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Research Article

Statistical Comparative Study of FACTS Devices in PSS Improvement

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ABSTRACT

The Power System Stability (PSS) has been one of the major concerns of modern electrical power systems. The UPFC, a versatile FACTS controller, allows simultaneous or independent control of parameters like line impedance, voltage or power angle so that it can be used for voltage support, transient/dynamic stability improvement and damping of low frequency power system oscillations. Various optimization techniques are also implemented with stability need in controller. The effect of voltage fluctuation, current and frequency variation are controlled using the ANN & Fuzzy logic, to make the power system stability in a smoother functionality. This paper presents a review of various applications which UPFC provides in a powersystem such as minimization of loss, enhancement of load ability, voltage stability, transient stability, damping of power oscillations etc. by setting up UPFC parameters. To seek better power flow control, optimal allocation and parameter settings of UPFC in power system can be done by various evolutionary techniques.

Key Words: UPFC, FACTS, MATLAB, Simulink, Transient stability, Dynamic stability, Swing Stability, Two-area power system, PSS

I. Introduction

The power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. As a consequence of increasing power demand, transmission lines are more progressively over-loaded than was installed. With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a transmission limiting factor. Recent development of power electronics introduces the use of FACTS controllers to enhance controllability and increase of power transfer capability in a very fast manner. FACTS has number of benefits, such as greater powerflow control, increased secure loading of existing transmission lines, damping of power oscillations, less environmental impact etc. FACTS controllers like Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor Controlled Series Capacitor (TCSC), Static Series Synchronous Compensator (SSSC), UPFC, IPFC etc. are capable of controlling the networkcondition in a very fast manner to improve voltage stability and power quality.

II. Overview of FACTS Devices in Power System

The occurrence of a contingency (due to the tripping of a line, generator) can result in a sudden increase/decrease in the power flow. This can result in overloading of some lines and consequent threat to system security. FACTS controllers are used for dynamic control of line impedance, voltage or power angle of high voltage AC transmission line. The FACTS devices are classified based on its location of the connection: shunt, series & combined or hybrid; also they are classified according to the power electronic devices used for the switching; Further, they are classified based on impedance variable. Some of them are discussed herewith.

1. *Static VAR Compensator (SVC):*

It is a first-generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation. SVCsare also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control.

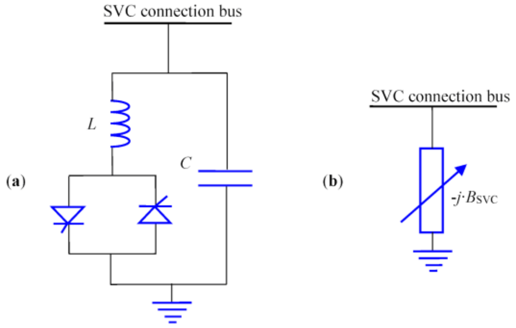

Fig. 1 Configuration of SVC

2. *Static synchronous compensator (STATCOM):*

It is a power electronic device using force commutated devices like IGBT, GTO etc. to control the reactive power flow througha power network and thereby increasing the stability of power network. STATCOM is a shunt device i.e. it is connected in shunt with the line. it consists of a voltage source converter (VSC), a coupling transformer and a dc capacitor. DC Capacitor is used to supply constant DC voltage to the voltage source converter, VSC.A Transformer is connected between the output of VSC and Power System. Transformer basically acts as a coupling medium. In addition, Transformer neutralize harmonics contained in the square waves produced by VSC. The voltage-source converter is used to convert the DC input voltage to an AC output voltage.

Two of the common VSC types are as below.

a) Square-wave Inverters using Gate Turn-Off Thyristors: In this type of VSC, output AC voltage is controlled by changingthe DC capacitor input voltage, as the fundamental component of the converter output voltage is proportional to the DC voltage.
b) PWM Inverters using Insulated Gate Bipolar Transistors (IGBT): It uses Pulse Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. In contrast to the GTO-based type, the IGBT-based VSC utilizes a fixed DC voltage and varies its output AC voltage by changing themodulation index of the PWM modulator.

