, the initial feasible solution, and the design specification.
2. Specify the length of TL, k_{max} , and the size of NS.
3. Initialize iteration counter k to zero and empty TL.
4. Execute TS procedure:
 - 4.1. Initialize the trial counter m to zero.
 - 4.2. Generate a trial solution from X_m^k from X_o^k .
 - 4.3. If X_m^k is not feasible, go to 4.8.
 - 4.4. If X_m^k is the first feasible solution, set $X_{cb}^k = X_m^k$.
 - 4.5. If X_m^k is tabued, then go to 4.8.
 - 4.6. If $F(X_m^k) < F(X_{cb}^k)$, set $X_{cb}^k = X_m^k$.
 - 4.7. If $F(X_m^k) < F(X_b)$, set $X_b = X_m^k$.
 - 4.8. If m is less than NS, $m = m + 1$ and go to 4.2.
 - 4.9. If there is no feasible solution, set $X_o^{k+1} = X_b$. Otherwise, set $X_o^{k+1} = X_{cb}^k$, and update TL.
5. If $k < k_{max}$, then $k = k + 1$, and go to 4.
6. TS is terminated and X_b is the best solution found.

5. EXPERIMENTAL RESULTS

Based on the proposed method, a HVDC-based controller is designed in a three-area interconnected system. System data are given in table 1. The design specification $M_{p,design}$ is set to 25% of that of no controller installed. For TS, the size of TL is set to 35 and the maximum allowable number of iterations is 100.

Table 1 : System Parameters.

System capacity ratio = 10 : 2 : 6

Inertia constant [pu.MW.s/Hz]	$M_1 = 0.167$	$M_2 = 0.15$	$M_3 = 0.2$
Damping coefficient [pu.MW/Hz]	$D_1 = 0.00833$	$D_2 = 0.005$	$D_3 = 0.006$
Synchronizing coefficient [pu.MW/rad]	$T_{12} = 0.064$		
Area capacity ratio	$a_{12} = 0.2$	$a_{23} = 3$	
Turbine time constant [s]	$T_{t1} = 0.3$	$T_{t2} = 0.25$	$T_{t3} = 0.25$
Governor time constant [s]	$T_{g1} = 0.08$	$T_{g2} = 0.1$	$T_{g3} = 0.1$
Regulation ratio [Hz/pu MW]	$R_1 = 2.4$	$R_2 = 2.4$	$R_3 = 2.4$
Bias coefficient [pu.MW/Hz]	$B_1 = 0.5$	$B_2 = 0.5$	$B_3 = 0.5$
Integral gain [1/s]	$K_{I1} = 0.5$	$K_{I2} = 0.5$	$K_{I3} = 0.5$

Table 2 : Eigenvalues of The Original System (1) and The Subsystem (7).

Original System (1)	Subsystem (7)
$\lambda_1 = -0.0474$	-
$\lambda_{2,3} = -0.0179 \pm j1.78$ ($\zeta = 0.0101, f = 0.283$ Hz)	$\lambda_{2,3} = -0.0167 \pm j1.64$ ($\zeta = 0.0102, f = 0.26$ Hz)
$\lambda_4 = -0.03$	$\lambda_4 = -0.03$

First, the subsystem (7) is extracted from the original system (1) by using overlapping decompositions. Table 2 compares eigenvalues of (1) and (7). In (1), only $\lambda_{2,3}$ are complex eigenvalues. Therefore, they correspond to the inter-area oscillation mode between areas 1 and 2. After the process of overlapping decompositions, the damping ratios (ζ) and the oscillation frequencies (f) of the inter-area mode in both systems have rarely changed. This clarifies that the physical characteristics of the inter-area mode are still preserved in (7). After applying the TS algorithm, a HVDC-based controller can be expressed as

$$\Delta u_{DC} = -4.9778 \frac{(0.5368s+1)(0.5709s+1)}{(2.9806s+1)(2.9952s+1)} \Delta f_2 \quad (10)$$

The effect of HVDC-based controller installed in (7) is illustrated in Fig.7, in comparison with the case of no controller installed. Subject to a 0.01 [pu.MW] step load, the maximum overshoot of area 1 frequency deviation is satisfactorily reduced from 0.04 [Hz] to 0.011 [Hz], that is about 25% of the original value.

