Federal-Kalman-filter-based Fault-Tolerant Wide-Area Damping Control for AC/DC Power System

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Abstract: Inter-area low frequency electromechanical oscillation deteriorates the stability of interconnected power system and limits the capacity of transmission system. In smart grid, with installation and development of phase measurement unit and wide-area measurement system, wide-area damping controller is a popular method to suppress electromechanical oscillation. However, the performance of wide-area damping controller will be deteriorated if associated sensors are corrupted or interrupted due to software/hardware failure. In this paper, Prony method and residue method are used to design a conventional wide-area damping controller firstly. Then, a novel federal-Kalman-filter-based fault-tolerant controller is proposed. Finally, the simulation verification is undertaken on a four-machine two-area parallel AC/DC system in MATLAB/Simulink. Compared with the conventional wide-area damping controller, the simulation results show that the proposed fault-tolerant wide-area damping controller is able to eliminate the electromechanical oscillation effectively when the remote feedback signal is subject to noise interference.

Key Words: low frequency electromechanical oscillation, wide-area damping control, sensor fault, fault-tolerant control, federal Kalman filter.

1 Introduction

The stability of inter-area low-frequency oscillation between interconnected synchronous generators is necessary for secure system operation, which refers to the ability of power system to remain in equilibrium after being subjected to a small disturbance. Damping of inter-area low-frequency oscillation is one of the major concerns for improving power system performance since inter-area oscillation would limit the reserve margin of transmission capacity between different areas of power grids [1].

The traditional approach to suppress inter-area oscillation is to install Power System Stabilizers (PSSs) with local feedback signal as input, which provides damping control action through the generator excitation systems. However, the oscillation-suppressing effectiveness of this type of PSSs in suppressing some inter-area modes is limited due to the lack of the observability of inter-area modes from the local signal [2].

In smart grid, with the development of phase measurement unit (PMU) and wide-area measurement system (WAMS), remote signals become available as feedback signals and inter-area oscillation modes can be effectively suppressed by WAMS-based wide-area damping controllers (WADC) [3]. However, the performance of WADC will be deteriorated if associated sensors, actuators, and communication networks are corrupted or interrupted due to failure, malfunction of software/hardware or even cyber-attack [4]. As the paramount importance in the fields such as nuclear and avionics industries, fault-tolerant control (FTC) is a control method to ensure nominal performance when taking into account the occurrence of faults. With the FTC, the effect of aforementioned contingencies can be mitigated to an acceptable level [5]. Therefore, advanced and reliable fault-tolerant WADC are desired to address aforementioned challenges for tackling the circumstances introduced from the remote signals and the hardware/software of the sensors/actuators of future smart grid.

This paper proposes a novel design of fault-tolerant wide-area damping control for High Voltage Direct Current (HVDC) system in order to suppress the low frequency oscillation on potential sensor-fault or noise interference. The oscillation analysis and system identification method based on Prony analysis are introduced firstly. Then a Kalman-filter-based fault-tolerant controller is introduced, which can maintain the performance of WADC when the remote signal is subject to noise. Moreover, case study is carried out on a four-machine two-area parallel AC/DC power system based on MATLAB/Simulink. The effectiveness of the proposed FTC and WADC is verified by simulation results.

2 WADC design

WADC design method introduced in this paper can be divided in three parts: oscillation analysis, system identification and controller design. Firstly, the key information is extracted from the measured signal via Prony method and the information can be used to identify the

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system transfer function and residue. Then, the parameters of WADC can be determined by residue method.

Prony method was introduced by Gaspard Riche de Prony in 1795, which can extract parameters, such as amplitude, phase, frequency and damping ratio, by fitting the given signal to a linear combination of weighted exponential terms. Consider the measured signal $\mathrm{y(n)}$ which can be fitting as:

$$\hat{y}(n) = \sum_{i=1}^{p} b_i z_i^n \tag{1}$$

$$b_i = B_i \exp\,(j\theta_i) \tag{2}$$

$$z_i = \exp\,[(\alpha_i + j2\pi f_i)T \tag{3}$$

Where $n = 0, 1, \dots, N-1. B_i, \theta_i, \alpha_i, f_i$ are the amplitude, phase, damping ratio, oscillation frequency of $\mathrm{i^{th}}$ signal respectively. Many methods such as the least-square fit method can be used to estimate parameters in equation (1). With the help of Prony analysis, critical information of oscillation modes can be extracted, therefore, system eigenvalue, transfer function and residue can be determined [6]. Prony analysis and oscillation identification are investigated in [6,7]. In [8], a general prediction model is proposed for the Prony analysis and the influence of several factors, such as decimation factors, model order and linear solvers, are investigated to provide a reference for applying Prony method to estimate low frequency electromechanical oscillation modes. The information of oscillation modes can be determined as:

