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WAMS-Based SSR Damping Controller Design for FACTS Devices and Investigating Effects of Communication Delays

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ABSTRACT

Recent technological progresses in the wide-area measurement systems (WAMS) are realizing the centralized controls as a breakthrough for improving the power systems stability. The most challenging deficiency against WAMS technology is related to communication delays. If this latency is neglected, it can deteriorate the damping performance of closed loop control or even degrade the system stability. This paper investigates a conventional Wide Area Damping Controller (WADC) for a static synchronous series compensator (SSSC) to damp out the Sub-Synchronous Resonance (SSR) and also investigation of the destructive effect of time delay in remote feedback signal. A new optimization algorithm called teaching-learning-based- optimization (TLBO) algorithm has been implemented to normalize and optimize the parameters of the global SSR damping controller. The IEEE Second Benchmark Model is considered as the system under study and all simulations are carried out in MATLAB/SIMULINK environment.

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1. INTRODUCTION

Series compensation of long transmission lines is an important approach to improve the power transfer capability of power networks [1]. However, in such compensated networks, the interactions between the electrical modes of the series compensated network and a mechanical mode of a turbine generator shaft can be led to a serious detrimental phenomenon referred to Sub-Synchronous Resonance (SSR) [2].

SSR mitigation has been a topic of research interest over several years. Several countermeasures have been recommended, ranging from limiting levels of series compensation through system planning, filtering, Power System Stabilizers (PSSs) [3], Flexible AC Transmission Systems (FACTS) [4]-[7], And DFIG based wind farm [8]. For example, in ref [4] a robust control strategy has been proposed based fuzzy logic control on FACTS devices to damp SSR. In [5] an economical phase imbalanced series compensation concept has been introduced and their ability for power system dynamic enhancement and SSR damping have been investigated. Ref [6] presents capability of the Distributed Static Series Compensator (DSSC) as a member of D-FACTS family in mitigating the SSR. In [7], two separate damping controllers have been granted to the conventional controllers of the SVC and the TCSC in order to damp the SSR in a series compensated wind farm. Furthermore, the damping controller of the SVC is a conventional lead-lag controller and the damping characteristic of the TCSC have been added through constant current control of the TCSC. In [8], a damping control approach for sub-synchronous resonance with Static Synchronous Series Compensator (SSSC) has been addressed and in [9] the capability of Type-2 wind turbines to damp SSR occurring in close synchronous generators connected to the grid by means of series-compensated transmission lines has been investigated.

In the literature, it is demonstrated that if remote signals are fed to the damping controllers, the system dynamic performance can be enhanced compared with the locally measured signals [10]. The wide-area measurement system (WAMS), enabled by broad deployment of phasor measurement units (PMUs), is capable to monitor dynamic data of the power system such as voltage, current, angle, and frequency. It hence proposes an unprecedented opportunity in controlling power system dynamics since the observable space becomes wider with WAMS information. The achievements are mostly due to time-stamped synchronous measurements applicable at any point of a geographically spread electric network [11].

All references above cited [4]-[9], have used global signals like generator rotor speed as a feedback signal to design the auxiliary SSR damping controller without considering communication time delay on remote feedback signal. The time demanded to render PMU data toward the system or regional control center plus that of transferring commands to control devices is totally referred to as the communication delay or latency. This time delay depends on the communication system loading and, in feedback control loop, diminishes the effectiveness of the control system and may even result in the complete system instability [12]-[13]. Accordingly, it is of critical importance to consider the latency during the controller design process. In the literature, different papers have been published to show the effects of latency in remote feedback signal and also compensate destructive effects of these latencies [13]-[17].

In [13] a fuzzy logic wide-area damping controller for inter-area oscillations damping and continuous latency compensation has been presented. References [14]-[16] have presented multi-agent H_∞, mixed H_2/H_∞, and predictor-based H_∞ controllers for time-delayed systems. In reference [17], an adaptive phasor power oscillations damping controller has been proposed wherein the rotating coordinates are adjusted for continuous compensation of time-varying latencies and many other references.

All of the papers published in this area proposed a WAMS based damping controller to damp low frequency oscillations and the most important note that should be investigate here is that what is the impact of communication time delay on SSR damping controllers that used global signals as damping controller input signal.

