Design of a Limited State Feedback Wide-Area Power System Damping Controller Without Communication Channels

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ABSTRACT The wide-area controller (WAC) is used to damp out inter-area oscillations in the power system. Conventionally, to implement WAC in the power system, efficient wide-area communication channels are essential. The performance of the WAC can get degraded with under-performing communication channels. Although, the communication are begin made efficient and redundant, data integrity may pose another threat to the performance of the WAC. In order to subside the dependency on wide-area communication channel, this paper proposes a communication free wide-area controller (CF-WAC) to damp out inter-area oscillations even in the worst scenarios (in terms of communication channels). The CF-WAC is designed based on the state feedback principle and with limited states. The chosen design path can be achieved by using structurally constrained $H_2$-norm optimization. The proposed CF-WAC is designed in a centralized manner and implemented in a decentralized way and yet retain the near conventional WAC performance. The performance of the proposed CF-WAC is compared with full-scale WAC (FS-WAC i.e., conventional WAC), sparsity-promoting WAC (SP-WAC), and reduced-scale WAC (RS-WAC). Simulation studies are carried out on the IEEE 68-bus test system to evaluate the potential of the CF-WAC in damping inter-area low-frequency oscillations by considering different disturbances and communication channel losses.

INDEX TERMS Centralized design, communication loss, communication free WAC, decentralized design, inter-area oscillations, structurally constrained $H_2$-norm optimization, wide area control.

I. INTRODUCTION
In an interconnected power system, two kinds of oscillations can happen frequently termed as local and inter-area mode oscillations [1]. The local mode oscillations can be damped out effectively by designing the power system stabilizers (PSSs) based upon local signals [2]. On the other hand, since PSSs use local input signals, these are not sufficient to damp out inter-area oscillations. Therefore, the wide-area controller (WAC) is required to overcome the shortfalls of local damping controllers [3], [4]. However, in reality, the WAC requires information from remote locations. With the advancements in wide-area monitoring systems (WAMS) [5], like phasor measurement units (PMUs), it is possible to transfer the synchronized measurements of the entire power system to the control center in short-span of time. After receiving the data at the control center, the WAC will utilize the system-wide information and delivers the corrective signal to damp out inter-area oscillations. The WAC can be designed by using either state feedback [6] or an output feedback control technique [3]. In a state feedback control technique, an additional state estimator is required to overcome the shortfalls of local damping controllers [3], [4]. However, in reality, the WAC requires information from remote locations. With the advancements in wide-area monitoring systems (WAMS) [5], like phasor measurement units (PMUs), it is possible to transfer the synchronized measurements of the entire power system to the control center in short-span of time. After receiving the data at the control center, the WAC will utilize the system-wide information and delivers the corrective signal to damp out inter-area oscillations. The WAC can be designed by using either state feedback [6] or an output feedback control technique [3]. In a state feedback control technique, an additional state estimator is required to estimate the system states. The estimated system states are used in later stages along with a state feedback gain matrix to generate control signals at the control center to damp out oscillations. On the other hand, the output feedback control technique does not require a state estimator. Therefore, in the output feedback controller, the control signals are generated directly by passing the data received from WAMS to a WAC gain matrix (i.e., feedback gain matrix). In general, for both the cases, the WAC gain matrix is deployed at a centralized control center. The state feedback gain matrix

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The design of gain matrix can be done in a centralized level. After calculating the gain matrix, take out the respective columns and rows of gain matrix related to each and every generator’s speed and angle states. Now, the controller output signals to the generator excitation system can be calculated by taking the product of speed and angle states and gain matrix of that generator. The required speed and angle states of generator can be estimated by using speed and position estimation algorithm which are available in literature [21]. In this paper, it is assumed that the speed and angle states of generator are readily available.

The rest of the article is organized as follows. In Section II, the outline of the proposed methodology is presented. The mathematical formulation of the proposed methodology is provided in Section III. In Section IV, the design and analysis of all controllers are verified by considering 68-bus test system. The comparative performance analysis between all controllers are analyzed by considering time delay in the communication channels in Section V. In Section VI, the comparative performance is analyzed considering communication failure on the controller input and output sides. The discussion between all controllers are presented in Section VII. Finally, the article is concluded in Section VIII.

II. OUTLINE OF THE PROPOSED WIDE-AREA CONTROLLER (CF-WAC) DESIGN

A. OUTLINE OF FS-WAC, SP-WAC, AND RS-WAC

Fig. 1(a.) represents the general WAC architecture layout of FS-WAC, SP-WAC, and RS-WAC. All these controllers are implemented with the help of the state feedback control technique. The main function of a PMU is to transfer the voltage and current signals to the control center through the WAM network. The global positioning system (GPS) is used to provide time stampings to the PMU data. After receiving the signals at the control center, the required dynamic states are estimated by using a state estimator, which is shown in Fig. 1(a.). The state estimator can be implemented by using either an extended Kalman filter (EKF) [22] or an unscented Kalman filter (UKF) [23]. Then, the WAC system’s output signals can be calculated by taking the product of system states and feedback gain matrix. These WAC output signals are transmitted to the generators’ excitation system with the help of a WAC communication network.

