Commencing the FACTS in Variable Energy Sources Network to Optimize Existing Transmission System with Stability

Manish Raval and Ved Vyas Dwivedi

Abstract: Growing concern for the environmental degradation has led to the world's interest in renewable energy resources. Due to the beneficiary policy, variable wind, solar and hydro generation is gradually increased in the world. The big mass of variable generation is creating fluctuation in voltage, frequency and power factor of grid network and it led to the instability in the existing grid system of utility and also create the power evacuation problem. To compensate the above problems the grid networks requires a careful design to maintain the system with continuous power flow operation without any limitations as well as optimization of existing transmission system. The focus of this research paper is to commence the FACTS (Flexible A.C. Transmission System) to control the power flow of the unbalanced transmission network due to impose of power from variable generating system. This project proposes a case study to control the power flow of power system with UPFC. In this study 5-Bus network system has selected and simulation has done with and without the UPFC to measure the power flow of the network. With the use of UPFC the power of overloaded transmission network regulated with good voltage profile and avoids the evacuation problem. This system is costlier and complex as compare to static voltage regulating system.

Indexing words*: Grid, Unified power flow controller, Load flow, Voltage Regulation*

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1. INTRODUCTION:

Grid connectively and transmission constants have often been cited as key constants in wind energy development in the country if the target of the National action plan on climate change of achieving 15 percent power generation through renewable energy sources by 2020 is to be met the country needs to add 25000 MW of wind power capacity. Though the Government has put in place the required policy support to attract and encourage investor, unless issues related to grid integration of wind power are sorted out this target will remain more wishful linking. At present, potential sites across the country remain undeveloped as evacuation of power is technically not feasible due to saturation of the local transmission system. Grid saturation has also resulted in the loss of several MUs of power from existing wind farms as grid managers impose back down instructions every time power intake from other sources increases. Grid managers instead of balancing the different elements (including wind) in the increasingly complex national grids, real wind as a risk to grid security. Erratic grid availability has become a bigger cause for concern for developers in recent times, especially because of the newly introduced generation-based incentives and renewable energy certificates. The benefits from which are entirely dependent on the power feel in to the grid.

Connectivity challenges for new farms:-

Evacuation of power is one of the basic investment decision criteria for wind power developers as the majority of high wind potential sites are located in remote areas. These areas, which have the potential for setting up large wind projects of 100-200MW, usually have low transmission capacity of about 20 MW. It is because of this scenario that developers face what Jami Hossain, Chief Member and Co-founder wind farm management services calls "chicken and eggs: situation while planning large wind farms for example, a given site may have excellent wind potential but may have poor grid infrastructure, investments in planning and land procurement risky.

Wind energy developers are also at a disadvantage when it comes to bearing the construction cost of evacuation infrastructure. Unlike conventional energy projects where the cost is usually born by the transmission or distribution companies.

The Mandavising author of article in renewable source [1] mentioned that the intermittent nature of wind power, Solar power and hydro power (variable source) are major cause for concern for grid managers as it leads to a low and unpredictable plant load factor, which upsets the voltage profile of the grid and also discussed about the evacuation problems for wind energy and solar energy development in India. The technology of power system utilities around the world has rapidly evolved with considerable changes in the technology along with improvements in power system structures and operation.

At the same time building of the new transmission circuits is becoming more difficult because of economic and environmental reasons and Wright of Way problems. Therefore, power utilities are forced to utilize existing system without spending extra expenditure. However, stability has to be maintained at all times. Hence, in order to operate power system effectively, without reduction in the system security and quality of supply, even in the case of contingency conditions such as loss of transmission lines and/or generating units, a new control strategies need to be implemented.

In present day highly complex and interconnected power systems, need to improve electric power utilization with maintaining reliability and security. Available power generation, usually not situated near a growing load center, is subject to maintain economical and environmental and power evacuation issues. In order to meet the increasing power demand, utilities prefer to rely on already existing generation and power transferring arrangements instead of building new transmission lines that are subject to environmental and economic issues. [1].

