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Scattering Transformation Based Wide-Area Damping Controller of SSSC Considering Communication Latency

AHMED HUSHAM[1], ALAA EL-DIN HUSSEIN[2], (Member, IEEE), MOHAMMAD A. ABIDO[2,3], (Senior Member, IEEE), AND INNOCENT KAMWA[4], (Fellow, IEEE)

[1]Department of Electrical and Computer Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada
[2]Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
[3]K. A. CARE Energy Research and Innovation Center (ERIC), Dhahran 34464, Saudi Arabia
[4]Hydro-Québec/IREQ, Power System and Mathematics, Varennes, QC J3X 1S1, Canada

Corresponding author: Mohammad A. Abido (mabido@kfupm.edu.sa)

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ABSTRACT This paper presents a new design of a scattering transformation-based wide-area damping controller for static synchronous series compensator (SSSC) to enhance power system stability in the presence of communication latency. The proposed control approach is comprised of a classical structure in addition to two scattering transformation ports. These ports are inserted between the power system and the wide-area damping controller (WADC) to regulate the signal exchange. Since the WADC is a centralized controller, the time delay imperfections are considered in the design stage. The proposed controller design is formulated as an optimization problem where the controller parameters are optimized using the particle swarm optimization (PSO) algorithm. The proposed controller improves the system damping performance due to the achieved time delay compensation. The proposed controller's effectiveness is demonstrated by implementing the controller in several case studies under different disturbance scenarios. The proposed controller performance is benchmarked with the classical WADC based on the lead-lag structure. The results confirm the robustness of the proposed WADC against time delay uncertainty. The proposed controller's efficacy is confirmed to reduce the time delay, resulting in better power system stability.

INDEX TERMS Scattering transformation, wide-area damping control, power system stability, flexible ac transmission systems, communication delay.

NOMENCLATURE

X	System dynamic states vector
$\boldsymbol{Y}$	Vector of network algebraic variables
F	Set of system differential equations
G	Vector of algebraic equations
U	Vector of control signals.
T_1, T_2, T_3, T_4	Phase-compensation parameters
$\boldsymbol{T_w}$	The washout filter time constant
K	The controller gain
$CONT_i$	Controllability measures of the i^{th} mode
OBS_i	Observability measures of the i^{th} mode
Ψ_{ik}	Left eigenvectors associated with k^{th} state variable and i^{th} oscillatory mode
Φ_{ki}	Right eigenvectors associated with k^{th} state variable and i^{th} oscillatory mode
$H(s)$	The representation of the plant
$H_1(s)$	Right-hand side scattering
$H_2(s)$	Left-hand side scattering
$H_{WADC}(s)$	The controller transfer function
$V_l(s)$, $U_l(s)$	The left-hand side scattering signals
$V_r(s)$, $U_r(s)$	The right-hand side scattering signals
β	The scattering-parameter, $\beta \in \mathbb{R}$
T_D	The communication delay
T_{D1}	The forward latency
T_{D2}	The backward latency
$\Delta\omega$	Speed deviation

I. INTRODUCTION

With the ongoing growth of electrical demands ruled by the desire to have a reliable operation, power systems

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transmission infrastructure has remarkably evolved. Such systems experience a significant drift in several dynamical properties and system stability margins. This evolution is accompanied by high complexity to handle various operating circumstances. Multiple power system utilities, therefore, are interconnected. This interconnection is vulnerable to undesired low-frequency oscillations (LFOs). Damping of such oscillations has become a major concern for improving power system stability. It would reduce the reserve margin of transmission capacity and limit the interconnected ability of large-scale systems. This problem could be solved using power system stabilizers (PSSs) and flexible AC transmission systems (FACTS) controllers. Moreover, these control devices can utilize remote signals, overcoming the limitation of using local measurements where some oscillatory modes are not observed [1].

Nowadays, FACTS devices have gained much attention as one of the available alternatives to strengthen the transmission system in electrical networks. FACTS controllers are very effective in suppressing interarea oscillations as they could guarantee adequate damping under multiple operating conditions at a comparatively low additional cost [2].

Due to the power system's complex nature, conventional communication methods have become less guarantee of modern power grids' control design requirements. Recently, the advent of phasor measurement units (PMUs) that emerged with satellite time service systems has led to the establishment of wide-area measurement systems (WAMSs) [3]. Unlike conventional communication systems, WAM communication is built on a powerful wide area network/local area network (WAN/LAN) technology [4]–[6]. WAMs technology supported by broad implementation of PMUs has opened the floor to develop wide-area damping controllers (WADCs) to gain effective damping for low-frequency oscillations (LFOs), compared to the locally measured signals, which lack observing some critical interarea modes [7]–[9]. With WAMs data, the observable space becomes wider. Besides, PMUs signals are time-synchronized and correlated at any point of a distributed electric network by a global positioning system (GPS), which provides accurate timing pulses for PMU signals [10], [11]. Since wide-area control systems include communication channels in the control loop, such systems could be considered typical network control systems (NCSs).

With the outstanding growth of communication technologies, communication networks have become more appealing for signal transmission in control systems than traditional point-to-point connections, which are considered more complex, more expensive, and less reliable. NCSs have presented a new type of spatially distributed control systems where sensors, actuators, and controllers are spatially separated and linked physically through a limited-bandwidth digital communication network. However, the remote signal transmission would constitute a major challenge in terms of time delay (or latency) induced in the control loop of the WADC. Communication latency is usually referred to as the time demanded to render PMU data towards the control center through the phasor data concentrator (PDC) in addition to the time required to transfer the control commands to control devices since the designed WADC is a centralized one. Wide-area signal transmission latency differs from a few to hundreds of milliseconds due to some factors such as transmission media, router selection, transmission protocols, and communication loads [12]–[14]. Generally, latency can be fixed or variable for each data transmission. Communication latency would cause linear phase shifts that limit the control bandwidth, degrade closed-loop stability, and deteriorate the damping performance of WADC, which may lead to control failure. Therefore, such time delays should be considered during WADC design [15].

