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Original Article

Design of Fuzzy Controller for PV Solar Plant as STATCOM (PV-STATCOM) to Mitigate SSR

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Abstract - *Power quality enhancement in series compensation of the transmission line may lead to a phenomenon called Sub Synchronous Resonance (SSR). SSR is a mechanical phenomenon of coincidence of the resonant frequency of the turbine shaft and that of the generator shaft units causing shaft failure in some extreme cases. Generally, the use of FACTS devices is one of the effective methods of mitigating SSR to improve the system's performance. This work utilizes PV solar farm as STATCOM to mitigate the sub-synchronous resonance (SSR). Here PV-STATCOM acts with the dual property to provide the real power support to the system and mitigate SSR in the system. The FUZZY's control technique with the PI controller is carried out to achieve this dual objective. The execution of the proposed controller is tested on MATLAB/SIMULINK software. These results in the improvement of system performance by damping the torsional oscillations. And the use of PV-STATCOM either hinders or reduces the use of FACTS devices to achieve the same objective, and the use of a fuzzy controller results in a fast response compared to the conventional PI controller. Keywords: Sub-synchronous resonance, PV-STATCOM, Fuzzy controller, PI controller.*

Keywords - *Sub-Synchronous Resonance, PV-STATCOM, Fuzzy controller, PI controller, and Damping controller.*

1. Introduction

Recent trends in renewable energy result in the enormous utilization of renewable resources such as PV, Wind, Geo-Thermal, and so on in the power system to enhance its power system performance. But the integration of these renewable resources into the grid causes huge risk factors in the power system because of the limited power availability of these systems. To increase the availability of Transmission capability of the systems, various techniques such as compensation using various FACTS devices such as STATCOM, SVC, UPFC, and so on are being considered. One effective means of increasing the power transfer capacity is by providing series capacitive compensation. However, these capacitances are utilized after a prior and needed addressing of the sub-synchronous resonance. Sub-synchronous is the phenomenon that includes the system condition in which there is a chance for the energy exchange at the sub-synchronous frequency level of the system. Due to this exchange, torsional stress on the turbine-generator shaft is experienced, which causes severe damage to the system.

Before the 1970s, Sub-Synchronous Resonance on the AC transmission line was considered an electrical phenomenon. But it was proved wrong; after the occurrence of the two-shaft failure at Mohave Generating station in the USA, a new theory of SSR began to evolve that describes the phenomenon of interaction between the electrical resonance due to the series compensated line and a mechanical resonance due to a turbine generator shaft system (Varma et al. 2012) setting a new defining concept for SSR phenomenon in the system. The second experience of SSR highlights the HVDC-torsional interaction in Square Buttee USA, let to the study of the adverse impact of the interaction of the HVDC converter control over the generator torsional system (Rajiv and Varma 2009). It comes out with the discovery of the degree of interaction depends on different system parameters such as AC transmission system configuration, level of loading in the line, characteristics, and the mode of control of the HVDC line terminals (Bowler et al. 1975). The third wave of SSR occurred due to the interaction between the control system of a doubly-fed induction generator (DFIG) and a transmission line with series compensation (Anderson et al. 1990; Padiyar et al. 1990). The detailed analysis of the definition of the concept of SSR finally leads to the identification of the parameters affected by the detection of SSR, such as torsional oscillation, turbine-shaft interactions, shaft failure, and so on. Hence, the mitigation of SSR starts to play a vital role which leads to the analysis of the detailed investigation of the alternate method of elimination of SSR phenomenon, including the utilization of different types of filtering and damping techniques, relaying and detecting devices, system switching, and generator tripping and the modification of generator and system parameters (*https://www.energiforsk.se/konferenser/genomforda/sub-synchronous-oscillations/*). Other than the technique mentioned above, the utilization of FACTS devices provides an effective solution for mitigating the SSR. The shunt connected reactive power compensator with the dynamic control to modulate the reactive power results in the damping of SSR is presented in . 5 Mostly, the available studies utilized STATCOM to produce the dynamic reactive power control to mitigate the SSR phenomenon, which utilizes the PI-controller for the detection of additional deviation in the generator- speed control. These Studies also used the Eigenvalue analysis to generate speed and voltage control feedback gain (Bahrman et al. 1998; Padiyar et al. 1999). The second widely used FACTS device is Thyristors Controlled Series Compensation (TCSC), operated in a Vernier mode which is utilized to mitigate the SSR by the dynamic control of the reactive power support to the system (Abi-samra et al. 1985). Some of the other studies also include using the Static Synchronous Series Compensator (SSSC), which is used as a synchronous voltage source in series with the fixed capacitor, to provide an effective solution for the alleviation of SSR in the series transmission line. It shows the advantage of the increase in the power coefficient because of the utilization of the fixed capacitor in series, and this also results in the decrease in the MVAR rating of the SSSC required to mitigate SSR(Ghorbani et al., 2012; Varma et al. 2014; Zhu et al. 1995).

Some minimum amount of the work includes the simultaneous control of active and the reactive power using a Superconducting Magnetic Energy Storage (SMES) unit that may also be utilized to damp out the oscillation of SSR (Pillai et al. 2003). Although there is a hand full of options for the employment of the mitigation techniques using FACTS devices, recent employment of the increased use of the renewables in the transmission line led to the development of the new trend where the renewables are used for the other purpose in addition to the normal operation of the renewable systems which may include voltage regulation (Thirumalaivasam et al. 2013), power transfer capability improvement (Bongiono et al. 2008), damping out the power oscillation and also to mitigate SSR (Farmer 1985; Varma et al. 2015). The maximum number of studies have tested the use of PV solar farms as STATCOM to achieve these additional applications because of the advantage of the abundant availability and the simple control techniques. There are various control techniques to achieve the dual character of the PV system as STATCOM. Most of the studies discussed above use the conventional PI controller; the limitation of the slow response of this controller can be overcome by using the other advanced controller such as Fuzzy Logic Controller, Artificial Neural converters, and other Artificial Intelligence oriented controllers. An effective number of 6 studies are there to explain the utilization of the fuzzy control method for damping out the oscillations in the FACTS devices resulting in increased stability and for the fast response of the system (Hussein et al. 199). The proposed work showed the variation of Fuzzy logic control to the PV solar farm rather than using it on the FACTS devices as in conventional cases. The above methods of damping out the SSR are tested and verified in the IEEE first benchmark system (Krause et al. 1986), and the results are analyzed. This has a six-mass spring mechanical system. The complexity of the mechanical system is reduced by the utilization of the design of the IEEE second benchmark system (Zdnko et al. 2006), which uses the Four-mass spring mechanical system of Generator, HP turbine, LP turbine. Therefore, IEEE's second benchmark system has been chosen as the test system for the proceeding work.

Recent trends in renewable energy result in the enormous utilization of renewable resources such as PV, Wind, Geo-Thermal, and so on in the power system to enhance performance of the power system. But the integration of these renewable resources into the grid causes huge risk factors in the power system because of the limited power availability of these systems. To increase the availability of Transmission capability of the systems, various techniques such as compensation using various FACTS devices such as STATCOM, SVC, UPFC, and so on are being considered.

The extensive use of FACTS devices results in controller complications and increased costs acquired by the system. Therefore, the recent system of PV solar plant is utilized as the STATCOM. The new technology of PV solar farm as the STATCOM generally referred to as PV-STATCOM, is used extensively in the power system as FACTS devices for achieving voltage profile improvement increases the power quality improvement.

One effective means of increasing the power transfer capacity is by providing series capacitive compensation. However, these capacitances are utilized after a prior and needed addressing of the sub-synchronous resonance. Sub-synchronous is the phenomenon that includes the system condition in which there is a chance for the energy exchange at the subsynchronous frequency level of the system. Due to this exchange, torsional stress on the turbine-generator shaft is experienced, which causes severe damage to the system. The first of these incidents were reported in the Mohave plant in Nevada, the USA, in 1970 and 1971. And the next incident was due to the interaction of HVDC converter controls and the generator turbine shaft system in North Dakota, the USA, in 1980.

Several measures are utilized to overcome the damage caused due to the sub-synchronous resonance; the perception of damping the SSR in the turbine shaft generator by the connection of SVC is demonstrated in and by STATCOM in. The main concept is that the reactive power from the compensator, controlled dynamically, is fine-tuned corresponding to the turbine-generator rotor oscillations resulting in the required voltage tuning at the point of contact (PCC) with the bus. This fine-tuning causes the sub-synchronous current flows through the turbine generator in the opposite direction, resulting in the cancellation of the original SSR current produced due to the interaction between the series-connected capacitor and inductance of the transmission network.