On the other hand, power flows in some of the transmission lines are below their thermal limits, while some lines are overloaded, which has as an overall negative effect on voltage profiles and decreasing system stability and security. In addition, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex, highly interconnected power systems. This overall situation requires the review of traditional transmission methods and practices, and the creation of new concepts which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security. Another reason that is forcing there view of traditional transmission methods is the tendency of modern power systems to follow the changes in today's global economy that are leading to deregulation of electrical power markets in order to stimulate competition between utilities [1].

Commencement of Flexible A.C. transmission system creates a tremendous quality impact on power system stability. These features become even more significant knowing that the UPFC can allow loading of the transmission lines close to their thermal limits, forcing the power to flow through the desired paths. This will give the power system operators much needed flexibility in order to satisfy the demands that will impose the deregulated power system.

This project proposes a case study to control the power flow of a power system with UPFC. In this study, a 5-Bus network for the analysis with and without the UPFC has been studied and presented.

Literature Survey

Many articles, journals and IEEE papers are found for UPFC operation, modeling and control.

The UPFC which was proposed by [2], outlines the technical and economic factors which characterize the uniform, all solid-state power-flow controller approach for real-time controlled, flexible AC transmission systems. The unified power-flow controller in its general form can provide simultaneous, real-time control of all basic power system parameters (transmission voltage, impedance, and phase angle), or any combinations thereof, determining the transmitted power.

The [3] had proposed the Unified Power Flow Controller (UPFC) for controlling power flow in modern power systems. Essentially, the performance depends on proper control setting achievable through a power flow analysis program. This paper aims to present a reliable method to meet the requirements by developing a Newton-Raphson based load flow calculation program through which control setting of UPFC can be determined directly.

The [4-5] presented their research work with digital simulation of 14-bus power system using UPFC to improve the power quality. The UPFC is also capable of improving transient stability in a power system. It is the most complex power electronics system for controlling the power flow in an electrical power system.

The [6] simulated IEEE 5- bus system using MATLAB Simulink to do the load flow analysis of the system. In this paper the author shows that with use of UPFC the power transfer capability of the same system can improve. While the [7]shows that shunt FACTS devices plays a very important role in controlling the reactive power flow when placed at the midpoint of a long transmission line. It also affects the system voltage regulation and transient stability of the system. Author also analyzed when transient fault occurs in the system FACTS devices connected to the system becomes important part for transient stability.

2. Flexible A.C. Transmission

Alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.

Flexibility of Electric Power Transmission: The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady-state and transient margins [8].

FACTS Controller: FACTS controller are the power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.

The controllers that are designed based on the concept of FACTS technology to improve the power flow control; stability and reliability are known as FACTS controllers. These controllers were introduced depending on the type of power system problems. Some of these controllers were capable of addressing multiple problems in a power system but some are limited to solve for a particular problem. All these controllers grouped together as a family of FACTS controllers categorized as follows as shown in figure1.

- First Generation of FACTS Controllers: Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC)
- Second Generation of FACTS Controllers: Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM)
- Third Generation of FACTS Controllers. The third generation of FACTS controllers is designed by combining the features of previous generation's series and shunt compensation FACTS controllers. : Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) are third generation FACT Controllers. They are discussed as below.