Generally, various methodologies have been used to manage the time delay impact.

In [16], a wide-area damping controller's hardware implementation based on bilinear transformation is presented. Dynamic output-feedback wide-area damping control of the HVDC transmission system considering signal time-varying delay was addressed in [17]. Ref. [18] presented power system stability agents using robust wide-area control to ensure guaranteed system performance with time delay existence. Delay-dependent stability analysis of the power system with a WADC was addressed in [19], where the design was formulated as an optimization algorithm with a set of linear matrix inequality constraints. Ref. [20] discussed continuous time-delay compensation based on rotating coordinates adjustment using adaptive phasor power oscillation damping (POD). In [21], the communication delay impact of HVDC-based WADC has been reported as practical experience in China's southern power grid. In [22], Padé approximation is used to compensate for the time delay in a wide-area power system as a second level control design. Ref. [23] presented an excessive regeneration detector design for stability augmentation by shifting the system's gain when a high delay in a wide-area damping system is experienced.

The major limitation of the reported techniques [13]–[20] lies in their dependency on the plant's full knowledge availability and time-delay. However, the impracticality of having an accurate plant model makes the whole design prone to modeling errors. Moreover, most of the reported methods are based on robust control theories, which are complex, as they require a proper selection of weighing matrices.

Scattering transformation (ST) is one of the delay-independent procedures, derived initially from classical network theory [24], and applied in the control context for the first time in [25]. Matiakis *et al.* [26] presented a new strategy to overcome the plant and controller's restrictive passivity assumption. The notion of scattering transformation has been extended to include non-passive linear time-invariant (LTI) systems to be stabilized independently of time-delay. Since communication delay can easily ruin system passivity, scattering transformation is able to passivate the communication subsystem with large latencies and ensures low sensitivity to time-delays. Therefore, it can guarantee a satisfactory performance for wide delay ranges.

In this work, a new scattering transformation-based wide-area damping controller (ST-WADC) design is proposed for the static synchronous series compensator (SSSC) as an example of a voltage source converter-based FACTS device. It is aimed at enhancing the power system stability in the presence of communication latency. The main feature of the proposed ST-WADC is its capability to improve interarea oscillation damping and provide active compensation of communication latencies in feedback control signals. The widely used conventional lead-lag structure is kept for the proposed ST-WADC, facilitating its implementation in real-life. The parameter settings of the proposed ST-WADC are tuned via the particle swarm optimization (PSO) algorithm. The proposed method is successfully applied to two different multi-machine power systems. Simulation results show the effectiveness of the proposed control strategy in enhancing the power system stability and increasing the system damping of interarea oscillations. In addition, the proposed technique is simple, model-free, and efficiently handles the delay uncertainty.

The remainder of this paper is organized as follows. A theoretical overview of the power system structure is introduced in section II, and the design problem is formulated. Section III presents the design of a scattering transformation-based wide-area damping controller (ST-WADC) considering the time delays. The effectiveness of the proposed design is discussed through time-domain simulation in Section IV. Finally, Section V concludes the paper with the major findings and remarks.

II. PROBLEM FORMULATION

A. POWER SYSTEM MODEL

In this work, multimachine power systems are considered. The machines are represented by a two-axis model in addition to the static exciter model. Generally, the power system dynamic model is given by a set of differential-algebraic equations as follows.

$$\begin{cases} \dfrac{dX}{dt} = F\left(X, Y, U\right) \\ 0 = G\left(X, U\right) \end{cases} \tag{1}$$

where X and Y are the state vector and network variables, respectively; F counts for the set of differential equations which model the dynamic part of the system; G represents the vector of algebraic equations describe the static part; U is the vector of control signals provided by power system stabilizers.

B. WIDE-AREA DAMPING CONTROLLER (WADC) STRUCTURE

The proposed ST-WADC structure consists of two lead-lag compensators, a washout filter, and the controller gain as follows:

$$H_{WADC}\left(\mathrm{s}\right) = K * \frac{T_w s}{1 + T_w s} * \frac{1 + T_1 s}{1 + T_2 s} * \frac{1 + T_3 s}{1 + T_4 s} \tag{2}$$

where T_1, T_2, T_3, and T_4 are the phase-compensation parameters, T_w is the washout filter time constant, which is usually set between 5-10 s, and K is the controller gain.

The purpose of this controller is to enhance the system damping to low-frequency inter-area oscillations by inserting a supplementary remote-control signal into the excitation system loops of most contributing machines to the interarea modes.

C. GEOMETRIC CONTROLLABILITY/OBSERVABILITY MEASURE

Applying control theories with an inappropriate system input/output could lead to some numerical difficulties. Therefore, modal analysis of controllability and observability is used to select the proper input/output signals. The following equations are used to obtain these measures:

$$\begin{cases} CONT_i = \left\| \Psi_{ik}^T B_j \right\| \\ OBS_i = \left\| C_j \Phi_{ki} \right\| \end{cases} \tag{3}$$

where $CONT_i$ and OBS_i represent the controllability and observability measures of the i^{th} mode, respectively. Ψ_{ik} and Φ_{ki} are left and right eigenvectors associated with k^{th} state variable and i^{th} oscillatory mode, respectively.

The interpretation of Eq. III-A is that if $CONT_i \neq 0$, then, the i^{th} mode is controllable by the j^{th} input and if $OBS_i \neq 0$, then, the i^{th} mode is observable in the j^{th} output.

III. PROPOSED CONTROL STRATEGY

Some of the main design concepts are discussed in this section, as follows:

A. PRELIMINARIES

A system is called a passive system if all its interconnected subsystems are passive and, thus, stable [27]. Any passive system has the following properties [27]:

1- The passive system does not produce energy on its own (only consume or dissipate energy), i.e., at $time = 0$, the energy generated should be equal to zero.
2- In a passive system, no initial stored energy.
3- Any increase in the input u is offset by an increase in the output y.
4- Any two passive subsystems connected in series, parallel, or feedback connection will result in a passive system.

