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Fault clearance in Nine-Bus system using Custom Power Devices

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Abstract--The power transfer capability of a system determines the power quality and the reliability of the power system. The transmission side of the power system is of different configuration. This paper involves the modeling of a three-phase multi-machine system with nine bus configurations. The system is subjected to different fault conditions. The system is modeled with the help of MATLAB- Simulink. The power quality of the system is analyzed. The system active and the reactive power can be compensated by the FACTS devices. The FACTS devices are power compensating devices that play a vital role in increasing the power quality of the system. The three-phase multi-machine system is integrated with the FACTS devices like STATCOM and UPFC and different parameters where analyzed.

Keywords: UPFC- Unified Power Flow Conditioner, STATCOM- Static Shunt Compensator, THD- Total Harmonic distortion, VSC- Voltage Source Converter

I. INTRODUCTION

The power system is a collective of generation, transmission, and distribution. The transmission side of the power system must be of more reliable. The transmission side is the reason for the effective transmission of the electrical power from the generating side to the distribution side. The power flow in the transmission line will not be constant. There are some breakpoints wherein the voltage quantity has to be stepped up or stepped down. This is carried out with the help of the transformers. The transmission line can be of 3-phase transmission or 1-phase transmission. The 3-phase transmission can be of three wire or four wire configurations. The transmission lines are responsible for transferring the energy from the generating side to the dispatch centers. The generation side voltage and the line side frequencies must be matching, and it must be in synchronism [4]. If more than one machine is connected to the grid, then all the machines must be in synchronism with the line frequency. The three-phase multi-machine nine bus system can be integrated with the FACTS devices to have more reliable control over the real and the reactive power flow. The Static Shunt Compensator is a shunt connected FACTS device and its modelling and the analysis are carried out in the paper [1]. The DSTATCOM is used at the distribution side of the power system [2]. The STATCOM operation under various fault conditions is discussed in paper [3].

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The Unified Power Flow Controller is a combination of shunt and series compensator devices, its modelling and control strategy is discussed in the papers [5]-[8]. The steady state and the transient operations of three-phase bus and its measurement techniques are discussed in the papers [9],[10].

The FACTS devices help in increasing the optimal power flow of a transmission network. This power flow has to be ensured with a proper security option [11].

II. MULTI-MACHINE NINE-BUS SYSTEM

The model implemented is a Three-phase three-machine nine bus system. The system is equipped with three generators and nine buses. The power system is more sensitive when the load is connected near to the source of generation. In a multi-machine system, more than one generator is connected to the power system. The generators are connected to three buses (bus 1, bus 2, bus 3). The three generators voltages are stepped up with the help of three step-up power transformers to a voltage level of 230 kV.

Table-I: Transformer Voltages

Transformer	Input Voltage (kV)	Output Voltage (kV)
1	16.5	230
2	18	
3	13.8	

The transmission line is rated for a nominal voltage of 230 kV, this can be inferred from the above table. The nominal power of the system is taken as 100MVA. The ratings of the generators are given in the below table.

Table-II: Generator Ratings

Generator	Power (MVA)	Voltage (kV)	Bus type
1	247.5	16.5	Slack
2	192	18	PV
3	85	13.8	PV

The system is equipped with three different loads at three buses (bus 5, bus 6, bus 8). The load is rated at different MW and MVAR, it is given in the below table.

Table-III: Load Ratings

Load	Real Power (MW)	Reactive Power (MVAR)
1	125	50
2	90	30
3	100	35

The overall circuit diagram of the three-phase multi-machine nine bus system is given in the below figure.

