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A Brief Overview of the Application of Unified Power Flow Controller in Power Systems

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Abstract

The most crucial approach for power and control system implementation is optimal power flow because it yields the lowest operating costs and maintains the safety margins for the control variables. An essential component of the flexible AC transmission system (FACTS) is the unified power flow controller (UPFC). It is designed to provide multiple types of energy system compensation and can be utilized for controlling the reactive and active electrical power in transmission lines and bus voltages independently and at the same time. Considerable studies have been published in the UPFC engineering applications area using various techniques. Due to its versatile capabilities, UPFC is recognized as one of the most promising FACTS devices for modern power systems. UPFC is used to improve reactive power mismatch control and system stability. A brief review of UPFC applications for increasing power system flexibility and controllability has been conducted and summarized. This paper also discusses the utilization of artificial intelligence in the placement of UPFC in power systems.

Keywords: flexible ac transmission system devices; unified power flow controller; voltage source converter.
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1. Introduction

The increasing expansion of the industry, along with increased consumption loads and the maintenance of dynamic stability, at the same time with providing a level of permissible voltage, has created a limitation of power transmission in the power system [1-4].

In order to enlargement the transferring capacity of modern power systems, transmission lines need to be built, which results in an increase in the operating costs of these energy systems. To supplying of network, load the compensator is used to improve the status of existing lines [5-8].

Maintaining the appropriate voltage quantities and qualities requires high voltage flexible AC transmission systems. The complex power system may not be able to properly regulate voltage or change the level of electrical power that is either injected into or absorbed by the power system if the FACTS are not accumulated and evaluated. Overall grid capacity and achievement are improved by FACTS [9-11].

In addition, they boost the large-scale energy system's reliability and efficiency. FACTS can provide a greater degree of control over electrical energy because they are capable of dampening power oscillations [12-17]. Therefore, these devices are utilized for proper control to achieve the flexibility of the power system [18,19]. There has been a substantial amount of investigation carried out in the field of FACTS devices [20,21]. They are a significant part of today's interconnected large-scale electrical networks [22,23]. FACTS devices are divided into three groups as shown in Fig. 1 [24,25]: the mechanical switches such as TCSC [26,27], the hybrid device such as STATCOM [28,29] and the voltage source converter such as IPFC [39,31]. In order to quickly compensate for reactive power on high-voltage transmission grids, an electrical device known as a UPFC is employed [32,33]. A UPFC is extremely distinct from traditional ac transmission technology due to its operation relies on the protection and control power system [34,35].