$$B_i = |b_i| \tag{4}$$

$$\theta_i = arctran(Im(b_i)/Re(b_i)) \tag{5}$$

$$f_i = arctran(Im(z_i)/Re(z_i))/\,2\pi T \tag{6}$$

$$\alpha_i = ln|z_i|/T \tag{7}$$

For a typical linear time-invariant system, system model after Laplace transform can be express as:

$$\mathrm{Y(s) = I(s)G(s) + W(s)} \tag{8}$$

Where $\mathrm{Y(s)}$, $\mathrm{I(s)}$, $\mathrm{W(s)}$, $\mathrm{G(s)}$ are system input signal, output signal, initial condition, transfer function, respectively. Let the input $\mathrm{I(s)}$, transfer function $\mathrm{G(s)}$, initial condition $\mathrm{W(s)}$ be:

$$\mathrm{I(s) = \frac{C_0 + C_1 e^{-sD_1} C_2 e^{-sD_2} + \dots + C_k e^{-sD_k}}{s - \lambda_{i+1}}} \tag{9}$$

$$\mathrm{G(s) = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i}} \tag{10}$$

$$\mathrm{W(s) = \sum_{i=1}^{n} \frac{A_i}{s - \lambda_i}} \tag{11}$$

Where $\mathrm{C_0, C_1, \dots, C_k}$ are constant, $\mathrm{D_0, D_1, \dots, D_k}$ are delay, respectively. $\mathrm{R_i, \lambda_i}$ are residue and eigenvalue of ith component, $\mathrm{A_i}$ is termed initial-condition residues. Assume that the input signal is impulse signal to stimulate low frequency oscillation and the initial condition is a constant, the residue of $\mathrm{i^{th}}$ mode can be determined as:

$$\mathrm{R_i = \lambda_i B_i \exp(j\theta_i) + \lambda_i} \tag{12}$$

The parameters of wide-area damping controller can be determined using the information of system residue. The objective of residue method is to move the system eigenvalues associated to electromechanical oscillation modes to the left side of complex plane. Lead-lag blocks are used in WADC to achieve movement of system eigenvalues and the parameters of lead-lag blocks can be determined as [9]:

$$\mathrm{\varphi_{com} = 180° - arg\,(R_i)} \tag{13}$$

$$\mathrm{\alpha = \frac{T_{lead}}{T_{lag}} = \frac{1 - \sin\,(\frac{\varphi com}{mc})}{1 + \sin\,(\frac{\varphi com}{mc})}} \tag{14}$$

$$\mathrm{T_{lag} = \frac{1}{\omega\sqrt{\alpha}}} \tag{15}$$

$$\mathrm{T_{lead} = \alpha T_{lag}} \tag{16}$$

3 Kalman-filter-based fault-tolerant controller

Kalman filter was introduced by Rudolf Kalman in 1960. Based on a prediction-update loop, this kind of filters is able to produce estimates of unknown variables. Modified Kalman filter can provide more functionalities for industrial process.

For a given system described as:

$$\mathrm{X(K) = AX(k-1) + BU(k) + W(k)} \tag{17}$$

$$\mathrm{Z(k) = HX(k) + V(k)} \tag{18}$$

Where $\mathrm{X(K)}$, $\mathrm{U(k)}$, $\mathrm{Z(k)}$ are system states, input, measurement, respectively. A, B and H are state matrix, input matrix and observation matrix, respectively. $\mathrm{W(k)}$ and $\mathrm{V(k)}$ are process noise and measurement noise which can be expressed as: $\mathrm{W(k) \sim N\,(0, Q)}$ and $\mathrm{V(k) \sim N\,(0, R)}$. Kalman filter is based on a loop containing two steps: prediction and update. In first step, system state estimate and covariance estimate can be predicted as

$$\mathrm{\hat{X}(k|k-1) = A\hat{X}(k-1|k-1) + BU(k)} \tag{19}$$

$$\mathrm{P(k|k-1) = AP(k-1|k-1)A^T + Q} \tag{20}$$

Where $\mathrm{\hat{X}(k|k-1)}$ and $\mathrm{P(k|k-1)}$ stand for predicted system state and covariance estimates of moment k. In second step, predicted system state and covariance estimates will be updated as:

