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PAPERS

Wide-area damping control using signal restoration under communication uncertainties

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In large-scale power systems, the wide-area damping controller (WADC) using remote input signals is an effective device that can be applied to deal with poor inter-area oscillation damping. However, its control effect will be degraded by communication uncertainties such as variable time delays in both input and output sides of WADC, partial and complete communication failures. This paper focuses on a new WADC design by regarding communication uncertainties. Such uncertainties are mathematically formulated and analyzed in order to signify its impact on the oscillatory stability. The signal restoration of input and output pairs of WADC is proposed to alleviate an adverse effect of communication uncertainties. Simulation study in an IEEE 50-machine 145-bus test system elucidates that the proposed WADC is superior to that of the conventional WADC without considering communication uncertainties in both performance and robustness.

K e y w o r d s: communication uncertainties, time variant delay, inter-area oscillation, signal failures

1 Introduction

In field of oscillatory stability in large power systems, the wide-area damping controller (WADC) is a promising device for the inter-area oscillation damping. This is due to the better choice of input signals that have high observabilityy of the target inter-area modes [1]. Although suitable remote input signals provide an effective stabilizing effect, such signals may be affected by communication uncertainties such as variable latency, and failure of input and output signals [2]. Ignoring such uncertainties, the damping performance of WADC will be deteriorated. To enhance the stabilizing effect of WADC, communication uncertainties should be taken into account in a design process.

Next, literature reviews of recent works relating to time delays and failure of signals are given with their most-likely solutions. Lastly, the article concludes the future research direction.

1.1 Communication uncertainty due to system latencies

As mentioned in [2-12], the time delay or latency in communication networks may lead to the degradation of small-signal stability, poor time-domain responses, and instability in the closed-loop systems. At the beginning, the time delay is assumed to be equal and constant in all control loops [3,4]. Subsequently, the constant time delay with several mean values is represented in [5,6]. These works demonstrated that when the time delay rapidly changes during simulation time, it significantly diminishes the stabilizing performance of WADC.

However, it was suggested in [2] that the time delay can be divided into two categories, *ie* constant and random time delays. The constant time delay results in a steady phase lag to the WADC irrespective of the time frame. On the other hand, the random time delay causes more serious problem to the WADC due to stochastic nature of the delay varying, and depending on the time domain. As a result, variable time delay should be regarded instead of constant time delay [7,8]. In [7], variable time delay is considered in the WADC of wind turbine with doubly-fed induction generator (DFIG) in a two-area four-machine interconnected power system. An input signal of such controller is a deviation of rotor angle of synchronous generator in each area. However, there is no backup controller when the communication failure occurs. Besides, the controller gain is fixed under variable time delay. [8] discloses that to handle variable time delay, because the controller with multiple gains is superior to the traditional fixed gain controller for compensating the random delay and packet drop, and damping out an inter-area oscillation, the controller with adaptive gain should be used instead of the controller with fixed gain. Nevertheless, the local backup and wide-area (centralized) controllers are simultaneously operated. In fact, such a combination of local and centralized stabilizing signals may initiate an interaction between local and centralized controllers, and thus results in the deterioration of stabilizing effect of both controllers. Besides, a small value of local time delay and large value of communication time delay may bring about non-synchronized stabilizing signals of damping controllers. Consequently, the two-level damping controller which yields an independent opera-

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tion of centralized and local controllers is a better option [9], [10].

More realistically, in [11,12], the mathematical models of variable time delay are presented. In [11], the impact of time-varying delays with pseudo-periodic, stochastic, and constant components on the dynamic behavior of power systems is thoroughly analyzed. This work clarifies that the time-varying delay causes the worst case among various types of delay. Additionally, small-signal and transient stabilities are differently influenced by various types of delay. However, the effective solutions to mitigate the impact of the delay models have not been mentioned yet. In [12], the influence of variable latencies, *ie* local and communication latencies on input and output pairs of local and centralized damping controllers is investigated. Robust control strategy is adopted to ameliorate the oscillatory stability against the impact of variable latencies. Nevertheless, variable latencies in each communication network are modeled by a single mean value.

1.2 Communication uncertainty due to failure of signals

In addition to system latencies, [14,15] report that the communication failure due to accidental and malicious disruptions is a vital problem in the WADC using remote input signals. In some operating points, this problem may worsen the oscillatory stability or even destabilize power systems. In [9-15], the hierarchical controller which has two layers of local and centralized controllers is applied when communication failure takes place. To avoid an interaction between local and centralized levels, [9] reveals that the decentralized controller should be firstly designed. Subsequently, the centralized controller should be added to improve the oscillatory stability. In [9,10], [12], a two-level controller which consists of local and centralized levels is used to overcome an interaction problem. Additionally, the local latency is also taken into account. Although the local latency has a small value between 25–50 ms, the study result in [9] makes clear that the local latency may bring about the system instability when the centralized controller is swiftly switched to the local controller during the transient state.

In fact, the failure of signals may influence some WADCs. Nevertheless, the remaining WADCs will operate properly to damp out the oscillation. In addition, variable latency may lead to partial failure or distortion of some input and output pairs of WADC. As a consequence, such input and output pairs may not provide good stabilizing effect.

1.3 Contribution of this work

This paper proposes the WADC design with the signal restoration of input and output pairs against various communication uncertainties. The mathematical model of the system including an impact of communication uncertainties, *ie* latency and communication failure on an oscillatory stability is developed. The signal restoration of the missing and distorted input and output signals under the partial communication failure is presented. Simulation study will be conducted to evaluate the control effect of the proposed WADC in comparison with the conventional WADC.

In this paper the communication uncertainties modeling is explained, the proposed signal restoration is described. And, subsequently, a simulation study is carried out.