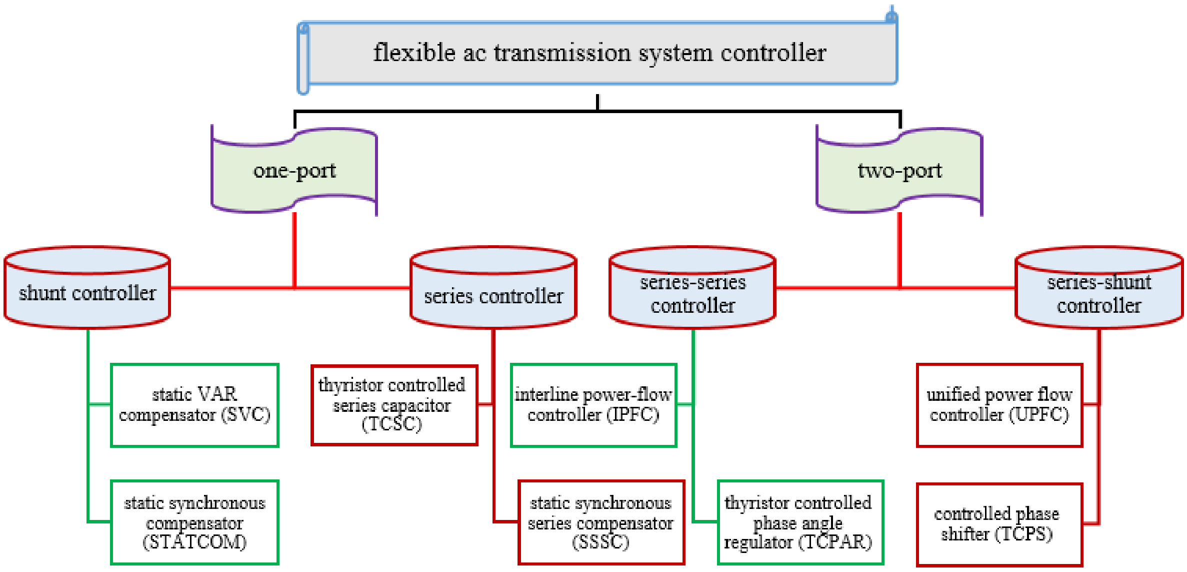

Fig. 1. Classification of FACTS devices

Table.1.
Overview of FACTS Controller

Type	***Devices***	***Devices principle***	***Basic control***	***Local modulation signal***
Series	TCSC	varying reactance	line compensation	synthesized frequencies synthesized voltages active power, current
	SSSC	reactive source	line compensation	
Shunt	SVC	varying reactance	bus voltage	
	STATCOM	reactive source	bus voltage	
Shunt-series	UPFC	series compensation and reactive source	active power flow compensation of bus voltage line	
Shunt-shunt	BTBL	reactive source and phase compensation	bus voltage active power flow	

It is adaptable enough to accommodate the operational requirements of specific functionality. UPFC have different uses in the power system for improve behavior of the grid such as security enhancement [36,37], backup protection [38] and oscillation damping [39].

So far, a lot of research has been done on UPFC application in power system [40-45].

The UPFC is a part of the FACTS family and retains numerous appealing characteristics. The UPFC is connected using a combination of shunt and series connections. The purpose of this research is to provide a review of the various applications of UPFC in the modern power system.

The categorized information in Table 1 provides a summary of the FACTS device family. This table furnishes a concise summary of the operating fundamental, the various possible main control approaches, and the local signals that are utilized for supplementary damping control in the research that has been published [46,47].

This paper is structured as follows: Section 2 presents the principles of unified power flow controllers. In Section 3, the coordination design of UPFC and PSS is summarized. Section 4 briefly reviewed the application of artificial intelligent in UPFC optimal placement research field. The congestion mitigation, SSR, and other FACTS devices are categorized in Section 5. In Section 6, the studies regarding how to improve power system oscillation with FACTS devices are outlined. Eventually, this paper is concluded in Section 7.

2. Unified Power Flow Controller

A) Compensating Structure

As depicted in Fig. 2, the UPFC is an amalgamation of an SSSC and a STATCOM that are paired using a prevalent DC voltage source [48,49].

A series transformer is employed to inject current into a power transmission line, which is developed by a pair of controllable three-phase bridges. Both reactive and active electrical Power flows in a transmission system can be controlled by an advanced control system.

It can only work properly when a balanced sine wave source is applied. UPFC can independently manage reactive and active power flows on the power line as well as the bus voltages thanks to the inverters that operate via a universal DC link and a DC storage capacitor. Internal reactive power interaction via a DC link between two inverters is not possible.

SSSC is utilized to control the capacity for the transfer of electrical energy in the line to which it is connected. At the point where there are typical connections, STATCOM is used to regulate the bus voltage [50].

There are three distinct categories of techniques for controlling the active and reactive power flow: (i) is designed to inject the series voltage in phase shift with the power transmission line current, allowing it to function similarly to a variable sense capacitor [51,52], (ii) is according to injecting the series voltage in phase shift with the UPFC bus [53], and (iii) the D-Q axis current in the power transferring line is independently controlled, enabling individual control of the reactive and active power flow [54].

B) Compensation Model

By modifying the parameters of the power transmission line, the UPFC can achieve real-time control over the power flow in an electrical transmission system. Node voltages, line impedances, and phase angle are the adjustable specifications. These three parameters cover all the controllable parameters of the other FACTS [55].

Since UPFC is a multi-variable power controller in the large-scale energy system, it is essential to investigate the impact of the various power system operating conditions. Fig. 3 illustrates the UPFC model with a regulated voltage source.

With the electric grid serving as a representation of the shunt and series voltage source inverters, this model is comprised of two power supplies, one of which is associated with series and the other in shunt. By transforming DC voltage to AC voltage, the power sources are established. The schematic representation of a UPFC with a controlled flow supplier can be found in Fig. 4 [56,57].

Fig. 5 depicts the model of the UPFC as a transformer with a shunt branch. In this model, the variable shunt susceptance and the turn ratio of the transformer are unaffected by the voltages and currents that are measured at the input and output of UPFC [58].

A dynamic model of UPFC was developed in [59], to boost the power transfer capability through the power transmission network. Series and shunt controllers were structured with fuzzy logic controllers in this approach. In [60], a comparative study on different techniques used to incorporate UPFC in load flow algorithms, such as the decoupled technique, load injection technique, matrix partitioning technique, and indirect technique, is presented.

