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Fuzzy Control Strategy for Damping Sub-Synchronous Resonance

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Abstract – Sub-Synchronous Resonance (SSR) is a phenomenon that harms turbine generator shafts because the phenomenon induces sub-synchronous wavering in the system. In the study presented in this paper, a dynamic resistance bank is used to mitigate the occurrence of sub-synchronous phenomenon. A fuzzy logic controller using rotor speed deviation and its derivative as inputs is implemented to damp sub-synchronous oscillations more efficiently. An eigenvalue technique is used to analyse the stability of the system, and a simulation in MATLAB is conducted, based on the IEEE Second Benchmark, to validate the effectiveness of the proposed method under a 3-phase fault condition at an infinite bus. The time-domain simulation and eigenvalues are used to observe the proposed method's superior ability to damp sub-synchronous oscillation.

Keywords: Sub-Synchronous Resonance (SSR), FLDC, FLC, Fuzzy controller strategy, Dynamic resistance.

1. Introduction

Modern power systems are widely interconnected, enabling operational economy, stability, and reliability through mutual assistance. Among the major challenges that power engineers confront are processes or events that are vulnerable to power system disturbances. One such event is the occurrence of sub-synchronous resonance (SSR), an electrical power system phenomenon in which the electrical network transfers energy to the turbine-generator network [1].

The turbine-generator network in a power system can be considered as a spring-mass system in which the masses of the generator, low-pressure (LP) turbine, and high-pressure (HP) turbine are in tandem on a single shaft, as shown in Fig. 1.

Under normal operating conditions, when the shaft is rotating at its synchronous frequency, these masses have their natural frequency of oscillation f_n, which can be calculated by the Eq. (1).

$$fn = \frac{1}{2*\prod} * \left(\frac{k_{12}}{(H1*H2)/(H1+H2)} \right)^{1/2} \tag{1}$$

where k represents the stiffness constant of the spring (or shaft, in this case), and $H1$ and $H2$ represent the inertial constants of the masses for the generator, and LP and HP turbines, respectively.

A series capacitor is a highly effective and economical means of improving power transfer, used primarily to compensate the reactance in the long transmission lines. However, this can lead to the occurrence of SSR, which is one of the main factors that can hinder the stability of the system [2].

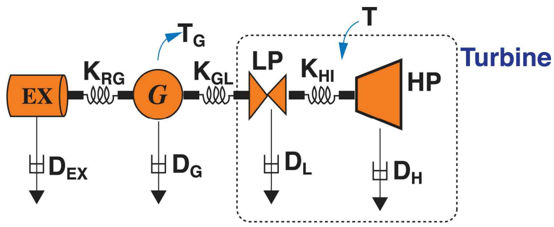

Fig. 1. Turbine-generator network

Low frequency motions in the system, ranging from 0.2 to 2.0 Hz and brought about by the generator's rotor swings, can be contrarily damped in the vicinity of quick-acting static exciters and high-gain automatic voltage controllers (AVRs) [3, 4]. A significant characteristic of these models is the representation of machine stators and external stationary systems by arithmetical comparisons based on the supposition of a semi-unfaltering system state. Another supposition utilized to examine low-frequency motion is that the pole on which the generator, turning exciter, and turbine rotors are mounted is exceptionally unbending, and all the rotor inertia can be grouped together [5, 6]. On the other hand, torsional oscillations in the frequency range of 10 to 50 Hz become significant when the individual rotors on the shaft can swing relative to each other on account of elastic shaft sections [7].

There are several modes of torsional motion that can be energized by unsettling influences, such as the changes in electromagnetic torque on the generator rotor caused by switching-induced drifters in the system [8]. These torsional motions can be delicately damped, requiring only a few seconds to damp out. When the torque on a pole is high, the condition can prompt exhaustion harm because of plastic deformation. The issue of softly damped

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torsional motions is intensified because of association with the outer system; for instance, an capacitor - compensated AC transmission line or a HVDC connection joined with a turbo-generator can prompt softly damped torsional motions [8]. In addition, there can be sub-synchronous motions in the armature current.