On the other hand, the inclusion of a time-delay communication network violates the system passivity as such a network generates energy, which may lead to system instability [25].

Therefore, scattering transformation is introduced to passivate the communication subsystem and guarantee networked control system stability with time-delay [28].

B. THE PROPOSED ST-WADC DESIGN

Consider the power system as a plant represented by $H\left(s\right) = \frac{Y_p(s)}{U_p(s)}$, where $Y_p(s)$ and $U_p(s)$ are the power system output and input, respectively. FIGURE 1 shows the proposed scattering transformation-based wide-area damping control scheme where scattering transformation is inserted between WADC, power system plant, and the communication network. In FIGURE 1, $H_1\left(s\right)$ represents the right-hand side scattering including the plant $H\left(s\right)$ while $H_2\left(s\right)$ represents the left-hand side scattering including WADC. H_1 and H_2 are

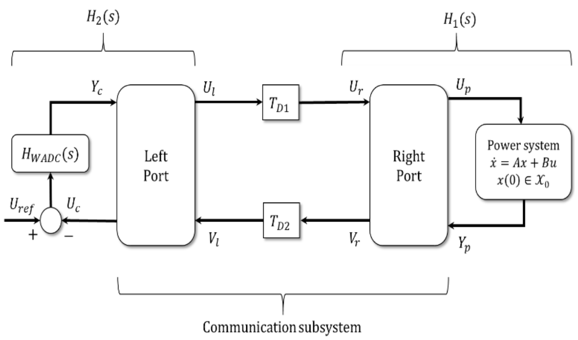

FIGURE 1. **The proposed ST-WADC scheme, where the signals are exchanged throughout the left and right scattering ports.**

defined as follows [26]:

$$H_1(s) = \frac{V_r(s)}{U_r(s)} = \frac{H(s) - \beta}{H(s) + \beta} \tag{4}$$

$$H_2(s) = \frac{U_l(s)}{V_l(s)} = \frac{1 + \beta . H_{WADC}(s)}{1 - \beta . H_{WADC}(s)} \tag{5}$$

where $H_{WADC}(s)$ represents the WADC transfer function as given in Eq. (2). $V_r(s)$ and $U_r(s)$ are the right-hand side scattering signals while $V_l(s)$ and $U_l(s)$ are the left-hand side scattering signals. β is the scattering-parameter, $\beta \in \mathbb{R}$.

The derivation of H_1 and H_2 is given in the Appendix. The right and left scattering signals are transmitted via a two-port delayed communication network that results in a violation of the passivity condition as such a communication network generates energy [25]. Therefore, scattering transformation is employed to passivate the communication subsystem when an arbitrarily large delay is introduced [28]. The round-trip communication delay T_D is equal to $T_{D1} + T_{D2}$, where T_{D1} is forward delay, and T_{D2} is backward delay. T_D is further assumed to be fixed unknown latency. The forward and backward delays are considered equal, i.e., $T_{D1} = T_{D2}$. The scattering signals are related to each other as follows:

$$\begin{cases} U_r(t) = U_l(t - T_{D1}) \\ V_l(t) = V_r(t - T_{D2}) \end{cases} \tag{6}$$

To mitigate the time delay impact, the system could be extended by scattering transformation, which represents a simple linear transformation of the signals exchanged between the plant and the controller over the network in the following form [28]:

$$\begin{cases} U_l = \frac{1}{\sqrt{2\beta}}(U_c + \beta Y_c) \\ V_l = \frac{1}{\sqrt{2\beta}}(U_c - \beta Y_c) \\ U_r = \frac{1}{\sqrt{2\beta}}(Y_p + \beta U_p) \\ V_r = \frac{1}{\sqrt{2\beta}}(Y_p - \beta U_p) \end{cases} \tag{7}$$

or equivalently,

$$\begin{cases} \begin{pmatrix} U_l \\ U_c \end{pmatrix} = S \cdot \begin{pmatrix} V_l \\ Y_c \end{pmatrix} \\ \begin{pmatrix} V_r \\ U_p \end{pmatrix} = S^{-1} \cdot \begin{pmatrix} U_r \\ Y_p \end{pmatrix} \end{cases} \tag{8}$$

where

$$S = \begin{pmatrix} \frac{1}{\sqrt{2\beta}} & \frac{\sqrt{2\beta}}{\beta} \end{pmatrix}; S^{-1} = \begin{pmatrix} -1 & \sqrt{\frac{2}{\beta}} \\ \sqrt{\frac{2}{\beta}} & -\frac{1}{\beta} \end{pmatrix}; \forall \beta > 0$$

In Eq. (7), U_p and Y_p are the plant input and output, respectively. U_c and Y_c are the controller input and output, respectively.

The design aims to minimize the H_∞ norm of $H_1(s)$ to be less than or equal to one. If this condition is satisfied, the system $H(s)$ is positive-real (PR). Consequently, the system will be stable [26].

With no time delay, the two scattering transformation ports cancel each other, and the basic feedback interconnection form is resembled. With delays, however, (U_l, V_l) is no longer equal to (U_r, V_r) and this scattering transformation alters the properties of the closed-loop system.

The practical implementation of ST-WADC could be done on two levels. The right-hand scattering port can be considered as a part of the plant implemented as a local controller, while the left-hand scattering port can be implemented along with the classical lead-lag structure. Therefore, one can easily implement the proposed control scheme in Real-time.

C. OPTIMIZATION PROBLEM FORMULATION

One of the advantages of the proposed approach is that it keeps the structure of the proposed ST-WADC as the widely used lead-lag structure, enhancing its readiness level of implementation. To design the proposed ST-WADC, the parameter-tuning task is formulated as an optimization problem. In this work, the optimized parameters are the gains and time constants. Also, the scattering-parameter β is optimized to minimize the adverse impact of the communication delay.