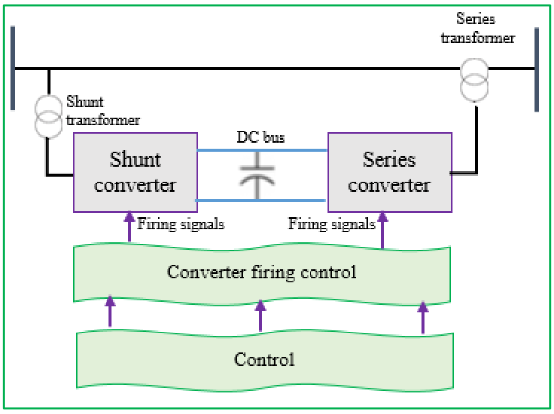

Fig. 2. Orbital structure of unified power flow controller

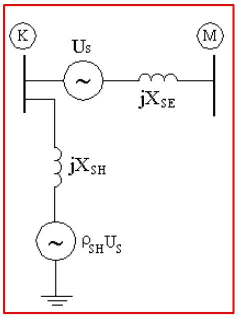

Fig. 3. Equivalent compensation circuit with controlled voltage source

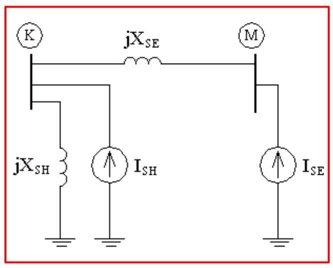

Fig. 4. Equivalent compensation circuit with controlled flow source

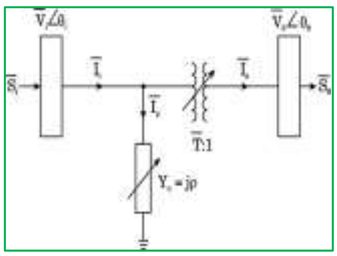

Fig. 5. UPFC Model as a transformer with a shunt branch

In [61], a reconfigurable cascaded multi-level inverter with a full-bridge converter is suggested. Each phase foot shunt has one end linked to the electrical power line and the other ends linked in parallel to the primary terminals of the series line transmitter and the alternating current inverter's output terminals.

3. Coordination Design of UPFC and PSS

Power system stabilizer (PSS) and UPFC controllers' coordinated design has been the subject of numerous studies employing a variety of techniques [62,63].

A strategy for coordinating UPFC with PSS to suppress oscillations generated by a small signal disturbance is presented in [64]. This procedure is used to determine the eigenvalue of the greatest real segment and then minimize it as a nonlinear optimization challenge. This model aims to suppress oscillations caused by small signal disturbances.

In [65], genetic algorithms are used in a coordinated configuration among a power system stabilizer (PSS) and a UPFC to optimize the damping proportion of electro-mechanical states by correlating various characteristics of PSSs with a UPFC. An optimal combination for simultaneously locating UPFC and PSS to augment the stability of the power system is addressed in [66], and a mixed integer nonlinear problem is developed for the analysis and design as a result of this presentation research. This architecture aims to boost the transient stability of the large-scale energy system.

The speed deviation of generator at nominal, light and heavy loading conditions with coordinated and uncoordinated design of the controllers in in single-machine infinite-bus power system is shown in Figs. 6, 7 and 8, respectively. Also, dynamic reponse for output electrical power at nominal loading condition is show in Fig. 9 [67].

Rotor angle waveforms of generators 1 with controllers are designed by continuous wavelet transform-Prony and modal methods and without those in 2-area 4-machine system are shown in Fig. 10 [68].