SSR is an electrical condition of the system in which the electrical network exchanges energy with the turbine generator at one or more natural frequencies of the combined system, below the synchronous frequency of the system [9]. This definition incorporates any system condition that promotes energy exchange at a given SSR, including what may be viewed as common modes of wavering that occur because of the system's innate qualities, as well as constrained modes of frequency that are determined by a specific device or control [2]. The most well-known example of the common mode of SSR is the set of systems that incorporates a series of capacitor-compensated transmission lines. In refreance [10] a unified approach based on model control theory proposed for designing a damping controller using thyristor controller conductance to series capacitor segments.

1.1 SSR in power systems

SSR can be considered as a phenomenon that may be significant when the mechanical system of the turbine generator exchanges energy with the electrical network. The series-compensated line might involve sub-synchronous currents with electrical frequency [7,11].

$$f_e = f_o \sqrt{\frac{X_C}{X_{L(eq)}}} \tag{2}$$

In Eq. (2), X_c represents the series capacitor reactance; $X_{L(eq)}$ represents the reactance of the transmission line, generator, and transformer; and f_0 represents the nominal frequency of the power system. The sub-synchronous currents generated would result in rotor torque at the complementary frequency f_r that can be calculated by Eq. (3).

$$f_r = f_o - f_e \tag{3}$$

The SSR interactions that might occur in the power system can be classified into two types: transient torque or transient SSR, and self-excitation or steady state SSR.

1.2 Self-excitation or steady state SSR

The sub-synchronous frequency that the rotor current renders to the generator terminals will generates sub-synchronous frequency components in the terminal voltage [1]. These elements can influence the current to generate self-excitation effects, which can be classified into two types: torsional interaction and induction-generator. In the induction-generator effect, the electrical resonance resulting from the series compensation generates a rotating field with a resonant frequency on the generator stator [9]. At high compensation levels, this resonance frequency is often less than the system's nominal frequency; thus, the resonant current generated from the electrical network produces a revolving field with a sub-synchronous frequency [2, 7]. In the case of synchronous generator, the rotor of the generator rotates at the synchronous frequency, and the synchronous machine accordingly operates as an induction-generator, along with the sub-synchronously rotating field. In contrast, power systems such as wind farms consist of self-excited induction generators (SEIGs). However, in both cases, the slip of the machine s can be calculated by Eq. (4):

$$s = \frac{f_e - f_o}{f_e} \tag{4}$$

Because the electrical resonance is less than the system's nominal resonance, the slip is negative; therefore, the safety of the rotor is negative at the SSR, from the perspective of the armature terminals [1]. In reference to the regulated proportionalilty of a SEIG circuits, a self-excitation condition appears when the size of this safety surpasses the safety of the whole armature and system at full resonance. The generator rotor's torsional wavering and electrical resonance are commonly energized, actuating armature voltage segments at the SSR frequencies, which are at or near the electrical resonance.

1.3 Transient torque or transient SSR

Transient torques are those that are induced by aggravations of the system that cause sudden changes in the system, causing unexpected changes in the currents and flows that then have a tendency to waver at the regular frequencies of the system [11]. In general, transient SSR occurs when harmonics of the electrical resonance correspond with one of the characteristic torsional frequencies.

1.4 Methods of SSR analysis

The purpose of the study presented in this paper is to develop a fuzzy logic damping controller (FLDC), based on the following methodology. Self-excitation is an enduring state matter that produces the unsteadiness of the system's optimized operational parameters. The dependability of the working point is examined using linearized models of the different system components, based on two noteworthy routines [7]: synchronizing and damping torque, which aides the examination of torsional interaction, and checking resonance, which can enable screening of the induction-generator impact and torsional interaction.

Examining eigenvalues is a precise technique that can take advantage of itemized system models to investigate the synchronization and damping of torque. In contrast, resonance space systems are less difficult to utilize and could be computationally advantageous for checking resonance; however, they tend to be less precise [9].

2. Fuzzy Logic Damping Controller (FLDC)

In recent years, FLDCs have been developed as effective tools for stabilizing the power network. The most significant advantage of FLDCs relative to conventional damping controllers is that FLDCs do not require an exact mathematical model [12]. They cannot control linearity with inaccurate inputs and are more robust and effective than the conventional damping controllers. SSR mitigation has been performed with FLDCs using dynamic braking, with rotor speed deviation as the input and the output of the controller acting as the input to the gate turn off (GTO) thyristor [11]. In the study presented in this paper the thyristor is connected to a 3-phase resistive bank rated at 10 MW, and this resistive bank absorbs the active energy exchange between the mechanical and electrical network during fault occurrences that can result in permanent shaft damage if the torsional interaction of the turbine and generator network is not damped [12]. The FLDC is designed in such a way that only it will be activated (and consume power) only if the rotor speed deviates outside certain constraints. Once the rotor speed is controlled to be within the constraints, the dynamic braking induced by the 3-phase resistive bank is discontinued from the system. Therefore, the objective of this study is to present the development of a fuzzy logic damping controller (FLDC).

