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Mitigation of Subsynchronous Resonance Torsional Torque Oscillations via Interval Type-2 Fuzzy Control Based Rectifier Controlled Braking Resistor

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Abstract— Implementation of series capacitor compensation of long transmission corridors has been long identified as posing a potential hazard to the steam turbine-generators after the unfortunate two Mohave shaft damage accidents back in the seventies due to the subsynchronous resonance (SSR) phenomenon. The dynamic braking resistor is an extremely functional, simple, and relatively inexpensive SSR mitigation candidate. The dynamic braking resistor linked to the electric grid via high-power thyristors is considered as a special purpose FACTS controller. A new brake model, namely rectifier controlled braking resistor (RCBR), has been recently proposed for enhancing the transient stability in electric power systems. RCBR controlled via Interval Type-2 fuzzy logic controller (IT2FLC) is suggested in this article for tempering SSR torsional torque oscillations. A control signal synthesized from the generator mass speed is utilized in this work as a local control input signal to the IT2FLC to orchestrate the switching strategy of the installed RCBR. For demonstrating the effectiveness of the proposed scheme, a non-linear time-domain simulation study is performed on the well-known IEEE second benchmark test system via MATLAB/Simulink-based modeling and simulation environment. Comparative simulation studies of the test system after being subjected to three-phase to ground fault condition should demonstrate the effectuality of the proposed system for the mitigation of SSR torsional torque oscillations.

Keywords— Subsynchronous resonance; Rectifier controlled braking resistor; Interval type-2 fuzzy logic controller.

1. INTRODUCTION

Implementation of series capacitor compensation of long transmission corridors has been long identified as posing a potential hazard to the steam turbine-generators after the unfortunate two Mohave shaft damage accidents back in the seventies [1-4]. Series capacitor compensation has been exceedingly implemented since 1952 for conveying bulk power transactions over long transmission distances in an economical manner [5]. The utility benefits from series compensation are so overwhelming that they made it so indispensable for long transmission corridors [6]. It augments the power transfer limit of long transmission lines, ameliorates the voltage profile of the grid, and consolidates the angular stability of the system and so forth [5]. Series compensated power systems are vulnerable to the subsynchronous resonance (SSR) phenomenon in which the steam turbine-generator mechanical shaft system and the electric system interchange energy at one of the natural frequencies of the combined electromechanical system beneath the nominal frequency of the network [1-4].

In most cases, the researchers consider the rotor of a steam turbine-generator as a single mass having a definite inertia constant in studying the vast majority power system dynamic problems [1]. Quite the contrary, the rotor of a steam turbine-generator set (i.e. shaft train) is not that simple [1]. It is a highly complicated

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mechanical system [1]. It is structured from a number of massive rotor elements characterized by their considerably high inertia and relatively large diameter [1]. These rotor elements are then rigidly linked in tandem at thinner rotor extensions [1]. The large utility-scale shaft system can reach up to 50 m in a total length with several hundred tons as a total weight [1]. The turbine-generator shaft is modeled as a spring-mass arrangement for studying the torsional torque oscillations experienced at the shaft extensions [1]. SSR torsional torque oscillations are a problem of an overwhelming attention inside the power engineering community [1-4]. SSR is a transmission system-based power system dynamic problem that certainly has adversely devastating effects on the turbine-generator sets operating under this circumstance [2]. Therefore, SSR could be considered as a multidisciplinary power utility problem. From the turbine-generator shaft system perspective, SSR torsional interaction causes severe torsional torque oscillations with ever-increasing amplitudes at the shaft sections and consequently a considerable loss of the fatigue life of the shaft metal. The shaft is then undoubtedly destined to experience irrevocable low-cycle fatigue cracks which are considered to be precursors to an eventual complete shaft fracture [1-4].

In 1970, and again in 1971, a 909 MVA cross-compound steam turbine-generator at Southern Nevada Mohave power plant in California USA experienced a collector ring failure in the high-pressure unit exciter shaft due to the SSR interaction [2]. The failure was in the shaft section between the generator and the exciter rotor at the inboard end of the outer main generator collector ring [2]. The growing magnitudes of SSR torsional torque oscillations caused that shaft section to be exceedingly heated by the mechanical working of the shaft material to the level that led to an electrical insulation failure at the collector ring inside the collector shaft bore [2]. The short circuit arcing between the positive and negative collector ring bars caused a large hole in the shaft metal [2]. To visualize the devastating consequences of that memorable accident, a picture of the collector shaft damage can be found in [2]. The SSR situations developed in Mohave and Navajo coal-fired power plants have fed off the industry's enthusiasm about this devastating phenomenon to discover countermeasures to the problem; and they emphasized the most urgent need for implementing them very quickly [6].

The dynamic braking resistor is an extremely functional, simple, and relatively inexpensive mitigation candidate [7-12]. The dynamic braking resistor linked to the electric grid via high-power thyristors is considered as a special purpose FACTS controller [12]. Firstly, the original intent for the implementation of the concept of dynamic braking was to boost the transient stability of hydroelectric power systems as an alternate for the fast valving concept utilized in steam turbines dominated power systems [12, 13]. The braking resistor functions as a pseudo artificial load bank characterized by its ability of consuming the excess electric power developed due to severe faults in the vicinity of hydrogenators [13]. By consuming that extra electric power, the balance between the electrical power and mechanical power is regained. Thereby the speed of the synchronous generator is restrained; and the generator pole slipping with the consequent loss of synchronism is prevented [13].

Bonneville Power Administration (BPA) has engineered one of the largest existing dynamic braking resistor installations in the world with a power dissipation ability of 1400 MW with 230 kV rated voltages [13]. It is sited at Chief Joseph substation in North Central Washington. Its main responsibility is to maintain the power balance of the Northwest power pool and the Southwest power pool of the Western Systems Coordinating Council (WSCC) [13]. Other countries have installed a braking resistor for improving the transient stability of their power systems such as Japan, China, Australia, and Russia [8].

Many works of literature have addressed the utilization of the braking resistor linked to the power grid via a 3-phase bi-directional, full wave, phase-controlled AC/AC converter (AC voltage controller), i.e. Thyristor Controlled Braking Resistor (TCBR) for tempering multi-modal shaft torsional oscillations [14-19]. The per phase model of the TCBR is built by using dual high-power thyristor valves, back-to-back connected, with a linear resistor bank connected in series. This means that three resistor banks were employed for the mitigation of SSR torsional oscillations [7-12].