The major contribution of this paper is to design a WAMS based conventional damping controller based on the teaching-learning-based- optimization (TLBO) algorithm for SSR damping. The TLBO method is appeared as a promising algorithm for managing the optimization problems that not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to be implemented [18]-[20]. In order to better analyze the performance of proposed controller, a comparison is also adopted between proposed TLBO based damping controller and PSO based damping controller presented on [8]. It is assumed that the controller is embedded in a static synchronous series compensator (SSSC) located in IEEE second benchmark power system.

To authors' best knowledge, this paper is the first research to explore the SSR damping yielded by a FACTS device equipped with a real wide-area damping controller (WADC). In the ideal TLBO based WADC, the TLBO technique has been used to normalize and optimization of parameters of the global damping controller without considering latency in remote feedback signal. In the following the latency is considered in damping controller input signal and effects of the latency are investigated.

2. STUDY SYSTEM

The power system considered in this study is the IEEE SBM [21] aggregated with SSSC, depicted in Figure 1. This figure illustrates the single line diagram of the power system which is used in this study. A single generator of 600 MVA, 22 kV is connected to infinite bus through one transformer and two parallel transmission lines. The mechanical system is composed of: two-stage steam turbine (High Pressure (HP) and Low Pressure (LP)), the Generator (G), and the rotating exciter (EX) all are coupled on the same shaft as depicted in Figure 1. The compensation level which is provided by the series capacitor is set to 55% of the reactance X_{L2}. Different cases of study are considered for clarifying the capabilities of the SSSC proposed controllers in SSR mitigation:

The case which there is no SSSC in the system and a three-phase to ground fault is applied at the generator bus in t = 3 sec and is removed after 0.0168 sec.

In the first case, the performance of the system is studied without any SSSC in the system. The main objective is to validate the dominant mode of oscillations in generator rotor shaft and also to clarify the fact that, without any controller, the rotor will be damaged and oscillations will increase in the system.

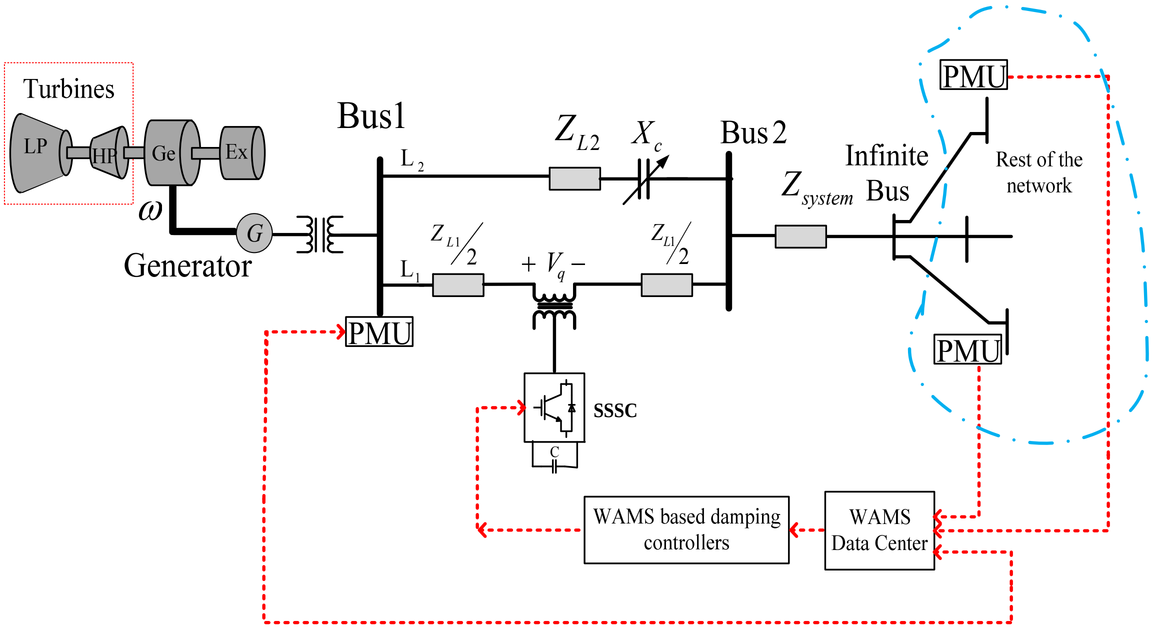


Figure 1. IEEE SBM model aggregated with SSSC

2.1. Simulation results for the first case

The transient simulation of the power system for the first case is conducted in this part. The three-phase to ground fault occurs at time 3 sec and it is removed after 0.0168 sec, as mentioned before and it is revealed in Figure 1. Simulation result for rotor speed deviation ($\Delta\omega$) is depicted in Figure 2. Due to unstable mode, when the fault is cleared, large oscillations will be experienced between sections of the turbine generator shaft. For this state, the system is completely unstable.