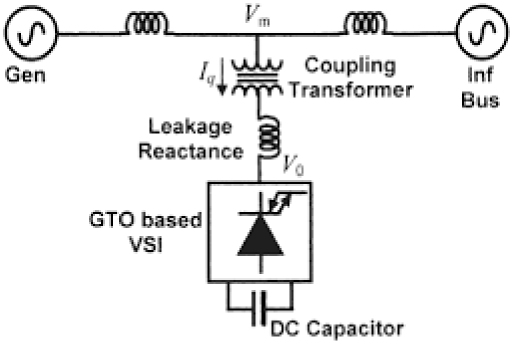

Figure 2. A GTO-based STATCOM

3. *Thyristor controlled series capacitor (TCSC):*

It is one of the most important and best-known FACTS devices, which has been in use for many years to increase the power transfer as well as to enhance system stability. The main circuit of a TCSC is shown in Fig. 3 (A). The TCSC consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR1 and SCR2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modelled as a fast switch between corresponding reactance's offered to the power system. All zones of operation of TCSC have been described in Fig. 3(B). [37].

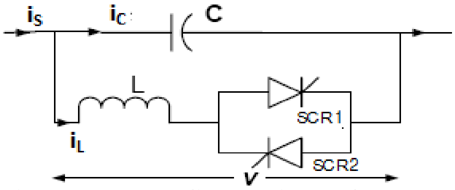

Fig. 3(A). Configuration of a TCSC

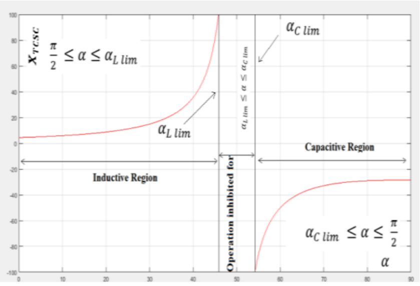

Fig. 3(B). Operation Zones of TCSC.

4. *Static Synchronous Series Compensator (SSSC):*

It is a member of FACTS family which is connected in series with a power system. It consists of a solid-state voltage source converter which generates a controllable voltage at fundamental frequency. When the injected voltage is kept in quadrature with the line current, it can behave as inductive or capacitive reactance so as to influence the power flow through the transmission line. While the primary purpose of a SSSC is to control power flow in steady state, it can also improve transient stability of a power system

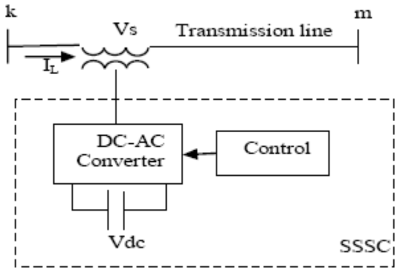

Fig.4 Simplified diagram of a SSSC

5. *Unified Power Flow Controller (UPFC):*

It is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability. The UPFCcan independently control many parameters since it is the combination STATCOM and SSSC. These devices also offer an alternative mean to mitigate power system oscillations

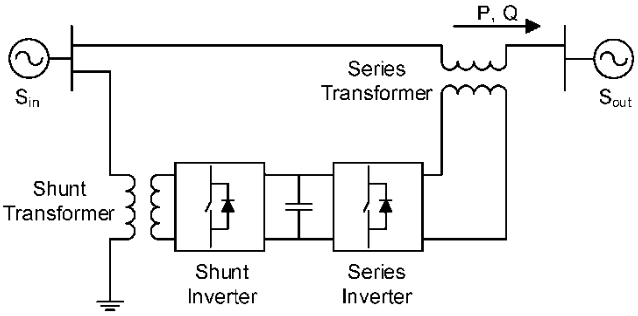

Fig. 5. UPFC

III. UPFC Controller

In (1994) Gyugyi introduced UPFC, which is capable of generating internally the reactive power necessary for network compensation, and is also able to interface with an appropriate energy storage device to negotiate real power exchange with the ac system. It uses solid-state synchronous voltage sources (GTO) for shunt compensation, series compensation, and phase angle control. UPFC controls all three network parameters (voltage, impedance, transmission angle) determining power transmission [1].

The UPFC as shown in figure 6 consist of two fully controlled inverters, series inverter is connected in series with the transmission line by series transformer, whereas parallel inverter is connected in parallel with the transmission line by parallel transformer, connected to each other by a common dc link including a storage capacitor. The real and reactive power flow in the transmission line can be controlled by changing the magnitude (0 to VSR max) and phase angle (0 to 360) of the injectedvoltage (VSR)produced by the series inverter. The basic function of the parallel inverter is to supply the real power demanded by series inverter through the common dc link. The parallel inverter can also generate or absorb controllable reactive power.