For example, the FACTs devices, Thyristor controlled series compensator Static Synchronous compensator SSSC are also used for the SSR mitigation purpose. The sub-synchronous resonance mitigation is done based on the control of generator speed regulation, the terminal voltage of the generator, point of contact voltage, and so on.

The proposed work utilizes a Sub Synchronous Damping Controller (SSDC) in the PV farm system considered STATCOM to mitigate the sub-synchronous resonance (SSR). Here PV-STATCOM acts with the dual property of generating real power in the absence of SSR and as a device to mitigate SSR in its presence. The controller's suggested analysis is verified on the IEEE second benchmark system model for SSR-related mitigation studies using MATLAB/SIMULINK.

The paper is structured as Part II exhibits the core idea of PV-STATCOM, Part III describes the system to be studied, Part IV presents the control system for PV-STATCOM, and Part V provides the SSR mitigation results of the proposed system utilizing MATLAB/ SIMULINK software. In Part V, the conclusion determined by the paper is presented.

2. Core Idea of PV-STATCOM

The following Fig 1 presents the general topography of the availability of the real and the reactive power from the PV solar plant for 24 hours. It shows the traces of two different operating modes.

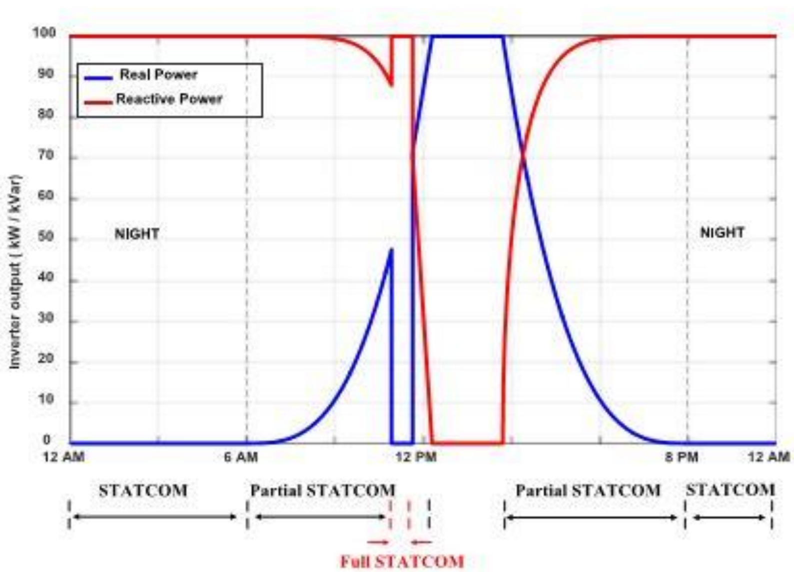

Fig.1. Real and Reactive power traces of the PV solar plant

2.1 Partial function as STATCOM

In this mode, there is a sustained supply of active power generation based on the availability of irradiance from the Sun. after the utilization of the real power generation, the remaining amount of the inverter capacity is utilized for the operation of STATCOM. This mode is generally witnessed at dawn and dusk.

2.2. Full operation as STATCOM

The entire amount of inverter capacity is used for STATCOM operation in the second mode. In general, during nighttime, the system act as a STATCOM as there is no availability of irradiance to generate real power. During the day hours, the system is widely used to generate real power until the detection of torsional oscillation creates SSR in the system. The PV system terminates its operation as a real power generator and supports the transmission system to mitigate SSR by the dynamic reactive power compensation. And the system resumes its operation after the mitigation of SSR.

3. Study System

The test system used in this work is given in Fig 2. The IEEE second benchmark system and the PV generation support at the generating terminal of the benchmark system given as PCC as presented in Fig. The mechanical element of the system is modeled with the Four mass-spring systems of the high-pressure turbine (HP), Low-pressure turbine (LP), the Generator (GEN), and the exciter (EXC).

The synchronous generator modeling and all the network is carried out in MATLAB/SIMULINK software with the values provided. AVR consideration for the synchronous generator is not used as per. The synchronous generator used is rated at 600MVA. The remaining needed capacity of the system is supported by the PV system connected through the Voltage source inverter connected at PCC. The torsional oscillation of four different modes occurs in this radial system, in which the first mode of torsional oscillation occurring at the frequency of 15.7 Hz is used. The value of the series capacitance to generate SSR is determined by using the formula,

$$f_n = f_s \sqrt{\frac{X_C}{X_L}}$$

Where X_C is the value of series capacitive reactance, $X_L$is the reactance value of the line, and $f_s$is the nominal frequency of the system.

The design of the PV system includes the required Voltage Source Inverter (VSI) consisting of three pairs of Insulated Gates Bipolar Transistor (IGBT) switches and a current source supplying DC. It also utilizes the MPPT technique of Incremental conductance to trace the maximum power from the PV system. The DC capacitor with a suitable value is selected such that the DC voltage is maintained approximately constant on the side of the inverter.

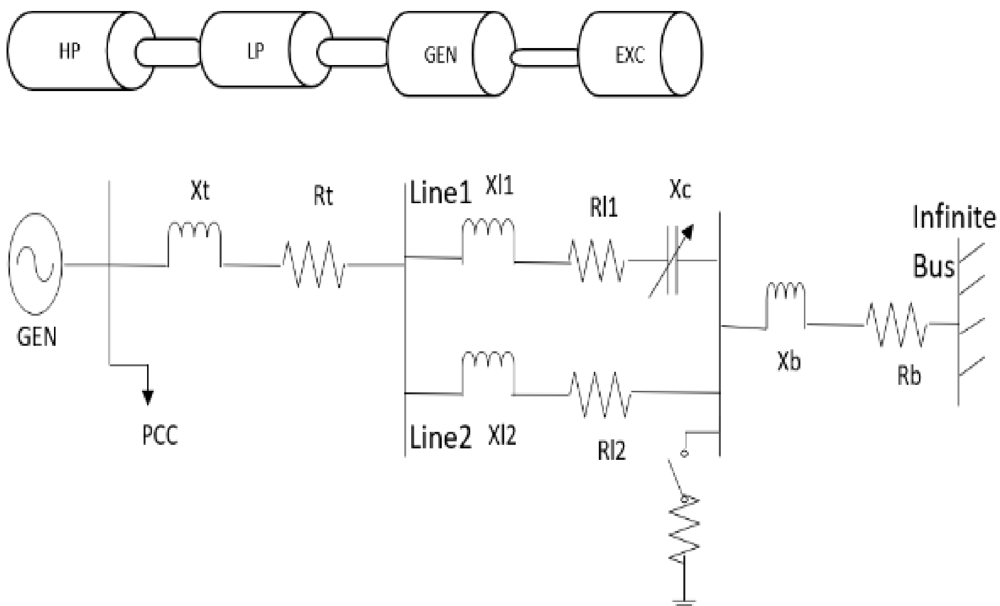

Fig. 2 IEEE second benchmark system

4. Controller Design

STATCOM is preferred over the other FACTS devices for dynamically controllable reactive power support because of its rapid response capability.

The system controller is initiated with the phase-locked loop (PLL) block, used to measure the angle of the system voltage. The dq-reference frame modeling calculates the current component i_d and i_q from the measured grid current at PCC. The damping controller block utilizes the speed of the synchronous generator as the control signal. It generates the current reference id-ref. The change in the speed deviation from the damping controller is utilized in the DC Voltage controller and the control signal V_{DC} and I_{PV}, which provides the reference current signal $I_{q\text{-}ref}$. The current controller block utilizes the reference current and produces the modulation signal to provide the gate control signal to the inverter through the PWM and gate drive block. These controllers are discussed in detail below and represented in Fig 3.