A new modern braking resistor model, namely a rectifier controlled braking resistor (RCBR), has been recently proposed as an innovative method for implementing the concept of dynamic braking interventions for enhancing the transient stability in electric power systems [20, 21]. In [20, 21], the performance of fuzzy controlled RCBR for the enhancement of the transient stability in a single machine infinite bus (SMIB) system and in the WSCC IEEE 3 machine 9-bus power system has been tested, respectively. While in [22, 23] RCBR controlled via a fuzzy logic controller has been proposed to mitigate the multi-modal torsional oscillations resulting from a high-speed reclosure of circuit breakers. In this work, the authors adopted RCBR controlled via Interval Type-2 fuzzy logic controller (IT2FLC) to treat the problem of SSR torsional torque oscillations which are basically a resonance condition developed as a collateral result for a conventional series compensation. The similarity between [22, 23] and this work is that both SSR and multi-modal torsional oscillations are categories of grid-induced torsional interaction in electric power systems. RCBR is simply a single linear resistor bank interfaced to the three-phase terminals of the synchronous generator via a three-phase full-wave rectifier bridge [20-23]. Honestly, the implementation of one resistor bank linked to the generator bus via a thyristor-controlled rectifier bridge was first introduced in [24] for considerably improving the electric power transferring limit of a transmission corridor using a simple proportional (P) controller without considering any artificial intelligence based controllers.

A control signal synthesized from the generator mass speed is utilized in this work as a local control input signal to the IT2FLC to orchestrate the switching strategy of the installed RCBR. It has been long recognized that the damping obtained by using the generator mass speed deviation is much better than the damping obtained by using the steam turbine masses speed deviations [15, 18, 22, 23].

Moreover, for strictly practical considerations, the generator mass speed signal is not so difficult to be measured like steam turbine masses speed signals because the steam turbine is covered with cases and thermal insulation [18, 22]. The RCBR is either energized or de-energized based on the control signal produced by the IT2FLC. For demonstrating the effectiveness of the proposed scheme, a non-linear time-domain simulation study is performed on the well-known IEEE second benchmark test system for SSR studies via MATLAB/Simulink-based modeling and simulation environment with the help of IT2FLC toolbox. Comparative simulation studies of the test system after being subjected to three different kinds of fault condition should demonstrate the effectuality of the proposed system for mitigation of SSR torsional torque oscillations.

The remaining of this article is structured as follows. In section II, the well-known system under study is briefly described. Section III presents the concept of utilizing the IT2FLC for orchestrating the braking interventions of the proposed dynamic braking scheme. Section IV delineates the comparative time domain simulation results with comments. Section V draws the main conclusions of the article. At last, the references used to accomplish this article are enumerated.

2. SYSTEM MODEL

To scrutinize the effectiveness of the proposed mitigation scheme, the IEEE second benchmark model for computer simulation of SSR is embraced in this article to test the capability of the IT2FLC based RCBR on mitigation of SSR torsional oscillations. Fig. 1 depicts the one-line diagram of the considered test system incorporated with the steam turbine-generator shaft system detail and IT2FLC based RCBR [23, 25]. The test system is composed of one synchronous generator (600 MVA/22 kV/60 Hz/3600 rpm) connected to an infinite bus via a generator step-up transformer (600 MVA/22 kV/500 kV) and two extra-high voltage (EHV) transmission lines, one of which is having a series capacitor with three different series-compensation ratios (i.e. 55%, 50%, and 48%) [25]. The prime mover of the generator is composed of one single-flow high-pressure (HP) steam turbine and one double-flow low-pressure (LP) steam turbine connected in tandem [25].

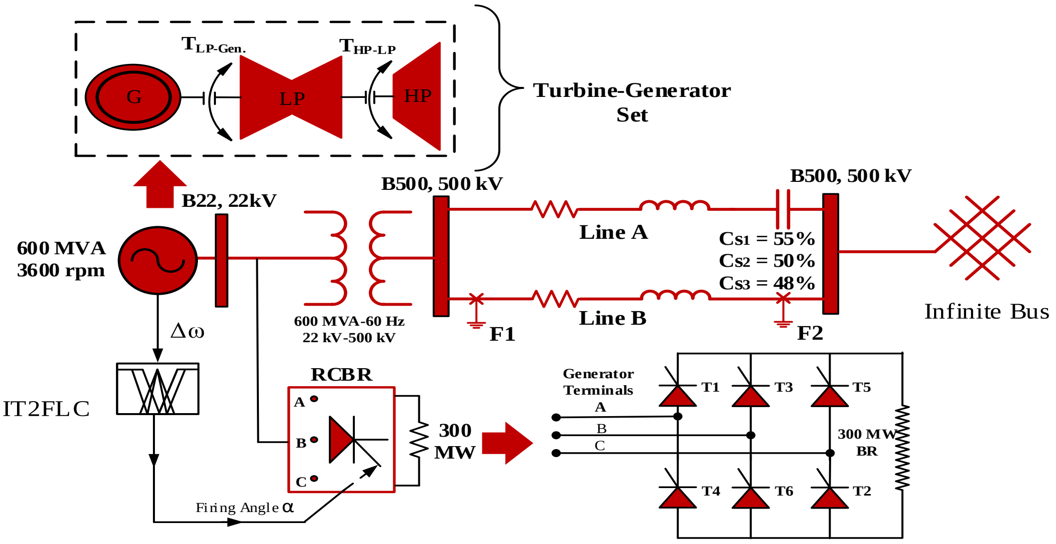


Fig. 1. IEEE second benchmark model with a turbine generator shaft multi-mass model incorporating RCBR.

The model of RCBR consists of one resistor bank linked to the generator bus through a six-pulse full wave-controlled rectifier bridge as shown in Fig. 1 [23]. The resistor bank is postulated to be capable of consuming 50% of the generator's rated output power (i.e. 300 MW). The RCBR is energized or deenergized to mitigate the shaft torsional oscillations by decreasing the net available energy for acceleration. Hence, the generator mass speed deviation develops due to severe perturbations such as network faults in the approximate of the generator high voltage (HV) bus. The system implements the local control signal represented by the generator mass speed deviation to help the IT2FLC determine whether the RCBR should be switched ON or OFF.