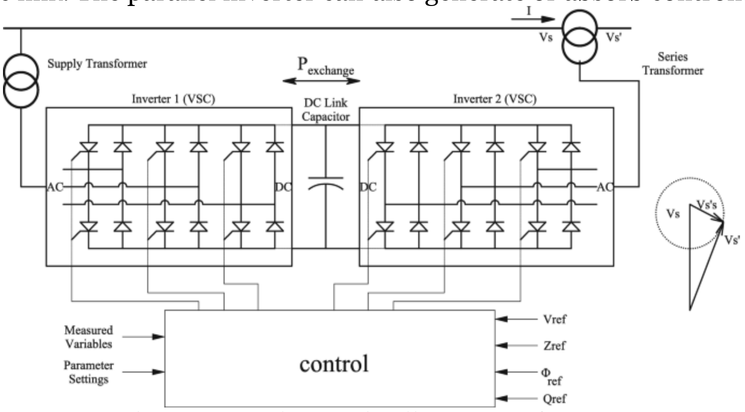

Figure 6. Schematic diagram of UPFC

In general, the shunt inverter will be operated in Automatic Voltage Control mode and the series inverter in Automatic Power Flow Control mode.

- Automatic Voltage control mode-In this case, Shunt converter reactive current is automatically regulated to maintain transmission line voltage to reference value at the point of connection
- Automatic Power Flow Control Mode- in this case, Magnitude and angle of VSR is controlled so as to force a line current, that results in desired real and reactive power flow in the line. VSR is determined automatically and continuously by closedloop control system to ensure desired P and Q.

IV. Role of UPFC in Improving Performance of Power System

In 1995, Gyuqyi and et al. described the basic concepts of the proposed generalized P and Q controller and compares it to the thyristor-Controlled Series Capacitor and Thyristor-Controlled Phase Angle Regulator. They also present results of computer simulations showing the performance of the UPFC under different system conditions [2].

In (1996) Round, and et al. studied the performance of a unified power flow controller (UPFC) with four different controllers and evaluated through simulation and implementation in an experimental laboratory model. The controllers which were investigatedare the PI controller, PI controller with decoupling, cross-coupling controller and robust H∞ controller. It is found that the cross- coupling and Robust H∞ controllers have the best performance when the exact value of the power transmission parameters is unknown [3].

In (1997) M. Noro Ozian, et al. deal with optimal power flow control in electric power systems by use of unified power flow controller (UPFC). And they developed and analyzed Models suitable for incorporation in power flow programs. And demonstratedthe application of UPFC for optimal power flow control through numerical examples. It is shown that a UPFC has the capability ofregulating the power flow and minimizing the power losses simultaneously [4]. In (2000) Zhengyu Huang, et al. discuss four principal main control strategies and the computer tests results support the discussion conclusion and also, they concluded the constant power flow control is good for steady state control and the constant series compensation control is useful for first swing stability. The supplementary control is very efficient in damping the power oscillation. The suggested UPFC control can realize the desired control strategy flexibly and improve system dynamic performancesignificantly [5].

In (2010) Muthukrishnan and Kumar deal with digital simulation and implementation of power system using UPFC to improvethe power quality. They deduce that UPFC is also capable of improving transient stability in a power system [6]. In (2010) Mathukrishanan and Kumar deal with digital simulation of 14 – bus power system using UPFC to improve the powerquality. They conclude that the UPFS has the capability of improving the transient stability in a power system [7]. In (2010) Murali, and et al. investigates the improvement of transient stability of a two-area power system using UPFC and simulations are carried out in MATLAB/Simulink environment for the two-area power system model. The performance of UPFC is compared with other FACTS devices such as Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), and Static Var Compensator (SVC) respectively. The simulation results demonstrate the effectiveness and robustness of the proposed UPFC on transient stability improvement of the system [8]. In (2011) Arup Ratan Bhowmik and Champa Nandi investigated the performance of Unified Power Flow Controller (UPFC) incontrolling the flow of power over the transmission line and they dialed with digital simulation of standard IEEE 14-bus power system using UPFC to improve the real and reactive power flow control through a transmission line by placing UPFC at the sendingend [9].