$$\hat{X}(k|k) = \hat{X}(k|k-1) + K(k)[Z(k) - H\hat{X}(k|k-1)] \quad (21)$$

$$K(k) = \frac{P(k|k-1)H^T}{HP(k|k-1)H^T + R} \quad (22)$$

$$P(k|k) = (I - K(k)H)P(k|k-1) \quad (23)$$

$Z(k) - H\hat{X}(k|k-1)$ is termed as residual, representing the inconformity between the measure and the predicted state estimate. $\hat{X}(k|k)$, the output of Kalman filter which is the linear combination of the priori predicted system state and the weighted residual, will be used in the prediction step in moment k+1. This recursive filter is able to estimate system state using noisy measurement. Moreover, the modified application of Kalman filter can achieve extra functions. In [10], Neal A. Carlson proposed a federal Kalman filter and a data fusion algorism for simulating a fault-tolerant navigation system. Federal Kalman filter utilises multiple independent Kalman filters which are working in parallel to process corresponding data from multiple sensors. A main filter is used to process all estimates of local filters, known as data fusion algorithm, and provide overall information. The structure of federal Kalman filter is shown in figure 1.

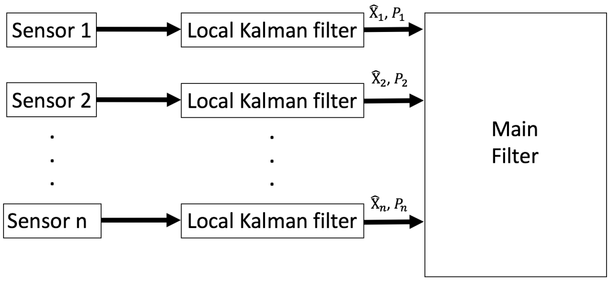

Fig. 1: The structure of federal Kalman filter

The objective of federal Kalman filter is to provide the functionality of fault diagnosis and signal reconfiguration by decentralizing the signal processing firstly and fusing all the estimate secondly. In order to achieve fault-tolerant control, main filter utilise a data fusion algorithm:

$$\hat{X}_m = P_m \sum_{i=1}^{n} P_i^{-1} \hat{X}_i \quad (24)$$

$$P_m^{-1} = \sum_{i=1}^{n} P_i^{-1} \quad (25)$$

The local Kalman filters act as conventional Kalman filters and output the state estimates and covariance. On the other hand, the main filter only fuses the information from local filter but does not save or provide feedback. The covariance can be used as a statistical measure of the reliability of associated signal. The final output is a weighted combination of all state estimates. The principle of data fusion algorithm is: the lower the covariance, the higher the reliability of associated signal, the higher the contribution to the final output.

4 Case study: four-machine two-area parallel AC/DC power system

To investigate the performance of proposed fault-tolerant wide-area damping controller, four-machine two-area parallel AC/DC power system model as shown in figure 2, is used to simulate the power system.

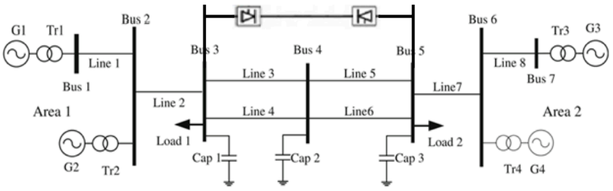

Fig. 2: Four-machine two-area parallel AC/DC power system.

The test system contains two areas connected by two parallel 220-km tie-line between Bus 3 and Bus 6. Being in parallel with AC transmission line, HVDC is installed between Bus 3 and Bus 5 as well. Four generators are distributed as shown in figure 2. On nominal condition, approximately 400 MW of active power is transferred from Area 1 to Area 2. In this case study, only HVDC is equipped with WADC and non of generator is equipped with PSS.

Step 1: Built up the power system model in MATLAB/Simulink. The proposed fault-tolerant WADC will be installed at rectifier side. The proposed scheme utilises active power reference value of HVDC (P_r) as output. With respect to the input, transferred active power (P_{3-5}) is used as local feedback signal and the rotor speed of generator G1, G2 and G4 (ω_1, ω_2 and ω_4) are used as remote feedback signals. The remote signals are potentially effected by noise. The block diagram of the proposed scheme is shown in figure 3.