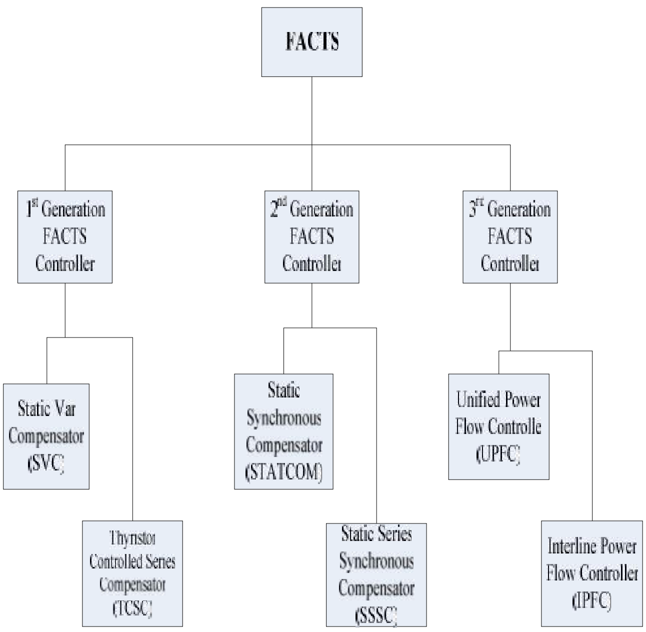

Fig.1 Block Diagram of FACTS Controllers [8].

Unified Power Flow Controller (UPFC):

It is designed by combining the series compensator (SSSC) and shunt compensator (STATCOM) coupled with a common DC capacitor. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle.As shown in Figure 2. it consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. The DC terminal of the two converters is connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence the series converter will exchange active and reactive power with the line.

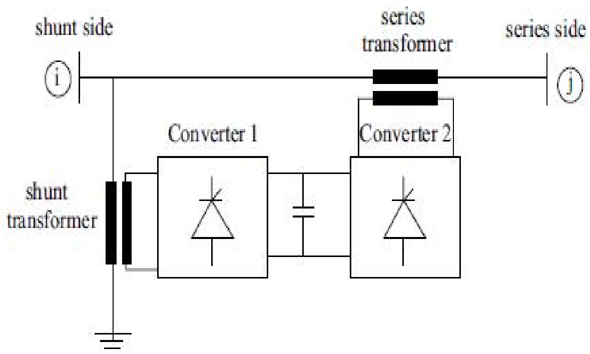

Fig.2 Unified Power Flow Controller (UPFC) [8].

Characteristic of UPFC:

The concept of UPFC makes it possible to handle practically all the power flow control and transmission lines compensation problems using solid-state controllers that provide functional flexibility which are generally not obtained by Thyristor-controlled controllers.

Interline Power Flow Controller (IPFC):

Its design is based on Convertible Static Compensator (CSC) of FACTS Controllers. As shown in Figure 3, IPFC consists of two series connected converters with two transmission lines. It is a device that provides a comprehensive power flow control for a multi-line transmission system and consists of multiple number of DC to AC converters, each providing a series compensation for a different transmission line. The converters are linked together to their DC terminals and connected to the AC systems through their series coupling transformers. With this arrangement, it provides series reactive compensation in addition any converter can be controlled to supply active power to the common dc link from its own transmission line [9].

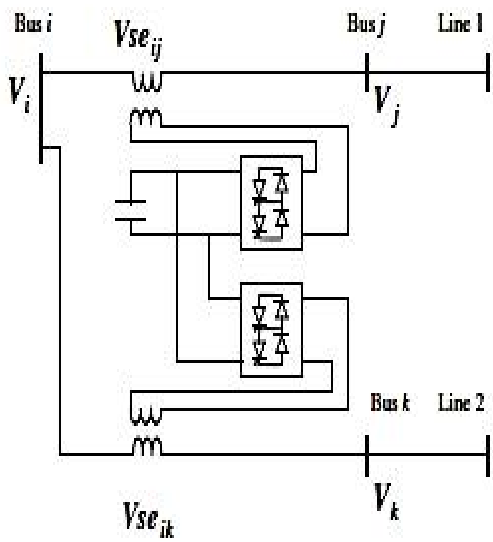

Fig. 3 Interline Power Flow Controller [9]

Characteristics of IPFC:

To avoid the control of power flow problem in one system with synchronization of power in other system, installation of IPFC with parallel inverter is required to meet the active power demand.

Advantages of FACTS controllers [8]

- **Power Quality and Reliability:**
  Modern power industries demand for the high quality of electricity in a reliable manner with no interruptions in power supply including constant voltage and frequency. The change in voltage drops, frequency variations or the loss of supply can lead to interruptions with high economic losses. Installation of FACTS device at the distribution system without increasing the short circuit current level considerably increases the reliability for the consumer.