In (2012) Aarti Rai includes first the optimal location of FACTS devices, second voltage stability analysis and third control of reactive power of system. The model can be simulated in MATLAB. The performance of the whole system such as voltage stability, transient stability, frequency and power swings are analyzed and compared without FACTS and with FACTS device [10]. In (2013) Rama Sekhara Reddy and Vijaya Kumar used a Unified Power Flow Controller (UPFC) to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle in wind energy generation. This controller offers advantages in terms of static and dynamic operation of the power system [11]. In (2013) Hakim Elahi Tooraji and Nekoubin Abdolamir designed and simulated a Unified Power Flow Controller in multi- machine power system. The on-line designed process is based on PWM method which all the power quality parameters representing as voltage sag and swell can be improved. In the proposed control method, the harmonic distortion of the system is decreased and the voltage oscillations of the DC capacitor will be improved. Simulations that are done by the PSCAD/EMTDC software show theeffectiveness and precision of this [12].

In (2013) Kumar Gaurav and Nitin Saxena investigate the enhancement in voltage stability margin as well as the improvementin the power transfer capability in a power system with the incorporation of UPFC. A simple transmission line system is modeled in MATLAB/Simulink environment. The load flow results are first obtained for an uncompensated system, and the voltage and powerprofiles are studied. The results so obtained are compared with the result obtained after compensating the system using UPFC to show the voltage stability margin enhancement [13].

In (2013) Vaibhav S Kale et, al. proposed the real, reactive power and voltage control through a transmission line by placing UPFC at the sending end using computer simulation. The control scheme has the fast dynamic response and hence is adequate for improving transient behavior of power system after transient conditions [14].

In (2013) K.Ravichandrudu and et al. introduced the concept of Distributed FACTS (D-FACTS) as an alternative approach to realizing cost-effective power flow control. They concluded that the UPFC is capable of improving transient stability in a power system and it is the most complex power electronic system for controlling the power flow in an electrical power system. The circuitmodel is developed for UPFC using rectifier and inverter circuits. The control angle is varied to vary the real and reactive powers at the receiving end [15].

In (2013) K. Ravichandrudu et, al. demonstrated the performance of the UPFC in achieving harmonic mitigation and stability of the wind energy grid by using MATLAB/SIMULINK [16].

In (2014) B.Gopinath et, al. proposed a method based on Model predictive control (MPC) and using Bacterial Forging Algorithm(BFA) for modeling Unified Power Flow Controller. Modeling of UPFC is designed with its unique capability to control simultaneously real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected.Therefore, this device creates a remarkable quality impact on power system stability. UPFC with additional PI controller is used along with the UPFC main controller. [17].

In (2015) Koganti et, al. studied Power quality and stability improvement of HVDC transmission System using UPFC for Different uncertainty conditions, they concluded that UPFC improves the system performance. It can control the power flow in thetransmission line, effectively. With the addition of UPFC, the magnitude of fault current reduces and oscillations of excitation voltage also reduce. The total harmonic distortion (THD) is also reduced well below the IEC standards. It is more economical for the HVDC transmission system to transfer more power [18].

In (2015) Shantha Soruban et, al. proposed an ANN based control scheme for a UPFC to be used as an active power filter. Theobjective is to guarantee power to the load at the required power quality. The ANN control unit monitors the voltage at the point ofcommon coupling. UPFC enables improved power quality by maintaining power factor nearer to unity rapid response time, the ability to provide reactive power at low voltage and to provide voltage compensation can be obtained. For unbalanced voltage compensation, two unbalanced controllers using the phase voltage amplitude and negative sequence component are proposed [19].

V. Different control techniques for better P and Q control

In 2015 Priyankakarwa, V. P. Rajderkar deals with the optimal placement of UPFC to maximize power transfer capability. Realpower sensitivity performance index has been used to find optimal location of UPFC on IEEE-5 and IEEE-14 bus system. [20]

In 2017. Kyaw Myo Lin, proposes a set of load curtailment sensitivity indices for optimal placement of Unified Power Flow Controller (UPFC) in power system network. [21]

In 2010 Suppakarn Chansareewittaya and Peerapol Jirapong proposes particle swarm optimization (PSO) technique to determine the optimal allocation of multi-type FACTS controllers to enhance power transfer capability of power transactions between sourcesand sink areas in power systems. [22]

In 2014 Sreerama Kumar R., Ibrahim M. Jomoah, and Abdullah Omar Bafail proposes the application of genetic algorithm forthe determination of the optimal placement of unified power flow controller (UPFC) in a power system so as to minimize the systemlosses and enhance the voltage profile. [23]