As mentioned earlier, the generated WAC signals are given to the generators’ excitation system, as shown in Fig. 1(b.). Acronym AVR represents the automatic voltage regulator, and ESS represents the excitation system stabilizer. From Fig. 1(a.), it can be observed that the feedback gain matrix and required dynamic states are varied from one controller to another control. In FS-WAC, at the input side, all generator states are estimated, and the required feedback gain matrix can be calculated by using the classical state feedback control technique. In SP-WAC, the required input states are not predefined, and the output signals are also not predefined. Thus, the structure of feedback gain matrix and system states
are formed by promoting sparsity [9]. Finally, in RS-WAC, the input signals are dominant generator states alone, and the output signals are given to the same dominant generators. For all these control techniques, the WAM network becomes highly constrained because it requires measurements from many generators. Therefore, it leads to costly WAM infrastructure.

B. OUTLINE OF THE PROPOSED CF-WAC

The proposed WAC architecture layout with feedback gain matrix is represented in Fig. 2. As mentioned earlier, the most dominating states in inter-area mode oscillations are rotor speed and angle. Therefore, it is good enough to obtain the speed and angle states in real-time for damping out inter-area oscillations. The primary function of a speed & position estimation algorithm is to estimate the speed and angle states in real-time. These states can be estimated locally and multiplied with the respective feedback gain matrix structure to obtain the WAC signals. In centralized manner, the structurally constrained $H_2$-norm optimization technique can be used to design the state feedback gain matrix. Initially, the feedback gain matrix is full matrix. It means that the feedback gain matrix having centralized structure and those values are related to all system states. Later, it can be designed to decentralized structures corresponding to all generators speed and angle states alone by maintaining the system stability.

In this paper, the decentralized generated WAC signals along with the PSS signals (optional) are fed to the excitation system of generators and it is shown in Fig. 3. It is to be noted that the objective of this particular work is to design the communication free wide area controller, not the power system stabilizer. The PSSs should be locally tuned beforehand by using any of the available techniques. After designing the PSSs, those should be included in the core power system model for the further investigation of inter-area oscillations. However, in this article, the PSSs signals are not included to the generator’s excitation system to validate the effectiveness of the WAC alone.

III. MATHEMATICAL FORMULATION OF THE PROPOSED CF-WAC

In this section, the mathematical formulation of proposed CF-WAC, FS-WAC, SP-WAC, and RS-WAC is illustrated. Consider the linearized state-space model of the total system, as shown in Fig. 3 is described as follows:

$$\Delta \dot{x} = A \Delta x + B_u \Delta u_{wac} + B_w \Delta w$$

$$\Delta y = C_z \Delta x$$

$$\Delta z = C_z \Delta x + D_z \Delta u_{wac}.$$  

where $x$ is the state vector, $u_{wac}$ is the wide area control signal, $w$ is the disturbance input vector, $z$ is the performance output vector, and $y$ is the measurement vector. Parameters $B_w$, $C_z$, and $D_z$ are to be specified by the user depending upon the specific performance requirement. Typically, $C_z$ and $D_z$ are chosen as follows.

$$C_z^T = \begin{bmatrix} Q_z^{1/2} \\ 0 \end{bmatrix}$$

$$D_z^T = \begin{bmatrix} 0 \\ R_z^{1/2} \end{bmatrix}.$$  

That is, $z$ is chosen as an $(N_y + N_s) \times 1$ vector to represent both the control effort as well as the state disturbance. Here, $N_y$ gives the number of state variables in the system. Matrices
$Q$ and $R$ are similar to those in the LQR control. Both are symmetric matrices. Matrix $Q$ should be positive semidefinite, whereas, matrix $R$ should be positive definite. The selection of $B_w$ depends upon the specific set of physical disturbances that are recognized as prime threats to the system. There is a scope of research for appropriately determining the value of $B_w$ for a power system. The WAC signals that are used for the excitation system are generated by using the following equation.

$$\Delta u_{\text{wac}} = K_{\text{wac}} \Delta x.$$  

(6)

A. CF-WAC FORMULATION

For the proposed CF-WAC, the number of rows in $K_{\text{wac}}$ is equal to the number of generators. All columns of the $K_{\text{wac}}$ matrix except generators’ speed and angle states columns should be set to zeros. The same is illustrated in Fig. 4. This, in turn, eliminates the need for establishing communication paths between remote locations and wide area control centre. In addition, certain states are usually not observable. The corresponding columns of the $K_{\text{wac}}$ matrix should also be set to zeros. Finally, the $K_{\text{wac}}$ structure consists of only generators’ speed and angle states. Therefore, only generators’ speed and angle states are considered to generate the required WAC signals.