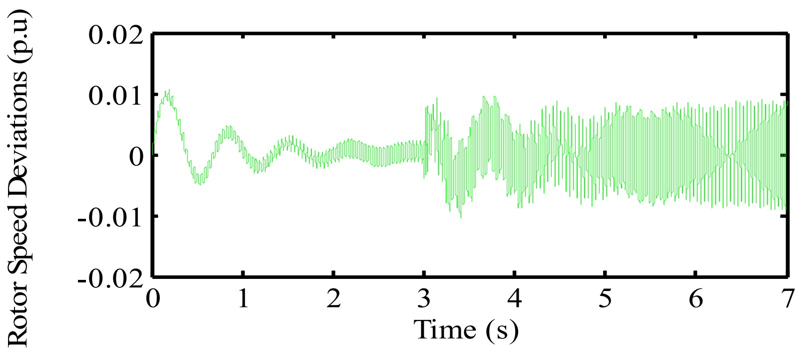


Figure 2. Simulation results for case 1, rotor speed deviation ($\Delta\omega$) in p.u

2.2. FFT analysis for the first case

For an assessment of the oscillatory modes of the system, the Fast Fourier Transform (FFT) analysis is performed by MATLAB program on the IEEE SBM. Figure. 3 depicts the FFT plot of generator rotor speed in time interval of 2 to 5 sec. it is revealed that, when the series compensation in line 2 is set to 55%, the complement of the electrical resonance frequency matches with critical mode 1 of the IEEE SBM and the system becomes unstable when there is no possible damping of oscillations. It is founded by FFT analysis that, three modes exist in the rotor speed in this study. Furthermore, the maximum destabilization is for mode 1 with frequency of 24.67 Hz, or in a technical expression, for 55% compensation, the torsional mode 2 is the dominant mode which has the sub-synchronous frequency of 24.67 Hz.

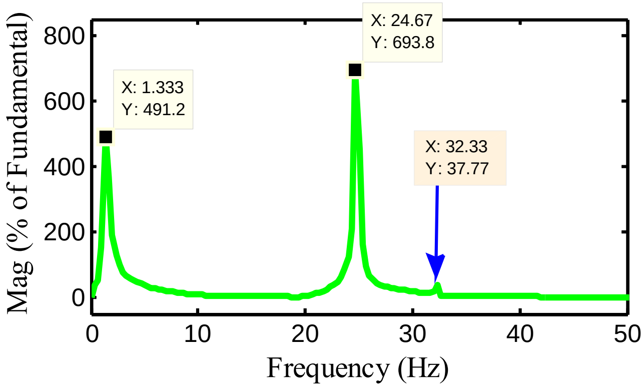


Figure 3. FFT analyses on generator rotor shaft in order to validate the dominant mode

The FFT analysis of the generator rotor speed is performed among 2 - 6 sec with the time division of 1 sec in order to expand the subject of resonance and amplification of the dominant mode. The results which are obtained from FFT analysis are displayed in Figure 4. Referring to this figure, it can be observed that, as the time progresses, dominant mode component increases significantly. So, there should be a controller in order to mitigate this adverse oscillatory component from rotor shaft in order to retrieve the power system from suffering.