In 2005 Weerakorn Ongsakul and Peerapol Jirapong, an evolutionary programming (EP) is proposed to determine the optimal allocation of FACTS devices for maximizing the total transfer capability (TTC) of power transactions between source and sink areas in deregulated power system. [24]

In 2013 R. Selvarasu and M. Surya Kalavathi, a new strategy has been proposed for optimal placement of Unified Power FlowController (UPFC) in power systems with a view to minimize the transmission loss. The proposed strategy uses Self Adaptive Firefly Algorithm (SAFA) and identifies the optimal locations for UPFC placement and their parameter. Simulations results are presented for IEEE 14-bus system and IEEE 30-bus system. Results have shown that the identified location of UPFC minimize thetransmission loss in the power system network [25]

In 2008 Sreekanth Reddy Donapati and M.K.Verma proposes a sensitivity based technique for optimal placement of Unified Power Flow Controller (UPFC) to enhance voltage stability margin under contingencies. [26]

In 2011, Kiran et al. proposed Particle swarm optimization method to solve the optimal power flow problem on power system by finding a location for UPFC device. The proposed algorithm is an effective method for finding the optimal choice and location of UPFC controller and also minimizing the overall system cost, which comprises of generation cost and the investment cost of theUPFC controller using PSO and conventional Newton Raphson's power flow method by verifying it on IEEE 14 bus test system. [27]

Saravanan et al. proposed the application of Particle Swarm Optimization to find the optimal location, settings, type and numberof FACTS devices including UPFC to minimize its cost of installation and to improve system load ability for single and multi-typeFACTS devices. [28] Singh et al. suggested the suitable locations of UPFC to enhance system load ability and tested it on IEEE 14 bus system. A sensitivity-based approach has been developed for finding suitable placement of UPFC. [29]

Shaheen et al. presented application of evolutionary optimization techniques for optimal location and parameter setting of multiple UPFC devices for maximizing load ability and minimizing installation cost in power system with respect to line thermal limits and bus voltage magnitude limits. This proposed method was tested on IEEE 6 and IEEE 14 bus test power system with desired results. [30]

Abdullah et al. presented the application of evolutionary computation technique for monitoring voltage profile of the power system network when UPFC is incorporated in the network. Evolutionary Programming and Artificial Immune system method havebeen applied in IEEE 30 bus RTS system to maintain stable voltage profile and minimize losses while increasing the power transfercapability. [31]

Taki et al. discussed the application of neuro –fuzzy controlled UPFC to improve transient stability of power system. Proposedmethod is tested on a single machine infinitive bus system to confirm its performance through simulation. By keeping the series (shunt) branch inactive, UPFC can operate as a STATCOM (SSSC) and the corresponding behavior is also evaluated and compared.The superiority of the proposed controlled UPFC over a STATCOM or a SSSC in improving transient stability of a single machineinfinitive bus has been demonstrated. [32]

Hosseini et al. proposed a transient model and control system of UPFC to enhance the voltage regulation and transient stabilityof a radial AC transmission system using UPFC. The control scheme has the fast dynamic response and therefore, improves the transient behavior of power system after a transient condition. Simulation results demonstrate that the presented control system actsproperly in steady state and transient condition. The presented UPFC control system can regulate line active and reactive power flow and voltage at line midpoint. The presented control system of UPFC not only responses to the step changing in the active and reactive power, but also is able to exchange the direction of line active power flows. Also, the proposed control system is regulatingthe DC link capacitor voltage. The simulation results indicate the fast dynamic response, validity and effectiveness of the presentedcontrol scheme. [33]

The authors YAZEED YASIN GHADI et al. used a recently developed metaheuristic optimization strategy (i.e., the Zebra Optimization Algorithm, or ZOA) to fine-tune the suggested controller parameters for the two-area hybrid power grids studied in this paper. The system model depicts physical constraints, such as the reheat turbine and the generation rate constraint (GRC). The superiority of ZOA is demonstrated by comparing its results to those of the recently developed optimizations Osprey Optimization Algorithm (OOA) and Jellyfish Search Optimizer (JSO). By comparing the performance of the proposed ZOA-based fuzzy PI-FOPDF λ controller to that of existing ZOA-tuned fuzzy-based controllers (such as fuzzy PIDF and fuzzy PIDD2), it has been demonstrated that the proposed controller is more effective. [35]

Ali Abdul & Ali Abdul Razzaq Altahir has represented the case study which concluded that the number of UPFC increased with load increased by (14% and 21%). One UPFC could not diminish from overloading in power lines, so using 2 NUPFC in various locations enhanced load ability and reduced power losses. In conclusion, this study has two contributions. The first contribution is specifying an optimal allocation of UPFC in the electrical power networks. The second contribution is improving the transient stability of power systems adopting UPFC. At last, we conclude that conducting UPFC is better for improving transient stability and critical clearing times. [36].