The electrical parameters for the synchronous generator are obtained from [25]. The configuration of the steam turbine under-study is suitably illustrated in [1, 25]. It consists of HP section, and LP section. The turbine contributing torque fractions to the turbine sections HP, and LP are 50%, and 50%, respectively [25]. The detailed turbine-generator shaft mechanical parameters are found in [23]. The parameters of the transmission system and the generator step-up (GSU) transformer in per-unit, with 100 MVA as a common base power, are also found in [25]. A complete MATLAB/Simulink model for the test system is built as shown in Fig. 2.

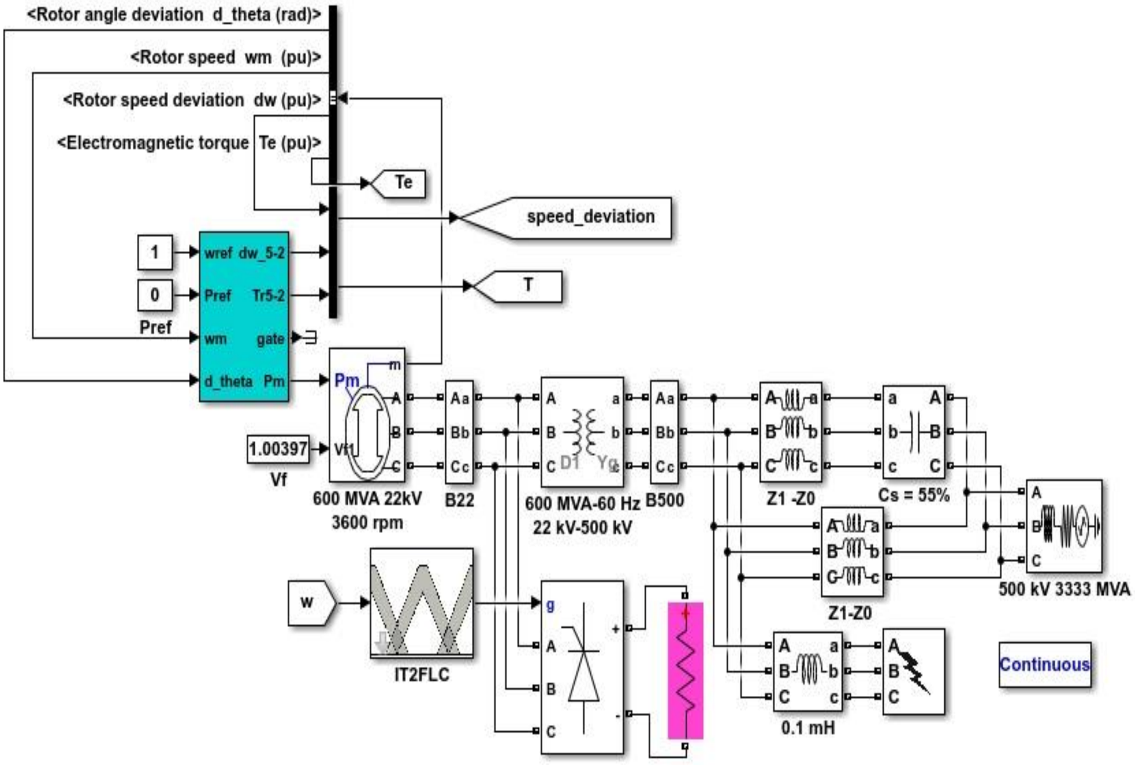


Fig. 2. IEEE second benchmark Matlab/Simulink model.

Basically, the torsional damping associated with the torsional oscillations is characterized by its very low values especially under low-load profiles [1-4]. Therefore, in this study, no-load condition is considered for the synchronous generator to suppose the most pessimistic conditions.

3. INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER DESIGN

It is well-established that traditional linear controllers, such as PI and PID controllers, are not capable of performing in an effective manner when the controlled systems are recognized by high degrees of nonlinearities and uncertainties [26]. Moreover, changing some system parameters could much more likely destabilize the controlled system [26]. Therefore, nonlinear intelligent controllers such as fuzzy logic controllers are widely implemented for controlling such nonlinear systems because intelligent controllers are much more robust than traditional controllers and are more capable of handling the changes in system parameters appropriately [26]. Type-1 and Type-2 fuzzy logic controllers are the main members of fuzzy logic controllers [26]. The vast majority of the implemented fuzzy logic controllers are of Type-1 [27]. Type-2 fuzzy logic controllers have much more uncertainties handling capability than those of Type-1 fuzzy logic controllers [27]. Therefore Type-2 fuzzy logic controller is proposed in this work due to its enormous uncertainties handling capability.

Recently, Type-2 fuzzy logic controllers have been emanated for achieving an innovational artificial intelligence control with very promising potentials in the various academic disciplines [28]. They have been implemented for appropriately treating many dynamic problems in electric power systems as a superior alternate for the traditional fuzzy controllers [28-34]. Some control applications are: power system stabilizer (PSS) design for improving the stability of power systems, Thyristor Control Series Capacitor (TCSC) control for providing an improved damping action to the power system oscillatory behavior, and the design of a control strategy for appropriately integrating doubly fed induction generator (DFIG) based wind turbines to the distribution network [28-34].

Type-2 fuzzy logic controllers are conceptually founded on Type-2 fuzzy set theory originally propositioned by L. Zadeh in 1975 as a complementary sequel to his classical Type-1 fuzzy set theory [35, 36]. Type-2 fuzzy sets have much more superiority in dealing with the inherent uncertainties involved in the controlled plant due to their highly non-linear nature and the acquisition of noisy data [33, 35, 36].

The researchers usually prefer implementing controllers based on Type-2 fuzzy logic in research subjects characterized by an uncertainty in determining the proper membership function of the input variable [28]. Fig. 3 presents a diagrammatic illustration of the structural components of a general Type-2 fuzzy logic controller [36].

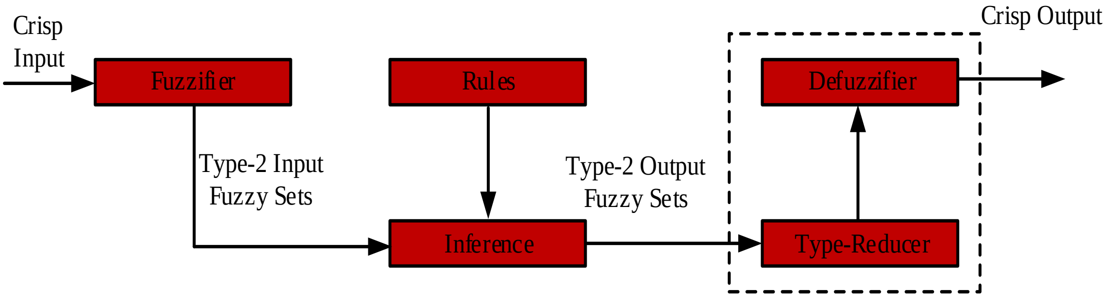


Fig. 3. General structure of Type-2 fuzzy logic-based controller.