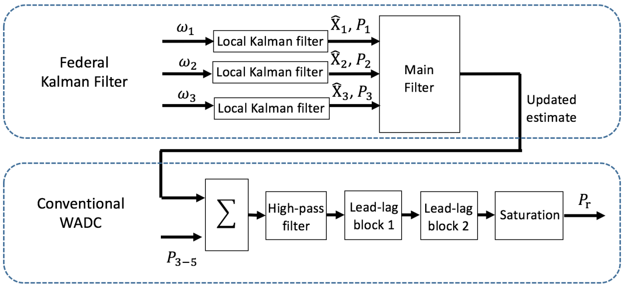

Fig. 3: The structure of the proposed fault-tolerant WADC

Step 2: Disable the WADC and give a stimulate (i.e. impulse input) on bus 1, bus 2, bus 6, bus 7 and apply Prony method to analyse the measured oscillatory signal (i.e. transferred active power between two areas). The result of Prony analysis is shown in table 1.

Step 3: Determine the parameters of WADC using residue method, enable and examine the proposed WADC without noise interference.

The performance of conventional WADC is shown in figure 4 and it illustrates that the designed WADC is able to suppress the low frequency electromechanical oscillation in four-machine two-area parallel AC/DC power system within 15 seconds.

Table 1: The results of Prony analysis

Mode	1,2	3,4
Amplitude	0.65	0.45
Damping	-0.22	-0.57
Frequency	0.6 Hz	0.4 Hz
Phase	±0.3756 rad	±0.2529 rad
Residue	-0.1251±0.5997i	-0.1042± 0.3429i
Eigenvalue	-0.0220+0.3769i	-0.0570+0.2513i

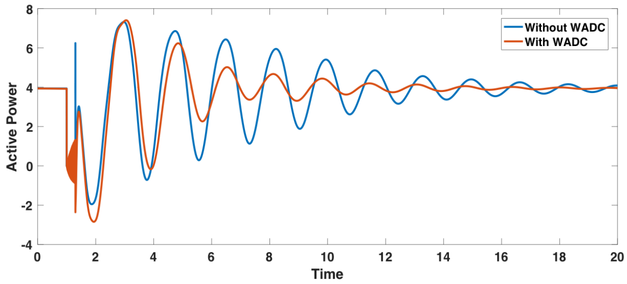

Fig. 4: The performance of WADC in four-machines two-area parallel AC/DC power system.

Step 4: Apply noise (~N (0,1)) to the remote feedback signal. Record the performance of the conventional WADC on sensor-fault condition and examine the proposed FTC.

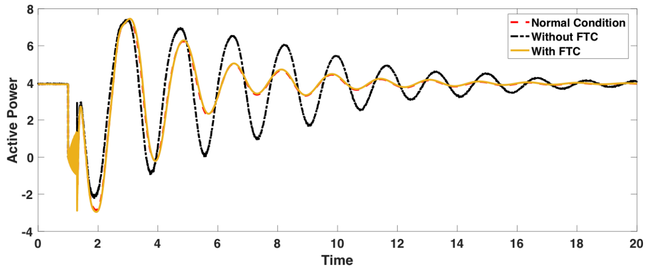

Fig. 5: The performance of fault-tolerant controller on noise interference condition.

Figure 5 shows the comparison between the performance of WADC with/without FTC when the remote feedback signal is subject to the noise interference. Obviously, the damping ratio of the proposed fault-tolerant WADC is greater than that of conventional WADC on sensor-fault condition. The proposed FTC is able to provide a proper estimate of remote feedback signals which have similar observabilities. When a signal is subject to noise, the associated covariance increase rapidly and its contribution to the final output decrease. Consequently, other healthy signals reconfigure the final output of FTC and the performance of WADC can be maintain at an acceptable level on sensor-fault condition.

5 Conclusion

In this paper, a fault-tolerant WADC scheme consisting of a FTC and a conventional WADC is designed and simulated based on MATLAB/Simulink in order to supress the low frequency electromechanical oscillation on a potential sensor-fault condition.

The conventional WADC is designed based on residual method using the system information provided by Prony method. The simulation result shows that the proposed WADC can suppress the electromechanical oscillation in the four-machine two-area parallel AC/DC power system. The proposed FTC is based on federal Kalman filter and it is able to ease or even remove the negative effect of noise interference. In FTC, local Kalman filters process the signals firstly and provide the state estimates and covariance to the main filter. The main filter utilises a data fusion algorithm to calculate an optimal estimate of remote signals. The simulation result shows that after applying FTC, the negative effect of noise interference of remote signal is eased. It is proved that the proposed FTC and WADC can suppress the low frequency electromechanical oscillation and the performance can be maintained on a noisy condition.

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