2 Communication uncertainties modeling

Consider the system in time (t) domain. including variable latencies, a general linearized state space model by assuming transmitted and received variable latencies to be equal or unequal is provided by

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{X}(t)}{\mathrm{d}t} &= \boldsymbol{A}_0\boldsymbol{X}_0(t)+\boldsymbol{B}_0\boldsymbol{U}_0(t)+ \\ &+\sum_{j=1}^{J}\big(\boldsymbol{A}_j\boldsymbol{X}_j(t-\tau_{\mathrm{R}j})+\boldsymbol{B}_j\boldsymbol{U}_j(t-\tau_{\mathrm{T}j})\big) \\ Y(t) &= \big(\boldsymbol{C}_0\boldsymbol{X}_0(t)+\boldsymbol{D}_0\boldsymbol{U}_0(t)\big)+ \\ &+\sum_{j=1}^{J}\big(\boldsymbol{C}_j\boldsymbol{X}_j(t-\tau_{\mathrm{R}j})+\boldsymbol{D}_j\boldsymbol{U}_j(t-\tau_{\mathrm{T}j})\big), \end{aligned} \tag{1}$$

where $\tau_{\mathrm{R}j}, \tau_{\mathrm{T}j} \in (0,\infty)$, are received and transmitted, latencies. It is assumed that in general $\tau_{\mathrm{R}j} \neq \tau_{\mathrm{T}j}$. Further, $\boldsymbol{A}_0, \boldsymbol{B}_0, \boldsymbol{C}_0$, and $\boldsymbol{D}_0$ are state, input/output, and feed-forward matrices without latency, $\boldsymbol{X}_0, \boldsymbol{Y}_0$, and $\boldsymbol{U}_0$ are state, output, and input vectors without latency, and $\boldsymbol{A}_j, \boldsymbol{B}_j, \boldsymbol{C}_j$, and $\boldsymbol{D}_j$ are state, input/output, and feed-forward matrices affected by variables latency pattern and $\boldsymbol{X}_j$ and $\boldsymbol{U}_j$ are state and input vectors affected by variable latency patterns.

In fact, there are various means of $\tau_{\mathrm{R}j}$ and $\tau_{\mathrm{T}j}$ during simulation time. Here, $\tau_{\mathrm{R}j}$ and $\tau_{\mathrm{T}j}$ are expressed by

$$\tau_{(\mathrm{R/T})j}(t) = \begin{bmatrix} \tau_{(\mathrm{R/T})j}(\Delta t_1), \tau_{(\mathrm{R/T})j}(\Delta t_2), \dots \\ \tau_{(\mathrm{R/T})j}(\Delta t_n), \tau_{(\mathrm{R/T})j}(\Delta t_N) \end{bmatrix}, \tag{2}$$

respectively. As depicted in Fig. 1, the step change of time

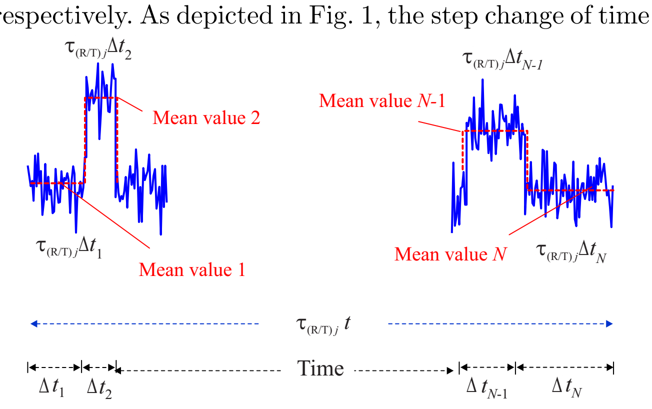

Fig. 1. Uncertainty due to received and transmitted variable latencies

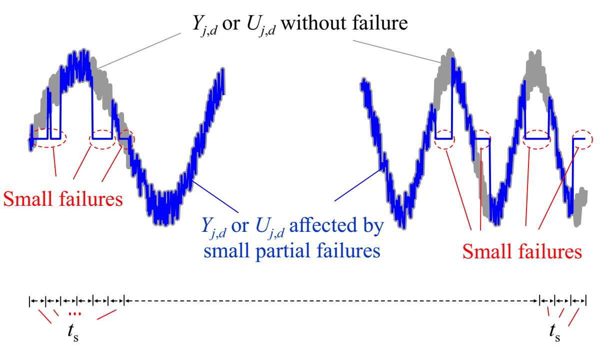

Fig. 2. Small partial failures in input and output signals

delay in (2) is assumed to be constant or inconstant. Here, $\Delta t_1 \Delta t_n, \ldots, \Delta t_N$ are time sequences of small deviations, where N is the total number of time delay steps in the time simulation as shown in Fig. 1. Uncertainty due to system latency $\tau_{(\mathrm{R/T})j}(t)$ in(2) is depicted in Fig. 1. All members of (2) can be expressed by

$$\tau_{(R/T)j}(\Delta t_n) = \overline{\tau}_{(R/T)j,n} \pm \left(\Delta\tau_{(R/T)j,n}(\Delta t_n)\right) \quad \text{for } n = 1, 2, \ldots, N, \tag{3}$$

where $\overline{\tau}_{(R/T)j,n}$ are mean values of $\tau_{(R/T)j}(\Delta t_n)$ and $\Delta\tau_{(R/T)j,n}$ are time variant latencies of the same. Substituting (3) into (2), variable latency with several means can be obtained.

Reconsidering the output equation in (1), the output signals including the impact of variable latency are expressed

$$\begin{aligned} &\mathbf{Y}'_j\big(t - F(\tau_{\mathrm{R}j}, \tau_{\mathrm{T}j})\big) = \\ &= \sum_{j=1}^{J}\big(\boldsymbol{C}_j \boldsymbol{X}_j(t - \tau_{\mathrm{R}j}) + \boldsymbol{D}_j \boldsymbol{U}_j(t - \tau_{\mathrm{T}j}\big) = \\ &= \begin{bmatrix} \mathbf{Y}'_1\big(t - F(\tau_{\mathrm{R}1}, \tau_{\mathrm{T}1})\big) \\ \mathbf{Y}'_2\big(t - F(\tau_{\mathrm{R}2}, \tau_{\mathrm{T}2})\big) \\ \ldots \\ \mathbf{Y}'_J\big(t - F(\tau_{\mathrm{R}J}, \tau_{\mathrm{T}J})\big) \end{bmatrix}, \end{aligned} \tag{4}$$

where $\mathbf{Y}'_j$ is a matrix of the output signals affected by functions $F(\tau_j) = F(\tau_{Rj}, \tau_{Tj})$ of variable latency, consisting of $\tau_{\mathrm{R}j}$ and $\tau_{\mathrm{T}j}$. All members of (4) can be declared by

$$\begin{aligned} Y'_j\big(t - F(\tau_j)\big) = \big[&Y'_{j,n}\big(\Delta t_n - F(\tau_j)\big), \\ &\ldots, Y'_{j,N}(\Delta t_N - F(\tau_j))\big], \end{aligned} \tag{5}$$

where $Y'_{1,1}, \ldots, Y'_{1,N}, \ldots, Y'_{J,1}, \ldots, Y'_{J,N}$ for $j = 1 \ldots J$ and $n = 1 \ldots N$ are output data sequencies. By substituting from (2) and (3) into (5), the output signals affected by variable latency can be achieved.