In this work, it is aimed at minimizing the objective function J that represents the integral time absolute error (ITAE) performance index over the simulation run-time, t_f, defined as follows:

$$J = \int_0^{t_f} t.|\Delta\omega| dt \tag{9}$$

where $\Delta\omega$ is the speed deviation.

The overall optimization problem can be formulated as follows.

Minimize J

$$\text{Subjected to}: \begin{cases} K^{\min} \le K \le K^{\max} \\ T_1^{\min} \le T_1 \le T_1^{\max} \\ T_2^{\min} \le T_2 \le T_2^{\max} \\ T_3^{\min} \le T_3 \le T_3^{\max} \\ T_4^{\min} \le T_4 \le T_4^{\max} \\ \beta^{\min} \le \beta \le \beta^{\max} \end{cases} \tag{10}$$

It is clear that the only difference in the proposed ST-WADC design compared to that of conventional stabilizers is the consideration of the scattering-parameter β in the design process. To solve the formulated optimization problem, particle swarm optimization (PSO) is employed as an efficient evolutionary technique [29]. For the sake of comparison, the proposed ST-WADC is compared against the conventional one without time delay compensation.

D. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population-based metaheuristic intelligent searching method that tackles massive computational optimization problems, which could be partially irregular, discontinuous, noisy, or time-varying. The solution is computed iteratively by improving the candidate solutions (called particles) based on the considered objective function. Each particle is an σ-dimensional, where σ represents the number of optimized parameters. PSO solves the problem by moving a population of candidate solutions (called a swarm) in a multidimensional search-space according to a few simple mathematical formulae to regulate each particle's position and velocity dynamically. The particle trajectory in the search-space is ruled by its own best-known position (personal best position) and the entire swarm best-known position (global best position). The discovered-improved positions will be the movement guidance of the entire swarm. By repeating this process, the optimal solution will most likely be discovered at the end [29].

The PSO procedure is described as follows:

Step 1) *(Initialization):*

1- Set the time counter $t = 0$.
2- Generate randomly n particles by a random selection of value with a uniform probability over parameters search-space.
3- For each particle in the initial population, the objective function J is evaluated, and the best objective function value is taken J_{best}. This value will be considered as a global best function J_{best} and the associated global best particle as $xbest$.
4- Set the initial value of the inertia weight that is a control parameter used to control the previous velocity's impact on the current velocity. Set the initial value of the inertia weight $\omega_{initial}$.

Step 2) *(Time updating):* Update the time counter $t = t+1$.

Step 3) *(Weight updating):* Update the inertia weight by $\omega(t) = \alpha\omega(t-1)$, where α is a decrement constant smaller than but close to 1, where ω is the inertia weight factor.

Step 4) *(Velocity updating):* Using the global best and individual best. One can update the velocity associated with the j_{th} particle the σ_{th} dimension by:

$$\mathcal{V}_{i,\sigma}(t+1) = \omega(t+1)\,\mathcal{V}_{j,\sigma}(t) + c_1 r_1 \left(P_{best}(t) - \mathcal{X}_{i,\sigma}(t)\right) + c_2 r_2 (g_{best}(t) - \mathcal{X}_{i,\sigma}(t)) \quad (11)$$

where σ number of the particles in the group. c_1 and c_2 are positive constants used to alter the particle velocity toward P_{best} and g_{best} and represent the cognitive and social acceleration factors, respectively. r_1 and r_2 are two uniformly distributed random numbers between in [0,1]. t is the iteration number [29].

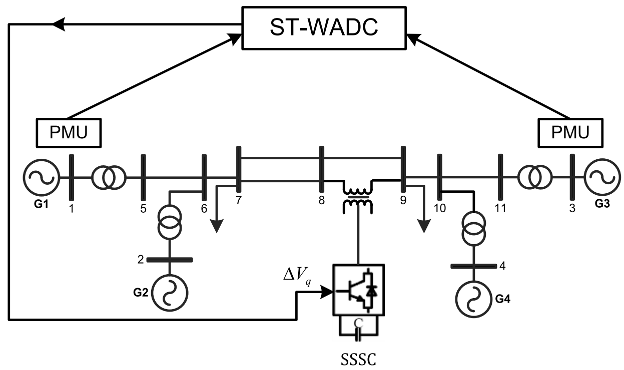

FIGURE 2. Two-area four-machine system with SSSC.

Step 5) *(Position updating):* Based on the updated velocities, each particle changes its position according to the following equation:

$$\mathcal{X}_{i,\sigma}(t+1) = \mathcal{X}_{i,\sigma}(t) + \mathcal{V}_{i,\sigma}(t+1) \quad (12)$$

where $\mathcal{X}_{i,\sigma}$ is the position of the i^{th} particle in σ^{th} dimension.

Step 6) *(Individual best updating):* Each particle is evaluated according to the updated position. If the cost function of this particle at this moment is less than the global best J_j^*, then update individual best as a global best and go to step 7; else go to step 7.

Step 7) *(Global best updating):* Search for the minimum value among the global best J_j^* where min is the index of the particle with minimum objective function value, i.e., if $J_{min} > J^{**}$ then update global best as $X^{**} = Xmin$ and $J_{min} = J^{**}$, and go to step 8; else go to step 8.

Step 8) *(Stopping criteria):* If one of the stopping conditions are satisfied, then the process could be terminated, or else go to step 2.

In this work, the following ranges of the optimized parameters have been set.

$$\begin{cases} K \in [0.01 - 40] \\ T_1, T_2, T_3, T_4 \in [0.01 - 2] \\ \beta \in [0.01 - 10] \end{cases} \quad (13)$$

IV. CASE STUDY I: FOUR-MACHINE/TWO-AREA TEST SYSTEM

The proposed ST-WADC is tested on the two-area four-machine system shown in FIGURE 2. Each machine has a rating of 900 MVA, and the complete system data is given in [30], [31]. This system experiences an interarea mode of oscillation with a frequency of 0.55 Hz and a damping ratio of 0.032 [30]. Here, SSSC is installed to control the power flow and mitigate the oscillations via providing virtual compensation of transmission line impedance by injecting a controllable voltage V_q in series with the transmission line. In pursuit of damping the inter-area oscillations, wide-area signals are taken as auxiliary signals for SSSC.