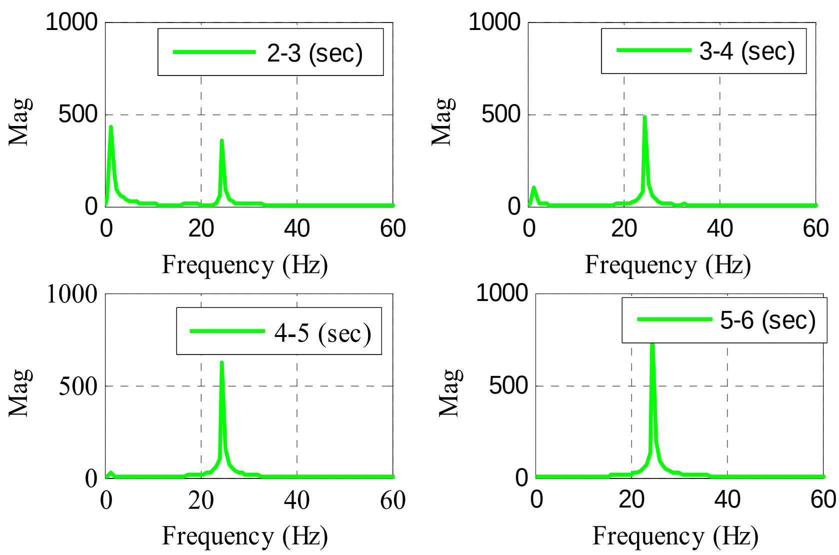


Figure 4. FFT analyses on $\Delta\omega$ of the generator rotor speed without damping controller

3. WADC DESIGN

This section is to demonstrate the ability of conventional damping controller in damping SSR with using an SSSC and WAMS signals in an ideal condition, i.e., no time delay of remote signals.

As it can be seen on Figure 1, the SSSC is placed in the compensated line between generator and infinite bus to control the power flow and damp the SSR. However, the optimal location of SSSC in practical and large power systems is vital point and requires comprehensive studies. The SSSC offers 10% compensation in the steady state and has a dynamic range of variation from 1% to 20%. SSSC is a well-known series connected FACTS controller based on voltage source converter (VSC). Figure 5 illustrates SSSC connection to the transmission line and its control structure [22]. Indeed, SSSC is an advanced type of controlled series compensation and controls the power flow and mitigates the oscillation, albeit by a proper controller design.

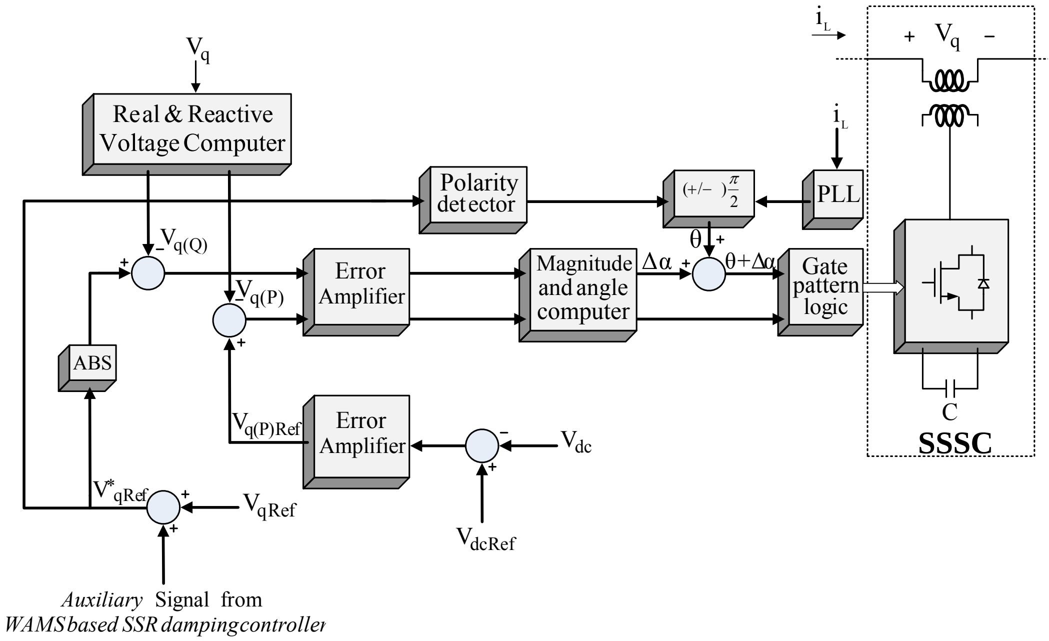


Figure 5. Block diagram of SSSC control system.

Figur 5 also displays the main control system of SSSC. It can be observed that V_{qRef}, as one of reference signals required for the control system, is the desired magnitude of the series reactive voltage and determines the reactive power exchange for series compensation. By injecting the series voltage, namely V_q, SSSC provides a variable reactance, X_q, in series with transmission line and adjusts the effective line reactance. Therefore, SSSC offers an active means for the reactive power compensation as well as SSR damping. The variable reactance realized by SSSC is expressed as (1) where i_L denotes the line current and V_q is obtained by (2) [22].

$$X_q = \frac{V_q}{i_L} \tag{1}$$

$$V_q = V_{qRef} + \Delta V_q \tag{2}$$

In steady state, ΔV_q and V_{qRef} are constant. While during dynamic conditions, the series injected voltage V_q is modulated to damp the system oscillations.