In the same way, an input vector $\boldsymbol{U}_j$ is written in a form of the product of controller and output matrices corresponding to j-th variable latency as

$$\begin{aligned} &-\boldsymbol{U}_j(t - \tau_{\mathrm{T}j}) = \boldsymbol{K}_j(t) \cdot \mathbf{Y}'_j\big(t - F(\tau_j)\big) = \\ &= \begin{bmatrix} K_1(t) & 0 & \ldots & 0 \\ 0 & K_2(t) & \ldots & 0 \\ 0 & 0 & \ldots & 0 \\ 0 & 0 & \ldots & K_J(t) \end{bmatrix} \cdot \begin{bmatrix} Y'_1(t - F(\tau_1) \\ Y'_2(t - F(\tau_2) \\ \ldots \\ Y'_J(t - F(\tau_J) \end{bmatrix}, \end{aligned} \tag{6}$$

where $\boldsymbol{K}_j$ is a diagonal matrix of WADCs $K_1, K_2, \ldots, K_J$. The structure of $\boldsymbol{K}_j(t)$ will be described in the next section. The negative sign in the leftt side of (6) indicates a negative feedback. Assuming the latency among control block diagrams is very small and can be neglected. As a result, $\boldsymbol{K}_j(t)$ depends solely on time t. Substituting $\mathbf{Y}'_j, j = 1, \ldots, J$, from (5) into (6), the stabilizing signals including received and transmitted variable latencies can be obtained.

Next, an uncertainty due to the failure of input and output signals is introduced. In this work, the communication failure can be divided into two major cases, *ie* complete failure and partial failure. For the complete failure, the input and output signals of WADC are completely absent [13]. Consequently, (4) and (6) can be rewritten by

$$\mathbf{Y}'_j\big(t - F(\tau_j)\big) = 0 \quad \text{and} \quad \boldsymbol{U}_j(t - \tau_{\mathrm{T}j}) = 0. \tag{7}$$

In this case, the local backup controllers of the two-level control are activated instead of the primary centralized controllers. In this work, however, the impact of partial communication failure which occurs at both input and output pairs of WADC is considered. This partial failure is divided into three minor cases.

The first case is a failure in input and output pairs of some WADCs. It can be described by the following equations.

The output signals (4) are – if at any value of j in $\mathbf{Y}'$ the failure

$$\mathbf{Y}'_j\big(t - F(\tau_j)\big) = \begin{cases} 0, \text{ occurs} \\ \text{no change, does not occur.} \end{cases} \tag{8}$$

For stabilizing signals $\boldsymbol{U}_j$ in (6), in the same way

$$\begin{aligned} &-K_j(t) \cdot \mathbf{Y}'_j\big(t - F(\tau_j)\big) = \\ &= \begin{cases} 0, \text{ occurs in } \mathbf{Y}'_j \text{ as (8) or in } \boldsymbol{U}_j \\ \text{no change, does not occur neither as (8) nor in } \boldsymbol{U}_j. \end{cases} \end{aligned} \tag{9}$$

It can be observed in (8) and (9) that the failure of output signals involves with only $\mathbf{Y}'_j$. On the other hand, the failure of stabilizing signal (9) is caused by both $\mathbf{Y}'_j$ and $\boldsymbol{U}_j$.

The second case of partial failure is small partial failures in the input and output signals. This event is a subset of (8) and (9). Small partial failures in input and output signals are demonstrated in Fig. 2.

Here, $\mathbf{Y}'_j$ is measured by phasor measurement units (PMUs) with equal time stamp , Δt_s. Sequences data d of input and output signals are formulated by a function of Δt_s, when $d = 1, \ldots, N_{\mathrm{T}}$ where d is a counter of time stamp sequence and N_{T} is a total number of data obtained from PMUs. As a result, (5) and (6) can be expressed by substituting sequence data $d = 1, \ldots, N_{\mathrm{T}}$ and Δt_s as

$$Y'_{j,d}\big(d\Delta t_s - F(\tau_j)\big) = \\ = \{Y'_{j,1}\big(\Delta t_s - F(\tau_j)\big), \ldots, Y'_{j,N_{\mathrm{T}}}\big(N_{\mathrm{T}}\Delta t_s - F(\tau_j)\big)\}, \tag{10}$$

$$U'_{j,d}\big(d\Delta t_s - \tau_{\mathrm{T}j}\big) = \\ = \{U_{j,1}\big(\Delta t_s - \tau_{\mathrm{T}j}\big), \ldots, U_{j,N_{\mathrm{T}}}\big(N_{\mathrm{T}}\Delta t_s - \tau_{\mathrm{T}j}\big)\}, \tag{11}$$

where $\{\Delta t_1, \ldots, \Delta t_N\} \in d\Delta t_s$. By substituting $j = 1, \ldots, J$ and $d = 1, \ldots, N_{\mathrm{T}}$ into (10) and (11), the sequences of all input and output data with equal Δt_s are obtained. Therefore, the right side of (10) and (11) can be used to express the sequence of $Y'_{j,d}$ and $U_{j,d}$, respectively.

Assuming g and h are any sequence data where $\{g_1, g_2, \ldots\} \in g, \{h_1, h_2, \ldots\} \in h, \{g_1, h_1, g_2, h_2, \ldots\} \in d$, and $g_1 < h_1 < g_2 < h_2 < \ldots$. The possibility of small partial failure in input and output signals in the ranges of $[g_1, h_1], [g_2, h_2], \ldots$ occurs when WADC sends the stabilizing signal to damp the oscillation. Therefore, the small partial failure in input and output signals can be expressed as follows.

The failure in output signals $Y'_{j,g}$ and $Y'_{j,h}$ depending on their occurrence in range of $[g_1, h_1], [g_2, h_2], \ldots$

$$\big[Y'_{j,g}(g\Delta t_s) - F(\tau_j), Y'_{j,h}(h\Delta t_s) - F(\tau_j)\big] = \\ = \begin{cases} 0, \text{if it occurs} \\ \text{no change, if does not occur.} \end{cases} \tag{12}$$

For the failure in input signals $U_{j,g}$ and $U_{j,h}$, similarly, occurrence in ranges: $[g_1, h_1], [g_2, h_2], \ldots$ or $\Big[Y'_{j,g}, Y'_{j,h}\Big]$

$$\big[U'_{j,g}(g\Delta t_s) - \tau_{\mathrm{T}j}), U'_{j,h}(h\Delta t_s) - \tau_{\mathrm{T}j})\big] = \\ = \begin{cases} 0, \text{if it occurs} \\ \text{no change, if does not occur,} \end{cases} \tag{13}$$

where $\{Y'_{j,g}, Y'_{j,h}\} \in Y'j, d$, and $\{\boldsymbol{U}_{j,g}, \boldsymbol{U}_{j,h}\} \in \boldsymbol{U}_{j,d}$.