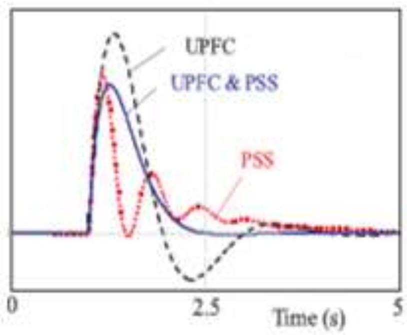

Fig. 6. Dynamic response for speed deviation at nominal loading condition

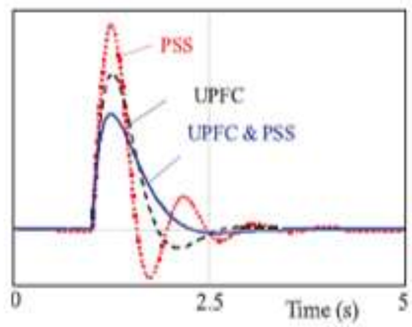

Fig. 7. Dynamic response for speed deviation at light loading condition

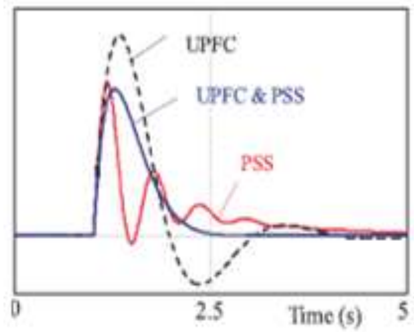

Fig. 8. Dynamic response for speed deviation at heavy loading condition

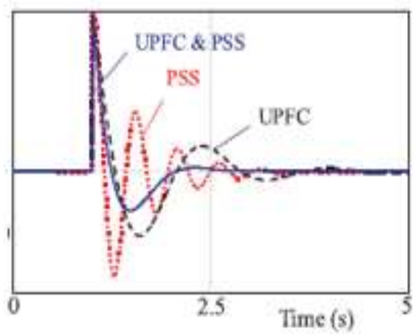

Fig. 9. Dynamic response for output electrical power at nominal loading condition

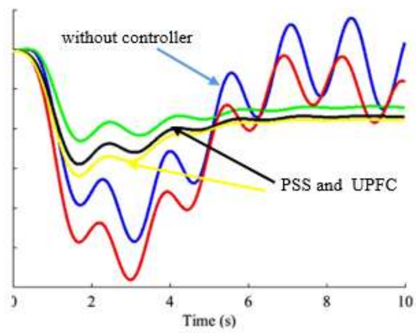

Fig. 10. Comparison of different methods of the designing of controllers

4. UPFC Optimal Placement

Finding the ideal positions and configurations for UPFC devices in power systems is very challenging, and a lot of data is frequently required. Three categories- conventional optimization (CO), sensitivity analysis (SA)-based, and Artificial Intelligence (AI)-based—can be used to categorize the techniques and approaches used in earlier research studies to determine the best locations and settings for the system equipped with UPFC. The most widely used techniques are those based on artificial intelligence, and these are also considered to be the best strategies. Power flow restrictions like reactive and active power, voltage, and power loss are all impacted by the generator failure. The ideal placement of the Facts devices as well as the selection of the appropriate signals in the power system are essential to its effective performance [69]. The best location for the FACTS controllers is extremely important to find the ideal location for UPFC controller placement in multiple applications [70]. Due to its ease of implementation in solving numerous challenging engineering optimization problems, AI is widely used [71]. To prove the practicability of the suggested method for choosing where the UPFC interface should be located in distribution or transmission networks, critical features should be investigated.

The parameters assessed include the phase angle, voltage profile, and proportion of power quality improvement, as well as the cost of the UPFC device during setup and operation, the cost of power generation, the location, number, and parameter of the UPFC device, the deviation of the voltage, the severity index, the voltage stability, and the mitigation of harmonics [72,73]. These analyses should be carried out in a specific power network, preferably the regular network of the IEEE bus system, under specific contingency conditions.

The approach to UPFC placement based on evolutionary programming and various sensitivity analyses is described in [74]. Note that, in the field of optimization, this problem was solved utilizing evolutionary algorithms.

In order to increase dynamic stability, a hybrid strategy based on optimal planning and sizing of UPFC using the combination of the Gravitational Search Algorithm (GSA) and artificial bee colony (ABC) algorithms is developed in [75]. The cuckoo search (CS) and firefly algorithm (FA) are suggested in [76], where the FA strategy optimizes the maximum power loss line as the suitable location of the UPFC, utilizing the best location and the UPFC's capacity to boost the multi-machine power system's transient and dynamic stability. In order to achieve optimal power flow and optimal placement of UPFC, a new gray wolf with a population-based update evaluation algorithm is demonstrated [77]. The real power loss before and after optimization is show in Fig.5. This reduction amounts to 28.47% of real power loss with the placement of UPFC [78].

5. Congestion Mitigation and SSR

There is an extensive power flow approach for the UPFC that is delivered in [79]. This strategy has the capacity to manage both reactive and active electrical powers as well as the voltage amplitude simultaneously. In [80], eigenvalue computation and fast Fourier transform (FFT) investigation against operating point deviations and uncertainties in the system are also analysed, along with a suggestion for mitigating sub-synchronous resonance (SSR) by employing fractional-order PI (FOPI)-based UPFC.