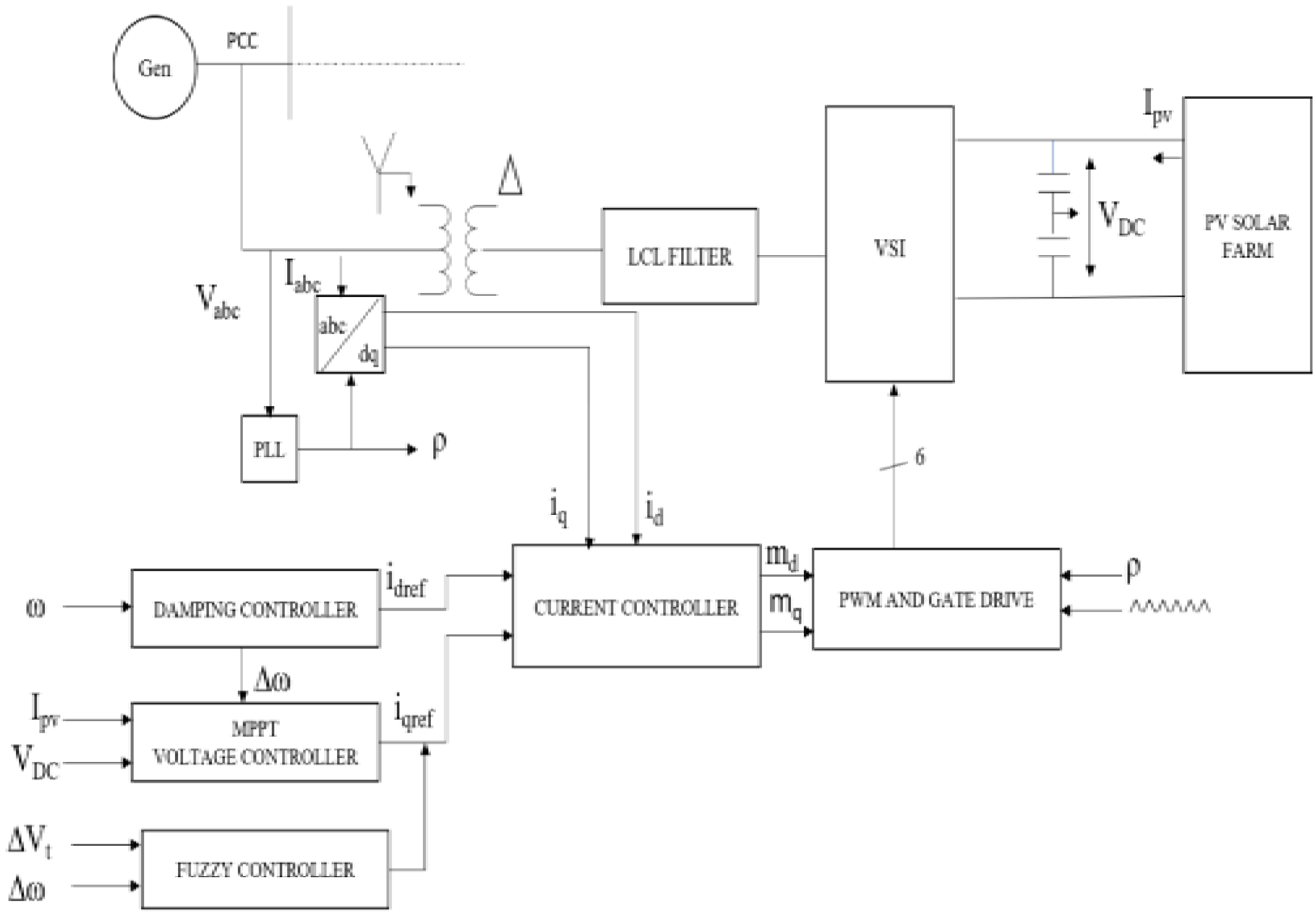

Fig. 3 Controller Design

4.1 Current Controller

The current control loop utilizes the reference current signals from the dq reference frame, i.e., i_d and i_q, compared with the current reference $i_{d\text{-}ref}$ from the damping controller block. For the IQ-ref current, DC voltage controller block combined with the fuzzy control system is used. Then the error signals obtained are refined through the proportional-Integral (PI) block, and its relative output is intensified with the decoupled feed-forward path as given in Fig 4.

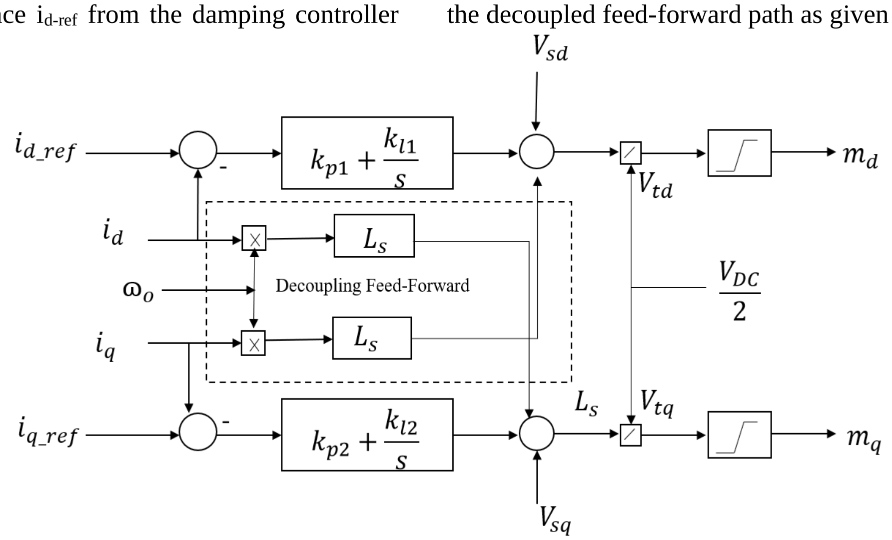

Fig. 4 Current controller

4.2 Damping Controller

The damping controller uses the speed of the synchronous generator as a control signal for the damping of the Sub-synchronous resonance. The damping controller consists of the washout block followed by the 180° phase shift block after augmenting with the gain block of K=150 and a saturation block that produces the $i_{d\text{-}ref}$ signal as described in Fig 5.

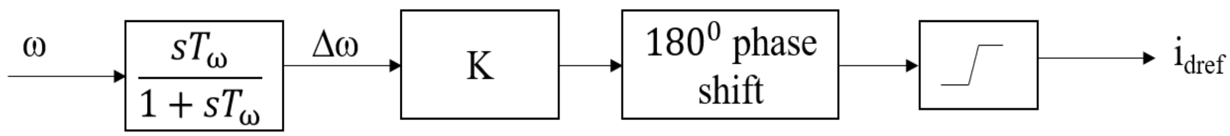

Fig. 5 Damping Controller

4.3 DC Voltage Controller

Fig 6 illustrates the concept of a DC voltage controller. The DC voltage controller consists of the MPPT block and a PI controller. The MPPT block using the incremental conductance technique is simulated using MATLAB/Simulink for tracing the maximum power from the PV system. The MPPT block provides $V_{dc\text{-}ref}$ to control the generation of real power form the PV system. The dc voltage measured is correlated with the reference voltage, and the error signal is generated, then processed using the Proportional Integral (PI) controller. The reference signal of $i_{q\text{-}ref1}$ is produced.

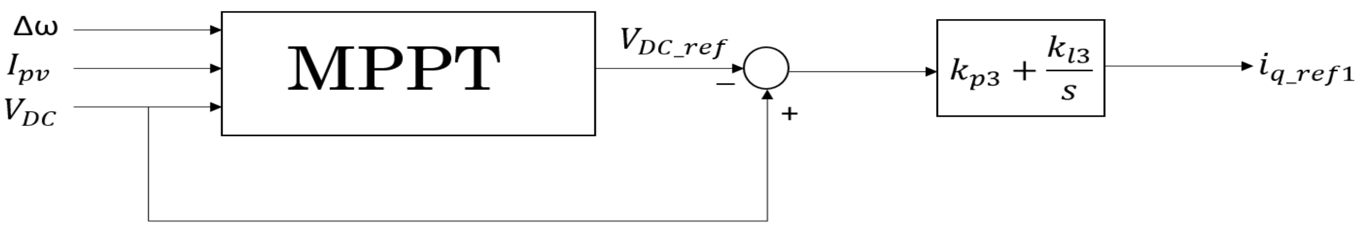

Fig.6 DC Voltage Controller

4.4 Fuzzy controller

The fuzzy logic controller generally consists of four main components given in Fig.7. They are Fuzzification, Fuzzy rule base, Fuzzy Inference Engine, and Defuzzification.