It should be noted that when small failures occur at all values of d but not all values of j, this means that (12) and (13) become partial communication failure (8) and (9). On the other hand, when small failures take place at all values of d and j, (12) and (13) become complete communication failure (7). After the appearance of small failures in the output signals of system in (10) in the ranges of $[g_1, h_1]$, $[g_2, h_2]$,..., the failure of the stabilizing signals in (11) consequently arises in the same ranges of $[g_1, h_1]$, $[g_2, h_2]$ *etc.* This implies that the small failures in stabilizing signals of WADCs directly depend on the output signals of system. However, the failure in stabilizing signals may occur after the failure of output signals. If the aforementioned cases take place simultaneously, they will intensify the small partial failures in (8) and (9).

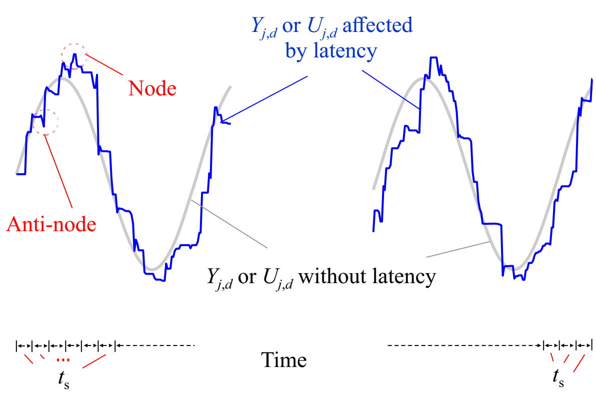

Fig. 3. Input and output signals affected by variable latency

The third case is the partial failure and signal distortion due to variable latency (2). In this case, when the sequences of data are shifted by variable latency, this scenario brings about the partial failure and distortion in both input and output pairs of WADC. An input and output pair affected by variable latency is illustrated in Fig. 3. It can be seen that variable latency causes nodes and anti-nodes in the signal. This event occurs when $\big(g\Delta t_s + \tau_{j,g}\big) \approx \big(h\Delta t_s + \tau_{j,h}\big)$, where $\tau_{j,g}$ and $\tau_{j,h}$ are j6-th variable latency at the g-th and h-th data, respectively, $\{\tau_{gj}, \tau_{hj}\} \in \{\tau_{\mathrm{R}j}, \tau_{\mathrm{T}j}\}$. Accordingly, this problem can be explained by the following equations.

Consider the sequence data $Y'_{j,g}$ as

$$Y'_{j,g}\big(g\Delta t_s - F(\tau_j)\big) = \\ = Y'_{j,g}\big(g\Delta t_s - F(\tau_j)\big) \pm Y'_{j,h}\big(h\Delta t_s - F(\tau_j)\big), \tag{14}$$

$$U'_{j,g}\big(g\Delta t_s - \tau_{\mathrm{T}j}\big) = \\ = U'_{j,g}\big(g\Delta t_s - \tau_{\mathrm{T}j}\big) \pm U'_{j,g+h}\big((g+h)\Delta t_s - \tau_{\mathrm{T}j}\big). \tag{15}$$

Substituting (14) and (15) into (12) and (13), respectively, the partial communication failures in second and third cases are combined. Such combinations of partial failure problem in (12)-(15) will aggravate the impact of communication uncertainties. The sign $\pm$ in the right sides of (14) and (15) depends on the following conditions. Accordingly, nodes and anti-nodes of Y'_j and U_j that occur in (14) and (15) are analyzed as follows.

When $(g\Delta t_s + \tau_g) \approx (h\Delta t_s + \tau_h)$; For Y'_j,

(i) If $(|Y'_{j,g+h}| \geq |Y'_{j,g}|)$ and $(Y'_{j,g+h} \leq Y'_{j,1})$ is true, then large anti-nodes will occur in $Y'_{j,g}$. The symbol $\pm$ is changed to "-".

(ii) If $(|Y'_{j,g+h}| \geq |Y'_{j,g}|)$ and $(Y'_{j,g+h} \geq Y'_{j,1})$ is true, then large nodes will occur in $Y'_{j,g}$. The symbol $\pm$ is changed to "+".

Table 1. Controller types used for communication failures

Types of failure	Complete failure (7)	Partial communication failure (8),(9)	Partial communication failure (12),(13)	Partial communication failure (14), (15)
Types of controller	Local backup controller	Local backup controller	WADC using signal restoration	WADC using signal restoration

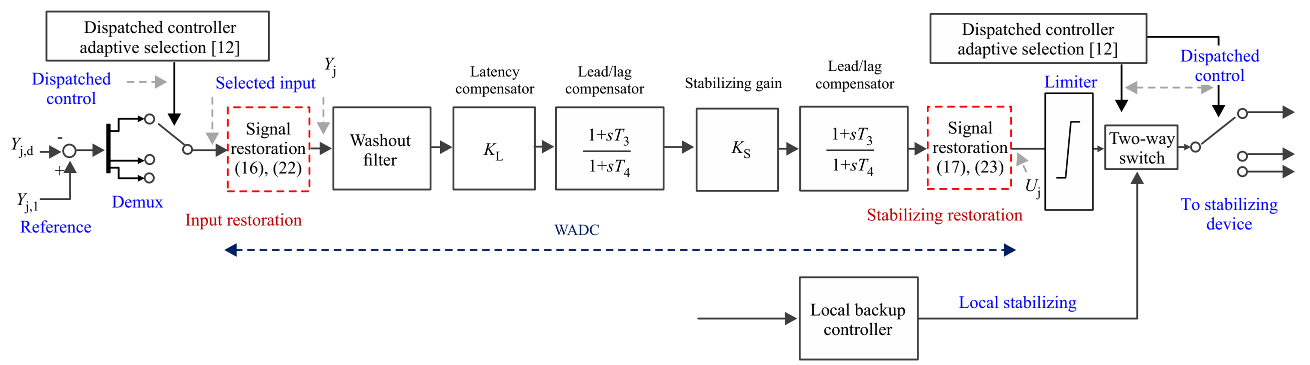

Fig. 4. The proposed WADC using signal restoration in the two-level damping control

(iii) If $(|Y'_{j,g+h}| \le |Y'_{j,g}|)$ and $(Y'_{j,g+h} \le Y'_{j,1})$ is true, then small anti-nodes will occur in $Y'_{j,d}$. The symbol $\pm$ becomes "-".