In this paper, the proposed CF-WAC is designed by means of the $H_2$-norm optimization with structural constraints. As it is known that, the $H_2$-norm optimized controller exhibits superior transient performance compared to the $H_{\infty}$-norm optimized controller. Moreover, forcing some columns to become zeros imposes structural constraints on $K_{\text{wac}}$. Thus, it would be difficult to obtain the $H_{\infty}$-norm optimized solution of the state feedback controller. For the dynamic system model (1), (2), (3), (4) and (5), the $H_2$-norm optimization can be formulated as follows.

$$\min \quad \text{trace}(B_w^T F B_w)$$

$$\text{s.t.} \quad F (A + B_u K_{\text{wac}}) + (A + B_u K_{\text{wac}})^T F$$

$$+ (C_z + D_z K_{\text{wac}})^T (C_z + D_z K_{\text{wac}}) = 0$$

$$K_{\text{wac}} \circ \Theta = 0$$

$$K_{\text{wac}} \circ \Theta = 0$$

(7)

(8)

(9)

(10)

More details about the $H_2$-norm optimization with and without structural constraints objective function can be found in [24]. To obtain the required CF-WAC feedback gain matrix, heavy penalties are assigned to the elements that are set to be zero, and no penalty can be added for the elements that are to be left free. The step by step procedure to design CF-WAC is as follows.

Step 1 — Perform small-signal stability analysis to find out eigenvalues of the system.

Step 2 — Identify the inter-area modes of the system.

Step 3 — Find out the full scale $K_{\text{wac}}$ matrix assuming that all generator states are available.

Step 4 — Define the structure of required CF-WAC matrix according to speed & angle states of all generators.

Step 5 — Apply the structural $H_2$-norm optimization to get the CF-WAC matrix.

Step 6 — Now, separate the CF-WAC matrix in a decentralized manner to send the WAC signals in a decentralized manner.

B. FS-WAC FORMULATION

In FS-WAC formulation, the controller inputs are all generators’ states, and output signals are given to all generators’ excitation systems. Therefore, it is a full matrix, and it is calculated by using the classical Linear Quadratic Regulator (LQR) technique. The same can be achieved by solving a $H_2$-norm optimization technique without adding constraints, as shown in equation (7).

C. SP-WAC FORMULATION

In SP-WAC formulation, the controller inputs and outputs are defined by creating sparsity [9] in the feedback gain matrix ($K_{\text{wac}}$). The sparsity is defined as follows:

$$\Theta_{ij} = 1/|K_{\text{wac}}|, \quad K_{\text{wac}} \neq 0;$$

$$\Theta_{ij} = 1/\epsilon, \quad K_{\text{wac}} = 0, \quad 0 < \epsilon < 1.$$  

where $\Theta_{ij}$ values chosen to be inversely proportional to the magnitude of $K_{\text{wac}}$ to define the sparsity in the feedback gain matrix ($K_{\text{wac}}$). More details about SP-WAC can be found in [9].

D. RS-WAC FORMULATION

The selection of inputs and outputs in RS-WAC design are calculated by performing dominance index analysis [10]. Total generators are classified into dominant and non-dominant generators by using dominance index analysis. Dominant generators refers to the generators with highest participation in inter-area oscillation modes. Therefore, the inputs in RS-WAC formulation are dominant generator states alone. The outputs of RS-WAC are given to the dominant generators only. The steps involved in RS-WAC design are as follows:

Step 1 — Perform small-signal stability analysis to find out eigenvalues of the system.
Step 2 — Identify the inter-area modes of the system.
Step 3 — Find out the participation factors of states that are involved in inter-area mode oscillations.
Step 4 — Find out each generator’s dominance index.
Step 5 — Identify the dominant and non-dominant generators of the system.

More details about RS-WAC can be found in [10].

IV. DESIGN AND ANALYSIS OF FS-WAC, SP-WAC, RS-WAC, AND CF-WAC FOR THE 68-BUS TEST SYSTEM

The effectiveness of the proposed fault-tolerant wide-area controller is validated by considering the 68-bus test system, which is shown in Fig. 5. Moreover, the proposed controller’s performance is compared with different wide area controllers, which are mentioned in the previous section. The test system consists of 16 generators, and each generator is provided with IEEE-ST1A type exciters. Exciter limits are set between 5 and -5 p.u. The modeling of generators is represented with sub-transient type, and loads are modeled by using a constant impedance model. The mechanical input torque of every generator is assumed to be constant. More information about the test system can be found in [1].

Table 1 gives the information about inter-area oscillation modes of the particular test system in the absence of wide area controller. It has 4 inter-area modes. Columns 3 and 4 of Table 1 gives the information about each mode damping ratio and frequency.