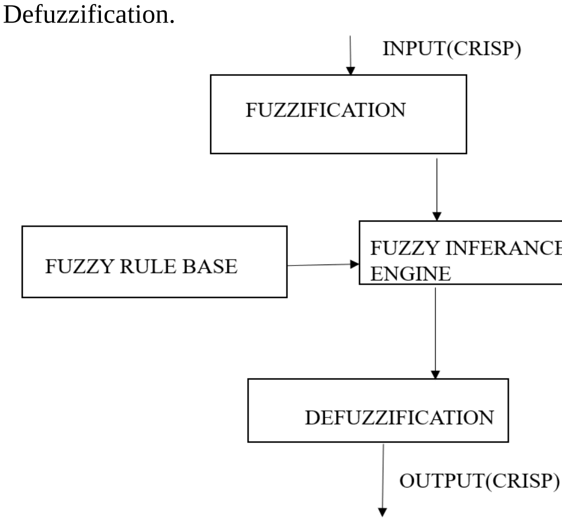

Fig. 7 Fuzzy Logic

The input signal is used for the generator terminal voltage (ΔV_t) and the generator speed deviation ($\Delta\omega$). The membership function, which is used to determine the required output signal based on the input signal, is chosen as a triangular membership function to achieve this objective, as depicted in Fig.8.

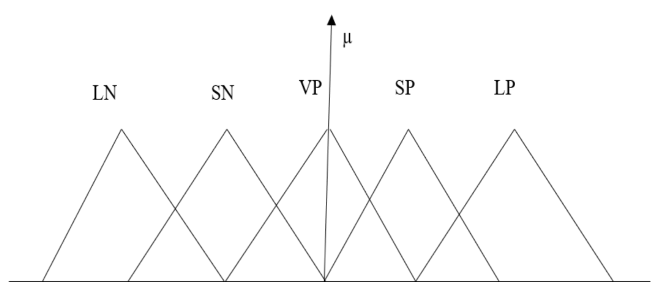

Fig. 8 Triangular membership function

Five variables of different characteristics are chosen for both the input and output, such as Large Positive (LP), Small Positive (SP), Very Small (VS), Small Negative (SN), and Large Negative (LN). A decision table is designed based on the respective inputs to obtain the required output as given as Rule I: when ΔV_t is LN and $\Delta\omega$ is also LN, the output is selected as SN.

The usage of 5 variables led to the generation of 25 rules. The remaining rules are tabulated in below Table 1.

Table 1. Fuzzy Logic Rules

$\Delta\omega$/ ΔV_t	**LN**	**SN**	**VS**	**SP**	**LP**
LN	SN	SN	LN	LN	LN
SN	SN	SN	SN	LN	SN
VS	SP	SP	VS	SN	SN
SP	LP	SP	SP	SP	SP
LP	LP	LP	LP	SP	SP

5. Simulation

5.1 Benchmark System Output

Fig 9 shows the real and the reactive power generation of the synchronous generator used in the system. The real power generated is 600MVA. The reactive power is given in per unit.

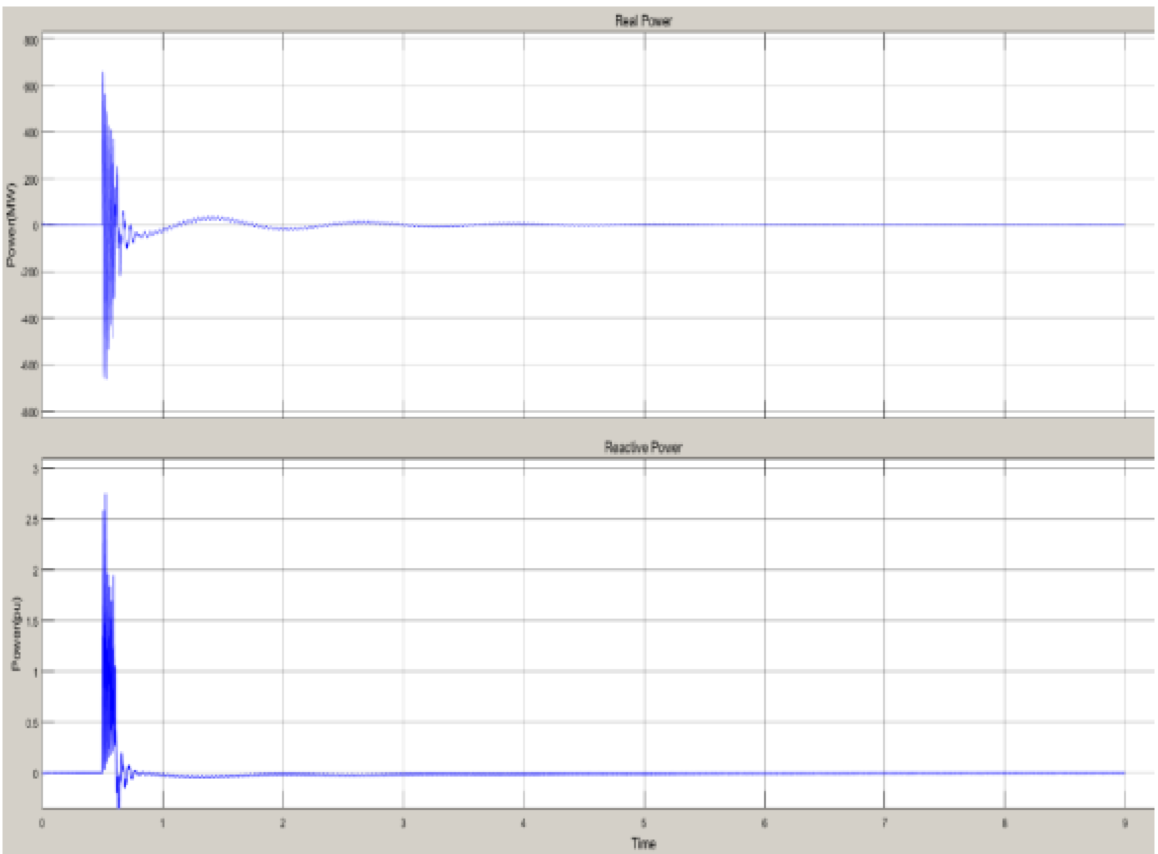

Fig. 9 Real and the reactive power generation of the synchronous generator

The fault was created in bus 2 at 0.5s and cleared at 0.6 s. The corresponding bus voltage at the point of contact and the bus current at the fault bus is shown in Fig 10. The values are given in per unit.

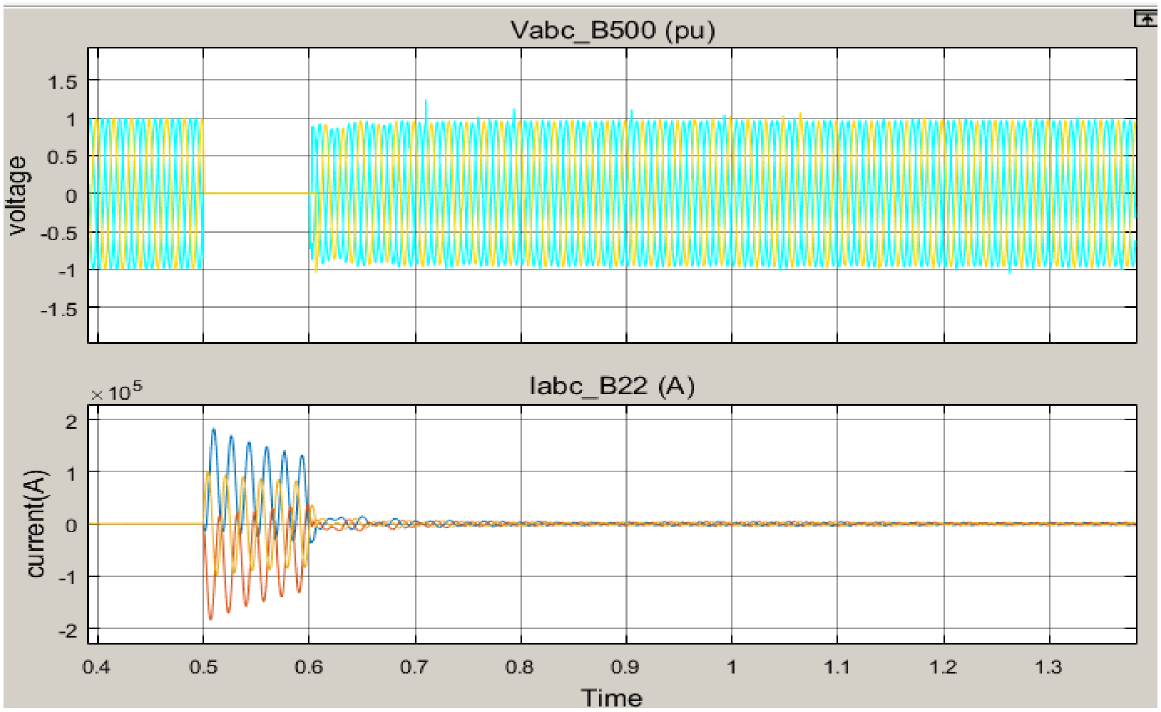

Fig. 10 Bus voltage and Bus current

5.2 PV System Output

The irradiance of 1000W/m^2 is maintained to obtain the required power of 250 KW, and for that, the DC-link voltage (V_{dc}) is maintained at 400V, which are provided in the following Fig 11 and 12. Fig 11 depicts the value before the connection of the benchmark system, and Fig 12 shows the value after the interconnection with the benchmark system.