Due to the involved computational burden, many researchers have dedicated their works on a more simplified version of Type-2 fuzzy based controllers known as IT2FLC [36]. In IT2FLC, the grade (or degree) of membership for each element of the fuzzified input is an interval-valued fuzzy set which is different from a Type-1 fuzzy based controllers in which the grade of membership is a crisp number having any value between zero and one [36]. So, IT2FLC will be employed in this work due to its relative simplicity. The proposed controller is designed with the aid of IT2FLC toolbox [37]. The type of fuzzy inference utilized in this work is of Takagi-Sugeno-Kang (TSK) in which the consequent of a fuzzy rule is constant (i.e. zero-order type-2 Sugeno model); and thus there is no requirement for type reduction and defuzzification which will further temper the computational burden [36].

Interval Type-2 triangular and trapezoidal membership functions are selected to represent the input control variable of the IT2FLC. Fig. 4 presents the membership functions for the input variable of the system in which three linguistic variables, namely NB (Negative Big), Z (Zero), and PB (Positive Big), realize the Interval Type-2 fuzziness of the input variable. Like the speed deviation range employed in [22, 23], the authors have selected the speed deviation range of -0.01 to 0.01 in p.u.

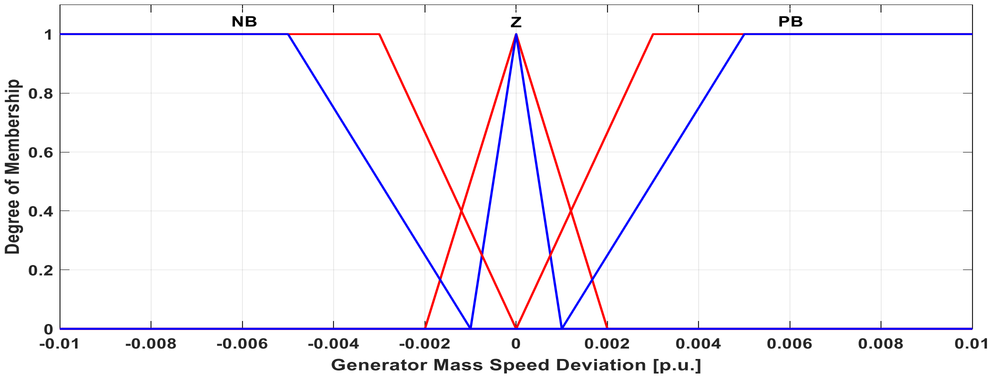


Fig. 4. Input membership functions of the Interval Type-2 fuzzy logic controller.

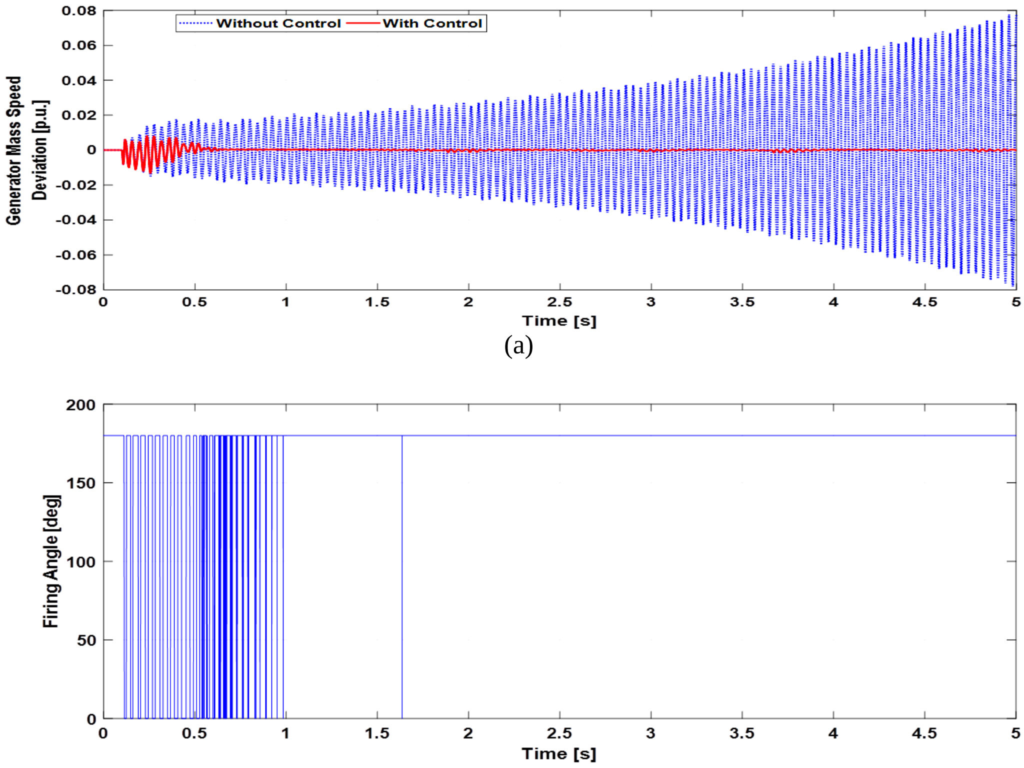
The parameters of the membership functions are determined by Hit-and-Trial approach. The output of the controller is the firing angle of the thyristors with either 0° or 180° values (180° for both Z and NB, and 0° for PB), where 180° indicates that the RCBR is fully deenergized and 1 indicates that the RCBR is fully energized. Thus, fuzzy rules should be as follows: If the input ($\Delta\omega$) is NB then the output is 180°; if the input ($\Delta\omega$) is Z then the output is 180°; and if the input ($\Delta\omega$) is PB then the output is 0°. It is worthy to mention that the adopted switching strategy in this work is the Type-2 fuzzy based bang-bang (ON-OFF) discontinuous control strategy in which dynamic braking interventions are conducted at appropriate moments determined by the implemented IT2FLC. This type of control can be used to control any power system shunt element whose parameters cannot be smoothly controlled. It is commonly used to control power system shunt elements in general and dynamic braking applications in particular [38].