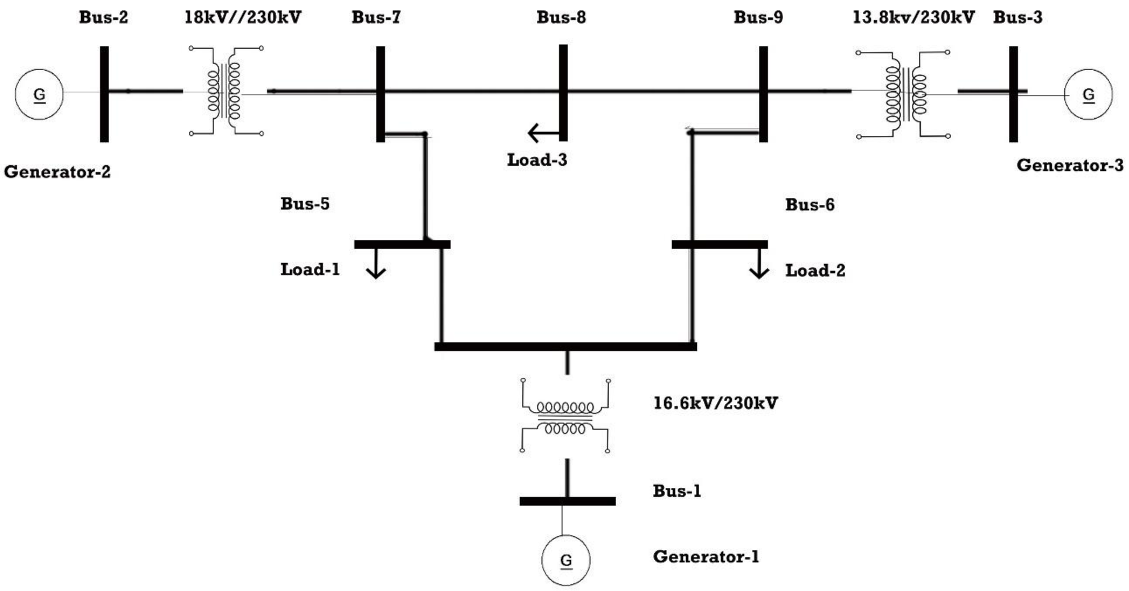

Fig. 1. Line diagram of Three-phase Nine-bus Multi-machine system

III. MATLAB – SIMULINK MODEL

The MATLAB-SIMULINK model of the system is given in the below figure.

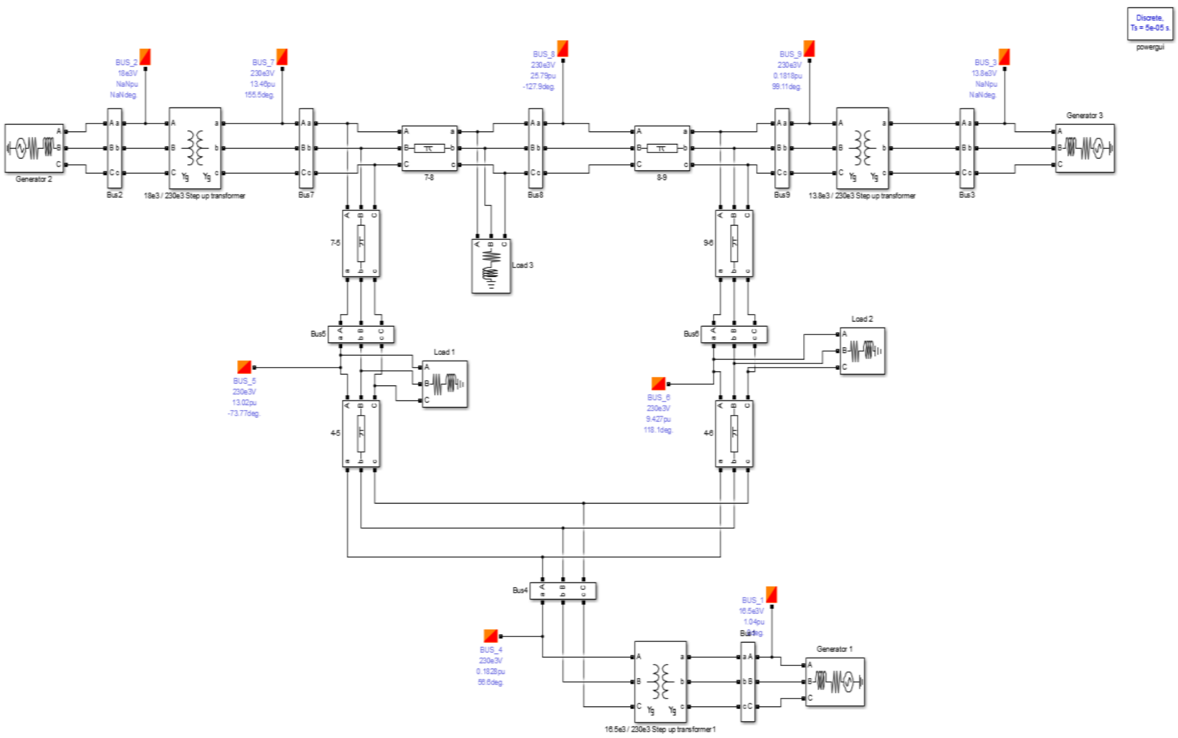

Fig.2. MATLAB Model of Three-phase Nine-bus Multi-machine system

The Bus5, Bus6, Bus8 acts as a PQ bus as the loads are connected to these buses. The Bus2 and Bus3 are taken as the PV bus. The simulation of the MATLABmodel is carried out without inserting any disturbance or the fault to the system.