A comprehensive optimization framework according to sequential interpretation to optimally distribute the UPFC and TCSC with wind power generators under deregulated large-scale energy system is furnished in [81], in which the suggested strategy for optimal planning of UPFC and TCSC has been experimented with, and verified on customized IEEE 14-bus and IEEE 118-bus multi-machine energy systems. The oscillations of the generator angular frequency difference are show in Fig. 12. This figure reveals different SSR mitigation effects under various operating conditions [82].

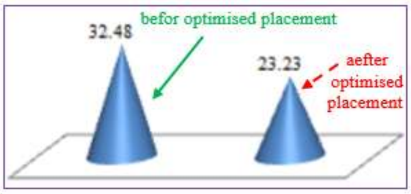

Fig. 11. Comparison of real power losses before and after optimized placement of UPFC

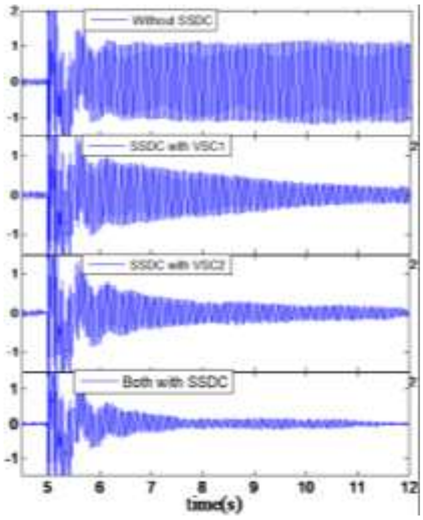

Fig. 12. SSR mitigation using subsynchronous damping controller in UPFC

6. Improve Power Oscillation Damping and Stability

Low-frequency oscillations are one of the primary problems that must be solved to guarantee the reliable operation of the power system [83,84]. Power oscillations can be triggered by a variety of factors, including faults in the transmission lines, power line switching, or a sudden change in the output of the generator [85,86]. Local plant mode oscillations, interplant mode oscillations, and inter-area mode oscillations are some of the different types of power system oscillations. The important advantage of increased energy transmission capability over the current interconnector is achieved through oscillation dampening. To reduce power system oscillations, several investigations have been carried out [87,88].

To identify the optimal control input parameters of a unified power flow controller (UPFC) for damping power system oscillations, a comparative analysis with the direct component of torque (DCT), minimum singular value (MSV), Hankel singular value (HSV), and residue has been proposed [89]. A damping control system, which is based on a generalized power-incorporated current controller, is a third-generation FACTS device that is presented in [90], to investigate its effect on reducing low-frequency oscillation. Coordinated excitation and control of UPFC to improve transient stability of power system is investigated in [91], where the power system is linearized using direct feedback linearization technique. Only local measurements are needed to design the excitation controller. Both series branch and shunt UPFC are found in the simulation results to help improve the transient stability. Fig. 13 shows the variation voltage magnitude under UPFC shunt branch control. The response power angle with UPFC control is show in Fig. 14.

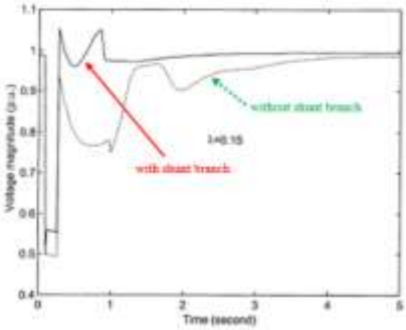

Fig. 13. Variation voltage magnitude under UPFC shunt branch control

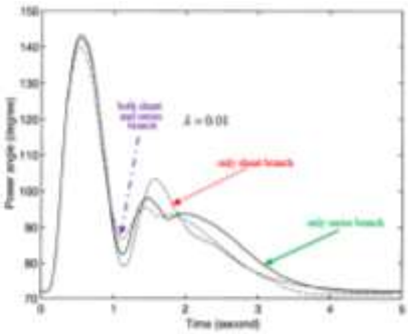

Fig. 14. Response power angle with UPFC control

7. Conclusions

By employing FACTS devices, better utilization of existing power can be recognized. An overview of one of the consequential members of the FACTS family namely UPFC is illustrated in this review paper. It is the universal FACTS controller that can control up to three tran-smi-ss-ion power system parameters individually or simultaneously in appropriate combinations. The main advantage of the UPFC is to manage the reactive and active power flows in the transmission line. Bus voltage and current flow throughout an energy system are controlled by UPFC and it is one of the most advantageous FACTS devices for load current control.

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