(iv) If $(|Y'_{j,g+h}| \le |Y'_{j,g}|)$ and $(Y'_{j,g+h} \ge Y'_{j,1})$ is true, then small nodes will occur in $Y'_{j,g}$. The symbol $\pm$ becomes "+".

Before occurrence of a large disturbance, $Y'_{j,1}$ is generally equal to the steady-state value of signal $Y'_{j,d}$. The input signal of WADC is generated by the subtraction of the reference signal and the output signal of system. For U_j, (i)-(iv) can be used by the same conditions as Y'_j. In this work, the complete communication failure (7) is solved by the local backup controllers. The adaptive WADC is applied for the first case of partial communication failure (8) and (9). The input and output signals restoration is used for the second and third cases of partial communication failure (12)-(15). The signal restoration will be described in the next section. Types of controller which are used to encounter communication failures are summarized in Table 1.

3 Proposed signal restoration

In this part, the signal restoration is explained as follows. First, the structure of WADC is delineated. Second, the signal restoration in input and output pairs of WADC is described. Third, the adaptive robust WADC design is explained.

3.1 WADC using signal restoration

The structure of two-level damping controller is depicted in Fig. 4. It consists of the primary WADC with signal restoration and the local backup controller. Note that K_L and K_S are latency compensator and stabilizing gains, respectively, T_1, T_2, T_3, and T_4 are time constants of lead/lag compensators.

For the local backup controller, an input signal is the deviation of local signal such as rotor speed or active power flow in a transmission line. The stabilizing signal of local controller is sent to a two-way switch so that the local backup controller can be used to suppress the oscillation under complete communication failure. Moreover, the small latency in a range of 0ms to 100 ms is regarded in the local backup controller. The small latency may result in a system instability, especially when WADC swiftly switches to the local backup controller during the transient state [9].

For WADC, an input signal is the phase difference between two buses, which has high observability of the target oscillation mode. Before gaining the phase difference, it should be noted that the phase angle of each generator is obtained from different areas in the power system. As a result, prior to the calculation of the phase difference, each phase angle is affected by different values of j^{th} variable latency in (2) and (3). Irrespective of changing in system operations, a deviation of output signal used as an input of WADC is selected by a dispatched controller using adaptive signal selection [12]. As a result, an input signal of WADC has the highest observability of the target oscillation mode. Subsequently, the selected input signal of WADC is sent to the signal restoration algorithm. The input and output signals which are affected by partial communication failure in the second and third cases (12)-(15) are repaired by this algorithm. Consequently, $\Delta \mathbf{Y}'_{j,d}$ is obtained. After the stabilizing process, the stabilizing signals of WADC are repeatedly stored since there is a possibility of partial failure in the stabilizing signals. Subsequently, $\Delta \boldsymbol{U}_{j,d}$ is achieved. Before sending control signals to stabilizing devices, the dispatched controller will select the control level to damp the oscillation.

3.2 Restoration of input and output signals

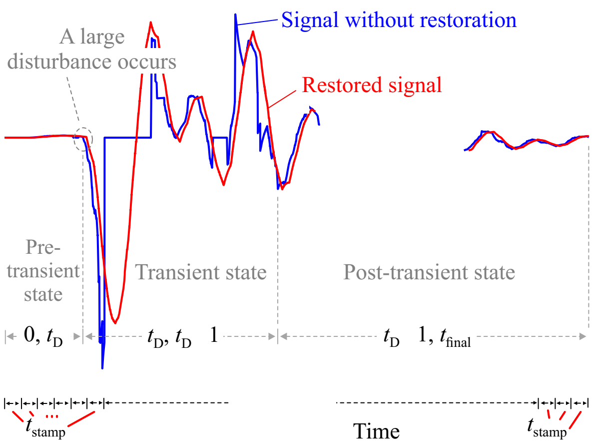

Fig. 5. Signals with and without restoration after an existence of a large disturbance

According to the failure of signals due to communication uncertainties, the signal restoration is applied to solve this problem. As depicted in Fig. 5, assuming the signal is affected by partial communication failure (12)-(15) under three states, *ie* pre-transient, transient, and post-transient states. In the pre-transient state, the signal restoration is not activated. During the transient state, since the transient response is very fast and nonlinearity, approximately 1 second after an occurrence of a large disturbance, the signal restoration is activated in order to restore the missing or distorted signal.

As demonstrated in the partial communication failure, if this is the case, the missing data will arise at any sequence of data. Accordingly, the signal restoration is able to restore such data in a range of $[t_D, t_{D+1}]$. Note that, since the transient state requires the controller with very fast response, the predicted data cannot be used to restore the signal. Only previous data are adopted to predict the missing signal instantly.

When $t_D \leq t \leq t_{D+1}$, if the missing data appear at g-th data, an estimation of any missing data $Y'_{j,g}$ and $U_{j,g}$ in the transient state is given by

$$Y'_{j,g+1} = Y'_{j,g} + \beta, \tag{16}$$

$$U_{j,g+1} = U_{j,g} + \alpha, \tag{17}$$

β and α are calculated by

$$\beta = (b_1\, Y'_{j,g-1}) + (b_2\, Y'_{j,g-2}) + \cdots + (b_k\, Y'_{j,g-k}) \pm \sigma_1, \tag{18}$$

$$\alpha = (c_1\, U_{j,g-1}) + (c_2\, U'_{j,g-2}) + \cdots + (c_k\, U'_{j,g-k}) \pm \sigma_2, \tag{19}$$

where k-th are previous data of any failure data d-th. Parameters β, and α are transient estimated values of $\boldsymbol{Y}'_{j,g}$ and $\boldsymbol{U}_{j,g}$, respectively, $b_1, \ldots, b_k$ and $c_1, \ldots, c_k$ are coefficients of previous data $\Delta \boldsymbol{Y}'_{j,g-1},\ q \ldots, \boldsymbol{Y}'_{j,g-k}$ and $\boldsymbol{U}_{j,g-1}, \ldots, \boldsymbol{U}_{j,g-k}$, and σ_1 while σ_2 are errors of β and α. Parameters $b_1, b_2, \ldots, b_k$ and $c_1, c_2, \ldots, c_k$ can be calculated by

$$b_k = \frac{Y'_{j,k} - Y'_{j,k-1}}{\Delta t_s}, \tag{20}$$

$$c_k = \frac{U_{j,k} - U_{j,k-1}}{\Delta t_s}. \tag{21}$$

Assuming Δt_s of PMUs is constant and equal to 20 ms. In (20) and (21), $b_1, \ldots, b_k$ and $c_1, \ldots, c_k$ are calculated by increased or/and decreased ratios of the previous data $\Delta Y'_{j,g-1}, \ldots, Y_{j,g-k}$ and $U_{j,g-1}, \ldots, U_{j,g-k}$, respectively. The errors σ_1 and σ_2 are set in a range of $[0.01, Y_{j,1}, 0.05, Y_{j,1}]$. This means that σ_1 and σ_2 are set between 1% and 5% of the output signal $Y'_{j,d}$ in the steady state.