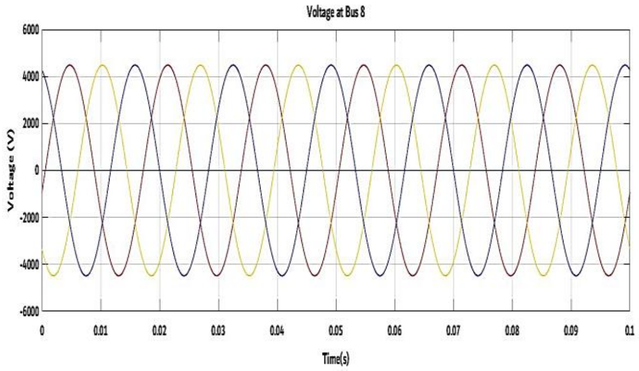

Fig. 3. Voltage at Bus-8

The above graph indicates the voltage, current, real power and the reactive power for the Bus8, i.e. Load3. The output voltage and the output current at each bus are sinusoidal in nature. The voltage at the Bus-8 is 5.8 kV and the current flowing at the Bus-8 is 97.59 A. This makes the three-phase multi-machine nine-bus system to be a stable system. The source side Generator-2 and Bus-2 are taken into consideration.

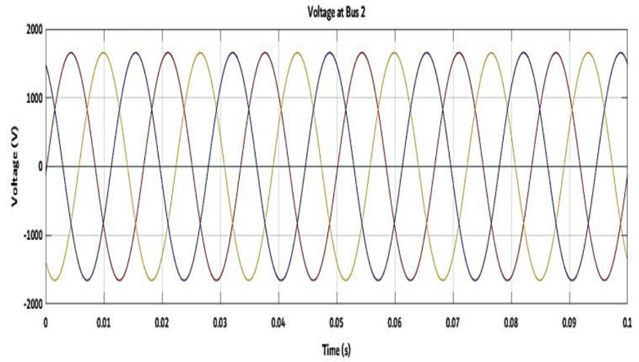

Fig. 4. Voltage at Bus-2

IV. FAULT-ANALYSIS

The above system model is a stable system. But if the system is subjected to a fault, then the system behavior changes according to the location of the fault and the nature of the fault. The system is subjected to a three-phase Line to Ground fault at two different locations for a period of 0.06 seconds. This fault is given in-between the Bus7 and the Load3 on the transmission line 7-8. After the fault, there occurs a drastic change in the voltage and the line current of the Bus-8. Due to this fault, the sinusoidal nature of the voltage and the current quantities of the Bus-8 gets disturbed.

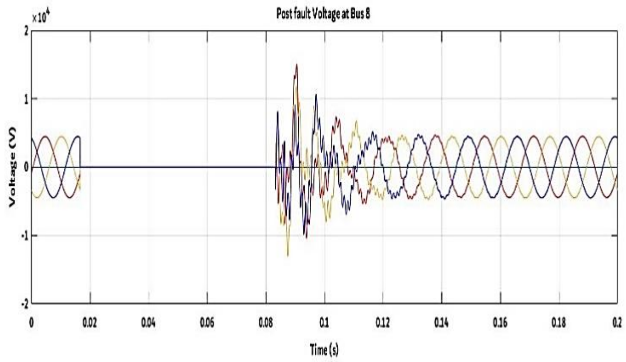

Fig. 5. Post-Fault Voltage waveform for Bus-8

The above graph, both the voltage and the current are not sinusoidal in nature at the initial stage. Due to the fault, at the transient state, an enormous amount of current and the voltage occurs for a short period of time. The inference that can be made from this fault at location 1 is that there is a voltage drop at the Bus-8 and there is an increase in the value of the current after the fault. Before the fault condition at the location-1 the Load-3 was extracting a minimum amount of current (0.01771A). The current flow has been increased at the Load-3 after the post-fault condition (8.978A). This sudden increase in the current can damage the loads. The post-fault oscillations in the voltage quantity are more compared to that of the current quantity. The circuit-breakers can be operated to prevent this sudden increased flow of current to the load.

The system is subjected to another Three-phase line to ground fault but with a different location. Now the fault is located near Generator 2. Due to this fault, the voltage and the current quantities at the Bus-2 get affected.