A. CONTROLLER DESIGN

In this system, buses associated with G1 and G3 are equipped with PMUs and, i.e., $\Delta f_{13} = f_1 - f_3$, is selected as remote

TABLE 1. Optimized WADC parameters using PSO.

Control Method	K	T_1	T_2	T_3	T_4	β
Conventional WADC	40	2.0	0.753	2.0	0.752	---
Proposed ST-WADC	40	2.0	0.819	2.0	0.757	2.370

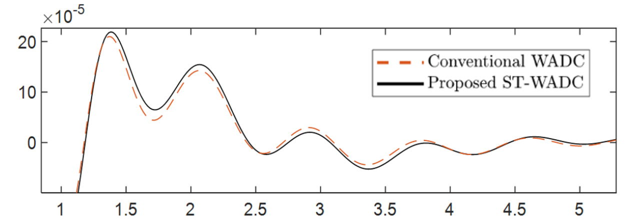

FIGURE 3. System interarea oscillations with no delay under 4-cycle 3-phase fault at bus 8.

input to WADC. Here, f_1 and f_3 are the area frequencies measured by the PMUs. It is worth mentioning that bus frequencies are used instead of rotor speeds to make the concept less idealized [32].

For the conventional design as well as the proposed one, PSO is implemented to find the optimal controller parameters. Several runs have been carried out to ensure the robustness of the technique. The solution with the lowest value of the objective function given by Eq. (9) is considered as the best solution. The optimal settings are listed in Table 1. It has been figured out that the best range of scattering-parameter β is between 0.01 and 10.

To examine the system performance, a three-phase fault is applied at one of the tie-lines at bus 8, at $t = 0.5$ *sec* and cleared after 4 cycles. The simulation is done over a time horizon of 10 *sec*. To demonstrate the robustness of the proposed ST-WADC in terms of the delay time of communication channels, three different cases of no delay, fixed delay, and variable delay are considered.

B. SYSTEM RESPONSE WITHOUT DELAY

When there is no delay, the system response is presented in FIGURE 3. The response with and without scattering transformation is almost identical, i.e., the proposed ST-WADC provides the same damping characteristic as conventional WADC in this case. It can be concluded that the scattering control does not alter system properties when there is no delay (ideal control action).

C. SYSTEM RESPONSE WITH FIXED DELAY

When time delay is considered, the interarea oscillation is well-damped using the proposed ST-WADC, and the system is perfectly stabilized, as shown in FIGURE 4. It can be observed that the proposed controller can attenuate the oscillations significantly compared to conventional WADC under the same fault conditions. The performance has been tested under two round-trip delay values with equally backward and forward delays ($T_{D1} = T_{D2} = \frac{T_D}{2}$, where T_D is the total time delay). The values of $T_D = 300$ *ms*, and 500 *ms* have been considered. As shown in FIGURE 4, the proposed controller can handle large delays and withstand

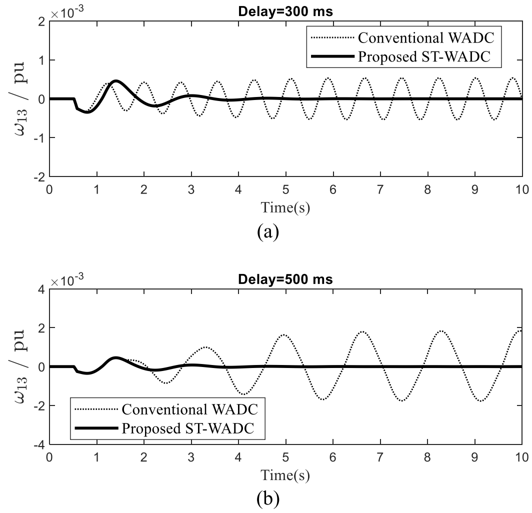

FIGURE 4. Speed deviation response due to 4-cycle 3-phase fault with different values of fixed delays: (a) 300 ms (b) 500 ms.

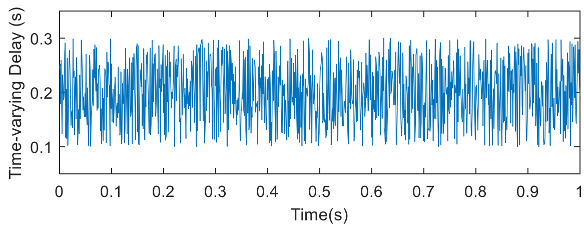

FIGURE 5. Variable time delay in the wide-area signal.

the oscillation, unlike the conventional one. As the communication latency gets larger, the performance with the conventional WADC becomes relatively poor, and the system failed to tolerate the oscillations. Furthermore, system oscillations grow and cause a loss of synchronism among generators, as shown in FIGURE 4. This result confirms that ST-WADC is robust enough to handle large delays. Besides, the proposed ST-WADC outperforms the conventional controller in terms of settling time and maximum overshoot. It is clear that the proposed ST-WADC guarantees delay-independent stability and shows less sensitivity to time delay, unlike conventional WADC.

D. SYSTEM RESPONSE WITH VARIABLE TIME DELAY

Since all the measured feedback signals are time-stamped by PMUs, i.e., the exact signal transmission time is recorded, the latency can be computed if the controller location's local time is available. It is worth mentioning that the communication latency is not usually constant due to some factors such as communication loading. This may cause a delay uncertainty, which is considered in the proposed design as well. Here, the control signal is assumed to have a total delay comprised of the fixed delay and a random value. This value has been taken arbitrarily to represent variable time delay, say $200 \pm rand\,(100)$ *ms*, as given in FIGURE 5.