6. Case Study

Using Kundur two area power sysytem [34] simulation results in MATLAB/SIMULINK platform shows the effects of UPFC ontransient stability performance of the system. Consider a two-area power system (Area-1 & Area-2) with series and shunt FACTS devices, connected by a single circuit long transmission line as shown in Fig. 7 and Fig. 8. Here, the series FACTS devices such as UPFC (combination of STATCOM and SSSC), SSSC, and TCSC are equipped between bus-2 and bus-3 and the shunt FACTS device such as SVC is equipped at bus-2.[8].

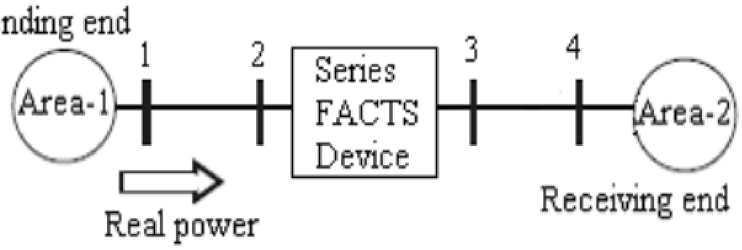

Figure 7. Series FACTS Devices connection on Two-area Power System

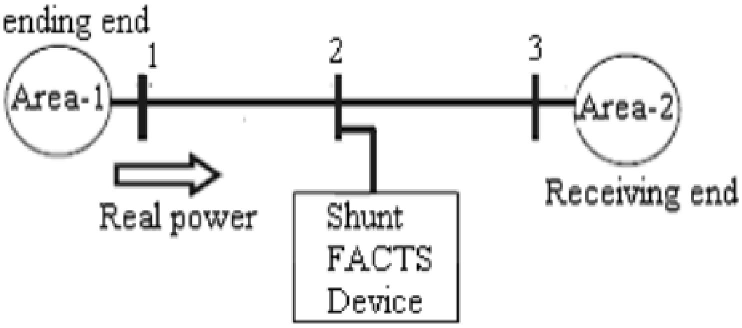

Figure 8. Parallel FACTS Devices connection on Two-area Power System

The following tables gives comparison for the SVC, TCSC & UPFC for their cost/kVAr, its technical benefits and settling time after fault period.

Table 1: Cost comparison of FACTS Devices

FACTs Device	Cost (INR/kVAr)
SVC	600
TCSC	2520
UPFC series	3120
UPFC shunt	3120

Table 2: Technical Benefits of the FACTs Devices – a Comparison

FACTs Devices	Voltage Control	Load Flow Control	Dynamic Stability	Transient Stability
SVC	High	Less	Medium	Low
TCSC	High	Less	Medium	Medium
UPFC	High	High	Medium	Medium

Table 3: Comparison of FACTS Devices

Two-area Power System with	Power System Stability Enhancement	Settling time in post fault period (in seconds)
SVC	YES	7
TCSC	YES	1.5
UPFC	YES	0.6

The performance of UPFC is compared with other FACTS devices such as SVC, TCSC, and UPFC The simulation results demonstrate the effectiveness and robustness of the UPFC on transient stability improvement of the system whichis shown in Table 1, 2 & 3. It is clear from the simulation results that with the presence of UPFC, the settling time in post fault periodis found to be around 0.6 second, it is having also good voltage control and load flow control but the cost / kVAr is almost five times than SVC and higher than TCSC. So, the cost wise, it is SVC + TCSC = UPFC.

7. Conclusion

After study of the various FACTS devices & UPFC, the comparative conclusion is made that UPFC requires the least time from all other FACTS Devices, Hence, by using various optimization techniques also, the settling time can be changed depending upon the ratings of the power transmission line & overall system. The location of the UPFC enhances power system stability. Some applications including the improvement of the transient stability, swing stability, optimizing the losses and enhancement of the load capability, voltage profile and optimal power flow control are already achieved by the researchers using the UPFC. It is also found from the case study that the UPFC is more effective for improving power system stability as compared to other FACTS devices.

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