Fig. 11 PV Output before interconnection

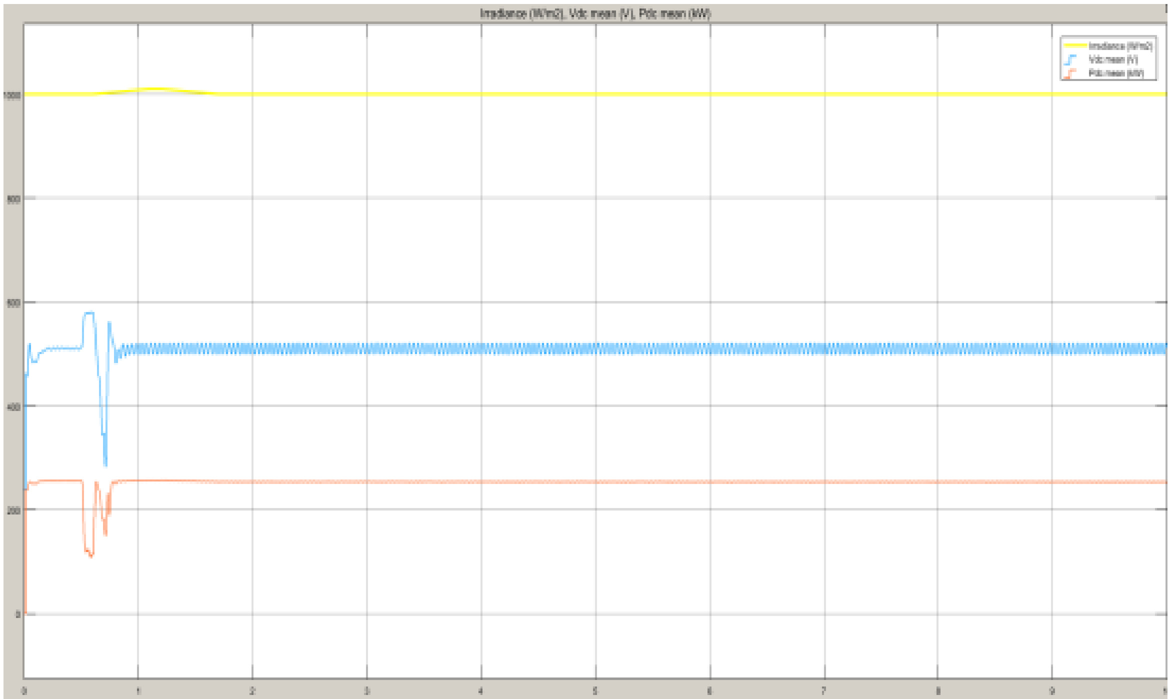

Fig. 12 (b) PV Output after interconnection

5.3 Rotor Speed

The following Fig13,14&15 speak about the rotor speed of the synchronous generator under three circumstances without using the damping controller, using the damping controller, and using Fuzzy as the damping controller. Here the rotor speed is measured in Rad/sec.

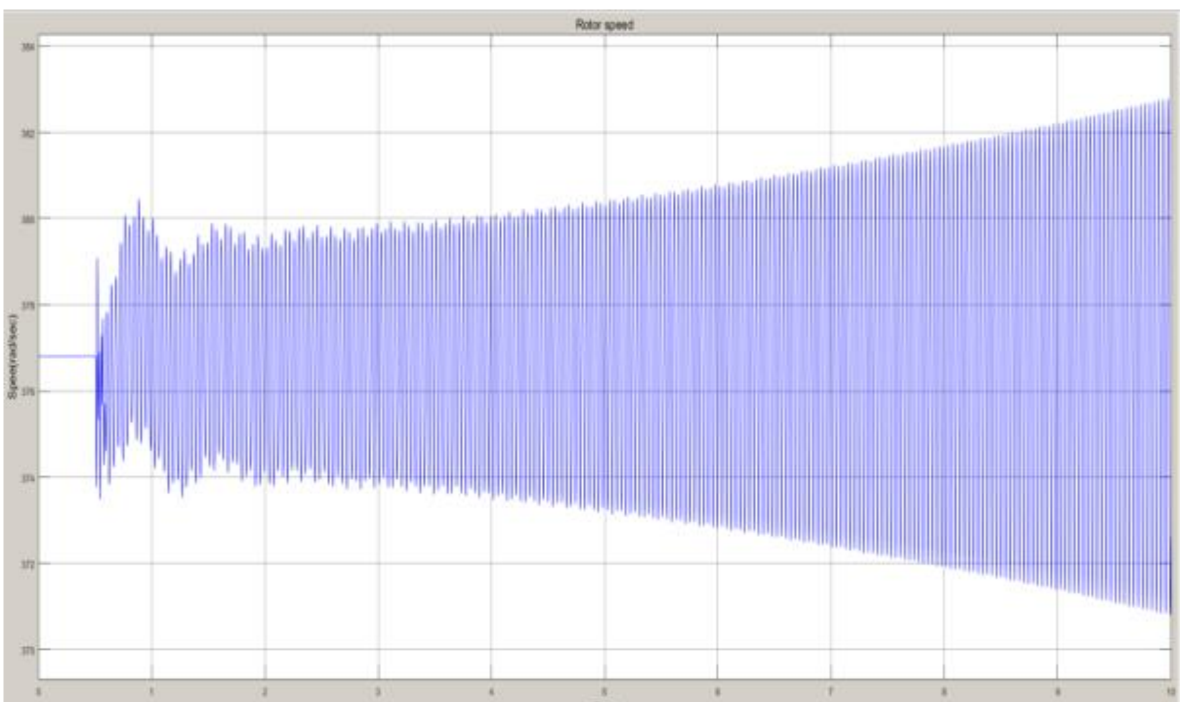

Fig. 13 Rotor Speed without damping Controller

Fig 13 indicates that the rotor speed of 377 rad/sec went uncontrol after the inducement of the fault at 0.5 sec.