FIGURE 6 shows the dynamic system response in the presence of large random communication delays, 300 ± 100 *ms* and 500 ± 100 *ms*. As shown in FIGURE 6, it is clear that

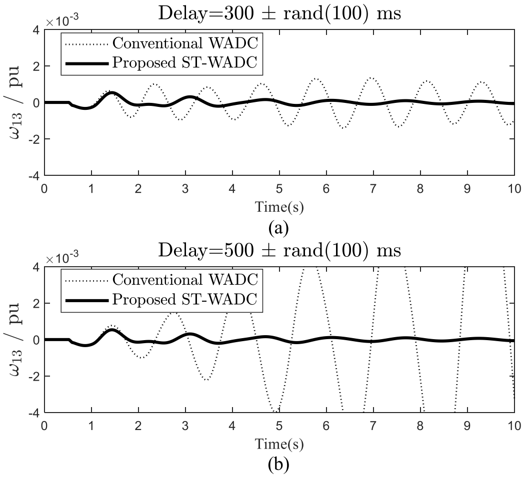

FIGURE 6. Speed deviation response under 4-cycle 3-phase fault with different time-varying delays: (a) 300 ± rand(100) ms; (b) 500 ± rand(100) ms.

TABLE 2. The performance index under different values of fixed and variable delays.

	Fixed Delay		Variable Delay	
	300 *ms*	500 *ms*	300 ± 100 *ms*	500 ± 100 *ms*
Conventional WADC	40.76	53.82	41.85	76.59
Proposed ST-WADC	1.64	2.65	1.71	9.92

the system performance with the conventional controller gets worse and collapses at 500±100 *ms* delay. On the other hand, the proposed ST-WADC is able to preserve system stability in both cases. This verifies the robustness of ST-WADC against wide-area signal delay uncertainty.

E. PERFORMANCE INDEX EVALUATION

In order to compare the performance of the proposed approach quantitatively, the following integral of time absolute error (ITAE) performance index is used:

$$ITAE = \int_{0}^{t_f} t \left(\sum_{i=1}^{n} |\Delta\omega_i| \right) .dt \quad (14)$$

where n is the number of generators, note that the performance index's low value indicates a better response. Here, this performance index has been calculated under the same previous fault conditions. The results are given in Table 2. It can be seen that the ITAE values with the proposed ST-WADC are much lower for all delay values. This confirms its robustness and indicates that the proposed controller offers better performance compared to conventional WADC.

V. CASE STUDY II: SIX-MACHINE SYSTEM

To explore further the effectiveness of the proposed strategy, another case study has been conducted. The controller has been implemented in a three-area; 6-machine system shown in FIGURE 7. The complete system data is given in [33]. This system experiences two interarea modes of oscillations. These modes have frequencies of 0.47 and 0.78 Hz, with a damping ratio of 0.272 and 0.035, respectively [33].

A. CONTROLLER DESIGN

Similar to the previous case, effective damping of interarea oscillations can be achieved by regulating the SSSC injected

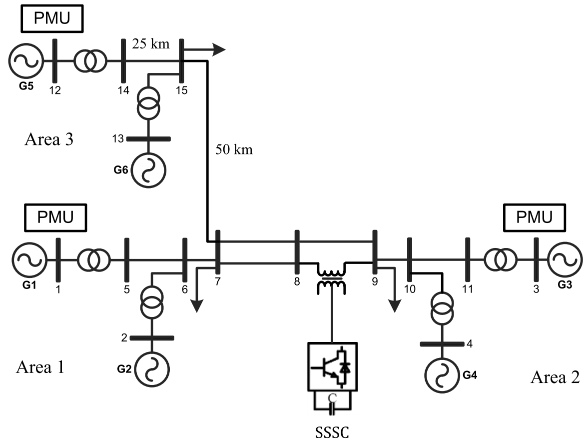

FIGURE 7. Six-Machine Power System with SSSC.

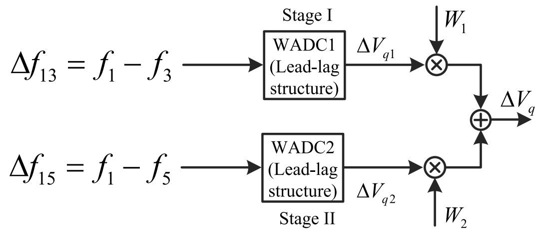

FIGURE 8. Block diagram of a multi-stage lead-lag controller.

TABLE 3. Optimized parameters of the conventional WADC.

	K	T_1	T_2	T_3	T_4
Stage I	28.082	1.395	0.542	0.680	0.455
Stage II	9.841	1.348	0.627	1.831	0.063

voltage V_q. The system in this case study has 2 interarea modes and 3 local modes, as revealed in [33]. Considering this fact, it has been demonstrated in [33] and [34] that it is essential to install a multi-stage lead-lag controller as represented in FIGURE 8, which provides a supplementary signal that contains enough information regarding both interarea modes. This would result in more effective damping of these multi-mode oscillations.

According to geometric measure, two remote signals are employed to the controller, $\Delta f_{15} = f_1 - f_5$ and $\Delta f_{13} = f_1 - f_3$. The overall control signal, ΔV_q, is obtained based on the following equation:

$$\Delta \mathrm{V_q} = W_2 \Delta \mathrm{V_{q1}} + W_2 \Delta \mathrm{V_{q2}} \quad (15)$$

where W_1 and W_2 are weighting factors ($W_1 = 1.15$, $W_2 = 1$) [33]. The objective function is then modified to:

$$J = \int_{0}^{t_f} \{t.|\Delta\omega_{13}| + t.|\Delta\omega_{15}|\} .dt \quad (16)$$

The parameters of the conventional controller and the proposed ST-WADC have been optimized using PSO algorithm. The optimized parameters of both the conventional and the proposed controllers are given in Table 3 and 4, respectively.