4. SIMULATION RESULTS

For verifying the effectiveness of the suggested scheme in mitigating SSR shaft torsional oscillations, time domain simulation studies via MATLAB/Simulink model are conducted. Also, power spectral density analysis with continuous plots formats uses Matlab environment before and after the implementation of the proposed scheme to show the effectiveness of the controller on mitigating the torsional torque profiles. Three case studies with different severity degrees are considered to examine the performance of the proposed scheme under various fault conditions.

4.1. Case Study 1: Self Healing Three-phase to Ground Bolted Fault with 55% Compensation Ratio

A three-phase to ground (3LG) bolted fault is applied at line B, very close to generator high voltage bus at fault point F1, as shown in Fig. 1. The disturbance stimulated is a 0.0169 s self-clearing fault, i.e. the involved circuit breakers are not anticipated to sever the faulted line; and it is applied at 0.1 s from the simulation time of 5 s. The generator mass speed deviation signal with and without the proposed scheme and the controller output versus time responses to the case study under consideration are depicted in Fig. 5.

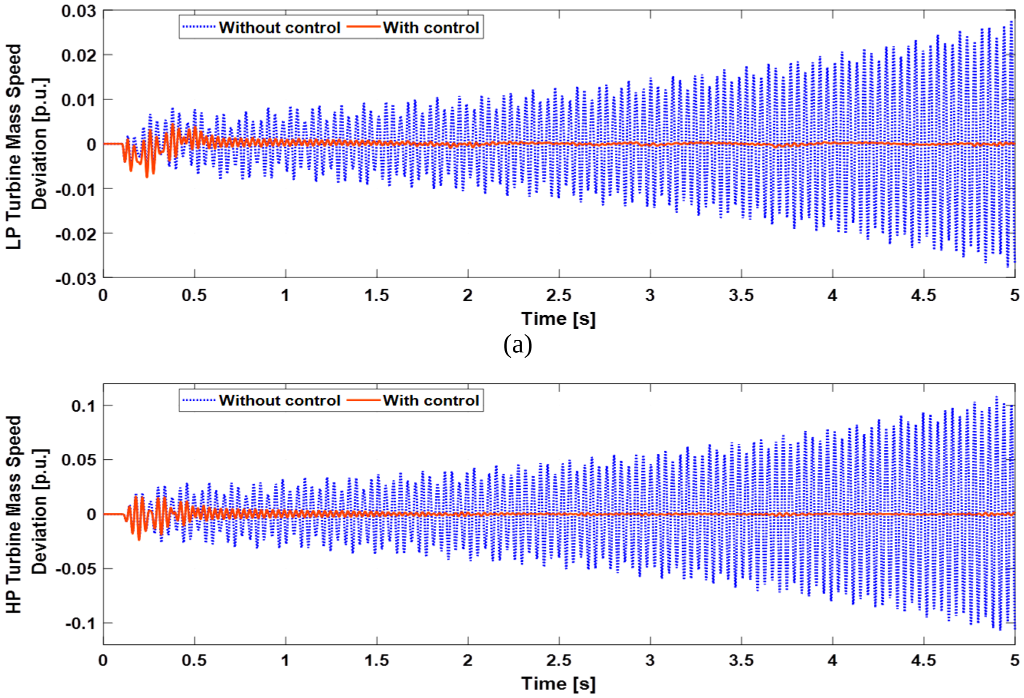


(a)

(b)

Fig. 5. Generator mass speed deviation signal with and without the proposed scheme and the controller output versus time for case 1: a) generator mass speed deviation; b) firing angle response.

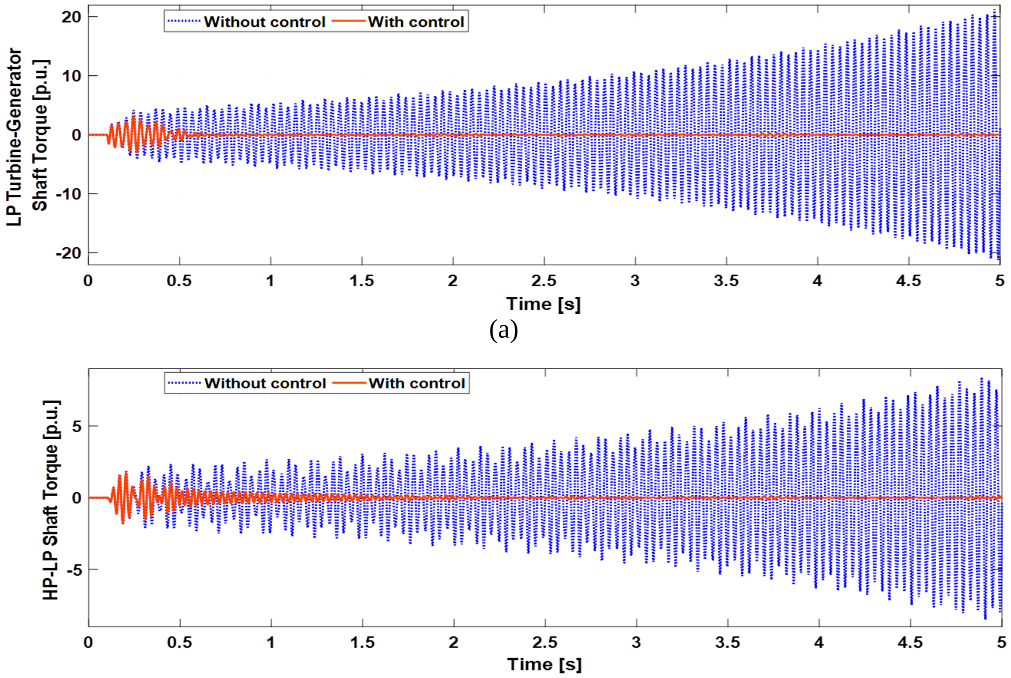
The relative speed responses of the turbine shaft system and the torsional torque profiles in p.u. with and without the proposed scheme are listed as a family of curves and shown in Figs. 6 and 7, respectively.



(a)

(b)

Fig. 6. Relative turbine mass speed responses due to the three-phase self-healing fault at the generator HV bus: a) LP turbine mass speed deviation; b) HP turbine mass speed deviation.