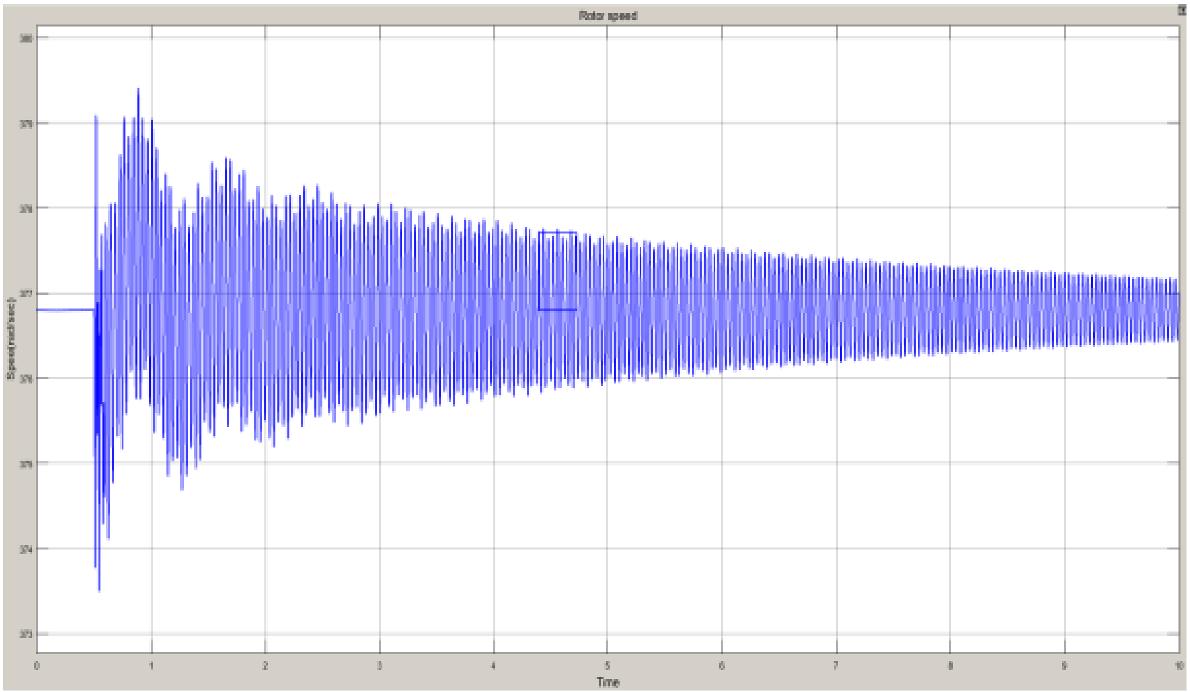

Fig. 14 Rotor Speed with damping Controller

Fig 14 shows that the rotor speed is settling after some period of oscillation, but the time taken for this is greater than 10 sec.

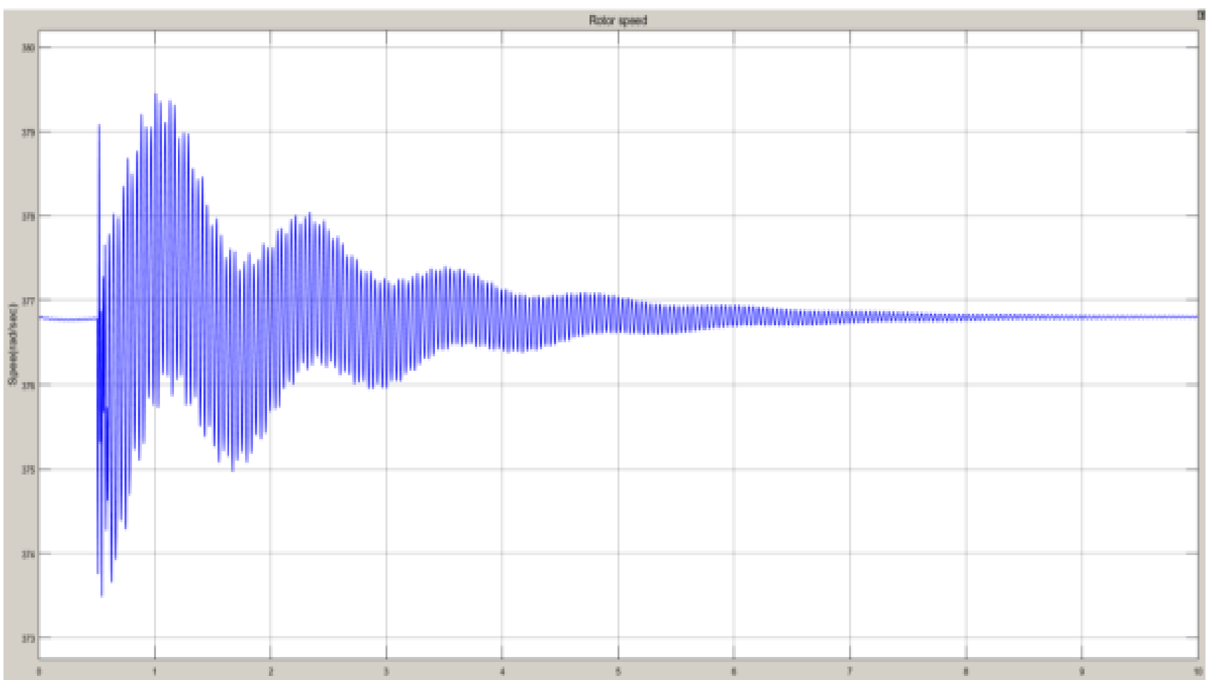

Fig. 15 Rotor Speed with Fuzzy Controller

Finally, Fig 15 shows the rotor speed response in the presence of a Fuzzy controller, which indicates that the oscillation starts to get settled as early as 8sec. Thus, indicating the improved and fast response while using the Fuzzy Controller for damping.

5.4 Change in Speed (Gen., Hp, LP).

The following Fig 16,17&18 speaks the change in rotor speed of the synchronous generator, HP turbine, and LP turbine under three circumstances without using the damping controller, using the damping controller, and using Fuzzy as the damping controller. Here the rotor speed is measured per unit quantity.

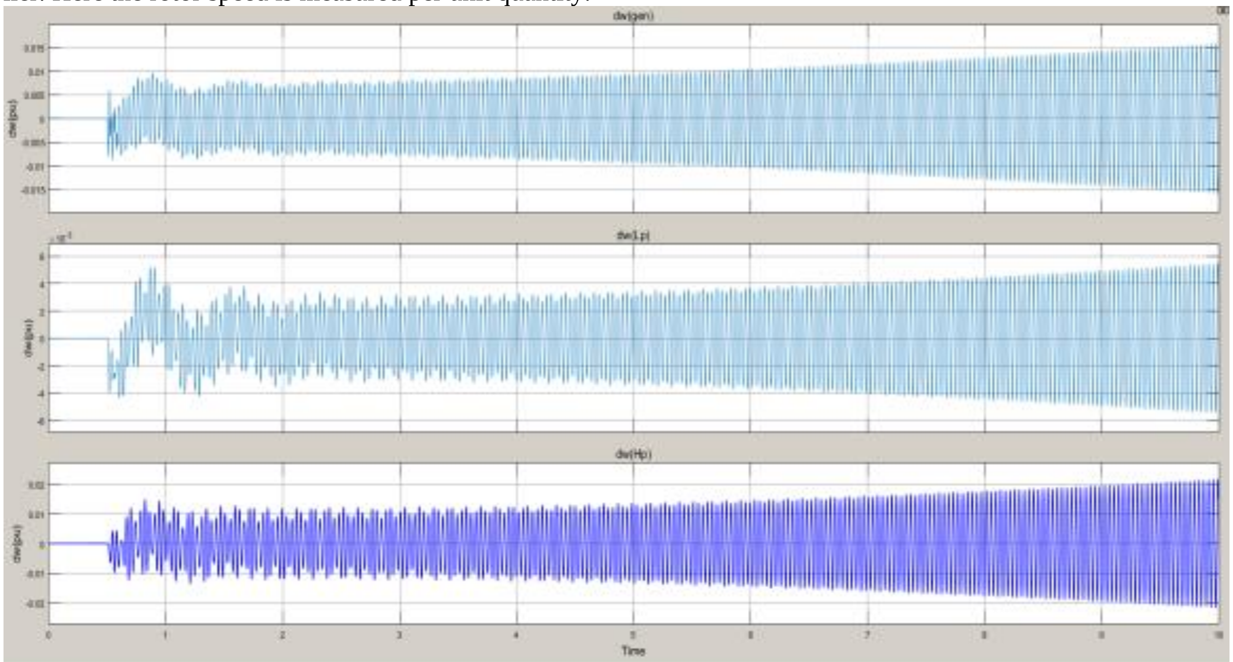

Fig. 16 Change in Rotor Speed (Gen, Hp, LP)-Without Damping Controller

Fig 16 indicates the change in rotor speed of the synchronous generator, HP turbine, and LP turbine without using any damping controller. This indicates that the presence of SSR results in the uncontrollable change in speed oscillation in all generators, HP turbine, and LP turbine.