To test the efficacy of the proposed approach, a nonlinear time-domain simulation has been carried out. A three-phase-to-ground fault is applied in bus 8 at $t = 0.5$ *s* and cleared

TABLE 4. Optimized parameters of the proposed ST-WADC.

	K	T_1	T_2	T_3	T_4	β
Stage I	39.892	1.991	0.833	1.101	0.397	8.241
Stage II	31.663	1.240	0.135	1.784	1.660	6.132

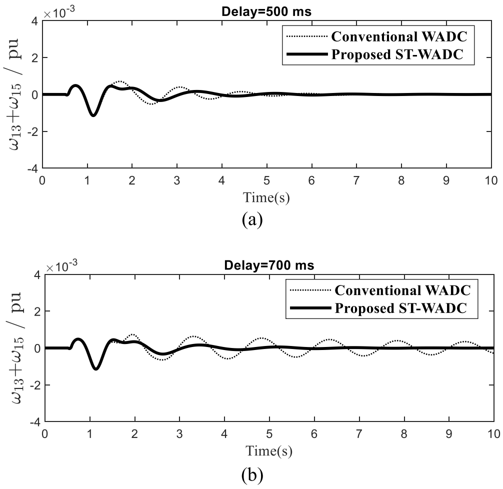

FIGURE 9. System response under 4-cycle 3-phase fault with different values of fixed delays: (a) 500 ms (b) 700 ms.

after 4 cycles. The simulation is carried out over a time horizon of 10 *sec*. To demonstrate the robustness of the proposed ST-WADC against the communication latency, two different cases of fixed delay and variable delay are considered.

B. SYSTEM RESPONSE WITH FIXED DELAY

System response for various communication delay values under the same fault conditions is shown in

FIGURE 9. It can be seen that the conventional design can control the oscillations until the delay reaches a value of 700 *ms* then the system failed to tolerate the oscillations, and eventually, the system becomes unstable. It can also be observed that the proposed ST-WADC offers a greater delay-compensation compared to the classical one, and it can provide the desired interarea oscillations damping characteristic for different values of latencies.

C. SYSTEM RESPONSE WITH VARIABLE DELAY

When Variable random delays are applied, the response is presented in V-D. A similar random delay described in FIGURE 5 is used in this test. The results reveal that the proposed damping control scheme is robust enough to operate under severe system disturbances. Interarea oscillations have been effectively damped, and the system settling time is significantly reduced. The response indicates that the proposed approach has the ability to maintain the system stability and ensure satisfactory robustness with communication latency uncertainty. In comparison, the conventional tuned WADC cannot effectively damp out the oscillations with the presence of random delays. It was observed that when the latency value becomes 700 *ms*, the conventional control methodology cannot stabilize the system and a clear degradation of control performance is experienced. On the other hand, the proposed

TABLE 5. Comparative studies of the performance index for different values of fixed and variable delays.

	Fixed Delay		Variable Delay	
	500 *ms*	700 *ms*	500 ± 100 *ms*	700 ± 100 *ms*
Conventional WADC	90.20	102.06	109.34	123.55
Proposed ST-WADC	3.12	50.36	2.87	66.32

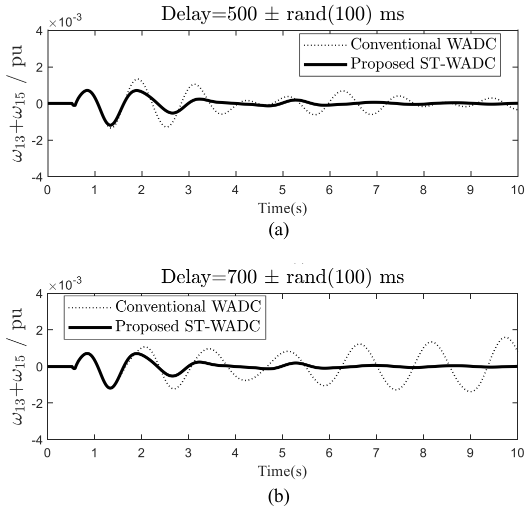

FIGURE 10. System response under 4-cycle 3-phase fault fault with different values of variable delays: (a) 500 ± rand(100) ms (b) 700 ± rand(100) ms.

ST-WADC can handle such a delay, perfectly compensating for latency and keeping the desired damping characteristic. It was observed that the proposed controller could work efficiently and damp out the system oscillations with time delays up to 1200 ms.

D. PERFORMANCE EVALUATION

For a clear insight into the controller performance, an index-based comparison has been conducted. The same index given in Eq. (14) is used. The lower index indicates better performance. The values of the index are presented in Table 5. It was observed that the proposed controller gives the lower indices for various delay values, and thus, a significant damping improvement is observed with the proposed ST-WADC.

The simulation results demonstrate the effectiveness of the proposed ST-WADC where the communication delay imperfections are considered in the design process. The simplicity of the design and the efficacy of the performance offer ST-WADC the ability to outperform other approaches. One of the proposed control methodology's main benefits is that it does not require prior knowledge of time-delay value to define the design objectives.

The effectiveness of the proposed controller is verified by a comparative study with the delay-dependent controller given in [19]. The performance has been evaluated considering random delays applied to the four-machine system. As shown in Figure 11-(a), it is clear that the performance of ST-WADC is superior as compared to the delay-dependent controller in terms of rotor speed maximum overshoot and settling time.