2.1 Fuzzy Logic Control (FLC) characteristics

In contrast to conventional control techniques, FLC is best utilized in complex ill-defined processes that can be controlled by a skilled human operator without much knowledge of the system's underlying dynamics [5]. A fuzzy logic – based supplemntery controller is proposed in referance [13] to dam the torsional oscillations due to SSR. The FLC method is intended to incorporate the expert experience of a human operator in the FLC design to control a process in which the input – output relationships are described by a collection of fuzzy control rules (e.g., If-Then rules) involving linguistic variables rather than a complicated dynamic mathematical model. A typical FLC architecture is shown in Fig. 2, comprising four principal components: a fuzzifier, a fuzzy rule base, an inference engine, and a defuzzifier.

2.2 FLC process

There are six steps involved in the creation of a rule-

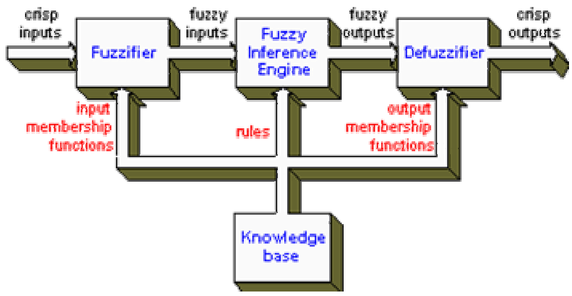

Fig. 2. Typical FLC architecture

based fuzzy system that can process inputs and obtain outputs:

- Identify the inputs and their ranges and name them.
- Identify the outputs and their ranges and name them.
- Create a fuzzy membership function for each input and output.
- Construct the rule base under which the system will operate
- Decide how the action will be executed by weighting the rules
- Combine the rules and defuzzify the output

3. Design of FLDC for resistance to SSR-induced torque variations

SSR alleviation has been performed with FLC using dynamic braking with a 3-phase resistive burden [14, 15]. In the study presented in this paper rotor speed deviation was used as the input to the FLDC, and the output of the FLDC became the input of a GTO thyristor associated with a 3-phase resistive bank rated at 10 MW that absorbs the dynamic SSR-induced torque variations.

3.1 Input membership function

A 3-phase resistive bank is placed in the turbine-generator network to damp SSR. The rotor speed deviation from the synchronous value Δw and its derivative $(\partial \Delta w / \partial t)$ are used as inputs to the FLDC .The membership functions of the two inputs are shown in Figs. 3 and 4. The speed deviation of the rotor shaft is evaluated with respect to a synchronous value (3600 rpm in this case) [9]. Three membership functions are defined for the input: negative (N), zero (Z), and positive (P); the types and ranges of these functions are shown in Table 1. The total range for the input membership function is from -3×10^{-3} to 3×10^{-3}.

3.2 Output membership function

The output of the FLDC is a gate signal. It contains two membership functions: small (S) and big (B), as shown in Fig. 5, with a total range of 0.7-1.2, as shown in Table 2:

Table 1. Input membership function definitions

No.	Membership function name	Type	Range
1	Negative	Trapezoid	[-0.003 -0.003 -0.002 -0.000119]
2	Zero	Triangular	[-0.0006111 0 0.000706]
3	Positive	Trapezoid	[0.0001032 0.00202 0.00302 0.00302]

Table 2. Output membership function of definitions

Sr.no	Membership function name	Type	Range
1	Small	Triangular	[0.771 0.8867 1.02]
2	Big	Triangular	[0.988 1.08 1.2]