(a)

(b)

Fig. 7. Torque responses with and without interval type-2 fuzzy controlled RCBR due to the three-phase self-healing fault at the generator HV bus: a) LP turbine-generator shaft torsional torque; b) HP-LP shaft torsional torque.

From the above simulation results, in the base case responses without the supplemental damping, it is distinctly observed that both relative speed and torsional torque responses seem to be increasing in the time frame of the simulation which indicates the torsional instability of the responses. These devastating torque oscillations will, for sure, end up causing a premature shaft fatigue life expenditure of the shaft and irrevocable shaft cracks or even a shaft fracture. As evidenced in the obtained time domain simulation results, the relative speed and the torsional torque profiles reach an excellent level due to the implementation of the proposed scheme. Neutralizing SSR condition further enables the employment of series capacitor compensation safely near steam power plants without any mechanical jeopardy.

Fast Fourier Transform (FFT) analysis is performed with a MATLAB platform to validate the obtained time domain simulation results. Fig. 8 shows the FFT plot for the LP turbine-generator shaft torsional torque signal depicted in Fig. 7(a) with and without the proposed scheme.

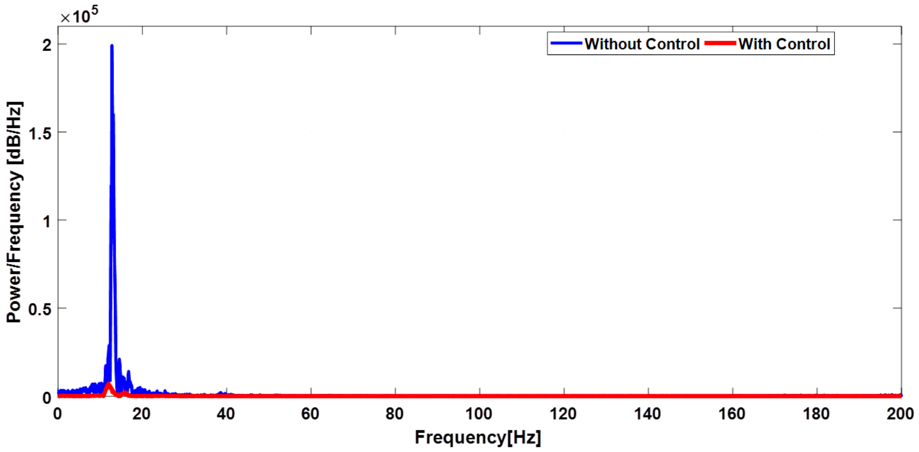


Fig. 8. FFT analysis of LP turbine-generator shaft torque signal for case 1.

The oscillatory behavior is well mitigated when the proposed control scheme is implemented.

4.2. Case Study 2: Self Healing Two-phase to Ground Bolted Fault with 50% Compensation Ratio

A two-phase to ground (2LG) bolted fault is applied at the end of line B, at fault point F2, as shown in Fig. 1. The disturbance stimulated is 0.0169 s self-clearing fault and is applied at 0.1 s from the simulation time of 5 s. The generator mass speed deviation signal with and without the proposed scheme and the controller output versus time responses for the considered case study are depicted in Fig. 9.

The turbine-generator shaft system torsional torque responses in p.u. with and without the proposed scheme are depicted in Fig. 10. The relative speed responses of the turbine shaft system will not be shown for brevity.

The torsional torque responses comparison plot portrayed in Fig. 10 visibly indicates the torsional instability of the torque responses without the proposed scheme. With the implementation of the proposed scheme, torsional torque responses of the shaft system will be satisfactorily mitigated.

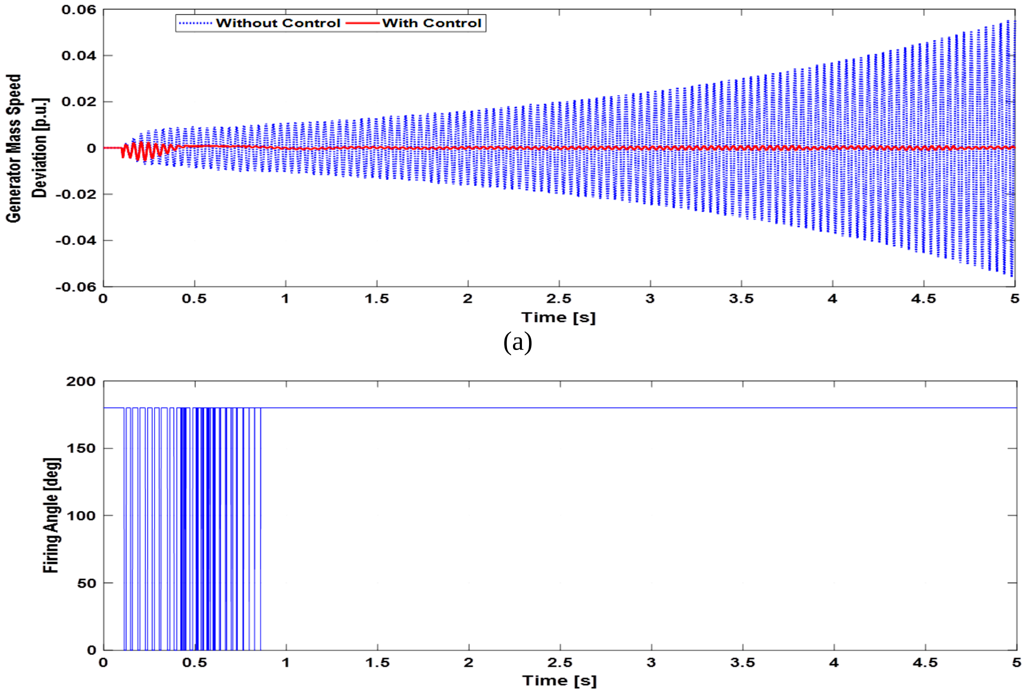


Fig. 9. Generator mass speed deviation signal with and without the proposed scheme and the controller output versus time for case 2: a) generator mass speed deviation; b) firing angle response.