One of fundamental issues in designing wide-area based damping controllers is the selection of feedback signals (which is directly dependent to the locations of PMUs) to achieve the best modal observability and optimal oscillation damping. Generally speaking, a PMU device measures the real-time three-phase voltage and current quantities. The PMU then computes the three-phase phasor values, the sequence components, the system frequency, as well as the rate of change of frequency and renders these data to the control center [23]. Although the PMU computed frequency and its rate of change are based on the local voltage measurement, there are several methods which let us calculate the generator speed through PMU measurements [24]-[26]. Frequency is a key indicator for the system stability and generation/demand balance. This parameter or its derivatives, such as rotor speeds and their rate of change, are usually employed as the damping controller feedback signals [4]-[9]. To this end, the generator bus is assumed to be equipped with PMU and $\Delta\omega$ signal is chosen as global feedback signal. However, in large power systems with hundreds of units and buses, a PMU placement study that maximizes the dynamic information would be in essence.

Another important subject in implementing the FACTS device's damping controller is identifying the best location for applying auxiliary damping signal to provide an effective damping of oscillations and to minimize the interactions between FACTS power flow and damping controllers. In [27], an example of applying the damping controller signal to the DC or AC voltage reference of FACTS was given. A method was developed to analyze the relative effect and to avoid the negative interactions between damping controller and other control loops. It has been shown that applying the damping controller signal to DC voltage reference of FACTS device causes a significant destructive interaction on its other control loops. This issue is examined here as well and it is found that applying the auxiliary damping signal to AC voltage reference of SSSC yields better results than the other signals as they are decoupled. In this study, the output of WADC is thus utilized to modulate V_{qRef} and consequently adjusts X_q to yield a proper damping of SSR. Change of X_q results in moving the active power between generator bus and infinite bus up and down and consequently adjusting the accelerating and decelerating of generator rotor speed according to the equal area criterion. Thus, the proper control of X_q during power swing situations will reduce the overall amplitude of oscillations.

So, for the sake of mitigating the unstable oscillation modes, in this study a TLBO based conventional damping controller namely WADC will be designed and added to the main control loop of the SSSC.

The damping controller here is a conventional lead-lag damping controller which has been widely used in the power system. It mainly consists of: a gain block, a washout filter, and a lead-lag compensator that is shown in Figure 6. The damping controller will be designed on a manner that provides the extra torque in phase with the power deviation of the generator that will result in suppression of oscillations. Here, the parameters of the controller are determined through the simulation studies by the TLBO method with the aim of achieving the best damping.

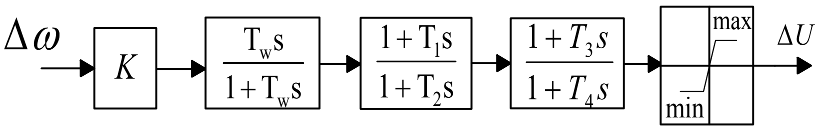


Figure 6. Classical damping controller block diagram

3.1. TLBO algorithm

One of the most recently developed metaheuristics is teaching-learning-based- optimization (TLBO) algorithm [18]. TLBO has many similarities to evolutionary algorithms (EAs): an initial population is randomly selected, moving on the way to the teacher and classmates is comparable to mutation operator in EA, and selection is based on comparing two solutions in which the better one always survives [19].

Similar to most other evolutionary optimization methods, TLBO is a population-based algorithm inspired by learning process in a classroom. The searching process consists of two phases, i.e. Teacher Phase and Learner Phase. In teacher phase, learners first get knowledge from a teacher and then from classmates in learner phase. In the entire population, the best solution is considered as the teacher ($X_{teacher}$).

On the other hand, learners learn from the teacher in the teacher phase. In this phase, the teacher tries to enhance the results of other individuals (X_i) by increasing the mean result of the classroom (X_{mean}) towards his/her position $X_{teacher}$. In order to maintain stochastic features of the search, two randomly-generated parameters r and T_F are applied in update formula for the solution X_i as:

$$X_{new} = X_i + r.(X_{teacher} - T_F.X_{mean}) \tag{3}$$

Where r is a randomly selected number in the range of 0 and 1 and T_F is a teaching factor which can be either 1 or 2:

$$T_F = round[1 + rand(0,1)\{2 - 1\}] \tag{4}$$

Moreover, X_{new} and X_i are the new and existing solution of i, [19]-[20].