A. DESIGN OF FS-WAC, SP-WAC, RS-WAC, AND CF-WAC

As mentioned earlier, the WAC can be implemented by using either state feedback or output feedback control technique. In this article, the WAC is implemented with state feedback control technique. FS-WAC uses all generator states as inputs to generate the WAC output signals. In other words, FS-WAC (full scale WAC) is the basic WAC using state feedback approach. Therefore, the WAC and FS-WAC both are same in this case. FS-WAC, SP-WAC, RS-WAC, and CF-WAC design for the test system shown in Fig. 5 is explained in this subsection. The structures of FS-WAC, SP-WAC, RS-WAC, and CF-WAC feedback gain matrices are shown in Fig. 6. Rows represents the number of generators and columns represents the total system states. In these matrices structures, dots represents the non-zero values and empty space represents zeros. FS-WAC uses all system states on the input side and transmitting signals to all generators on the output side. The feedback gain matrix \( K_{wac} \) of FS-WAC is designed by using the classical LQR control technique. This is achieved by solving the equation (7) without imposing constraints. In the classical LQR control technique, the matrix \( R \) taken as identity matrix and matrix \( Q \) set as a diagonal matrix. The diagonal entry corresponding to an angle or speed state is set to 100. All other diagonal entries are set to 0. The feedback gain matrix \( K_{wac} \) can be modified for SP-WAC, RS-WAC, and CF-WAC based upon the design. The design of SP-WAC is illustrated in [9]. In this case, the structure of the feedback gain matrix depends upon the weights of the matrix. RS-WAC is designed by using dominant generators alone. RS-WAC uses dominant generators’ states on the input side and transmitting the signals to the same dominant generators’ excitation systems. The dominant generators for the test system are calculated by applying the dominance index analysis. The dominant
generators are G13, G14, G15, and G16. CF-WAC is designed by using speed and angle states of all generators on the input side and providing signals to all generators on the output side. The design of the CF-WAC is completely offline procedure. The design task may be repeated if the corresponding system subjected to a significant architectural changes. On the other hand, the run-time efficiency is indeed very critical to the success of any WAC. In a centralized regime, as the scale of the system increases, the controller processing burden also increases, which surfaces the scalability issues in the implementation. However, the proposed approach is devised to be a decentralized run-time process, i.e., the CF-WAC is distributed over the system. Each decentralized module takes only the corresponding local measurements. Hence, the processing burden is also distributed over the network. Therefore, the scalability concerns are eliminated through decentralized implementation.

**B. TIME AND FREQUENCY DOMAIN ANALYSIS**

The eigenvalues of the test system are calculated by performing small signal stability analysis. The eigenvalues of the test system with FS-WAC, SP-WAC, RS-WAC, CF-WAC and with out WAC for normal operating point are shown in Fig. 7. It can be seen that some of the eigenvalues are lying behind the 10% damping line in the absence of wide area controller. On the other hand, with FS-WAC, SP-WAC, RS-WAC and CF-WAC, the eigenvalues of test system are moved towards the left. Non-linear simulation studies are carried out to validate the effectiveness of the proposed controller performance. The time domain analysis is accomplished by considering different disturbances that are represented in Table 2.

**TABLE 2. List of disturbances considered.**

| Disturbance | Type of disturbance | Location | Time     |
|-------------|---------------------|----------|----------|
| TL_OUT      | Line outage         | Between Buses 60 and 61 | 15.2871 |
| LD_SHD      | Load shedding       | At Bus 23 | 15.2871 |
| 3_PHFLT     | Three phase fault   | At Bus 59 | 15.2871 |

**TABLE 3. The settling times of all generators considering line outage between buses 60 and 61.**

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | 4.2008 | 6.1171 | 11.2729 | 15.2871 |
| G2      | 3.3365 | 4.7687 | 12.0364 | 18.4921 |
| G3      | 3.2093 | 4.9703 | 12.0038 | 21.0448 |
| G4      | 4.0373 | 5.0602 | 13.0901 | 22.0763 |
| G5      | 4.1555 | 4.4937 | 14.6107 | 23.4381 |
| G6      | 4.0938 | 5.0467 | 13.0900 | 23.1987 |
| G7      | 4.0839 | 6.5280 | 12.6508 | 22.1127 |
| G8      | 4.0404 | 4.9746 | 11.2838 | 21.5982 |
| G9      | 4.7564 | 9.0506 | 15.0283 | 16.5432 |
| G10     | 4.0776 | 6.2364 | 9.5887  | 15.5062 |
| G11     | 3.6880 | 5.6243 | 9.7000  | 20.1000 |
| G12     | 3.7359 | 6.4645 | 9.1190  | 21.8193 |
| G13     | 4.0198 | 5.8622 | 9.1487  | 12.5077 |
| G14     | 4.5357 | 5.8589 | 11.8543 | 17.6271 |
| G15     | 4.3266 | 5.3907 | 7.9544  | 19.5275 |
| G16     | 5.1210 | 5.4181 | 12.3135 | 17.1647 |

**1) LINE OUTAGE BETWEEN BUSES 60 AND 61**

In this subsection, the controller performances are evaluated by disconnecting the one of the line between buses 60 and 61. The corresponding dynamic responses of rotor angle of generator 13 (G13), terminal active power of generator 13 (G13) and active power flow in line connected
between buses 53 and 54 are shown in Fig. 8. It can be seen that the oscillations which are occurred in the absence of controller are damped out by employing different controllers (FS-WAC, SP-WAC, RS-WAC and CF-WAC). The comparison between these controllers are shown in Table 3 in the form of settling times. The settling times are calculated by considering 2% tolerance band. It can be observed that FS-WAC gives the good performance compared to the remaining controllers. However, as mentioned earlier, FS-WAC needs the information from all PMUs. Likewise, SP-WAC and RS-WAC also requires the information from some PMUs. Whereas, CF-WAC doesn’t requires any information from PMUs.