- **Power system stability:**
  Instabilities in power system are created due to long length of the transmission lines, interconnected grid, changing system loads and line faults in the system. These instabilities results in reduced transmission line flows or even tripping of the transmission. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of transmission line trips.

- **Flexibility:**
  The construction of new transmission lines take several years but the installation of FACTS controllers in a power system requires only 12 to 18 months. It has the flexibility for future upgrades and requires small land area.

- **Environmental Benefits:**
  Construction of new transmission line has negative impact on the economical and environmental factors. Installation of FACTS devices in the existing transmission lines makes the system more economical by reducing the need for additional transmission lines.

- **Reduced maintenance cost**:
  Maintenance cost of FACTS controllers are less compared to the installation of new transmission lines. As the number of transmission line increases, probability of fault occurring in a line also increases resulting in system failure. By utilizing the FACTS controllers in a transmission network, power system minimizes the number of line faults thus reducing the maintenance cost.

UPFC Basic Principle and Operation Modes

The Unified Power Flow Controller (UPFC) is a multi-function controller which can play an important role in solving various transmission systems problems.

Construction of the UPFC

The UPFC concept was proposed by Gyugyi in 1992 [2] within the concept of using converter based FACTS technology. It consists of two voltage source inverter connected back to back through a common DC link, as illustrated in fig 4. This arrangement function as an ideal AC to AC power converter in which the real power can freely flow in either direction between the AC sides of the two inverters. The reactive power on the two AC sides of the inverters can be controlled independently.

The series inverter (inverter 2) is connected to the transmission line through a series (booster) transformer in a manner similar to the SSSC. The shunt inverter is connected to the system bus through an shunt (excitation) transformer in same way as an Advanced Static VAR Compensator (ASVC). Therefore, the UPFC can be considered as a multi-function controller which is capable of providing the performance of one or two FACTS devices. Because of its structure, the UPFC provides new dimensions of controllability, which have not been achieved with other FACTS controllers.

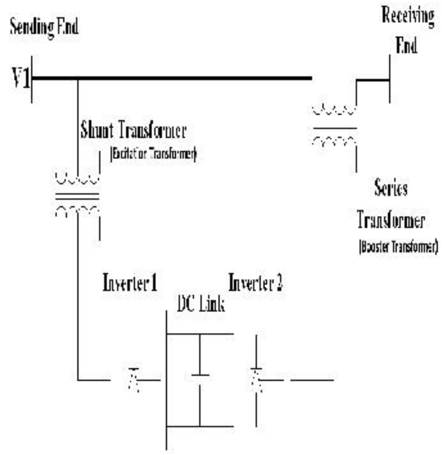

Fig. 5 Schematic diagram of a UPFC system [9]

Principles of Operation [9]

SSSC part of the UPFC performs the main function of the UPFC by injecting a voltage V_{ser} in series with the transmission line. The injected voltage can be controlled with theoretically little restrictions/ that is, the phase angle of V_{ser} can be controlled independently of the line current between 0 and 2π, and the magnitude is ranging from zero to predefined maximum value. This maximum value is determined by the VA rating of the UPFC series inverter.

In the transmission line current flows through the injected voltage resulting in active and reactive exchange between the series inverter and the AC system. The real power measured at the inverter output is supplied or absorbed by the DC link side. The reactive power is generated or absorbed internally between phases connected by the inverter switches. As the magnitude and phase angle of the series inverter injected voltage is fully controllable, it can be used to achieve different conventional compensation e.g. voltage regulation, series compensation or phase angle regulation.

Inverter 1 (the exciter) which is connected in shunt with the AC system is used essentially to provide the active power demand of the series inverter at the common DC link. As inverter 1 is a voltage source (viewed from the system), it can generate or absorb reactive power at the connection point. Such reactive power is independent of both the reactive power generated by the series inverter and the active power through the DC link. Therefore, the shunt inverter can fulfill the function of the ASVC in providing reactive power compensation at the system bus bar and at the same time performing an indirect DC voltage regulation within the UPFC.