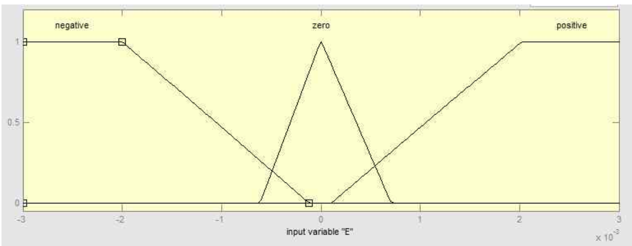

Fig. 3. Membership function of input1

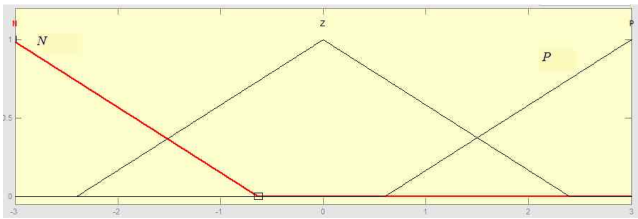

Fig. 4. Membership function of input2

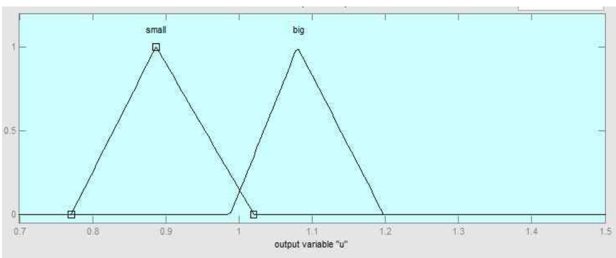

Fig. 5. Membership function of output

3.3 FLDC rules

The FLDC rules are defined as a series of If-Then logic statements. In this way, the controllers are implemented as follows:

1. If (Δw is N) and $(\partial \Delta w / \partial t)$ is N) then (Gate is S)
2. If (Δw is N) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is B)
3. If (Δw is N) and $(\partial \Delta w / \partial t)$ is P) then (Gate is B)
4. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is P) then (Gate is S)
5. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is S)
6. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is N) then (Gate is S)
7. If (Δw is P) and $(\partial \Delta w / \partial t)$ is N) then (Gate is B)
8. If (Δw is P) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is B)
9. If (Δw is P) and $(\partial \Delta w / \partial t)$ is P) then (Gate is S)

Table 3 below shows the fuzzy rules with respect to both the input and output membership functions.

Table 3. Fldc rules

IF		Result
Input is Negative	Then	Output is BIG
Input is Zero	Then	Output is SMALL
Input is Positive	Then	Output is BIG

The following three possible scenarios show the respective outputs relative to the inputs.

1) When the input is N, in the range [-0.003 -0.003 -0.002 -0.000119]:
The FLDC commands a big output in the range [0.988 1.08 1.2].
2) When the input is Z, in the range [-0.0006111 0 0.000706]:
The FLDC commands a small output in the range [0.771 0.8867 1.02], and the gate signal of the GTO thyristor is not forward biased or conducting current because the minimum requirement for the gate signal is 1.
3) When the input is P, in the range [0.0001032 0.00202 0.00302 0.00302]:
The FLDC commands a big output in the range [0.988 1.08 1.2], and the gate signal to the GTO thyristor is forward biased and conducting current because the minimum requirement for the gate signal is 1.

4. Fldc Simulation

The IEEE Second Benchmark model is used to simulate dynamic resistance controlled with the proposed FLDC. This simulation is performed for a single self sustaining machine joined with limitless transport. The model contains a synchronous generator (600 MVA, 3600 rpm, 22 kV) driven by a steam turbine with two chambers: LP and HP [16]. The system is considered as a spring mass system with the three masses of the LP turbine, HP turbine, and generator. The generator is joined with a transformer of 600 MVA/60 Hz, rated at 22-500 kV. The transformer is associated with two parallel transmission lines, one of which is arrangement adjusted. A 3-phase fault occurrence is present near the beginning of the transmission line, and the fault is applied in the system between the times 0.0169 and 0.022 seconds. The other end of the transmission lines is associated with limitless transport, which maintains the voltage and dynamic force of the system to be 1 pu and 0 MW, respectively. The SSR mode introduced by the compensating capacitor after a fault has been applied can be