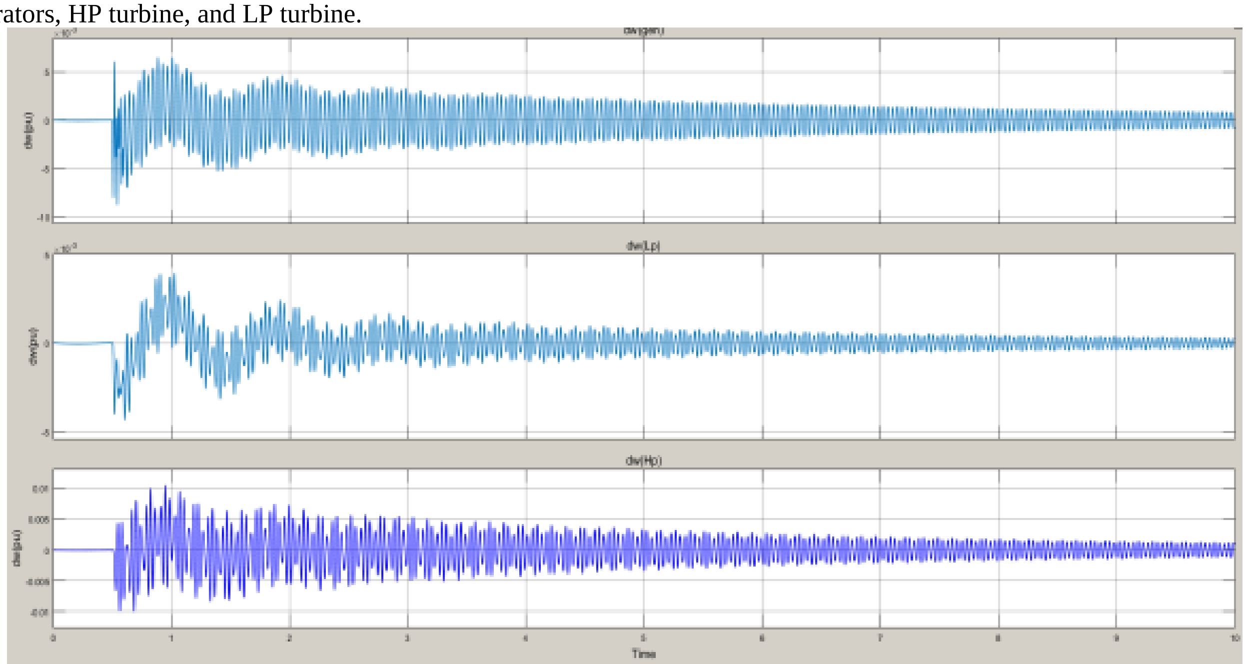

Fig. 17 Change in Rotor Speed (Gen, Hp, LP)-With Damping Controller

Fig 17 indicates the change in rotor speed of the synchronous generator, HP turbine, and LP turbine using a damping controller. The change in the rotor speed gets settled down after some period of oscillation, i.e., more than 10 sec while using the damping controller.

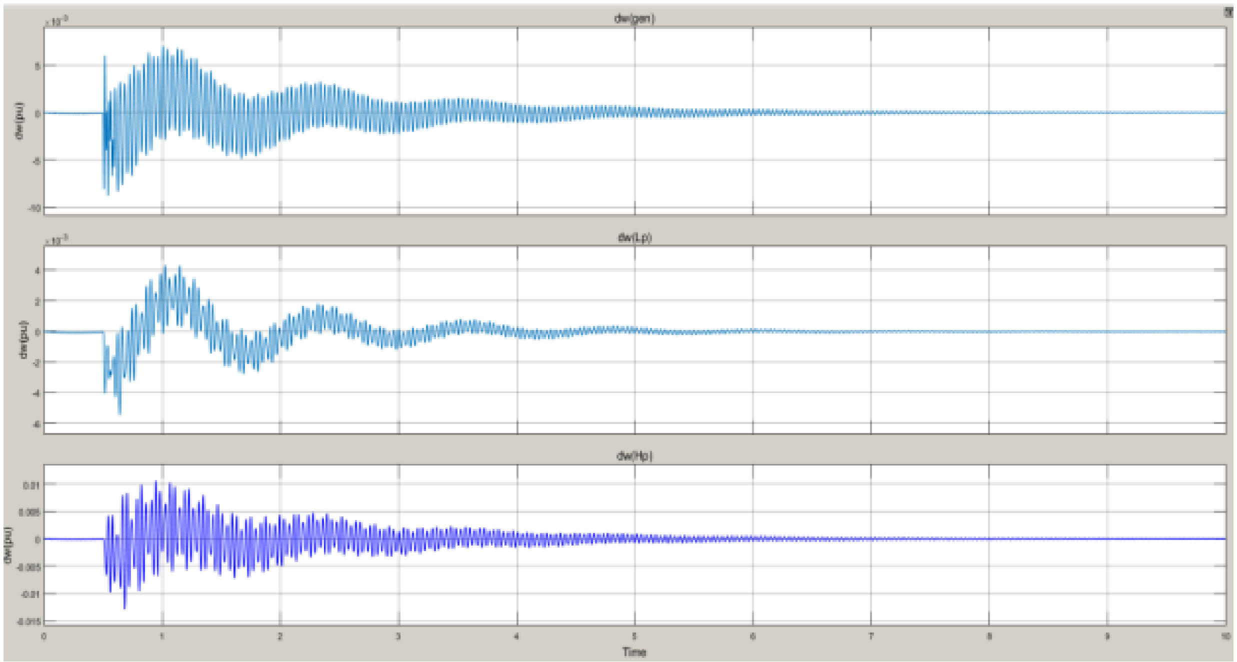

Fig. 18 Change in Rotor Speed (Gen, Hp, LP)-With Fuzzy Controller

Fig 18 indicates the change in rotor speed of the synchronous generator, HP turbine, and LP turbine while using a Fuzzy controller as damping control. The change in the rotor speed gets settled down faster than using a previous controller. Almost at 7sec, all the change in speed of Gen, HP, and LP turbine reaches stability.

5.5 Torque [(Gen-Hp) &(Hp-Lp)]

Torque characteristics between GEN - HP turbine and that of HP turbine - LP turbine at three circumstances without using the damping controller, with using damping controller, and with the use of Fuzzy as the damping controller is given in Fig 19,20&21. Here the value of the torque is measured per unit quantity. When there is an SSR generation, the Torque response is uncontrollable, which may lead to shaft failure. Hence the torque oscillation should be damped out to mitigate the SSR in the system.

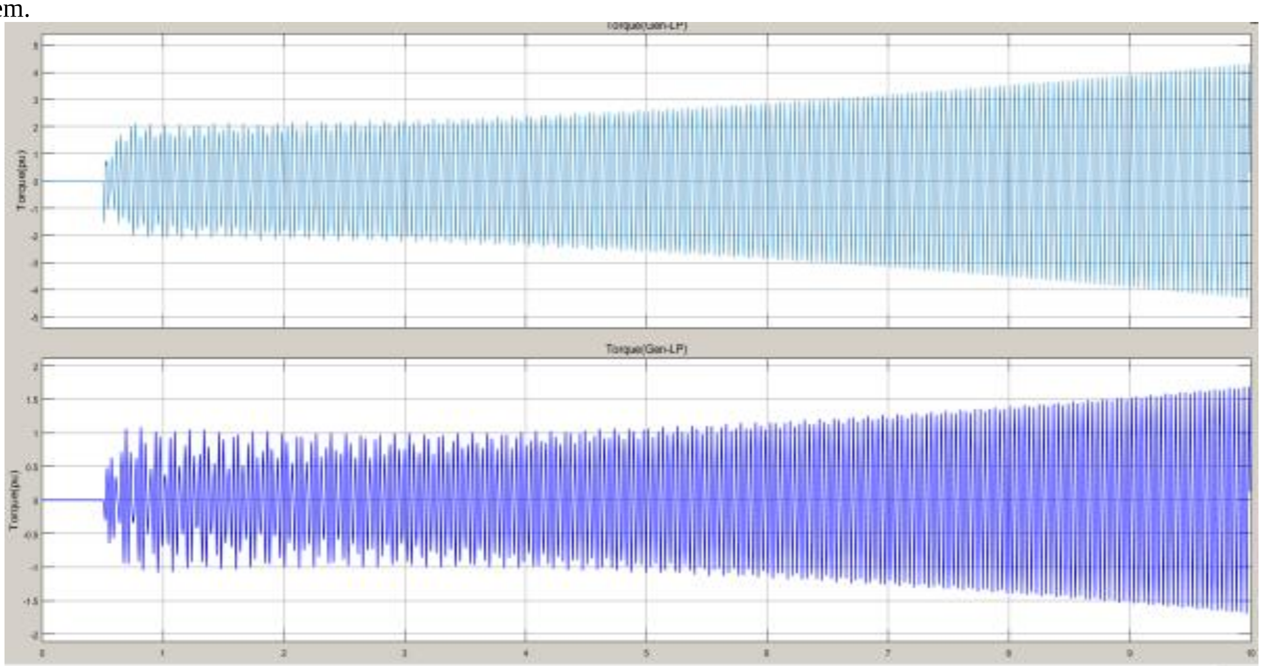

Fig. 19 Torque [(Gen-Hp) &(Hp-Lp)]- Without Damping Controller

Fig 19 shows the torque characteristics between the GEN - HP turbine and the HP - LP turbine without using any damping controller. This indicates that due to the inducement of fault at 0.5 Sec, SSR gets induced results in uncontrollable torque characteristics.