For the post-transient state; when $t_{D+1} < t < t_J$, since the signals oscillate at the dominant frequency, if missing data occur at the g-th data, then any missing data $Y_{j,g}$ and $U_{j,g}$ are restored by

$$Y'_{j,g+1} = Y'_{j,g} \pm \sum_{c=1}^{n_c} \Big(p_c \frac{q \sin(\omega_c t)}{\omega_c t}\Big), \tag{22}$$

$$U_{j,g+1} = U_{j,g} \pm \sum_{c=1}^{n_c} \Big(q_c \sin \frac{\omega_c t}{\omega_c t}\Big), \tag{23}$$

where $\omega_c = 2\pi f_c$ is the angular frequency of critical oscillation modes in the system at an operating point. Value of f_c is calculated by linearization and n_c is a total number of the critical frequencies. Value $f_c \in f_{os}$, $os = 1, \ldots, n_{os}$ where f_{os} is the dominant oscillation mode in a range of 0.2 Hz to 2 Hz at an operating point in the system and n_{os} is total number of oscillation modes, when $n_c = n_{os}$. In this work, f_c is determined by the observability of signal Y'_j and the controllability of signal U_j at the corresponding operation. For example; if any frequency f_c is a major component of the oscillation mode in signals Y'_j and U_j, the corresponding frequency f_c is used to calculate (22) and (23); otherwise, f_c is neglected. The number of oscillation frequencies used in (22) and (23) are less than or equal to the total number of oscillation frequencies. It should be noted that the signal restoration of transient and post-transient states in (16), (17), (22), and (23) is used when the following conditions are detected; for input signals of WADC, when $Y'_{j,g+1} > 1.25\, Y'_{j,g}$ or $Y'_{j,g+1} < 0.75\, Y'_{j,g}$ or $Y'_{j,g+1} = Y'_{j,g}$; for stabilizing signals of WADC, when $U_{j,g+1} > 1.25\, U'_{j,g}$ or $U + j, g + 1 < 0.75\, U'_{j,g}$ or $U_{j,g+1} = U'_{j,g}$. Since the stabilizing signal U_j is subjected to its minimum limit $U_j^{\min}$ and maximum limit $U_j^{\max}$, this means that $U_j^{\min} = \leq \Delta U_j \leq U_j^{\max}$. The constraint in stabilizing signals is described as follows; if $\Delta U_{j,g+1} < U_j^{\min}$, then $|Delta U_{j,g+1} = U_j^{\min}$; if $\Delta U_{j,g+1} > U_j^{\max}$, then $\Delta U_{j,g+1} = U_j^{\max}$.

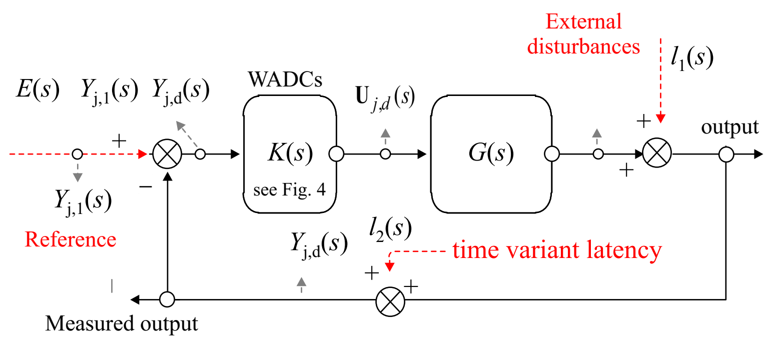

Fig. 6. Closed-loop system including communication uncertainties

3.3 Adaptive robust control strategy

To handle stochastic factors due to parameter variations, random nature of delay, poor tracking of reference signals *etc* , the adaptive robust controller is adopted from [12]. A closed-loop system including system uncertainties and communication uncertainties is depicted in Fig. 6, where l_1 is unknown external disturbance, l_2 is unknown time variant latency and communication uncertainty, $E(s)$ is an error between input and reference signals, $K(s)$ is controller and $G(s)$ is a nominal plant of a power system. Next, the state space (1) is converted to the frequency domain as

$$\boldsymbol{X}(s) = \big(\boldsymbol{A}_0\boldsymbol{X}_0(s) + \boldsymbol{B}_0\boldsymbol{U}_0(s)\big) + \sum_{j=1}^{J} \boldsymbol{A}_j\boldsymbol{X}_j(s)\exp(-s\tau_{\mathrm{R}j}) + \boldsymbol{B}_j\boldsymbol{U}_j(s)\exp(-s\tau_{\mathrm{T}j})$$

$$\boldsymbol{Y}(s) = \big(\boldsymbol{C}_0\boldsymbol{X}_0(s) + \boldsymbol{D}_0\boldsymbol{U}_0(s)\big) + \sum_{j=1}^{J} \boldsymbol{C}_j\boldsymbol{X}_j(s)\exp(-s\tau_{\mathrm{R}j}) + \boldsymbol{D}_j\boldsymbol{U}_j(s)\exp(-s\tau_{\mathrm{T}j}), \tag{24}$$

where s is complex variable in the frequency domain, $\exp(-s\tau_{Rj})$ and $\exp(-s\tau_{Tj})$ when using first-order Padé approximation, as proposed in [12], for input and output pairs of WADC and local controller, the adaptive input and output signals selection can be performed by

$$g_{cgj}^{(i)}(os) = \cos\big(B_{gj}^{(i)\top}, \Psi_{os}^{(i)}\big), \tag{25}$$

$$g_{ohj}^{(i)}(os) = \cos\big(C_{hj}^{(i)\top}, \Phi_{os}^{(i)}\big), \tag{26}$$

$$J_{coj}^{(i)}(os) = g_{cgj}^{(i)}(os) \times_{ohj}^{(i)}(os), \tag{27}$$

where the superscript (i) means the i-th operating point, OS is OS-th oscillation mode, $J_{coj}^{(i)}$, $g(i)_{cgj}$, and $g_{ohj}^{(i)}$ are joint of controllability and observability, geometric measure of controllability and observability corresponding to j-th variable latency at any i-th operating point, respectively, $B_{gj}^{(i)}$ and $C_{hj}^{(i)}$ are g-th row input and h-th column output matrices corresponding to j-th variable latency at any i-th operating point, respectively, $\Psi_{os}^{(i)}$ and $\Phi_{oc}^{(i)}$ are right and left Eigen vectors at ith operating point, respectively. In this work, the input signals of WADC and local controller are the phase difference between the related buses, and the rotor speed of local synchronous generator that have highest value of (25), respectively. The output signals of WADC and local controller are sent to stabilizing devices that provide highest value of (26). When the highest values of (25) and (26) are found, the joint value (27) can guarantee the highest controllability and observability at all operating points.