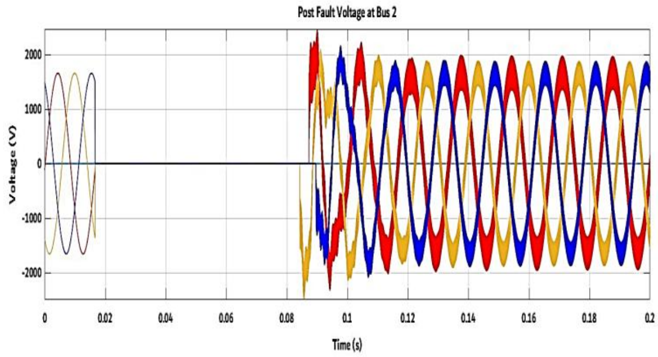

Fig. 6. Post-Fault Voltage waveform of Bus-2

The current at the Bus-2 has been increased after the fault condition. There is a drop in the voltage level at the Bus-2. On comparing, both the faults at different locations, the fault at the source Generator-2 has a more adverse effect on the system when compared with the fault at the mid-point of the transmission line 7-8. Also, the fault occurring in the middle of the transmission line is severe when compared to the fault that is occurring at the load side. The system can be protected from the faults with the help of a circuit-breaker. The harmonic distortion is an unwanted electrical quantity which reduces the power quality of the system. The Total Harmonic Distortion (THD) is the measure of the harmonic distortion in the AC quantity.

$$THD_F = \frac{\sqrt{I_2 + I_3 + \cdots I_N}}{I_1}$$

I_1- RMS value of current of 1st harmonic

I_2- RMS value of current of 2nd harmonic

I_3- RMS value of current of 3rd harmonic

I_n- RMS value of current of nth harmonic

The total harmonic distortion of the Three-phase nine-bus multi-machine system is analyzed, and it is a pure sinusoidal waveform with a low THD value i.e., 0.07%. This is shown in the below figure.

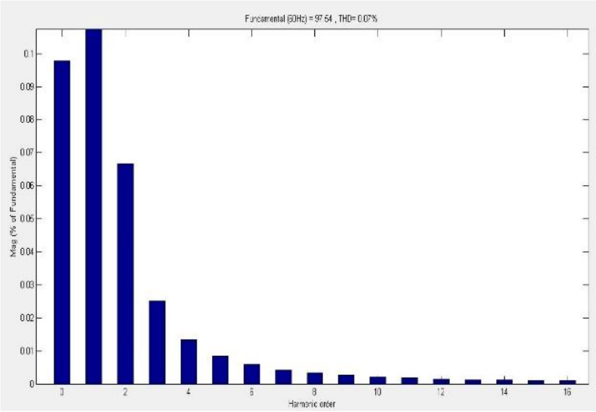

Fig. 7. THD level Pre-Fault Condition

After the fault, the harmonic content is increased, and the sinusoidal waveform is distorted. The THD value is increased to 3.94%. This is shown in the below figure.

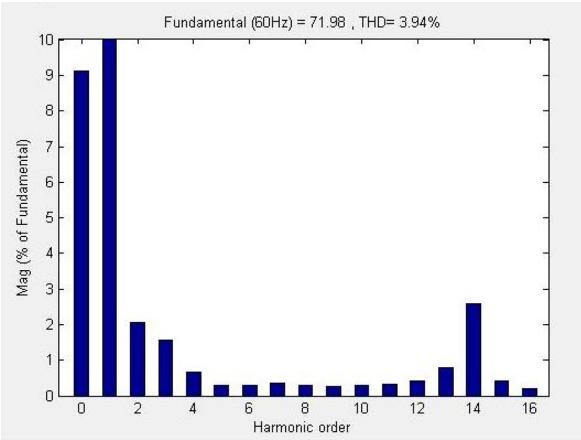

Fig. 8. THD level Post-Fault Condition

As per the IEEE standards IEEE-519, it is desirable to have the THD of the current within that of 3%. The THD value can be brought within the limits with the help of compensators. The compensators can be of active or passive in nature. The passive control corresponds to the use of fixed inductors or fixed capacitors and this absorbs or generates the reactive power. The active control corresponds to the reactive power control with respect to the terminal voltage. The FACTS devices like STATCOM and UPFC are connected with the three-phase nine-bus multi-machine system and the system is analyzed.