In the second phase, i.e. the learner phase, the learners attempt to increase their information by interacting with others. Therefore, an individual learns new knowledge if the other individuals have more knowledge than him/her. Throughout this phase, the student X_i interacts randomly with another student X_j ($i \neq j$) in order to improve his/her knowledge. In the case that X_j is better than X_i (i.e. f (X_j) <f(X_i) for minimization problems), X_i is moved toward X_j. Otherwise it is moved away from X_j:

$$X_{new} = X_i + r.(X_i - X_j) \, iff \, f(X_i) < f(X_j) \tag{5}$$

If the new solution X_{new} is better, it is accepted in the population. The algorithm will continue until the termination condition is met. The pseudo code shown in Table 1 demonstrates the TLBO algorithm step by-step [20]. The parameters yielded from TLBO algorithm are included in Table 2.

Table 1. The pseudo code for TLBO [20]

Set k=1 ;
Objective function f(X) , X=(x_1, x_2,....., x_d)^T d=no. of design variables
Generate initial students of the classroom randomly X^i,1,2,..., nn=no. of students
Calculate objective function f(X) for whole students of the classroom
WHILE (the termination conditions are not met)
{ Teacher Phase }
Calculate the mean of each design variable X_{Mean}
Identify the best solution (teacher)
FOR i=1 → n
Calculate teaching factor $T_F^i = round[1 + rand(0,1)\{2-1\}]$
Modify solution based on best solution(teacher)
$X_{new}^i = X^i + rand(0,1).[X_{teacher} - (T_F^i.X_{mean})]$
Calculate objective function for new mapped student $f(X_{new}^i)$
IF X_{new}^i is better than X^i , i.e. $f(X_{new}^i) < f(X^i)$
$X^i = X_{new}^i$
END IF *{End of Teacher Phase}*
{ Student Phase}
Randomly select another learner X^j, such that $j \neq i$
IF X^i is better than X^j, i.e $f(X^i) < f(X^j)$
$X_{new}^i = X^i + rand(0,1).(X^i - X^j)$
Else
$X_{new}^i = X^i + rand(0,1).(X^j - X^i)$
END IF
IF X_{new}^i is better than X^i, i.e $f(X_{new}^i) < f(X^i)$
$X^i = X_{new}^i$
END IF *{End of Student Phase}*
END FOR
Set k=k+1
END WHILE
Postprocess results and visualization

Table 2. Parameters obtained from TLBO algorithm

parameter	K	T_1	T_2	T_3	T_4
value	4.4	0.9106	0.0497	0.3532	0.7757

3.2. Simulation Results

For the sake of simulation, it is assumed that in the system shown in Figure 1, a three-phase to ground fault occurs at time 3 sec and it is removed after 0.0168 sec. Simulation results for rotor speed deviations (in p.u) and the torque between low pressure turbine and Hi pressure turbine are depicted in Figure 7 and Figure 8 Where, the blak line corresponds to the condition in which the SSSC is enhanced with PSO based conventional damping controller and the green line corresponds to the situation in which the SSSC is enhanced with TLBO based damping controller. It should be noted that the SSSC firstly should be charged in order to hold their duty in power system, so, in this study, the fault time is set to 3sec in order to provide time for SSSC to charge its DC link. It is observed from Figure 7 that, when the TLBO based WADC is active, it tries to alleviate the sub-synchronous component of the generator rotor speed dawn to zero. Due to the selected series compensation of the transmission line, the dominant sub-synchronous frequency component is 24.67 Hz. Due to Fig.8, when the fault is cleared, the sub-synchronous component of the torque between low pressure turbine and Hi pressure turbine raises up to 1p.u. Then, the SSSC which is enhanced with TLBO based WADC slowly controls this component to zero. As a result, the turbines of the generator shaft will still experience oscillations due to the perturbation in the gird, but they will be mitigated and the shaft torque will slowly go back to the pre-fault value as shown in Figure 8.