To cope with important issues in uncertain power systems such as poor damping performance, external disturbance, communication uncertainties, and reference tracking, the optimization problem is formulated by minimizing the following function.

Minimize

$$\left(\overset{O_1}{\begin{bmatrix} \zeta_{os}^{(i)} < 0.05, O_1 = 1 \\ \zeta_{os}^{(i)} < 0.05, O_1 = 0 \end{bmatrix}}\right) \cdot \big(J_{\mathrm{d}}^{(i)}\big) + \left(\overset{O_2}{\begin{bmatrix} J_{\infty}^{(i)} > \alpha, O_1 = 1 \\ J_{\infty}^{(i)} \le \alpha, O_1 = 0 \end{bmatrix}}\right) \cdot \big(1/J_{\infty}^{(i)}\big) + \left(\overset{O_3}{\begin{bmatrix} J_{2}^{(i)} \ge \beta, O_1 = 1 \\ J_{2}^{(i)} \le \beta, O_1 = 0 \end{bmatrix}}\right) \cdot \big(1/J_{2}^{(i)}\big). \tag{28}$$

Subject to

$$J_{\mathrm{d}}^{(i)} \ge J_{\mathrm{d}}^{(d)}, \quad J_{\infty}^{(i)} \le J_{\infty}^{(d)}, \quad J_{2}^{(i)} \le J_{2}^{(d)},$$

where O_1, O_2 and O_3 are logic operations, ζ_{os} is damping ratio of os-th oscillation mode, $J_{\mathrm{d}}^{(i)}$, $J_{\infty}^{(i)}$, and $J_{2}^{(i)}$ are damping, robustness, and reference tracking performances of controller at i-th operating point, respectively, $J_{\mathrm{d}}^{(d)}$, $J_{\infty}^{(d)}$, and $J_{2}^{(d)}$ are desired values of J_{d}, J_{∞}, and J_{2d}, respectively. Note that, more detail about this objective function (28) and signal selection can be found in [12].

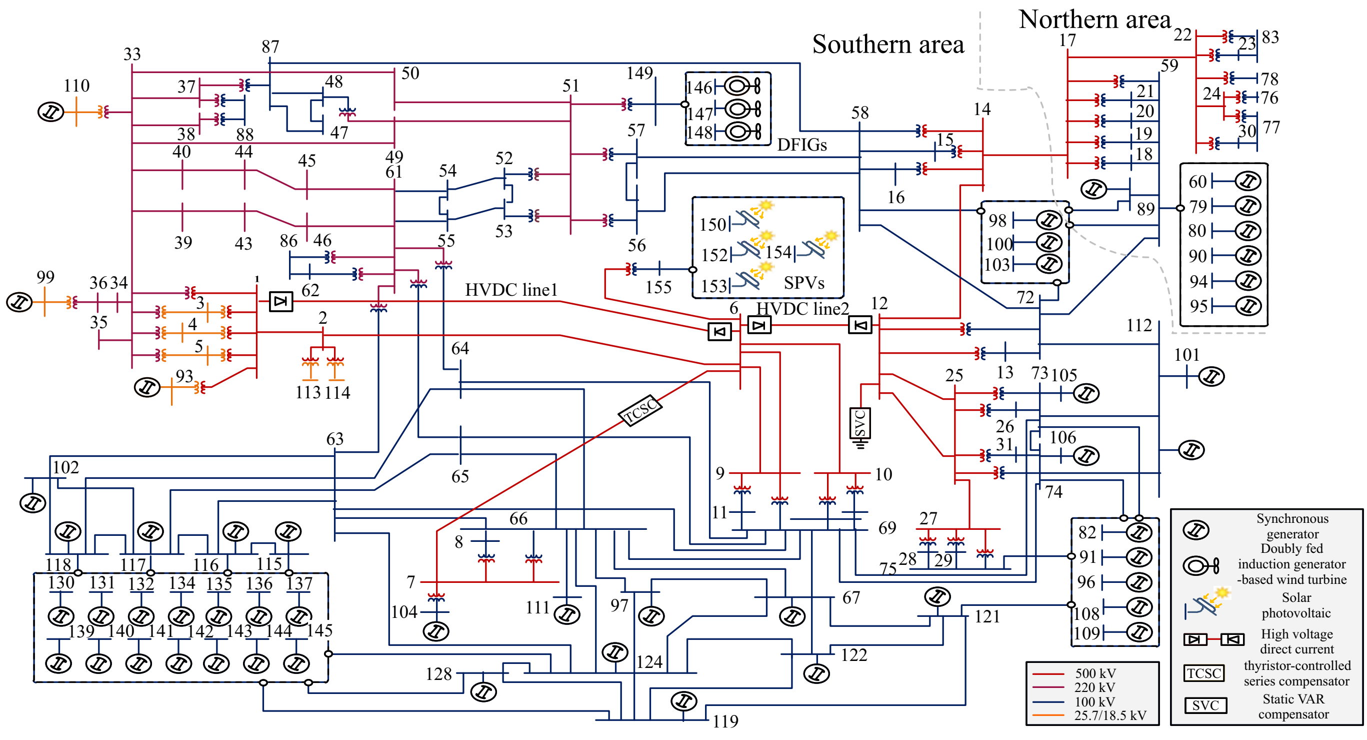

Fig. 7. A test system (system base 100 MVA, 60 Hz)

4 Study results

4.1 Test system

Figure 7 shows an IEEE 50-machine 145-bus test system used to evaluate performance of the proposed WADC. In this system, total loads are 2.83 GW and 0.8 Gvar. This system is modified by placing high voltage direct current (HVDC) transmission systems and between buses 1 and 6, and buses 6 and 12 to control the power transfer. The thyristor-controlled series compensator (TCSC) and static var compensator (SVC) are installed between buses 6 and 7, and at bus 12, respectively. Three aggregated DFIGs with 250 MW each and four aggregated solar photovoltaics (SPVs) with 175 MW each are installed at buses 149 and 155, respectively. DFIGs and SPVs operate at 75 % of their maximum capacities. Note that, the robust adaptive signal selection in [12] is used to find suitable stabilizing devices, *ie* SGs, HVDCs, TCSC, SVC, DFIGs, and SPVs for two-level damping control.