Modes of operation

Conventional power transmission systems employ shunt compensation, series compensation and phase angle regulation. The UPFC can fulfill all these functions and thereby meet multiple control objectives by an appropriate choice of the injected voltage magnitude and angle, as illustrated in the diagram given in figure 6. Therefore, there are different modes of operation for each of the inverters comprising the UPFC depending on the available local reference signals. The UPFC global controller needs to be able to switch between these modes according to the system requirements.

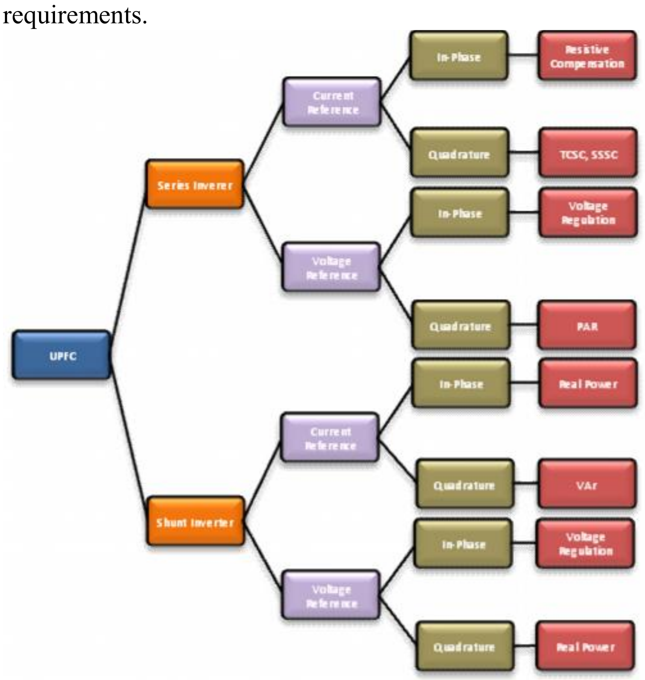

Fig. 6 UPFC modes of operation **[9]**

Series inverter Modes of operation

Operation of the series inverter is divided into different modes with distinctive characteristics. These modes are dependent on the reference signal used to derive the magnitude and phase angle of the injected voltage. In power systems the local reference signals normally available are the line current and the system bus voltage. These two signals are recommended by many power systems researchers [10] to be the reference signals for UPFC control variables.

System voltage as a reference

In these modes, the series inverter generates a voltage vector, which is controlled in both magnitude and phase-angle with reference to the voltage of the system bus at which the UPFC is connected.

- **Voltage regulation mode**

The series converter simply generates the voltage vector V_{ser} with the magnitude and phase angle requested by the reference input as shown in fig.7. These operating modes may be advantageous when a separate system optimization control coordinates the operation of the UPFC and other FACTS controller employed in transmission system.

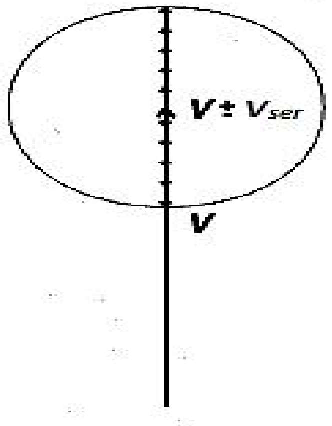

Fig.7 UPFC working as a voltage regulator [11]

- **Phase angle regulation mode**

The injected voltage vector $V_{ser}$is controlled with respect to the input bus voltage vector V_1so that the output bus voltage vector $V_2$is phase shifted relative to $V_1$by an angle specified by the reference input as shown in figure 8.