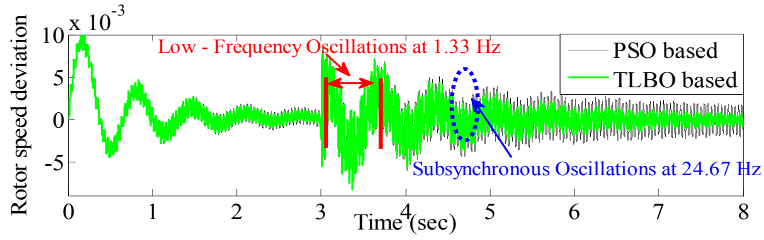


Figure 7. Generator Rotor speed deviation with WADC.

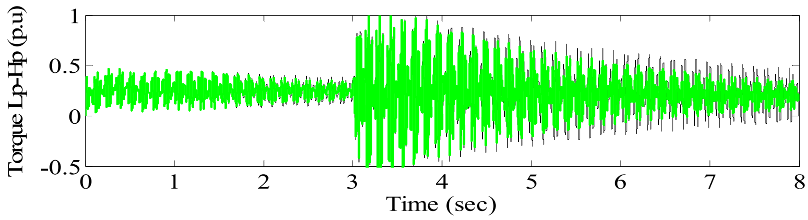


Figure 8. the torque between low pressure turbine and Hi pressure turbine with WADC

4. IMPACT OF LETENCY

In the preceding section, it was revealed that an ideal WADC (ignoring time delay) can effectively damp the SSR. However, this is not the case in the real world where we have communication delays in WAMS signals. That is, the feedback input signals are received at the controller station after a while, and the control command applies in the system after a time interval. This section intends to illustrate how a conventional WADC responds in the presence of time delays. First, a brief review on communication links used in WAMS along with their typical time delays are presented; then, the simulation results are given.

4.1. Communication Links

Communication links employed in WAMS include both wired (telephone lines and fiber-optics) and wireless (satellites and microwave links) options. Delays associated with the specified links act as a fundamental indicator to the amount of time-lag happening before the action is commenced. The followings are among the communication options for WAMS:

Telephone lines: The main advantage of telephone lines is that they are easy to install and also cost-effective to use.

Fiber-optic cables: The benefits of utilizing fiber-optics include its immunity to RF & atmospheric interference, and its considerable bandwidth that can be used by the utilities for other telecommunication needs [28]. In spite of high investment cost, fiber-optic cables are nowadays quite standard and broadly deployed by utilities.

Satellites: The disadvantages of using a satellite are its high cost, narrow bandwidth, and associated link delays.

Microwave links: Microwave links have been used by utilities to a great extent. These links are considered as a better option compared to leased lines, since they are easy to set up and are highly reliable. Signal fading and multipath propagation are the main disadvantages of microwave links. High-speed data rate capability and noise immunity of digital microwave links makes them a more suitable choice than analog microwave links to serve the needs of utilities [29].

Table 3 indicates the typical values of time delays in various communication links. Also, practical experiences and statistics of PMU deployments could provide other useful data for the sake of simulation and performance analysis of WAMS [29].

Table 3. Delay Values in Various Communication Links [29]

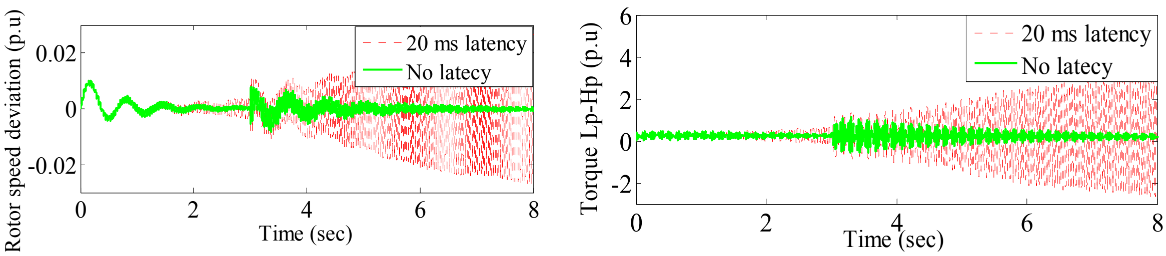
Communication link	Associated delay (ms)
Fiber-optic cables	100-150
Digital microwave links	100-150
Power line (PLC)	150-350
Telephone lines	200-350
Satellite link	500-700