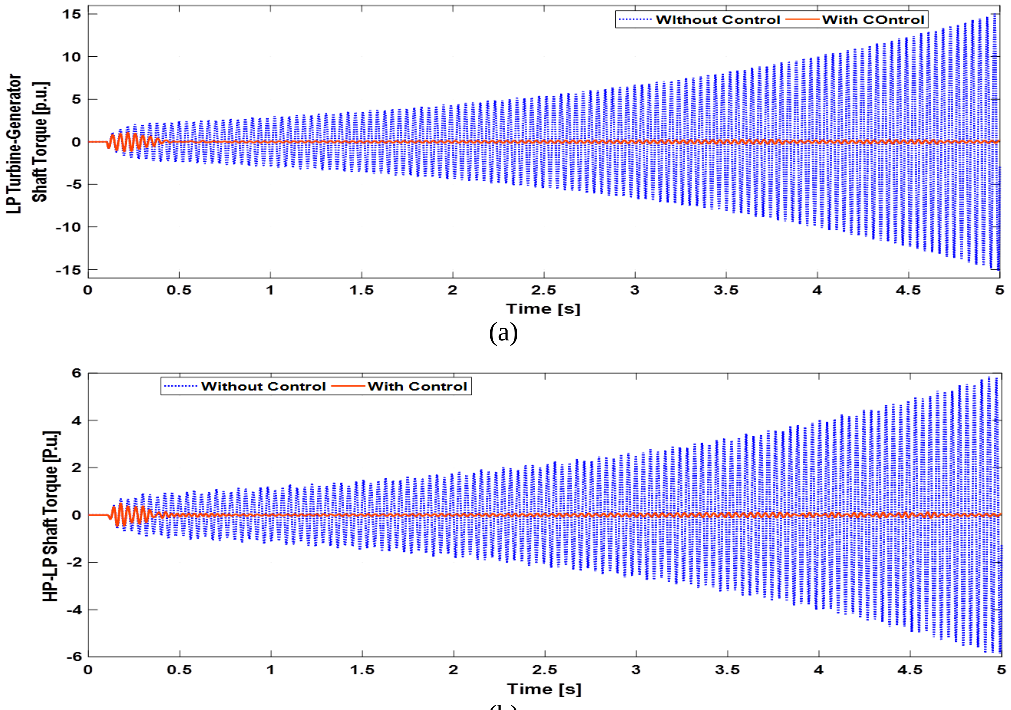


Fig. 10. Torque responses with and without interval type-2 fuzzy controlled RCBR due to the two-phase self-healing fault: a) LP turbine-generator shaft torsional torque; b) HP-LP shaft torsional torque.

Fig. 11 shows the FFT plot for the LP turbine-generator shaft torsional torque signal depicted in Fig. 10 (a) with and without the proposed scheme. Fig. 11 shows that the oscillatory behavior is well mitigated when the proposed control scheme is implemented for that case study.

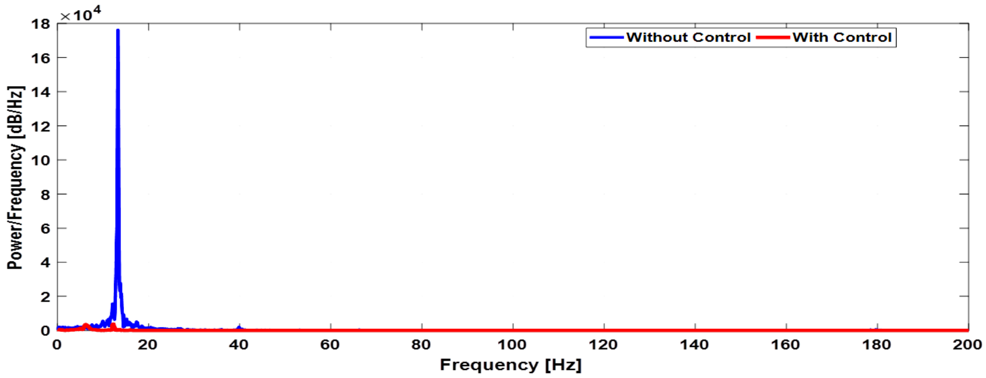
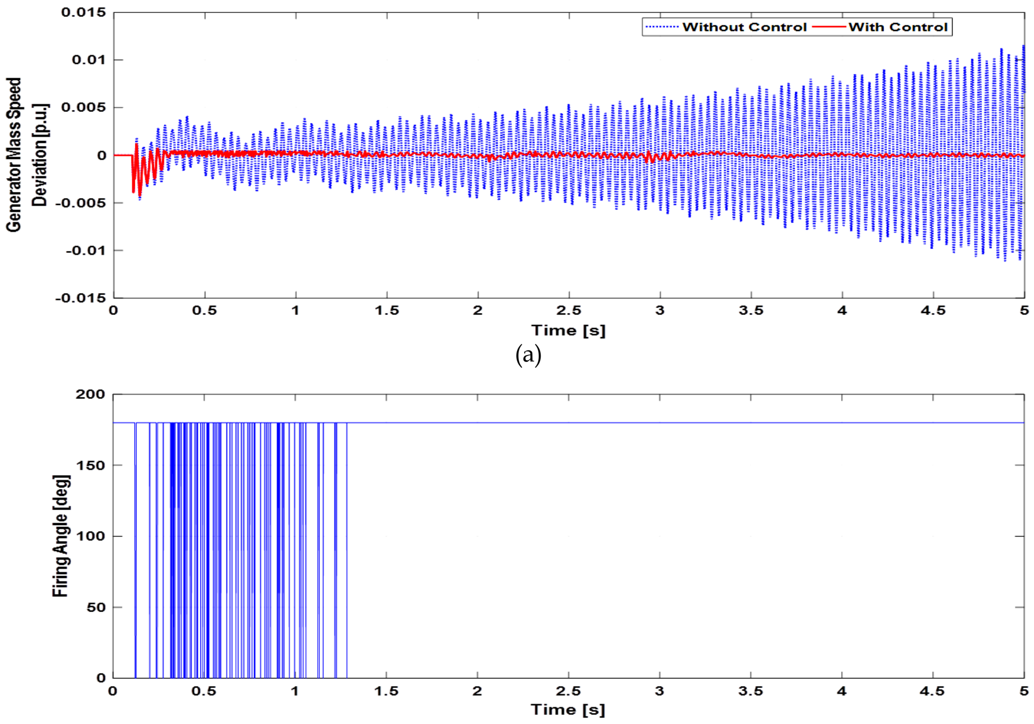


Fig. 11. FFT analysis of LP turbine-generator shaft torque signal for case 2.