2) LOAD SHEDDING AT BUS 23
By considering load shedding at bus 23, the performance of FS-WAC, SP-WAC, RS-WAC, and CF-WAC are shown in Fig. 9. It can be observed that the oscillations are effectively damped out with the incorporation of wide-area controllers. The corresponding settling times are listed in Table 4. The settling times of all generators are close to 10 sec when FS-WAC and SP-WAC are employed.

3) THREE PHASE FAULT AT BUS 59
The effectiveness of controllers are evaluated by applying three phase fault at bus 59. The fault is immediately cleared by opening the lines which are connected to that particular bus. The dynamic responses are shown in Fig. 10. In addition, the corresponding settling times of all generators are shown in Table 5. It is observed that the settling times of all generators are close to 20 sec when RS-WAC and CF-WAC are employed.
FIGURE 9. The dynamic simulation waveforms for the load shedding at bus 23 with and without WAC.

TABLE 4. The settling times of all generators considering load shedding at bus 23.

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | 4.4732 | 7.0839 | 21.5939| 22.6567|
| G2      | 5.4815 | 5.0999 | 10.7631| 22.6787|
| G3      | 4.8762 | 5.1203 | 21.5740| 19.5846|
| G4      | 4.0665 | 4.7790 | 21.7872| 23.5891|
| G5      | 5.6149 | 4.3590 | 21.9794| 22.6589|
| G6      | 3.3666 | 4.4669 | 21.6926| 23.2071|
| G7      | 3.0676 | 3.6338 | 22.6208| 20.0018|
| G8      | 4.7587 | 4.9654 | 21.5454| 23.9782|
| G9      | 5.4904 | 7.5703 | 7.9050 | 19.7081|
| G10     | 6.2176 | 6.2661 | 5.6534 | 20.9905|
| G11     | 4.7929 | 5.6974 | 15.3307| 23.0377|
| G12     | 5.5116 | 7.4298 | 20.6028| 21.0700|
| G13     | 4.0754 | 5.9325 | 21.2323| 21.2699|
| G14     | 4.5518 | 4.8256 | 18.5233| 22.2071|
| G15     | 4.1988 | 4.7969 | 20.9228| 23.0376|
| G16     | 3.6353 | 4.7733 | 14.3759| 14.4941|

TABLE 5. The settling times of all generators considering three phase fault at bus 59.

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | 4.2173 | 12.0060| 20.6022| 21.6293|
| G2      | 3.1337 | 4.2229 | 11.8947| 18.1929|
| G3      | 3.2196 | 4.3511 | 20.4095| 21.5222|
| G4      | 4.8133 | 10.9841| 22.7470| 21.6337|
| G5      | 11.1095| 15.9712| 22.0599| 22.9321|
| G6      | 4.8470 | 10.0062| 22.3246| 23.1310|
| G7      | 4.8510 | 14.1599| 22.4087| 23.5986|
| G8      | 4.2528 | 9.2049 | 20.6448| 21.9883|
| G9      | 10.5289| 19.3599| 6.9077 | 13.3103|
| G10     | 5.4837 | 5.6274 | 7.9738 | 16.1771|
| G11     | 4.7930 | 5.0042 | 19.8427| 15.6846|
| G12     | 6.7985 | 6.7487 | 21.0818| 21.6340|
| G13     | 4.0454 | 5.8145 | 20.6128| 13.3886|
| G14     | 5.1651 | 6.8974 | 20.1354| 12.4449|
| G15     | 4.1789 | 4.5727 | 11.2336| 21.2758|
| G16     | 3.6261 | 6.9464 | 17.4357| 19.2585|
In order to verify the potential of the different wide-area damping controllers, it is assumed that the transmission delay in the communication channels is fixed on the input and output sides of the controller. The fixed time delay of 200 ms considered on input and output sides. Therefore, the total time delay in the WAC loop is 400 ms. Traditional Padé approximation [6] is used to model the time delay in this paper. The transfer function of this time delay is included in the original plant model (equations (1)-(3)) for the analysis. The line outage between buses 60 and 61 along is considered for the time-domain simulation. As mentioned earlier, the fixed time delay of 200 ms is included in the input and output sides. Fig. 8 represents the dynamic simulation waveforms of different wide-area damping controllers. The proposed CF-WAC does not require any communication paths. Hence, it is free from time delay issues. From the plots shown in Fig. 8, it can be observed that the SP-WAC gives the good damping performance compared to the remaining controllers. On the other hand, the proposed CF-WAC gives satisfactory performance compared to the remaining controllers (FS-WAC and RS-WAC).