V. STATCOM

The Static Compensator is a shunt compensation FACTS device. In the power system, the power flow is from the sending end to the receiving end. The power flow in a transmission line is given by the below equation.

$$P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$

V_1- Sending end voltage in volts

V_2- Receiving end voltage in volts

X – Impedance of the transmission line in ohms

δ_1 – Power angle at the sending side in degrees

δ_2 – Power angle at the receiving side in degrees

The shunt compensation is used for voltage control. The sending end voltage and the receiving end voltages can be controlled by the shunt compensators.

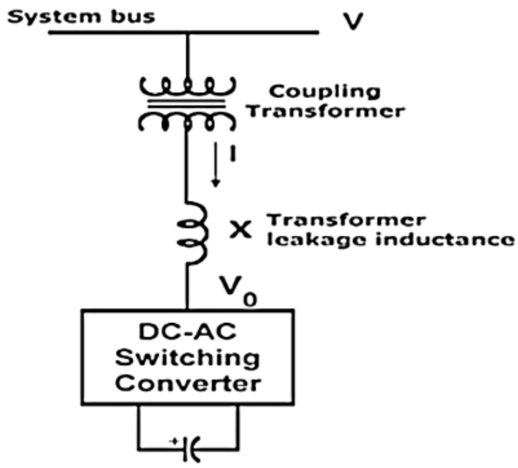

Fig. 9. STATCOM structure

The STATCOM is a Voltage controlled FACTS device. The STATCOM consists of a DC-AC Voltage Source converter coupled with a DC link Capacitor. The STATCOM is connected to the Voltage Source converter via a coupling Transformer. The output voltage from the STATCOM is V_o. The system AC Voltage is represented as V. The STATCOM can control both the active and the reactive power in the transmission line. The reactive power control can be achieved with the help of the STATCOM. By varying the output voltage V_o, the reactive power control can be done. There are two conditions based upon which the STATCOM works.

1. If V_0>V, then the current will be flowing from the Voltage Source Converter to the transmission line and hence the converter generates the reactive power.
2. If V_o<V, then the current will be flowing from the transmission line to the Voltage Source Converter and hence the converter absorbs the reactive power.

When the system is in the steady state condition, both the V_o and V are in-phase with each other. The active power is the real power that flows from the sending end to the receiving end. The active power can also be controlled with the STATCOM. This is done by a phase shift between the two voltages V_o and V.

1. If V_o lags V, then the Voltage Source Converterabsorbs active power.
2. If V_o leads V, then the Voltage Source Converter generates active power.

The operation of the STATCOM is a Voltage Source Converter coupled with a DC link. The Voltage Source Converter is controlled with the help of a controller circuit. This controller is a PI controller with an AC Voltage Regulator and a Current Regulator. In the above system, the STATCOM is mainly used at the time of fault condition to maintain the reactive power compensation and bring the system to a steady state. The load angle variations between the three loads are considered during the reactive power compensation.

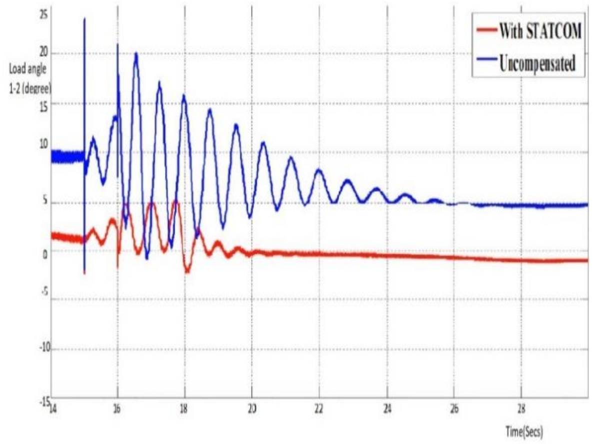

Fig. 10. Load angle 1-2 variations with respect to STATCOM

The above graph indicates the load angle variations between the Load-1 with respect to the Load-2 during the time of fault by using STATCOM. The load angle variations between the Load-2 with respect to the Load-3 during the time of fault by using STATCOM is given in the below graph.