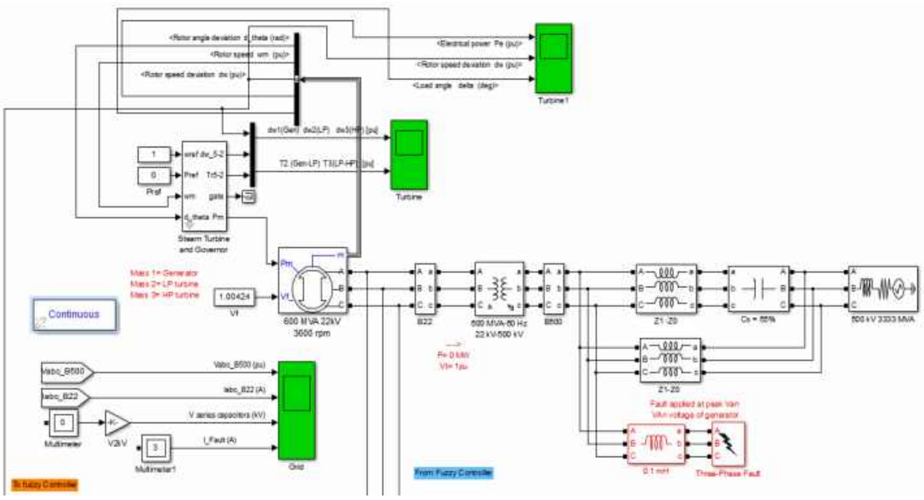

Fig. 6. Simulation of FLDC

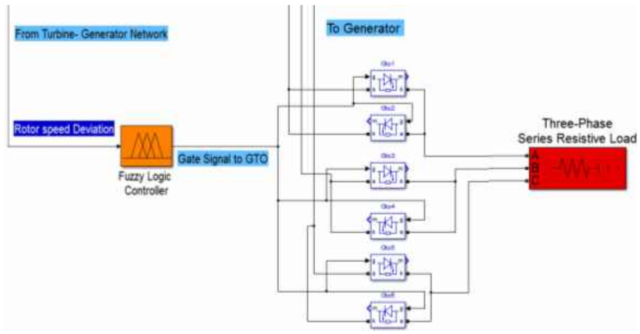

Fig. 7. Relationship between FLDC and resistive bank

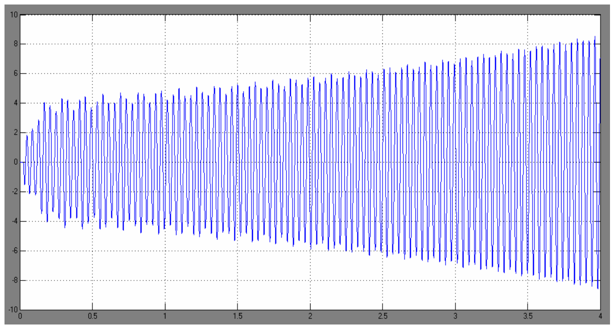

Fig. 8. Variation of torque between LP turbine and generator

clearly observed to excite the oscillatory torsional interactions of the multi-mass shaft. Figs. 6 shows the FLDC simulation model, and Fig. 7 illustrates the relationship between the FLDC and the resistive bank.

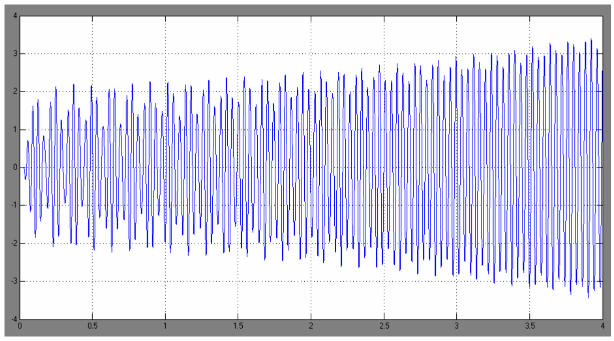

Fig. 9. Variation of torque between HP and LP turbines

5. Simulation Results and Discussion

The SSR simulation described above was conducted to prove the effectiveness of the applied control strategy and to evaluate its capacity for damping resistance.

The simulation clearly demonstrated the occurrence of the SSR phenomenon. From Figs. 8 and 9, it is apparent that both the torsional interactions between the HP and LP turbine and between the LP turbine and the generator are significantly enhanced during fault occurrence. The eigenvalues also suggest the same, as shown in Table 4.