**V. COMPARATIVE PERFORMANCE EVALUATION CONSIDERING COMMUNICATION NETWORK**

The performance of the wide-area controller mainly depends upon input signals which are acquired from PMUs and output signals, which are transmitted to the power system. Therefore, in this subsection, the effectiveness of controllers are validated by considering communication loss on input and output sides. Line outage between buses 60 and 61 is considered.
TABLE 6. The settling times of all generators considering one communication failure on output side.

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | 4.2655 | 8.0726 | Unstable | 15.2871 |
| G2      | 3.1296 | 4.8980 | Unstable | 18.4921 |
| G3      | 3.2146 | 5.0897 | Unstable | 21.0448 |
| G4      | 5.4980 | 5.0728 | Unstable | 22.0763 |
| G5      | 7.2750 | 4.9523 | Unstable | 23.4581 |
| G6      | 5.4965 | 5.0597 | Unstable | 23.1987 |
| G7      | 5.5340 | 7.5779 | Unstable | 22.1127 |
| G8      | 5.4686 | 4.9916 | Unstable | 21.5982 |
| G9      | 7.2651 | 9.5971 | Unstable | 16.5432 |
| G10     | 5.5009 | 6.3950 | Unstable | 15.5062 |
| G11     | 5.4682 | 6.3550 | Unstable | 20.1000 |
| G12     | 5.4269 | 8.3680 | Unstable | 21.8193 |
| G13     | 6.2751 | 6.6598 | Unstable | 12.5077 |
| G14     | 9.6633 | 5.4328 | Unstable | 17.6271 |
| G15     | 13.5528 | 9.0715 | Unstable | 19.5275 |
| G16     | 20.1559 | 5.5450 | Unstable | 17.1647 |

TABLE 7. The settling times of all generators considering two communication failures on controller output side.

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | 13.4563 | 9.4721 | Unstable | 15.2871 |
| G2      | 11.5237 | 4.8753 | Unstable | 18.4921 |
| G3      | 12.4169 | 5.4062 | Unstable | 21.0448 |
| G4      | 15.9846 | 7.3364 | Unstable | 22.0763 |
| G5      | 16.0989 | 10.5606 | Unstable | 23.4381 |
| G6      | 15.9573 | 7.3166 | Unstable | 23.1987 |
| G7      | 15.9995 | 10.6158 | Unstable | 22.1127 |
| G8      | 16.0263 | 7.2513 | Unstable | 21.5982 |
| G9      | 17.6348 | 12.2592 | Unstable | 16.5432 |
| G10     | 16.9121 | 13.2628 | Unstable | 15.5062 |
| G11     | 17.6818 | 11.5805 | Unstable | 20.1000 |
| G12     | 16.9816 | 12.1148 | Unstable | 21.8193 |
| G13     | 16.6428 | 16.4449 | Unstable | 12.5077 |
| G14     | 18.5764 | 14.9585 | Unstable | 17.6271 |
| G15     | 23.0805 | 18.1906 | Unstable | 19.5275 |
| G16     | 20.2410 | 14.9316 | Unstable | 17.1647 |

A. LOSS OF ONE COMMUNICATION SIGNAL ON CONTROLLER OUTPUT SIDE

Here, the performances of FS-WAC, SP-WAC, RS-WAC, and CF-WAC are evaluated by considering communication loss of transmitted signal to the generator 15 (G15). Fig. 12 represents the waveforms with the incorporation of individual controllers: FS-WAC, SP-WAC, RS-WAC, and CF-WAC. Each sub-figure consists of a rotor angle of generator 15 (G15), AVR output of G15, the terminal active power output of G15, and active power flow in a line connected between buses 53 and 54. It can be seen that FS-WAC, SP-WAC, and CF-WAC gives the excellent performance in damping out oscillations. As mentioned earlier, in the case of RS-WAC, output signals are given to the generators 13, 14, 15, and 16. But, here, the signal to the generator 15 is lost. Hence, RS-WAC not able to damp out the oscillations. The corresponding settling times are listed in Table 6.

B. LOSS OF TWO COMMUNICATION SIGNALS ON CONTROLLER OUTPUT SIDE

In this case, the performances of the controllers are evaluated by considering the transmitted signals to the generators 13 and 15 lost. The corresponding dynamic waveforms are shown in Fig. 13 and the settling times of all generators are shown in Table 7. From the results, it can be observed that FS-WAC and SP-WAC performances are degraded compared to the previous case. On the other hand, CF-WAC performance does not deteriorate due to communication loss on the controller’s output side.

C. LOSS OF ONE COMMUNICATION SIGNAL ON CONTROLLER INPUT SIDE

Fig. 14 represents the dynamic waveforms for the communication loss on the input side of the controller. The loss of
FIGURE 12. The dynamic simulation waveforms for the loss of one communication channel on the controller output side.