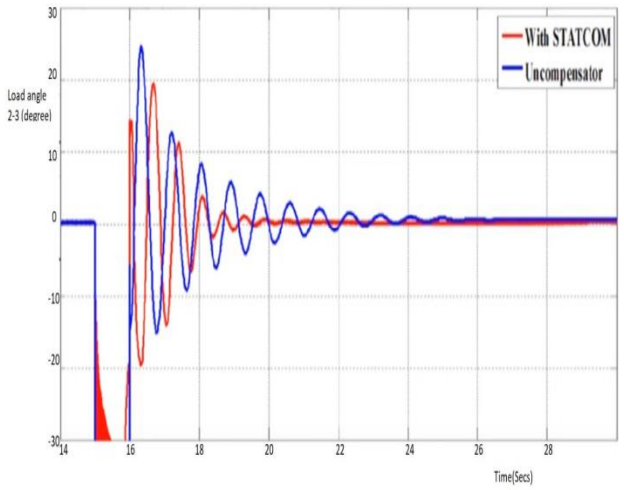

Fig. 11. Load angle 2-3 variations with respect to STATCOM

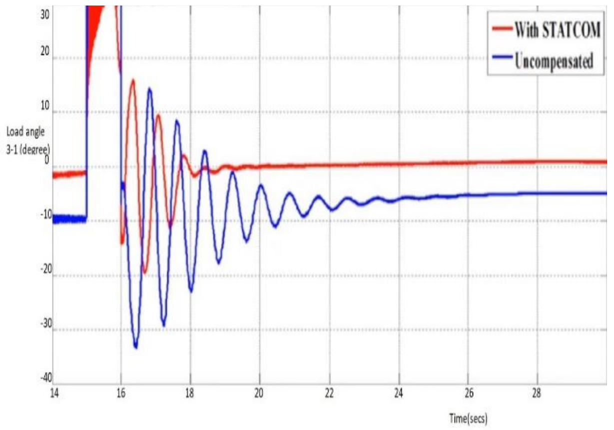

Fig. 12. Load angle 3-1 variations with respect to STATCOM

The above graph indicates the load angle variations between the Load-3 with respect to the Load-1 during the time of fault by using STATCOM.The time taken due to the post-fault oscillations is minimized by compensating with the STATCOM and the system reaches the stability condition quickly. In the absence of STATCOM, the time taken for the post-fault oscillations is more. The STATCOM is connected in the transmission line 8-9. The fault clearing time is taken to be 1 second and the time taken to attain stability is given in the following table.

Table IV: Time taken to attain stability by using STATCOM

Loc	Load angle between 1-2		Load angle between 2-3		Load angle between 3-1	
	Uncompensated (Secs)	**Compensated (Secs)**	**Uncompensated (Secs)**	**Compensated (Secs)**	**Uncompensated (Secs)**	**Compensated (Secs)**
LOC 1	10.0	3.5	10.0	5.1	9.5	4.0
LOC 2	11.2	4.5	10.0	3.9	10.0	3.7

After the compensation with the STATCOM, the system attains stability in a shorter duration of time. The post-fault oscillations are damped effectively in a shorter duration of time. From the above table, the fault at the Location-2 is more severe than the fault at Location-1 as the time taken to compensate is more. The time taken to attain stability increases with the increase in the fault clearing time.

VI. UPFC

Unified Power Flow Conditioner is a FACTS device that mainly improves the power quality of the system. The UPFC is a combination of both the shunt and series compensators. Form the Power angle equation of equation 5.1, it can be determined that the shunt compensation is carried out by controlling the voltages at the sending end voltage and the receiving end voltage. The series compensation is carried out by controlling the impedance value of the transmission line and the power angle. The transmission line parameters can be controlled with the help of UPFC. The block diagram of the UPFC is given in the below figure.

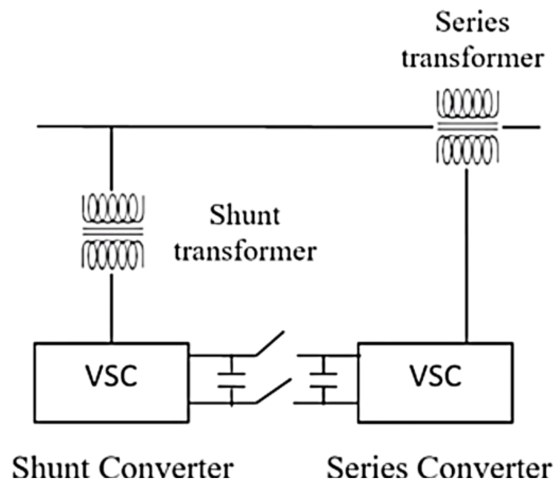

Fig. 13. UPFC structure

In UPFC, two of the Voltage Source converters are connected to the transmission line via a series transformer and a shunt transformer. The two VSCs are coupled with each other with the help of a DC-link capacitor. The UPFC is a combination of STATCOM and an SSSC. There is a switch in-between the DC link capacitor. If the switch is closed, then he system acts as a UPFC. If the switch is open, then the system acts as a STATCOM and an SSSC acting individually.