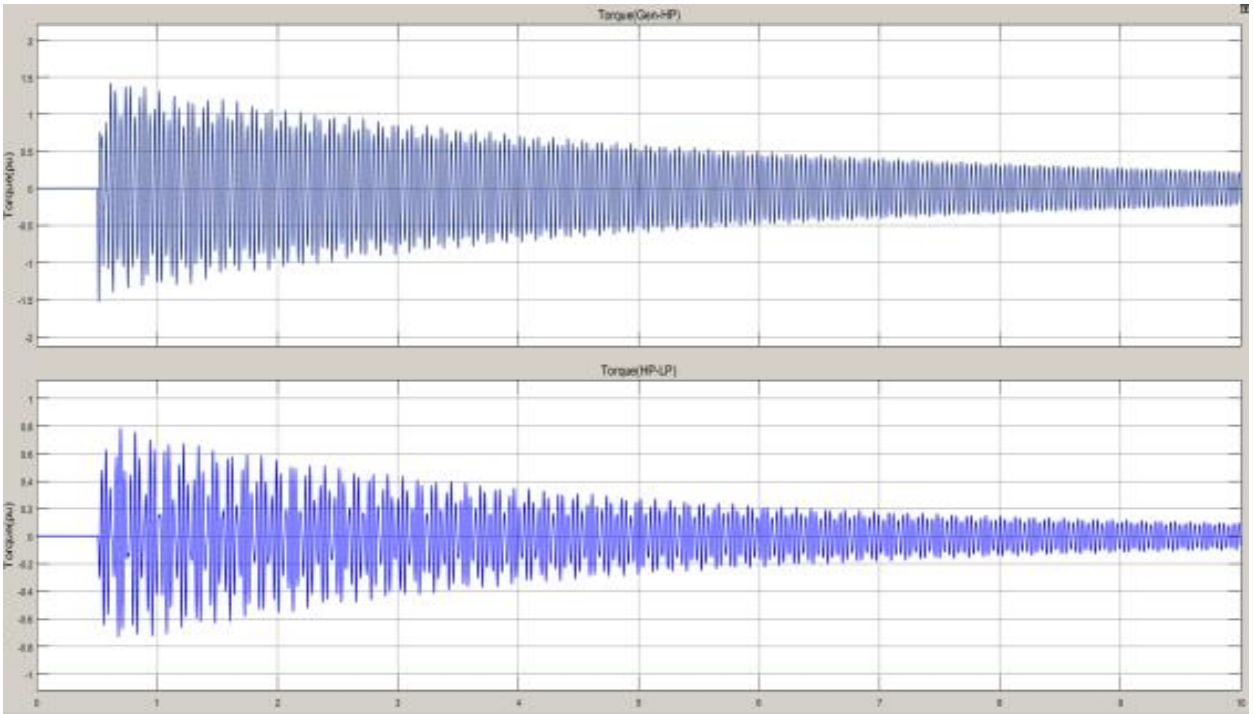

Fig. 20 Torque [(Gen-Hp) &(Hp-Lp)]- With Damping Controller

Fig 20 shows the torque characteristics between the GEN - HP turbine and the HP - LP turbine using a damping controller. Here, the torque oscillation reaches stability after some period of oscillation resulting in the damping of SSR. But the time period required for it is more than 10 Sec.

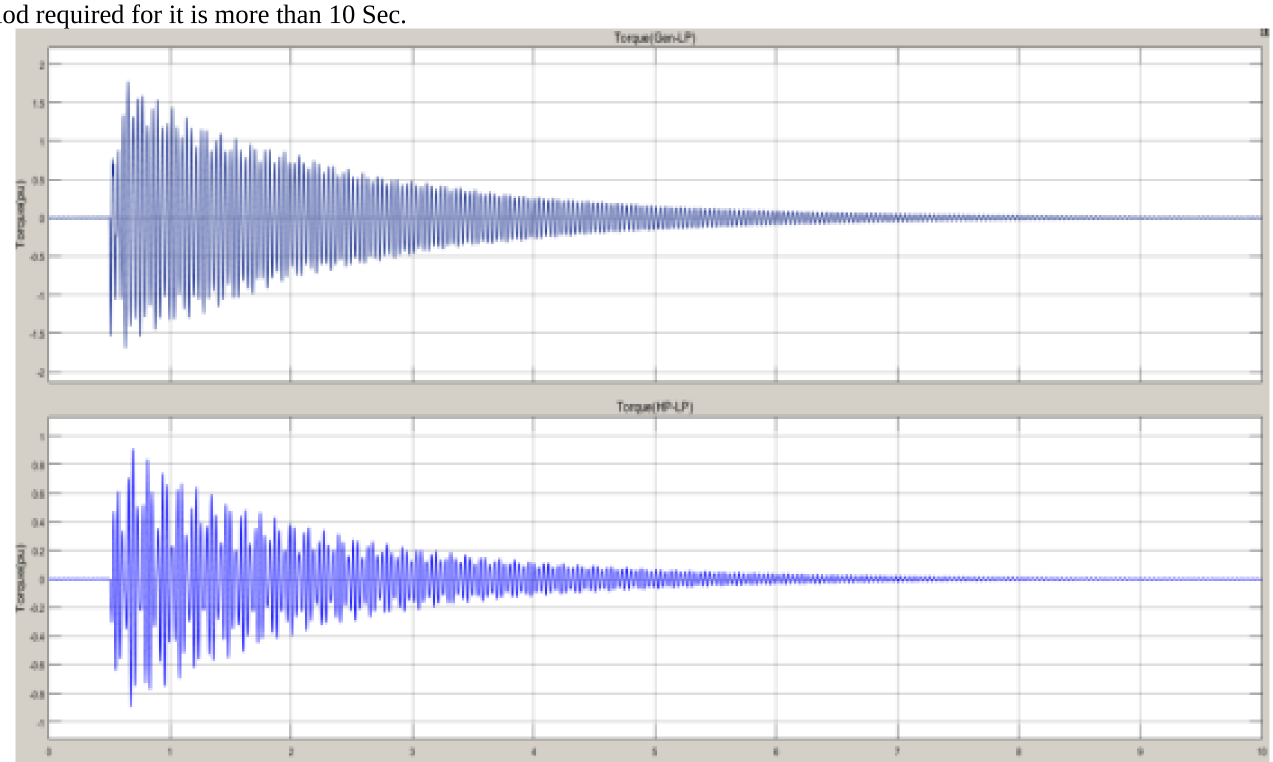

Fig. 21 Torque [(Gen-Hp) &(Hp-Lp)]- With Fuzzy Controller

Fig 21 shows the torque characteristics between the GEN - HP turbine and the HP - LP turbine using a damping controller. Here, the torque oscillation reaches stability as early as possible. i.e., at 7sec.

6. Conclusion

The work utilizes the PV solar farm rather than functioning it as the competitor for the synchronous generator in the system. It acts as a PV-STATCOM for the dynamically variable reactive power compensation to mitigate the SSR phenomenon produced due to the series compensation in the transmission line. In the nighttime, the PV-STATCOM entirely operated to mitigate the SSR phenomenon. But in the daytime, it has a dual function as supplying the real power in the absence of SSR and a reactive power compensator during the induction of SSR in the system. The utilization of PV-STATCOM is itself a new concept engaged in achieving the required objective. The utilization of Fuzzy has the added advantage of fast response over the conventional controllers. The proposed Fuzzy with PI- Controller and the PV-STATCOM show the successful damping of torsional oscillation due to SSR in the system, verified through the time domain simulations presented.

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