The simulation was run for 4 seconds, with the fault occurring at 0.1722 s and cleared at 0.22245 s. The dynamic graphs in Figs. 11-13 show the simulation results, including the turbine and rotor speed deviation. From these results, the FLDC influence on the system's dynamic resistance achieves damping of the torsional interaction, and the rotor speed deviation is brought within steady limits.

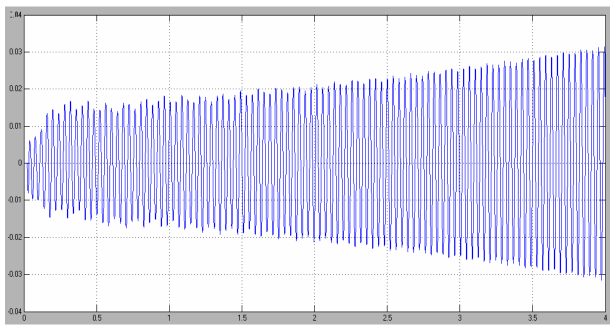

Fig. 10. Rotor speed deviation during fault occurrence

Table 4. Eigenvalues of undamped mode

Eigen values	Comments
-0.037 ± 8.28j	Low frequency mode
-0.53 ± 204.6j	Sub-synchronous mode
0.84 ± 202.92j	Sub-synchronous mode

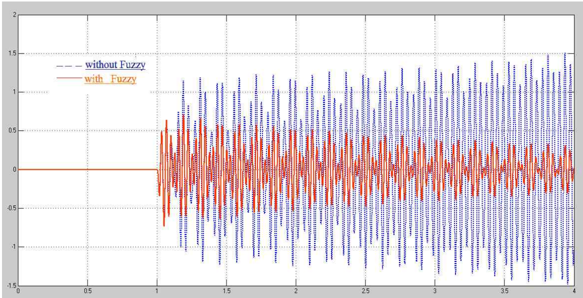

Fig. 11. Torsional oscillation on HP-LP turbine shaft

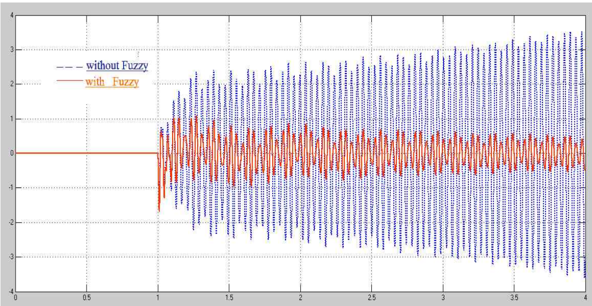

Fig. 12. Torsional oscillation on LP turbine-generator

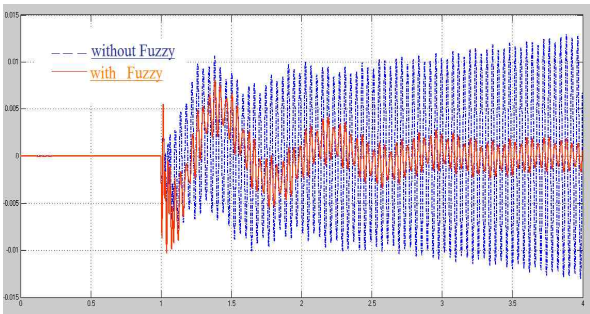

Fig. 13. Variation of rotor speed deviation

The main inconvenience of this system is that deficiencies can happen at any location along the transmission lines, which are a few miles long, introducing a variable that could have calamitous results if not considered. Therefore, for practical applications, the FLDC should be designed to control and damp SSR at any location along the transmission lines.

6. Conclusion

In this study, a FLDC method to address the SSR effect is analysed based on the IEEE Second Benchmark model. Simulations were conducted with the proposed FLDC in a series-compensated system. The proposed FLDC was shown to successfully damp torsional interactions among system components, and constrain the rotor speed within steady limits. The suppression of torsional oscillations is displayed by the use of various distinctive waveforms. The typical conventional methods are non – optimized fuzzy designs, the propositioned method however, demonstrates an optimized procedure for damping control and thud is advantaged. Since the proposed fuzzy algorithm is associated with exceptionally fewer fuzzy variable, it is exceedingly competent and productive.

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