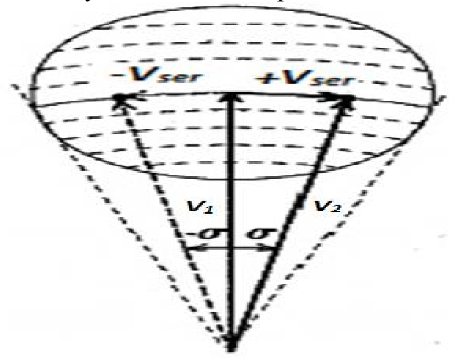

Fig.8UPFC working as a phase angle regulator/shifter [11]

Line current as a reference

In these modes the injected voltage generated by the series inverter is determined by the transmission line current.

- **Line resistive compensation**

In this mode, the injected voltage is maintained to be in-phase with the line current in order to compensate the transmission line voltage drop. The key point of such a compensation scheme is to keep the transmission system X/R ratio within an acceptable range based on the line voltage rating.

- **Line reactive compensation**

Magnitude of the injected voltage vector V_{ser} is controlled in proportion to the magnitude of the line current *I,* so that the series insertion emulates reactive impedance when viewed from the line. The desired impedance is specified by reference input and in general it may be complex impedance with resistive components of either polarity. When the injected voltage is kept in quadrature with respect to the line, current to emulate purely reactive (capacitive or inductive) compensation. This operating mode matches with series compensation in the system like SSSC and TCSC.

Power flow mode

The unified power flow control approach (series inverter) can be broadening the basic power transmission concepts. It is possible to implement the individual compensation scheme discussed above but also a combine or real time transition from one mode of operation to another and in order to handle particular system contingencies, more effectively than the other single function FACTS controllers.

In theory, the UPFC may be used to maintain a prescribed and independently controllable real and reactive power flow in a certain transmission corridor. In this case, the injected voltage V_{ser} is stipulated to have no phase angle restriction and its magnitude is variable between zero and a maximum permissible value. In practice, the UPFC may be used to maintain or vary the active and reactive power flow in a transmission system within a specific margin. The operating point can be anywhere inside a circle with a radius $|V_{sermax}|$, as shown in figure 9. The particular, but more general, mode of operation has been chosen in this work to analyze the capabilities of the UPFC to control the system power flow.

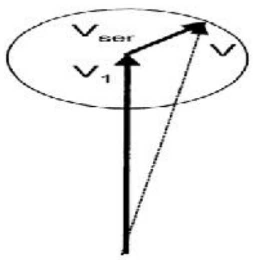

Fig. 9 UPFC in the power flow mode [11]

Shunt inverter modes of operation

The shunt inverter is operated to absorb or generate certain amount of reactive power from/to the AC system. In addition, it provides the real power demand of the series inverter and power losses. Similar to the series, the shunt inverter modes of operation are dependent on the reference signal used to derive the magnitude and angle of the inverter output voltage.

- **System bus voltage as a reference**

The inverter output (V_{sh}) may be split into two components ($V_p$and V_q) with respect to the AC system bus voltage (V_1) at which the UPFC is connected, as shown in fig. 10. The in-phase component may be used to control the system bus voltage in order to immune the controlled transmission line from the changes within the rest of the network.

The quadrature component allows the shunt inverter to exchange real power with the AC system which is required for the series inverter. This mode of operation is quoted as "Bus Voltage Control Mode.

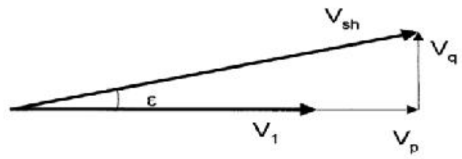

Fig.10 Shunt Inverter in "Voltage Control Mode" [11]

- **Shunt inverter current as a reference**

When the current is used as a reference signal, the inverter output voltage may be divided into two perpendicular components. The in-phase component will allow the shunt inverter to exchange real power with the DC link and provide for the power losses.

The quadrature component is responsible for the exchange of reactive power with the AC system. This in turn supports the reactive power in the transmission system irrespective of the variation of the bus voltage.

