SUB-SYNCHRONOUS RESONANCE ALLEVIATION IN POWER SYSTEMS USING FACTS DEVICES

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Abstract - Flexible AC transmission systems (FACTS) have been extensively used in recent past for solving various power system steady state control problems. Additionally, series compensation of transmission lines is being done using capacitor banks so that overall power transfer capacity can be improved to ensure stable operation. However, this gives rise to sub-synchronous resonance (SSR) phenomenon under which there may be exchange of energy between mechanical and electrical system at frequencies below the synchronous value, damaging the axis system of generator. This paper investigates the effect of FACTS devices like Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) for alleviation of SSR in a single machine infinite bus system. Simulation studies have been carried out (i) with no FACTS device and (ii) with FACTS device. These studies have shown that SSR in the system can be alleviated to a great extent by using STATCOM. With UPFC the system oscillations are damped out i.e. mitigation of SSR achieved and by equipping fuzzy logic controller better results have been obtained.

Keywords - FACTS, Fuzzy logic control, STATCOM, Sub synchronous Resonance (SSR), Torsional Interaction, Unified Power Flow Controller (UPFC).

I. INTRODUCTION

The method of series capacitor compensation is widely used to improve the power transfer capability of transmission lines and hence the overall system stability is enhanced. The present power systems around the world incorporate more and more renewables, distributed generators etc. and that usually results in additional burden on transmission system. Although, series capacitors are a supportive tool allowing proficient use of the transmission infrastructure but there is one negative aspect associated with it in the form of sub-synchronous resonance (SSR) that can at times emerge between the electrical system and the torsional systems of close by generation which can cause equipment damage.

As per IEEE Committee Report (1985), SSR is defined as an, “Electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.” [1]. Owing to SSR phenomenon high amplitude transient torques can occur in the system which can result in the fatigue damage of the whole axis of generator axis. As such it becomes essential to restrain this effect in series compensated lines to ensure stability and quality power. [2] [3]. In past many methods have been investigated for mitigation of SSR effects which include poleface amortisseurs, static blocking filter, dynamic filter, dynamic stabilizer, excitation control, hvdc, reactive power control, NGH scheme, protective relays and Flexible AC Transmission Systems (FACTS) [4]. Of late FACTS technology has been widely used for solving a range of power system control problems including SSR.

In this paper the effect of FACTS devices viz. Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) is examined for easing of SSR in a single machine infinite bus system. Simulation studies have been performed on IEEE second benchmark model without and with assimilation of FACTS devices. These studies have shown that SSR in the system can be alleviated to a large extent by using STATCOM. Further improvement in damping is seen with UPFC having fuzzy logic based controller. The proposed schemes have been executed in Matlab/Simulink.

II. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. Its operation is similar to that of synchronous condenser but it is all the way a more superior device. It uses various thyristor devices such as Gate Turn Off Thyristor (GTO), Integrated Gate Commutated Thyristor (IGCT), Insulated Gate Bipolar Transistor (IGBT), etc. for switching purpose. In STATCOM the voltage source is created from a DC capacitor as shown in Fig.1. Here, any change in magnitude of voltage on the dc side across the capacitor will directly affect the voltage on ac side. The voltage on dc side can be held constant if we make use of a battery. The device can draw both capacitive as well as inductive reactive currents, depending upon the magnitude of the voltage on ac side.

For the purpose of switching, we can use different controllers depending upon our requirement. Since there is an energy source with the STATCOM, the operational range of the device is highly increased and the performance is improved as compared to other shunt devices.
III. UNIFIED POWER FLOW CONTROLLER (UPFC)

The UPFC is the most versatile FACTS controller developed so far, with all-encompassing capabilities of voltage regulation, series compensation, and phase shifting [5]. It is that family of FACTS devices which is used for optimal power flow in the system. The UPFC when sectionalized consists of two devices, STATCOM and Static Series Synchronous Compensator (SSSC) as shown in schematic Fig. 2. There is a dc common link and dc storage capacitor that connects the two devices together. Between the two-ac branches, the direction of real power flow can be from either converter. Each converter has the property of absorbing or delivering the reactive power individually from the ac coupling point of the line. The gating signals to the converter valves are provided by the controller to give the required series voltages. Shunt currents are drawn simultaneously by it, which are necessary to provide the series injected voltages required. The inverter requires the dc voltage with the regenerative capability [6], [7].

UPFC provides the dynamic compensation response and real time turn-off control of transmission systems. It contains two switching converters which are known to be voltage sourced inverters (VSCs) and they use thyristor gating valves, as demonstrated in Fig. 2. Both the inverters marked as "VSC1" and "VSC2" shown in the Fig. can work on a dc link provided with a capacitor which acts as dc storage. The flow of real power between the two converters can be in either direction depending upon the need by the series converter and the reactive power can be supplied to the line individually. The voltage with variable magnitude and phase angle can be injected by the series converter, thus it controls the real power flow into the line depending on our requirement. But, the UPFC considered overall is not able to absorb or even supply the real power in stable steady state condition (with the exception that when the power is withdrawn so that the losses can be compensated). Here DC terminals provide the power source. Thus for the compensation of any real power which is to be drawn or supplied to the series converter is provided by the shunt branch. The reactive power can also be independently supplied or drawn by the shunt branch with the system when required.