FIGURE 13. The dynamic simulation waveforms for the loss of two communication channels on the controller output side.
generator 7 (G7) signal carried by PMU to the controller input is considered. The corresponding settling times are tabulated in Table 8. From the results, it can be observed that FS-WAC and SP-WAC cannot be able to damp out the oscillations. On the other hand, RS-WAC and CF-WAC are damped out of the oscillations effectively. RS-WAC takes the input signals from generators 13, 14, 15, and 16 only. Therefore, RS-WAC gives excellent performance compared to the remaining controllers.

D. LOSS OF TWO COMMUNICATION SIGNALS ON CONTROLLER INPUT SIDE

In this case, it is assumed that the remote signals of generators 7 (G7) and 15 (G15) transmitted to the controller are lost. The corresponding waveforms are shown in Fig. 15. It can be seen that FS-WAC, SP-WAC and RS-WAC are not able to damp out the oscillations. Since G15 signal is lost, RS-WAC not able to damp out the oscillations. However, CF-WAC alone gives the good performance in damping out the oscillations. The settling times of all generators are listed in 9.

E. LOSS OF ONE COMMUNICATION SIGNAL ON CONTROLLER INPUT SIDE AND ONE SIGNAL ON CONTROLLER OUTPUT SIDE

Here, the loss of generator 7 (G7) signal on controller input side and the loss of transmitted signal to the generator 15 (G15) are considered. Fig. 16 represents the dynamic waveforms of FS-WAC, SP-WAC, RS-WAC and CF-WAC. The settling times are displayed in Table 10. From the results, it is observed that CF-WAC alone gives the good damping performance.

VII. DISCUSSION

The comparison between FS-WAC, SP-WAC, RS-WAC, and CF-WAC is illustrated in this subsection. As mentioned earlier, the proposed CF-WAC does not require any

| Gen. Id | FS-WAC | SP-WAC | RS-WAC | CF-WAC |
|---------|--------|--------|--------|--------|
| G1      | Unstable | Unstable | 11.2728 | 15.2871 |
| G2      | Unstable | Unstable | 12.0364 | 18.4921 |
| G3      | Unstable | Unstable | 12.0037 | 21.0448 |
| G4      | Unstable | Unstable | 13.0900 | 22.0763 |
| G5      | Unstable | Unstable | 14.6107 | 23.4381 |
| G6      | Unstable | Unstable | 13.0900 | 23.1987 |
| G7      | Unstable | Unstable | 12.6508 | 22.1127 |
| G8      | Unstable | Unstable | 11.2837 | 21.3982 |
| G9      | Unstable | Unstable | 15.0263 | 16.5432 |
| G10     | Unstable | Unstable | 9.5887  | 15.5062 |
| G11     | Unstable | Unstable | 9.6999  | 20.1000 |
| G12     | Unstable | Unstable | 9.1190  | 21.8193 |
| G13     | Unstable | Unstable | 9.1487  | 12.5077 |
| G14     | Unstable | Unstable | 11.8542 | 17.6271 |
| G15     | Unstable | Unstable | 7.9544  | 19.3275 |
| G16     | Unstable | Unstable | 12.3134 | 17.1647 |
FIGURE 15. The dynamic simulation waveforms for the loss of two communication channels on the controller input side.

FIGURE 16. The dynamic simulation waveforms for the loss of one communication channel on the controller input and output sides.
TABLE 9. The settling times of all generators considering two communication failures on controller input side.

| Gen. Id | FS-WAC  | SP-WAC  | RS-WAC  | CF-WAC |
|---------|---------|---------|---------|--------|
| G1      | Unstable| Unstable| Unstable| 15.2871|
| G2      | Unstable| Unstable| Unstable| 18.4921|
| G3      | Unstable| Unstable| Unstable| 21.0448|
| G4      | Unstable| Unstable| Unstable| 22.0763|
| G5      | Unstable| Unstable| Unstable| 23.4381|
| G6      | Unstable| Unstable| Unstable| 23.1987|
| G7      | Unstable| Unstable| Unstable| 22.1127|
| G8      | Unstable| Unstable| Unstable| 21.3982|
| G9      | Unstable| Unstable| Unstable| 16.5432|
| G10     | Unstable| Unstable| Unstable| 15.5062|
| G11     | Unstable| Unstable| Unstable| 20.1000|
| G12     | Unstable| Unstable| Unstable| 21.8193|
| G13     | Unstable| Unstable| Unstable| 12.5077|
| G14     | Unstable| Unstable| Unstable| 17.6271|
| G15     | Unstable| Unstable| Unstable| 19.5275|
| G16     | Unstable| Unstable| Unstable| 17.1647|

TABLE 10. The settling times of all generators considering one communication failure on controller input side and controller output side.