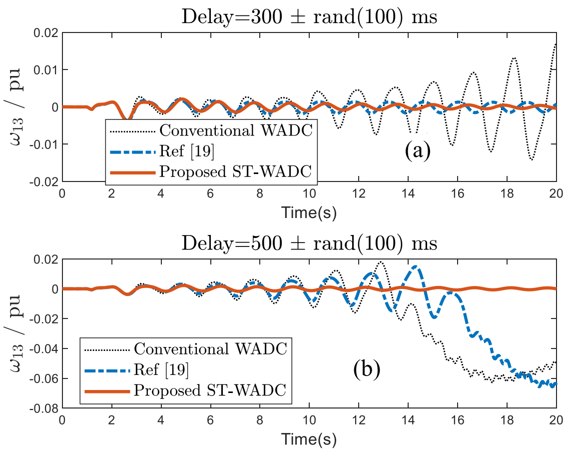

FIGURE 11. **Performance verification at different delays: (a) 300 ± rand(100) ms (b) 500 ± rand(100) ms.**

As the latency increases, the performance of the conventional design and the delay-dependent controller degrades substantially and collapses at 500 ± 100 *ms* delay as shown in Figure 11-(b). On the other hand, the proposed WADC is able to preserve system stability for the same delay values, which confirms the robustness of the proposed ST-WADC.

VI. CONCLUSION

This paper proposes an efficient scattering transformation-based wide-area damping controller for SSSC. To resolve the destabilizing effect of the communication latency, scattering transformation is implemented in the form of two ports between the SSSC and WADC. The controller parameters are optimally adjusted via PSO. It has been demonstrated the conventional WADC does not offer acceptable performance for large delays. Moreover, the system cannot guarantee the desired behavior when the signal delay is present and might render the system unstable. The efficacy of the proposed ST-WADC controller has been examined under fixed as well as variable delays. It was revealed that the proposed ST-WADC shows a significant damping performance and satisfactory robustness against time-delay uncertainty.

APPENDIX

The derivation of $H_1(s)$ and $H_2(s)$ is given as follows [28]:

Consider the set of equations (7):

$$\begin{cases} U_l = \dfrac{1}{\sqrt{2\beta}}\left(U_c + \beta Y_c\right) \\ V_l = \dfrac{1}{\sqrt{2\beta}}\left(U_c - \beta Y_c\right) \\ U_r = \dfrac{1}{\sqrt{2\beta}}\left(Y_p + \beta U_p\right) \\ V_r = \dfrac{1}{\sqrt{2\beta}}\left(Y_p - \beta U_p\right) \end{cases}$$

then we have the following:

$$H_1(s) = \frac{V_r}{U_r} = \frac{Y_p - \beta U_p}{Y_p + \beta U_p}$$

We know that $H(s) = \frac{Y_p}{U_p}$, then $H_1(s) = \frac{H(s)-\beta}{H(s)+\beta}$

In the same manner, we can derive H_2 as follows:

$$H_2(s) = \frac{U_l}{V_l} = \frac{(U_c + \beta Y_c)}{(U_c - \beta Y_c)}$$

Since $H_{WADC}(s) = \frac{Y_C}{U_c}$, then $H_2(s) = \frac{1+\beta . H_{WADC}(s)}{1-\beta . H_{WADC}(s)}$

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AHMED HUSHAM received the B.Sc. degree in electrical engineering from the Sudan University of Science and Technology, Khartoum, Sudan, in 2014, and the M.S. degree from the King Fahd University of Petroleum and Mineral, Dhahran, Saudi Arabia, in May 2018. He is currently pursuing the Ph.D. degree with the Laval University, Quebec City, QC, Canada.

ALAA EL-DIN HUSSEIN (Member, IEEE) was born in Cairo, Egypt, in 1970. He received the B.S. and M.S. degrees in electronics and communications engineering from Ain Shams University, Cairo, Egypt, in 1992 and 1997, respectively, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2002.

From 1992 to 1997, he was a Research Assistant with Ain Shams University, Cairo. Since 2003, he has been an Assistant Professor with the Electrical Engineering Department, KFUPM, Dhahran, Saudi Arabia. He is the author of more than 20 articles and one invention.

MOHAMMAD A. ABIDO (Senior Member, IEEE) received the B.Sc. (Hons.) and M.Sc. degrees in EE from Menoufia University, Shebin El-Kom, Egypt, in 1985 and 1989, respectively, and the Ph.D. degree from the King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 1997. He is currently a Distinguished University Professor with KFUPM. He also a Senior Researcher with the K. A. CARE Energy Research and Innovation Center, Dhahran, Saudi Arabia. He has published two books and more than 400 papers in reputable journals and international conferences. He participated in more than 60 funded projects and supervised more than 50 M.S. and Ph.D. students. His research interests include power system control and operation and renewable energy resources integration to power systems. He was a recipient of the KFUPM Excellence in Research Award, 2002, 2007, and 2012, the KFUPM Best Project Award, 2007 and 2010, the First Prize Paper Award of the Industrial Automation and Control Committee of the IEEE Industry Applications Society, in 2003, the Abdel-Hamid Shoman Prize for Young Arab Researchers in Engineering Sciences, in 2005, the Best Applied Research Award of 15th GCC-CIGRE Conference, Abu-Dhabi, United Arab Emirates, in 2006, and the Best Poster Award, International Conference on Renewable Energies and Power Quality (ICREPQ'13), Bilbao, Spain, in 2013. He has been awarded the Almarai Prize for Scientific Innovation 2017–2018, Distinguished Scientist, Saudi Arabia, in 2018, and Khalifa Award for Education 2017–2018, a Higher Education, a Distinguished University Professor in Scientific Research, Abu Dhabi, United Arab Emirates, in 2018.

INNOCENT KAMWA (Fellow, IEEE) received the B.S. and Ph.D. degrees in electrical engineering from Laval University, Québec City, in 1985, and 1989, respectively. He has been a Research Scientist and a Registered Professional Engineer with the Hydro-Quebec Research Institute, since 1988, specializing in system dynamics, power grid control, and electric machines. After leading System Automation and Control program for years, he became the Chief Scientist for the smart grid in 2009, the Head of Power System and Mathematics in 2014, overseeing the Hydro-Quebec Network Simulation Centre, known worldwide, and the Acting Scientific Director of IREQ in 2016. He has been an Adjunct Professor position in electrical engineering with Laval University, since 1990, and McGill University, since 2011, mentoring more than 35 graduate students.