The major role of VSC2 is to inject a voltage $V_{pq}$ with controllable magnitude $V_{pq}$ ($0 \leq V_{pq} \leq V_{pq\text{max}}$) and phase angle $\rho$ ($0 \leq \rho \leq 360^\circ$), at the nominal frequency of the system, in the line through a series transformer. The injected voltage source can also be considered as the synchronous source voltage. The real power and reactive power exchange between the voltage source converter and ac power system is resulted from the transmission line current flow through the voltage source. The main role of VSC1 is to provide the real power which is required by VSC2 at the common dc link. In case the demand of reactive power by the system is more, the converter can also provide the required reactive power through the connected shunt transformer.

IV. SSR DUE TO TORSIONAL INTERACTION BETWEEN ELECTRICAL AND MECHANICAL SYSTEMS

The torsional interaction involves both the electrical and mechanical system having one or more natural frequency. The turbo generators have many types of rotors depending upon the steam turbine they use, which may be a high pressure, intermediate pressure and low pressure. These may also comprise of an exciter mounted on the shaft and all of these are connected by means of a flexible shaft which may be mechanically represented by a spring. Thus the interconnection between the rotor and the shaft is slightly damped mass-spring system which is analogous to capacitors and inductors of an electrical network. From the structure of this model mass spring system, there exists three torsional modes (mode 1, mode 2, and mode 3) and one electromagnetic mode (mode 0) in the system. These four-modes are called SSR modes or torsional modes since their natural frequencies are all less than synchronous frequency or power frequency. External sources (generators) connected to the line network can have an impact on the damping of torsional modes. A series compensated power line connected to the generator has following resonant frequency [8], [9], and [10].
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\[ f_{er} = f_0 \sqrt{\frac{x_c}{x_a + x_T + x_E}} \]  
(1)

Where, \( f_{er} \) = resonant frequency, 
\( x_T \) = leakage reactance of transformer 
\( x_c \& x_E \) = reactances connected externally 
\( x_a \) = reactance of transmission line 
\( f_0 \) = system frequency

Also, \( f_m = f_0 - f_{er} \)  
(2)

In the SSR phenomenon, if the resonance frequency coincides with the swing frequency, the whole turbine-generator assembly may come out from its foundation, and /or if the frequency of the torque developed coincides with the natural frequency of oscillation of some shafts and if oscillations build up sufficiently, it results in the breaking of the shaft. [11]

V. POWER SYSTEM CONFIGURATION FOR SSR STUDY

The single line diagram of the model is given in Fig. 3. It is shown that there is a series compensator connected to the transmission line. This compensator in series is responsible for the occurrence of SSR in the system. Due to this, the system oscillations are produced and the torsional disturbances are observed. The system studied is an IEEE second benchmark Simulink model for SSR and the same is used for the purpose of studying the SSR as well as techniques for damping out the oscillations caused by it [12]. The system is modeled by implementing it in MATLAB/Simulink environment.

VI. FUZZY LOGIC CONTROL

The Fuzzy Logic Control (FLC) can be implemented as shown in the Fig. 5. The FLC consists of four components, fuzzification interface (fuzzification), the knowledge base (rule base), fuzzy interface engine and the defuzzification interface (defuzzification).

Fuzzy Logic Control

Mamdani type FLC with double input single output has been designed. Inputs given to the fuzzy controller that has been implemented in this research are error and change in error. In this study, membership functions that are used are the trapezoidal membership functions (trap). The FLC designed has an output that is represented by \( \Delta U \) and output membership function designed is also trapezoidal membership function (trap). The membership functions are shown in Fig.7 with seven linguistic variables chosen as (NS) negative small, (NM) negative medium, (NL) negative large, (Z) zero, (PS) positive small, (PM) positive medium, (PL) positive large, for both inputs and outputs. The fuzzy set implemented is given in Table 1. The surface plot is given in Fig. 6.
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Proceedings of ISER 10th International Conference, Mecca, Saudi Arabia, 23rd-24th February 2018

V. TYPICAL SIMULATION RESULTS

The following results show presence of oscillations in the system when UPFC is present and when UPFC is not present. The various parameters taken for analysis are: Generator speed deviation shown in Fig. 9, Generator speed in Fig. 10, Generator-LP turbine torque shown in Fig. 13, LP-HP turbine torque shown in Fig. 14.

From these all these results it can be seen that the oscillations caused due to occurrence of SSR have been damped out by installing STATCOM in the system. In all these results from Fig.11 to Fig. 15, the blue colour shows oscillation without FACTS and the red colour shows the damped oscillations when STATCOM is installed in the system.