4.2 Evaluation of control effect

To evaluate the control effect of the proposed WADC, two case studies are conducted under the same variable latency. Figures 8(a) and (b) depict the variable latencies of the phase angle measurement at buses 14 and 17, respectively. The phase difference between buses 14 and 17 is used as the input signal of WADC. Figure 8(c) shows the variable latency of the stabilizing signal from WADC to HVDC line 1.

Case study 1: all power generations are increased by 20% from a normal operating point. The transmission line between buses 63 and 64 is out of service. The three phase fault takes place at the transmission line between buses 50 and 51 at $t = 1$ s for 150ms and is cleared naturally. The proposed WADC using signal restoration (red line) is compared with the WADC without signal restoration (green and black lines) under communication uncertainties (12)-(15). Note that both WADCs are designed by the same objective function (25). Figures 8(d) and (e) show the input and output signals of WADC, respectively. The pattern of restored signal (red line) is very close to that of the signal without communication uncertainties (blue line). The signal restoration shows the significant effect on the missing and distorted signals against communication uncertainties. On the other hand, the signals of the WADC without signal restoration are much different from the signal without communication uncertainties.

Case study 2: all power generations are increased by 25% from a normal operation. The transmission line between buses 6 and 9 is out of service. The three phase fault occurs at bus 14 at $t = 1$ s for 150ms and is cleared naturally. Figures 8(f) and (g) depict the input and output signals of WADC, respectively. Obviously, in case of the WADC without signal restoration, the input signals largely fluctuate while the output signals severely crash upper and lower limits. As a result, the system is unstable. On the contrary, the input and output signals of proposed WADC can be maintained effectively.

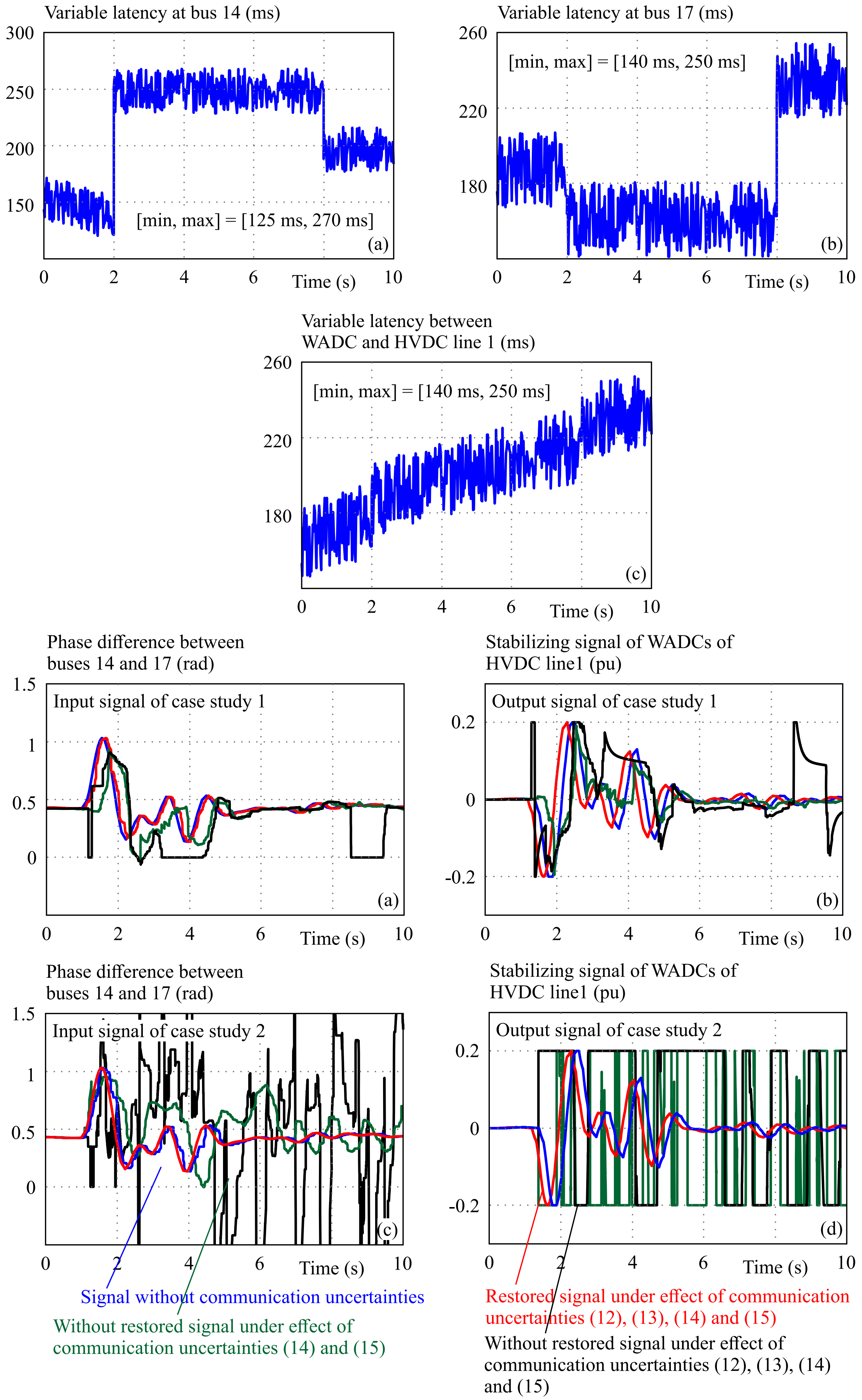

Fig. 8. Transient responses under communication uncertainties

5 Conclusion

The WADC design using signal restoration to enhance an oscillatory stability against communication uncertainties *ie* latency and communication failures has been proposed.

(i) The system model considering communication uncertainties is established. using this model, the robust adaptive robust wadc with signal restoration can be designed to handle such uncertainties.

(ii) Variable latency, in some operating points, causes the partial communication failure in input and output pairs of wadc. when the partial failure occurs, the proposed signal restoration of input and output pairs is able to repair the missing and distorted signals effectively.

(iii) Study results ensure the higher effectiveness of the proposed wadc over the conventional wadc in the face of communication uncertainties.

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