Next, the coordinated control of HVDC-based controller and conventional governors is investigated in the power system model including governor³ as depicted in Fig. 8. All parameters are given in table 1. Note that, the dynamic characteristic of HVDC link representing by the time constant

Figure 7 : Area 2 Frequency Deviation in the Subsystem (7).

Figure 8 : Linearized System Model of Area i Including Governor.

T_{DC} is also taken into consideration in the simulation study. The effectiveness of designed controller is evaluated under several load disturbances and various system operating conditions as follows.

Case 1. Step load change

It is assumed that a step load, e.g. large steel mill and arc-furnace factories⁸, increase of 0.01 [pu.MW] occurs in an area 2 at $t = 1.0$ [sec]. Figures 9-12 illustrates the control effects of the designed controller. First, consider the control area 2 in Fig.10, the overshoot of frequency deviation in area 2 is rapidly suppressed from that in case of no controller. Subsequently, the steady-state error is slowly eliminated by governors. This implies the coordinated control effects of both devices. In addition, as depicted in Fig.9, the frequency deviation in area 1 is also improved. The frequency in area 3 shown in Fig.11, however, is inevitably deviated from the operating frequency about 0.007 [Hz] in case of with designed controller. This is due to the rapid transferred energy from area 3 to area 2 by a HVDC link. In practice, this small deviation of frequency is acceptable. In addition, the tie line power deviation (ΔP_{T12}) between areas 1

Figure 9: Area 1 Frequency Deviation.

Figure 10: Area 2 Frequency Deviation.

Figure 11: Area 3 Frequency Deviation.

Figure 12: Tie Line 1-2 Power Deviation and Power Output Deviation of HVDC.

and 2 is effectively damped as delineated in Fig.12. The peak value of ΔP_{T12} is reduced from 0.0065 to 0.0017 [pu.MW]. For the maximum value of power flow control by a HVDC controller (ΔP_{DC}), it is only 0.0032 [pu.MW], which is about 32% of the load change. This signifies that the necessary MW capacity of HVDC-based controller is much less than the size of step load.

Case 2. Sinusoidal load change at the frequency of inter-area oscillation mode

It is assumed that the sinusoidal load change is installed in an area 2. The frequency oscillation of this load is equal to that of the inter-area oscillation mode between areas 1 and 2. Accordingly, this load change is represented by

$$\Delta P_{1,2}(\omega t) = 0.01 \sin(2\pi f t) \quad (11)$$

where the frequency of the inter-area oscillation mode (f) is 0.283 Hz (see Table 2). Figures 13-15 show the frequency deviations of areas 1, 2 and 3, respectively. In case of no controller, the sinusoidal load change causes the severe oscillations at the frequency of inter-area mode.

After the controller is operated, the frequency oscillations are suppressed significantly. The tie line 1-2 power deviation depicted in Fig. 16, is also stabilized effectively. Furthermore, the maximum power output of HVDC- based controller (Fig. 17) is about 0.0025 pu.MW which is much less than the magnitude of sinusoidal load change.

Figure 13: Area 1 Frequency Deviation.

Figure 14: Area 2 Frequency Deviation.

Figure 15: Area 3 Frequency Deviation.

Figure 16: Tie Line 1-2 Power Deviation.

Figure 17: DC Power Output Deviation.

Case 3. Combined sinusoidal load changes

The changing load assumed here consists of three different components in the frequency domain, one of which has a frequency of the inter-area mode as follows.

$$\Delta P_{L2}(\omega t) = 0.004 \sin(2\pi \times 0.283t) + 0.003 \sin(2\pi \times 0.79t - 2\pi/3) - 0.005 \sin(2\pi \times 0.47t + \pi/2) \quad (12)$$

Figures 18-22 express the stabilizing effects of HVDC-based controller. Without controller, the frequency oscillation in area 2 and the power oscillation in a tie line 1-2 drastically fluctuate. After applying a HVDC-based controller, they are significantly alleviated.