TABLE 1: FUZZY SET

<table>
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<tr>
<th>error</th>
<th>NL</th>
<th>NM</th>
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<th>Z</th>
<th>PS</th>
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Method for defuzzification used, is centroid method. And it is given by the control signal as

\[ Z = \frac{\int \mu(x) x \, dx}{\int \mu(x) \, dx} \]  

(3)

VII. SIMULATION RESULTS AND DISCUSSION

Fast Fourier transform (FFT) analysis of the rotor speed has been done in order to show that there is presence of mode 1 oscillations in the absence of UPFC device. The Fig. 8, shows that there is 24.8 Hz mode i.e. mode 1 oscillations present in the generator.

![FFT analysis of generator speed.](image)

The table 1, given below gives us the basic concept of how the fuzzy rule base has been designed. The two inputs have been taken as the error and change in error.

![Surface plot of Fuzzy logic control.](image)

![Membership functions of FLC.](image)

![Generation speed deviation without any FACTS devices.](image)
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The following results show damped oscillations in the system when UPFC is equipped with FLC and with STATCOM. The various parameters taken for analysis are, generator speed deviation shown in Fig. 16, generator speed shown in Fig. 17 and generator-HP turbine speed deviation as shown in Fig. 18. From all these results it can be seen that the oscillations caused due to occurrence of SSR have been damped out by UPFC with FLC in the system. In all these results from Fig. 16 to Fig. 18, the blue colour shows damped oscillations when STATCOM is used and the green colour shows the damped oscillations when UPFC is installed with FLC in the system.
The results of all three conditions are shown in comparison. Fig. 19, shows the generator speed and Fig. 20, shows generator speed deviation. The blue colour shows the oscillations without FACTS and they are increasing. The black colour shows the damped oscillation with STATCOM. The red colour shows the oscillations further damped with implementing of FLC with UPFC.

**CONCLUSION**

In this study, a MATLAB simulation of a single machine infinite bus system is done for whole purpose of studying the SSR phenomenon, its effects on the power system and how to mitigate the oscillations caused by it. During the whole process, starting from literature reviewing to the final results, it has been observed that the SSR phenomenon has devious effects on the power systems and its study is very important for improvement of power quality.

The work done so far can be summarized in the following points:

1. The SSR phenomenon occurs in the system due to the presence of series compensation in the power system.
2. Various oscillations are produced in the system due to occurrence of SSR which are very harmful for power system.
3. These oscillations can cause damages to the generators, motors, power electronic devices, protective and switch gear equipments, transmission lines, etc.
4. By installing STATCOM in the system, the system oscillations are damped out, i.e. mitigation of SSR is achieved in the system.
5. By equipping the UPFC with fuzzy logic controller better results have been obtained.
6. Some other optimization techniques can be used in future to improve the results

**APPENDIX**

Generator data:
Ratings: 600MVA, 22KV.

Stability data:
\[ X_1 = 0.14 \text{ pu} \quad R_e = 0.0045 \text{ pu} \]
\[ X_0 = 1.65 \text{ pu} \quad X_q = 1.59 \text{ pu} \]
\[ X'_d = 0.25 \text{ pu} \quad X'_q = 0.46 \text{ pu} \]
\[ X''_d = 0.20 \text{ pu} \quad X''_q = 0.20 \text{ pu} \]
\[ T_{do} = 4.5 \text{ s} \quad T_{dq} = 0.67 \text{ s} \]
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- \( T_{d0} = 0.040 \text{ s} \) \( T_{q0} = 0.09 \text{ s} \)

Transmission line data
500KV
Line with series capacitor:
- \( R_1 = 0.0074 \text{ pu} \)
- \( R_o = 0.022 \text{ pu} \)
- \( X_l = 0.08 \text{ pu} \)
- \( X_o = 0.240 \text{ pu} \)
Line without series capacitor
- \( R_2 = 0.0067 \text{ pu} \)
- \( R_o = 0.0186 \text{ pu} \)
- \( X_l = 0.0739 \text{ pu} \)
- \( X_o = 0.210 \text{ pu} \)

Transformer data:
- 600MVA, 60HZ, \( \Delta/Y \)
- 22KV/500KV
- \( R_p = 0.0006 \text{ pu} \)
- \( R_s = 0.0006 \text{ pu} \)
- \( X_p = 0 \text{ pu} \)
- \( X_s = 0.12 \text{ pu} \)

UPFC parameters:
- System nominal voltage = 500kV, \( f = 60 \text{Hz} \)
- Shunt converter rating = 100MVA
- \( R_1 = 0.0073\Omega, L_1 = 0.22H, C = 325\mu F \)
- Series converter rating = 100MVA
- \( R_2 = 0.0053\Omega, L_2 = 0.16H \)

STATCOM parameters:
- System nominal voltage = 500kV, \( f = 60 \text{Hz} \)
- Converter rating = 100MVA
- \( R = 0.0073\Omega, L = 0.22H \)
- \( C = 325\mu F \)

REFERENCES


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Proceedings of ISER 108th International Conference, Mecca, Saudi Arabia, 23rd-24th February 2018

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