The voltage with a controllable magnitude (V_{pq}) is provided by the series compensator SSSC. The phase angle is made to be inseries with the transmission line is controlled with the help of SSSC. The reactive power fed to the line via the series transformer is generated from the SSSC. The real power transfer is converted into the power demand at the DC-link capacitor. The common DC-link power is converted back to AC by the Shunt converter and fed back to the transmission line via the shunt transformer. The shunt connected STATCOM can also absorb or generate controllable reactive power. The active power controlled in the UPFC is independent of the reactive power control.

The UPFC can be operated in one of the four modes of operations. The mode of the power flow is determined by the phase angle of the series injected voltage. These modes of operations are as follows

1. In regulating the terminal bus voltage.
2. It can operate as a phase shifter by regulating the active power flow.
3. It can operate as a variable series compensator by regulating the active power flow.
4. It can operate as a combination of a voltage regulator, phase shifter and a series compensator.

The UPFC is connected to the Three-phase Three-machine Nine-Bus system in-between the Bus-7 and Bus-8. The system is given a fault near the Bus-7 for a time period of 1 second (Location-1) and another fault is given near the Load-1 for the same time period (location-2). The load angle variations between the three loads are considered.

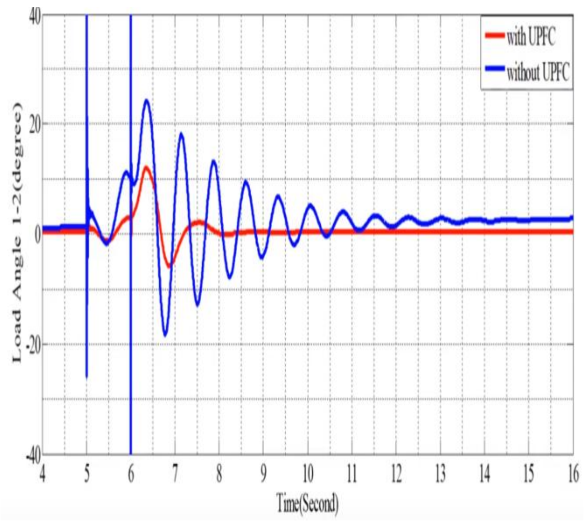

Fig. 14. Load angle 1-2 variations with respect to UPFC

The above graph indicates the load angle variations of Load-1 with respect to Load-2 during the time of fault by using UPFC.

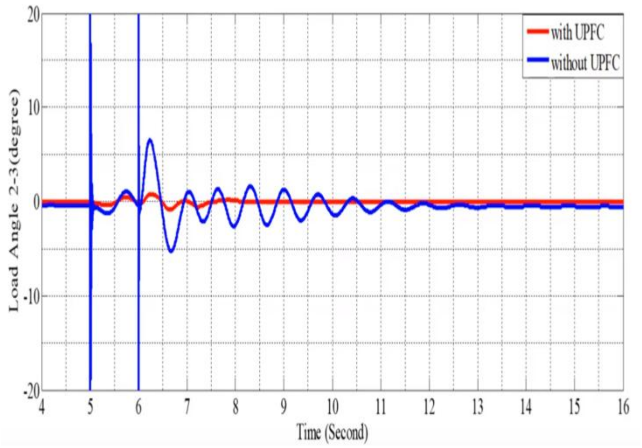

Fig. 15. Load angle 2-3 variations with respect to UPFC

The above graph indicates the load angle variations of Load-2 with respect to Load-3 during the time of fault by using UPFC.

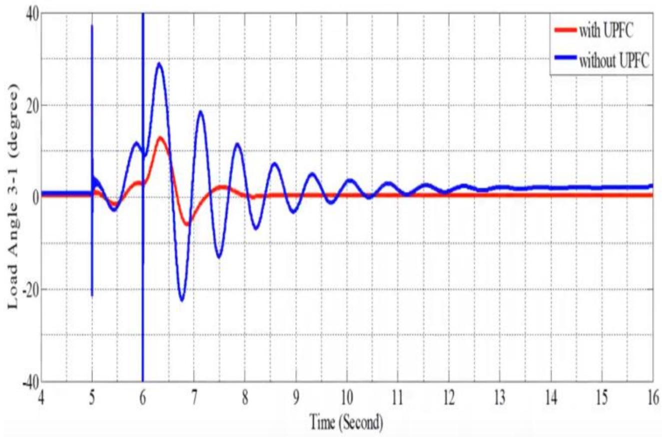

Fig. 16. Load angle 3-1 variations with respect to UPFC

The above graph indicates the load angle variations of Load-3 with respect to the Load-1 during the time of fault by using UPFC. The maximum overshoot has been drastically reduced with the help of UPFC, this can be inferred from the above graphs. The time taken to attain the stability condition is also reduced. The fault clearing time is taken to be 1 second and the time taken to attain stability is given in the following table.