(3) Simulation And Results of Test Case, 5-Bus System

Here for simulation work IEEE 5-bus system is chosen. In this the UPFC is connected at bus 3. The simulation is done for load flow analysis for without / with UPFC connected to system.

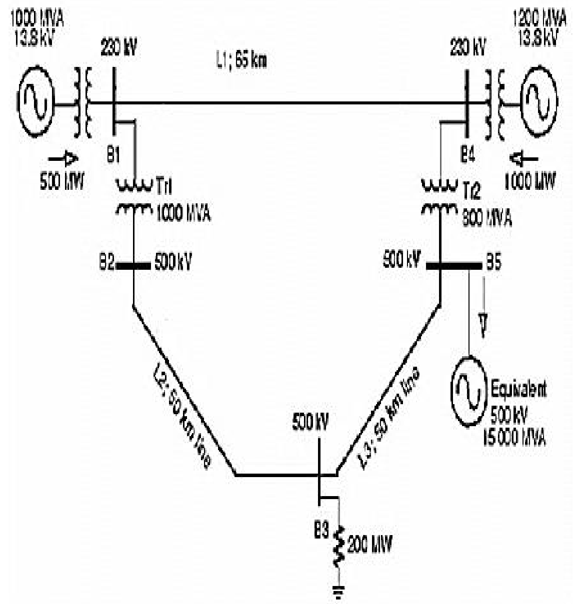

Fig 11 One line diagram of 500/230 kV Transmission System [12]

A UPFC is used to control the power flow in a 500 KV /230 KV transmission systems. The system, connected in a loop configuration, consists essentially of five buses (B_1 to B_5) interconnected through three transmission lines (L_1, L_2, L_3) and two 500 kV/230 kV transformer banks Tr1 and Tr2. Two power plants located on the 230KV system generate a total of 1500 MW which is transmitted to a 500 KV, 15000 MVA equivalent and to a 200 MW load connected at bus B3 as shown in fig.11.

Simulation for without UPFC system

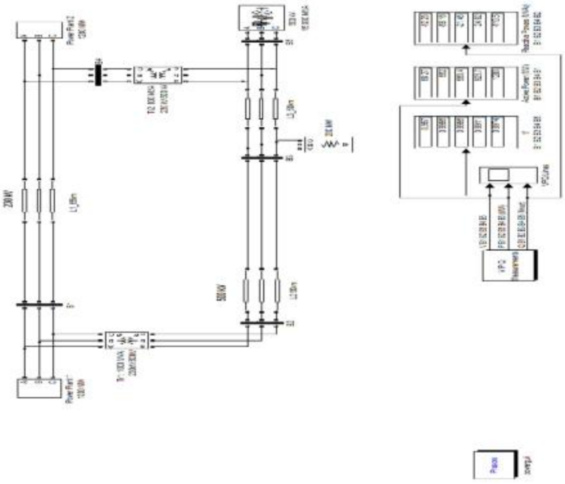

Fig. 12. Simulation without UPFC [12]

As shown in figure 12, in the normal operation, most of the 1200 MW generation capacity of power plant 2 is exported to the 500 KV equivalents through 800 MVA transformer connected between buses B_4 and B_5. The load flow shows that most of the power generated by plant 2 is transmitted through the 800 MVA transformer bank (925 MW out of 1000 MW). Transformer Tr-2 is therefore overloaded by 125 MVA. This will now illustrate how a UPFC can relieve this power congestion.

As shown in figure13, the UPFC located at the right end of line L_2 is used to control the active and reactive powers at the 500 KV bus B_3, as well as the voltage at bus B_UPFC. The UPFC consists of two 100 MVA, IGBT-based, converters (one shunt converter and one series converter interconnected through a DC bus). The series converter can inject a maximum of 10% of nominal line-to-ground voltage in series with line L_2.