Figure 18: Area 1 Frequency Deviation.

Figure 19: Area 2 Frequency Deviation.

Figure 20: Area 3 Frequency Deviation.

Figure 21: Tie Line 1-2 Power Deviation.

Figure 22: DC Power Output Deviation.

Case 4. 30% increase in system parameters

It is assumed that not only the sinusoidal load change in case 3 is applied to the area 2, but also the parameters of a three-area interconnected system are increased by 30%. Figures 23-27 clearly show the effectiveness of HVDC-based controller. Without controller, the frequency deviations in areas 1 and 2, and the tie line 1-2 power deviation severely oscillate and diverge. The interconnected areas 1 and 2 lose their stability. On the other hand, the frequency and tie line power deviations are perfectly stabilized after the controller is operated. This implies the robustness of the designed controller against system parameter variations.

Figure 23: Area 1 Frequency Deviation.

Figure 24: Area 2 Frequency Deviation.

Figure 25: Area 3 Frequency Deviation.

Figure 26: Tie Line 1-2 Power Deviation.

Figure 27: DC Power Output Deviation.

Case 5. Negative damping due to a severe fault

Here, it is assumed that the severe fault such as a short circuit etc. occurred in the area 2. This fault causes the area 2 to be unstable. As a result, the damping coefficient D_2 becomes negative. In this study, the same sinusoidal load change in case 3 is applied to the area 2 while D_2 is set to -0.16 [pu.MW/Hz]. The effectiveness of HVDC-based controller is demonstrated in Figs. 28-32. Without controller, the oscillations of frequency deviations in areas 1 and 2, and tie line 1-2 power deviation severely fluctuate and finally diverge. After applying the proposed controller, frequency and tie line power oscillations are significantly damped. A stability of the interconnected areas is effectively maintained.

Figure 28: Area 1 Frequency Deviation.

Figure 29: Area 2 Frequency Deviation.

Figure 30: Area 3 Frequency Deviation.

Figure 31: Tie Line 1-2 Power Deviation.

Figure 32: DC Power Output Deviation.

These case studies explicitly confirm that the proposed HVDC-based controller is very effective in load change compensation as well as suppressing inter-area oscillations against any load disturbances. Additionally, the designed controller is considerably robust to various system operating conditions, parameter variations and several load disturbances.

6. CONCLUSIONS

In this paper, the new design method of HVDC-based controller for load change compensation and stabilization of inter-area oscillation is presented. The proposed design utilizes the technique of overlapping decompositions to acquire the subsystem where the inter-area oscillation mode is preserved. Subsequently, the tabu search is employed for optimizing parameters of the controller in this subsystem. Since, the design specification is selected based on the required overshoot of frequency oscillation, this is not only suitable for a real problem but also simple for any designer. Furthermore, the controller has a structure of second-order lead/lag compensator, this makes it easy to implement in the practical power system. Simulation studies clearly confirm both load change compensation and damping effects of the designed controller against several load disturbances. Moreover, a HVDC-based controller can be effectively coordinated with the conventional governors. From the simulation results, the high robustness of the designed controller against system parameter variations, operating conditions, several load disturbances has been clarified.

REFERENCES

1. Povh, D. (2000), Proceedings of the IEEE, vol. 88, no. 2, pp. 235-245.
2. Anderson, B. and Baker, C. (2000), IEE Review, pp. 33-39.
3. Elgerd, O.L. (1985), Electric Energy System Theory, An Introduction 2nd. McGraw-Hill.
4. Jaleeli, N. et al. (1992), IEEE Transactions on Power Systems, vol. 7, no. 3, pp. 1106-1122.
5. Ikeda, M., Siljak, D.D. and White, D.E. (1981), Journal of Optimization Theory and Applications, vol. 34, no. 2, pp. 279-310.
6. Glover, F. and Laguna, M. (2000), Tabu Search, Kluwer Academic Publishers.
7. IEEE Committee Report (1991), IEEE Transactions on Power Systems, vol. 6, no. 2, pp. 743-752.
8. Wang, L. and Jen, Y.P., Proceedings of IEEE PES Winter Meeting, vol. 2, pp. 1337-1341.