Table V: Time taken to attain stability with UPFC

Loc	Load angle between 1-2		Load angle between 2-3		Load angle between 3-1	
	Uncompensated (Secs)	**Compensated (Secs)**	**Uncompensated (Secs)**	**Compensated (Secs)**	**Uncompensated (Secs)**	**Compensated (Secs)**
LOC 1	8.4	2.4	7.5	2.2	9.0	2.2
LOC 2	7.2	1.8	6.8	1.6	5.2	1.2

The time to attain stability by using UPFC is very less when compared with that of the STATCOM.

VII. CONCLUSION

The reactive power flow control is an important aspect in terms of power transfer capability. The power system must be compensated to ensure reliable power to the consumers. The compensation of the power system is done at the substations by the power companies. The FACTS devices can be used to improve the power quality by providing voltage regulation, real and reactive power. The three-phase nine-bus multi-machine system has been given fault at different locations and the system has been analyzed by connecting with both STATCOM and UPFC. The shunt compensation devices have limitations like the positioning of the device, power rating, and the cost. The series compensators can be connected at any position at the transmission line and the cost is minimal compared to the shunt. The UPFC connected system attains the system stability in a minimum amount of time period and the maximum overshoot is also reduced. The UPFC also has some limitations. The UPFC is expensive as it consists of two VSCs, and the control of UPFC is complex. The UPFC system functionality can be extended by coupling with renewable energy resources.

REFERENCES

1. “Design and analysis of STATCOM for reactive power compensation and transient stability improvement using intelligent controller”, P. K. Dhal, C. Christober Asir Rajan, 2014 International Conference on Electronics and Communication Systems (ICECS).
2. “Modelling and simulation of a distribution of STATCOM (D-STATCOM) for power quality problems-voltage sag and swell based on Sinusoidal Pulse Width Modulation (SPWM)”, Ravilla Madhusudan, G Ramamohan Rao, IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM - 2012).
3. “STATCOM Operation Strategy under Power System Faults”, Zhengping Xi ; Subhashish Bhattacharya, IEEE Power Engineering Society General Meeting, 2007.
4. “Grid Integration of 10kW Solar Panel”, S. S. Dheeban ; V. Kamaraj, 3rd International Conference on Electrical Energy Systems (ICEES), 2016.
5. “Multi-mode Coordination System Control Strategy and Its Operation Performance of Western Nanjing Power Grid UPFC Project”, Jinjiao Lin ; Baoshun Zhang ; Lei Gao ; Peng Li, 2018 International Conference on Power System Technology (POWERCON)
6. “Coordination strategy and its realization of UPFC control protection system and power grid protection for improving fault ride-through capability”, Jinjiao Lin ; Peng Li ; Xiangping Kong ; Haosheng Huang ; Baoshun Zhang, China International Electrical and Energy Conference (CIEEC), 2017
7. Damping of Low Frequency Oscillations in power systems with neuro-fuzzy UPFC controller”, Nasser Talebi ; Ali Akbarzadeh, 10th International Conference on Environment and Electrical Engineering, 2011.
8. “An Ideal Transformer UPFC Model, OPF First-Order Sensitivities, and Application to Screening for Optimal UPFC Locations”,Seungwon An ; John Condren ; Thomas W. Gedra, IEEE Transactions on Power Systems, 2007, Volume: 22 , Issue: 1.
9. “Steady-state loss and short-circuit force analysis of a three-phase bus using a coupled finite element+circuit approach”, M.R. Shah ; G. Bedrosian ; J. Joseph, IEEE Transactions on Energy Conversion, 1999, Volume: 14 , Issue: 4.
10. “Wide-Area Measurement-Based Backup Protection for Power Network With Series Compensation”, Paresh Kumar Nayak ; Ashok Kumar Pradhan ; Prabodh Bajpai, IEEE Transactions on Power Delivery, 2014 Volume: 29 , Issue: 4.
11. “Security Constrained Optimal Power Flow with FACTS Devices Using Modified Particle Swarm Optimization”, P. Somasundaram, N. B. Muthuselvan, International Conference on Swarm, Evolutionary, and Memetic Computing, SEMCCO 2010.

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