In this simulation model the Power data parameters that the series converter is rated 100 MVA

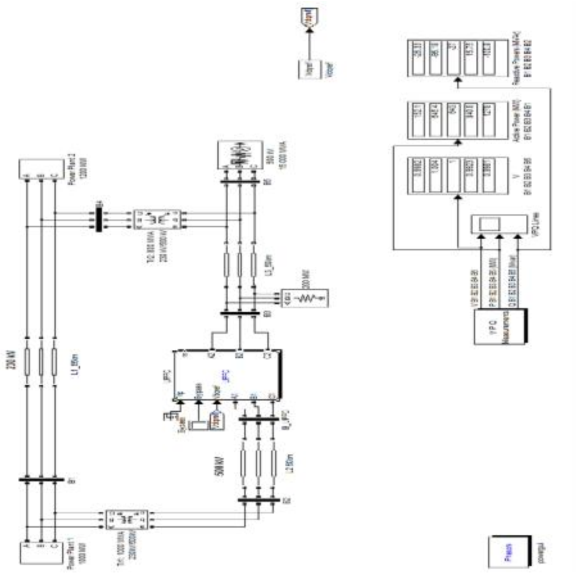

Fig. 13 Simulation with UPFC

with a maximum voltage injection of 0.1 pu. The shunt converter is also rated 100 MVA. Also in the control parameters, that the shunt converter is in Voltage regulation mode and that the series converter is in Power flow control mode.

Results for 5-Bus system

Table 1 Results for 5-bus system without UPFC

Voltage (pu)	Active Power (MW)	Reactive Power (MVAr)
0.997	68.27	-12.25
0.9996	563	-59.16
0.9996	560.4	-21.45
0.9911	925.7	24.92
0.9974	1280	-110.5

Table 2 Results for 5-bus system with UPFC

Voltage (pu)	Active Power (MW)	Reactive Power (MVAr)
0.9982	152.1	-26.33
1.004	645.4	-95.18
1	643	-27
0.9923	840.8	15.75
0.9981	12780	-100.8

Table -1 shows that when UPFC is not connected in the network, the actual active power flow is 68.27MW and reactive power is -12.25 MVAr and voltage is 0.997 p.u. After installation of UPFC at BUS B3, power flow from the trf.2 will increase from 68.27MW to 152 MW with decreasing of reactive power from -12.25MVAr to -26.33 MVAr with improving of voltage from 0.997 p.u.to 0.9982 p.u as shown in Table 2. In order the power flow will be shared in the line -1, line-2 and line-3 with decrease in overloading of Trf.2 (as results no.4 of table-1 &2), and with improvement of voltage and decreasing of reactive power.

In test case we can see that the UPFC improves the voltage level of the system buses and also the voltage angle of the receiving end bus. So we can say that with help of UPFC connected to the power system the overall performance of the system improves.

After connection of UPFC in the substation, the power flow will be regulated and overloading of the existing line will be shared with other unloaded line means load distributed on the other connected network, therefore without erecting new transmission line we can use existing infrastructure with installation of UPFC.

Conclusion

The test results show that the use of FACTS system in the variable power flow transmission system maintain and improve the power system operation, stability, and optimum control of power flow increases the efficiency of transmission network. The use of flexible transmission system in the variable sources grid network balance the system demand as well as optimize the existing transmission system by unified power flow controller which provides simultaneous or individual control of basic system parameters like transmission voltage, impedance and phase angle there by controlling the transmitted power. If the UPFC is not connected in the network, the over loading on line resulted in erection of new electrical line and substation to full fill the system requirement But with the incorporation of UPFC the power flow will be regulated and the existing line will be used to fulfill the requirement of network and remove the problem of evacuation of power.

The unscheduled interchange mechanism also needs to be reviewed and frequency control through this mechanism can perhaps be phased out and replaced by ancillary services. The load dispatch centers need to be empowered so they can take autonomous decisions relating to operation and security of the grid. The role of technology in system maintenance and up gradation is also important. Transmission planning criteria need to be reviewed in light of the growing complexity of the system. Then latter has made the system vulnerable to cyber attacks, necessitating appropriate solutions to be put in place.

The cost of UPFC is very much higher than other static reactive power regulators and it is mostly suitable for more than 220KV electrical system.

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