4.3. Case Study 3: Self Healing High-resistance Single-phase to Ground Fault with 48% Compensation Ratio

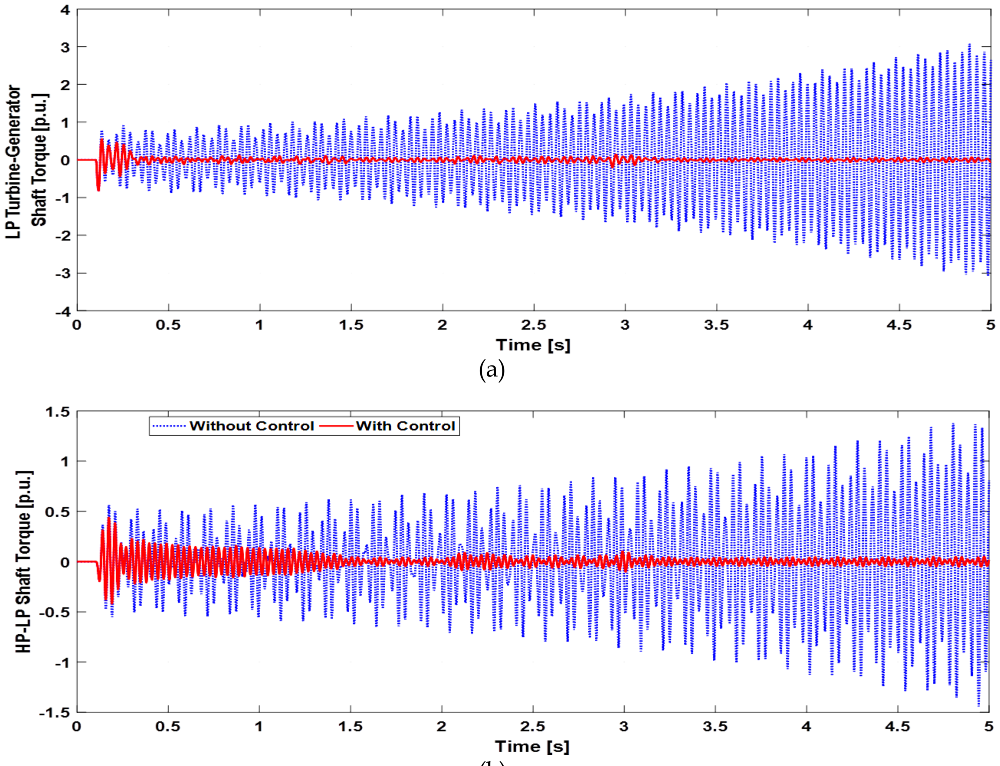
A single-phase to ground (1LG) high-resistance tree fault is applied at line B at fault point F1. Found practical in many of the well-documented fault cases in the American network [39], a tree fault resistance of 50 ohms is considered in this case study. The disturbance stimulated is 0.0169 s self-clearing fault; and is applied at 0.1 s from the simulation time of 5 s. The generator mass speed deviation signal with and without the proposed scheme and the controller output versus time responses are depicted in Fig. 12.



(b)

Fig. 12. Generator mass speed deviation signal with and without the proposed scheme and the controller output versus time for case 3: a) generator mass speed deviation; b) firing angle response

The turbine-generator shaft system torsional torque responses in p.u. with and without the proposed scheme are depicted in Fig. 13. The torsional torque responses comparison plot depicted in Fig. 13 visibly shows that torsional torque responses will increase in magnitude as the simulation time proceeds. Fig. 13 also indicates the instability of the torque responses without the proposed scheme. With the employment of the proposed scheme, the torsional torque responses of the shaft system will be satisfactorily mitigated.



(a)

(b)

Fig. 13. Torque responses with and without fuzzy controlled RCBR due to a high-resistance single-phase self-healing fault at the generator HV bus: a) LP turbine-generator shaft torsional torque; b) HP-LP shaft torsional torque.

Fig. 14 shows the FFT plot of the LP turbine-generator shaft torsional torque signal depicted in Fig. 13 (a) with and without the proposed scheme.

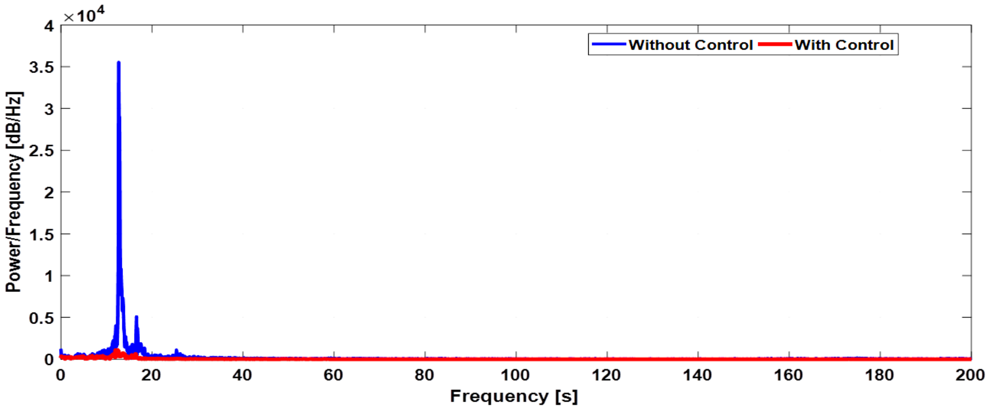


Fig. 14. FFT analysis of LP turbine-generator shaft torque signal for case 3.

From the outline of Fig. 14, it is obviously noticed that the oscillatory behavior is well mitigated when the proposed control scheme is implemented in this case study.

5. CONCLUSIONS

IT2FLC based RCBR is a local contingency SSR mitigation scheme, where it is built inside the power plant and controlled via a local control signal synthesized from the generator mass speed. This paper demonstrates the effectiveness of IT2FLC based RCBR as SSR countermeasure. From the results, the speed and torque profiles of the turbine-generator manifest a significantly excellent supplemental damping which enables torsional responses to die out rapidly. The IT2FLC based RCBR could be viewed as a mean for consolidating the operational security of the grid by dilating the fatigue life of turbine-generators to the maximum possible potential by neutralizing any developed SSR situation. Finally, the implementation of the proposed scheme should capacitate series capacitor compensation of long transmission lines emanating from thermal power plants safely and soundly without jeopardizing the mechanical integrity of the shaft system of the involved turbine-generator set. No similar article could be found in the literature regarding the implementation of IT2FLC based RCBR for mitigation of SSR oscillations.

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