| Gen. Id | FS-WAC  | SP-WAC  | RS-WAC  | CF-WAC |
|---------|---------|---------|---------|--------|
| G1      | Unstable| Unstable| Unstable| 15.2871|
| G2      | Unstable| Unstable| Unstable| 18.4921|
| G3      | Unstable| Unstable| Unstable| 21.0448|
| G4      | Unstable| Unstable| Unstable| 22.0763|
| G5      | Unstable| Unstable| Unstable| 23.4381|
| G6      | Unstable| Unstable| Unstable| 23.1987|
| G7      | Unstable| Unstable| Unstable| 22.1127|
| G8      | Unstable| Unstable| Unstable| 21.3982|
| G9      | Unstable| Unstable| Unstable| 16.5432|
| G10     | Unstable| Unstable| Unstable| 15.5062|
| G11     | Unstable| Unstable| Unstable| 20.1000|
| G12     | Unstable| Unstable| Unstable| 21.8193|
| G13     | Unstable| Unstable| Unstable| 12.5077|
| G14     | Unstable| Unstable| Unstable| 17.6271|
| G15     | Unstable| Unstable| Unstable| 19.5275|
| G16     | Unstable| Unstable| Unstable| 17.1647|

communication paths on both input and output side of the controller. On the other hand, FS-WAC, SP-WAC, and RS-WAC requires communication paths. Table 11 represents the performances of controllers for different disturbances. From Table 11, it can be observed that FS-WAC and SP-WAC gives the superior performance in the case of line outage, load shedding and three phase fault. In the case of communication signal loss, the proposed CF-WAC alone gives the excellent performance compared to remaining all controllers.

A. PERFORMANCE OF CF-WAC AGAINST LOSS OF SPEED AND ANGLE MEASUREMENTS

In previous sections, the performance of FS-WAC, SP-WAC, RS-WAC, and CF-WAC against the loss of communication channels are illustrated. However, CF-WAC doesn’t require any communication paths. Therefore, in this subsection, the performance of CF-WAC against missing of speed and angle measurements is illustrated by considering two cases. In first case, missing of generator 7 (G7) speed and angle measurements is considered. The corresponding dynamic waveforms are shown in Fig. 17. In second case, missing of speed and angle measurements of G7 and G15 are considered. The corresponding dynamic waveforms are shown in Fig. 18. From these results, it can be observed that the proposed WAC (CF-WAC) gives the good damping performance even under the loss of measurements.

B. VALIDATION OF THE PROPOSED CONTROLLER’S (CF-WAC) ROBUSTNESS

In this subsection, the robustness and reliability of the proposed controller is verified against changes in power system network structures such as continuous line outages and three line outages at a time. In continuous line outages, three lines are opened at different time intervals. The first
In this paper, fault-tolerant wide-area controller design is proposed to damp out inter-area oscillations, which requires no communication channels. In addition, the performance of the proposed CF-WAC is compared with FS-WAC, SP-WAC, and RS-WAC. The structurally constrained $H_2$-norm optimization technique is used to design FS-WAC, SP-WAC, RS-WAC, and CF-WAC. The proposed CF-WAC is designed in a centralized manner. However, later, it is separated into different groups that give a decentralized structure corresponding to speed and angle states alone. Thus, no communication lines are required to transmit wide-area controller signals to the excitation system of generators. The effectiveness of CF-WAC is verified by considering different disturbances and loss of communication channels. From the results, it is observed that the proposed CF-WAC is able to damp out low-frequency oscillations within a specific amount of time. On the other hand, FS-WAC and SP-WAC give good performance compared to the proposed CF-WAC. RS-WAC and CF-WAC are offering almost the same performance. However, the performances of FS-WAC, SP-WAC, and RS-WAC are deteriorated when the data is lost due to communication channels. The proposed CF-WAC performance is constant when there is communication loss or not. Therefore, it is quite enough to design the wide-area controller by considering speed and angle states, which requires no communication paths.

VIII. CONCLUSION

In this paper, fault-tolerant wide-area controller design is proposed to damp out inter-area oscillations, which requires no communication channels. In addition, the performance of the proposed CF-WAC is compared with FS-WAC, SP-WAC, and RS-WAC. The structurally constrained $H_2$-norm optimization technique is used to design FS-WAC, SP-WAC, RS-WAC, and CF-WAC. The proposed CF-WAC is designed in a centralized manner. However, later, it is separated into different groups that give a decentralized structure corresponding to speed and angle states alone. Thus, no communication lines are required to transmit wide-area controller signals to the excitation system of generators. The effectiveness of CF-WAC is verified by considering different disturbances and loss of communication channels. From the results, it is observed that the proposed CF-WAC is able to damp out low-frequency oscillations within a specific amount of time. On the other hand, FS-WAC and SP-WAC give good performance compared to the proposed CF-WAC. RS-WAC and CF-WAC are offering almost the same performance. However, the performances of FS-WAC, SP-WAC, and RS-WAC are deteriorated when the data is lost due to communication channels. The proposed CF-WAC performance is constant when there is communication loss or not. Therefore, it is quite enough to design the wide-area controller by considering speed and angle states, which requires no communication paths.

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