4.2. Latency Computation from Time-Stamp Information

The phasor data concentrator (PDC), or super PDC, is used to communicate remote signals from PMUs to the control center. The global positioning system (GPS) renders an exact timing pulse. By exploiting the GPS signal, the WAMS precise time synchronization is accomplished. The main task for PDC is to synchronize the measurements of entire PMUs and to send the data every 20 ms to the control center. In the case of congestion in one or more communication lines, the PDC waits until completing the data of all PMUs. Hence, the total delay of delivering the WAMS data for control center applications is the latency of most congested line plus the time needed for synchronization. Once the PDC has gathered the data from all channels, it starts sending the data to the control center at a much faster rate (1 kHz max) until it clears the back-log. More likely the damping controller is not located at the control center; thus, a fraction of data are sent toward the controller location. The total latency of received data is calculated by subtracting the local time at the control center or the ions in previous section are repeated again with considering the latency in feedback signals and the conventional WADC.

4.3. Simulation Results

In the literature many papers investigate the impact of communication latency on WAMS based low frequency oscillation (LFO) damping controllers [12]-[13] and many papers published about calculating the delay margin, the maximal delay which allows the closed-loop power system to retain stable. To authors' best knowledge, this paper is the first research to explore the impact of time delay on WAMS based SSR damping controller and determining the delay margin for WAMS based SSR damping controller. In ref [13] to investigate impact of latency on WADC, 200-410 ms latency is considered on damping controller input signals or in [30] 60- 450 ms time delay is considered or remote feedback signals, but in all of the papers published in this subject the WADCs are designed to damp LFO and it seems that the delay margin for WAMS based SSR damping controller should be less than delay margin for WAMS based LFO damping controllers. To investigate this subject simulations are repeated with considering a small latenct (20 ms) on designed WAMS based SSR damping controller input signal. Simulation results are shown in Figure 10 (a) and (b). It can be seen from this figures that with considering a small time delay on remote signal, the WADC performance destroyed completely and this small time delay destabilize the system after clearing the fault.



(a) (b)

Figure 10. Impact of time delay on conventional WADC performance

5. PERFORMANCE INDEX

In order to compare the results of proposed TLBO based WADC with PSO based WADC, a Performance Index (PI) is utilized based on the behavior of the power system. This index which is mainly consists of the integral of the time multiplied absolute value of the power system errors, can be defined as:

$$PI = t_{sim} \cdot \int_0^{t_{sim}} t.(|\Delta\omega| + |\Delta\delta| + |\Delta\omega_{HP}| + |\Delta\omega_{LP}|)dt \qquad (6)$$

Where, $\Delta\omega$ is the speed deviation of generator, $\Delta\delta$ is angle deviation, $\Delta\omega_{HP}$ is the speed deviation of high pressure turbine, and $\Delta\omega_{LP}$ is the speed deviation of low pressure turbine. It should be noted that, the lower value of the PI, the better performance of controller will be guaranteed. Numerical results for two cases of study include PSO based WADC and TLBO based WADC is conducted in Table 4.

Table 4. PI index for proposed controllers

Controller	PSO based WADC	TLBO Based WADC
PI Value	1.05	0.43

It is observed that, the value of PI in a case of TLBO based damping controller is much lower than its counterpart PSO based WADC. So, the TLBO based damping controller operates efficiently than conventional damping controller. Alo It can be obsrved from PI values that after considering 20 ms time latency on remote feedback signal, the WADC fails to stabilize the system and the PI value with considering time delay is not a stable value.

6. CONCLUSION

A TLBO-based conventional SSR damping controller design, for an SSSC, utilizing global signals as the feedback input signals is developed. The TLBO method is appeared as a promising algorithm for managing the optimization problems that not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to be implemented. In order to better assess the proposed TLBO based WADC abilities, a PSO based WADC is also designed and performance of these two control strategies are compared. Furthermore, a performance index is also defined to assess the superior performance of damping controllers. The IEEE second benchmark model aggregated with an SSSC is employed as the case study. In order to provide a comprehensive understanding of issue, Several FFT analyses are provided. It was found that for the selected level of series compensation, mode 2 (with the corresponding frequency around 24.67 Hz) has been the most dominant one which makes the system unstable. It was also shown that a zero mode with a frequency around 1.33 Hz appears in the system. It is found that an ideal WAMS based SSR damping controller of SSSC can successfully damp all SSR modes but a real WAMS based SSR damping controller does not work satisfactorily and even destabilize the power system when the input signals have small latencies so in these applications, the most critical point is the time-varying communication system latency destructive effect compensation. These issues are open future research topics in the field of smart transmission grids.

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