# Impact of Unified Power Flow Controller on ATC Enhancement by Continuation Power Flow Method

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***Abstract :*** *Operational and planning point of view, this paper focuses on the impact of UPFC on available transfer capability (ATC) enhancement. Available Transfer Capability (ATC) is a key concept in the restructuring of power systems. ATC is used by system operators to determine the ability of transmission system to transfer power and by system planners to indicate a system's strength. This paper presents the application of unified power flow controller (UPFC) to enhance the available transfer capability of a power system. Study on IEEE 14 bus power system model is presented to illustrate the effectiveness of UPFC.*

*IndexTerms - **FACTS, UPFC, ATC, Voltage Collapse, CPF, MATLAB.***

## I. INTRODUCTION

In recent years, the electricity supply industry has been undergoing restructuring or deregulation which introduces open electricity market for trading electricity between generators and suppliers in competitive environments. This transformation consists of two aspects that are related to each other, which are restructuring and privatization. Restructuring is a change in structure of commercial arrangements in selling energy. Mean while privatization is a change of ownership from the government to the private sector that helps create choices and competition [1].
The use of power electronic controllers - Flexible AC Transmission Systems (FACTS) - in electric power systems is becoming increasingly widespread due to rapid progress in power electronic technology. In the family of FACTS, there are recently developed converter based controllers, for example the Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC)**,** and Unified Power Flow Controller (UPFC) **.**
Among the converter based FACTS controllers, the UPFC is a versatile FACTS controller, which can simultaneously control a local bus voltage and power flows of a transmission line[1]. However, in the most recent research work, the UPFC is primarily used to control a local bus voltage and active and reactive power flows of a transmission line[2].
With the practical applications of the UPFC in electric power systems, it becomes of interest to explore and investigate possible control capabilities of the UPFC[3]. Power flow analysis, which has been widely used in power system operation, control and planning, is one of the fundamental power system calculations[4].

## II. FACTS DEVICES

The limitations of a power transmission network arising from environmental, right-of-way and cost problems are fundamental to both bundled and unbundled power systems. Patterns of generation that results in heavy flows tend to incur greater losses, and to threaten stability and security, ultimately make certain generation patterns economically undesirable. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS). Thyristor controlled series capacitors, thyristor controlled phase angle shifters can be utilized to change the power flow in lines by changing their parameters to achieve various objectives [4]. FACTS devices [5] provide new control facilities, both in steady state power flow control and dynamic stability control. The possibility of controlling power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably [5,6]. Using controllable components such as controllable series capacitors and phase shifters line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margin increased, contractual requirement fulfilled etc, without violating specified power dispatch. The increased interest in these devices is essentially due to two reasons.
1. The recent development in high power electronics has made these devices cost effective.
2. Secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs. There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems [6,7]. If there is no congestion, the placement of FACTS devices, from the static point of view, can be decided on the basis of reducing losses but this approach is inadequate when congestion occurs. Therefore UPFC is used and a Continuation power flow method has been considered, in this paper, for this purpose due to security and stability reasons.

## III. UNIFIED POWER FLOW CONTROLLER

The UPFC may be seen to consist of two VSCs sharing a common capacitor on their DC side and a unified control system. The UPFC allows simultaneous control of active power flow, reactive power flow, and voltage magnitude at the UPFC terminals. Alternatively, the controller may be set to control one or more of these parameters in any combination or to control none of them[8]. The active power demanded by the series converter is drawn by the shunt converter from the AC network and supplied to bus m through the DC link. The output voltage of the series converter is added to the nodal voltage, at say bus k, to boost the nodal voltage at bus m. The voltage magnitude of the output voltage $V_{se}$ provides voltage regulation, and the phase angle $\theta_{se}$ determines the mode of power flow control.
In addition to providing a supporting role in the active power exchange that takes place between the series converter and the AC system, the shunt converter may also generate or absorb reactive power in order to provide independent voltage magnitude regulation at its point of connection with the AC system.

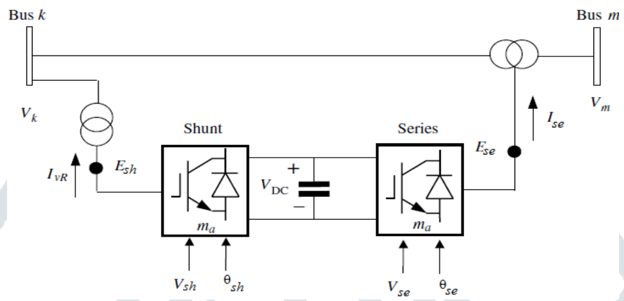
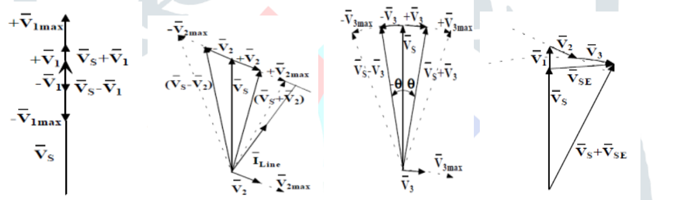



Fig-1 Unified power flow controller (UPFC) system:- two back-to-back voltage source converters (VSCs), with one VSC connected to the AC network using a shunt transformer and the second VSC connected to the AC network using a series transformer[8].



(a) (b) c) (d)
Fig. 2 Phasor diagrams

Voltage regulation is shown in Fig. 2(a). The magnitude of the sending bus voltage $V_s$ is increased (or decreased) by injecting a voltage $V_1$, of maximum magnitude $V_{1max}$, in phase (or out of phase) with $V_s$. Similar regulation can be accomplished with a transformer tap changer. Series reactive compensation is shown in Fig. 2(b) It is obtained by injecting a voltage $V_2$, of maximum magnitude $V_{2max}$, orthogonal to the line current I line . The effective voltage drop across the line impedance X is decreased (or increased) if the voltage $V_2$ lags the current Line I by 90º (or $V_2$ leads current Line I by 90º). A desired phase shift is achieved by injecting a voltage that shifts the phase angle of $V_3$, of maximum magnitude $V_{3max}$, that shifts $V_s$ by $\pm\theta$ as shown in Fig. 2(c). Simultaneous control of terminal voltage, line impedance and phase angle allows the UPFC to perform multifunctional power flow control. The magnitude and the phase angle of the series injected voltage $V_{se} = V_1 + V_2 + V_3$ shown in Fig. 2(d), are selected in such a way as to produce a line current that will result in the desired real and reactive power flow on the transmission line.

### *A. Steady State Model*

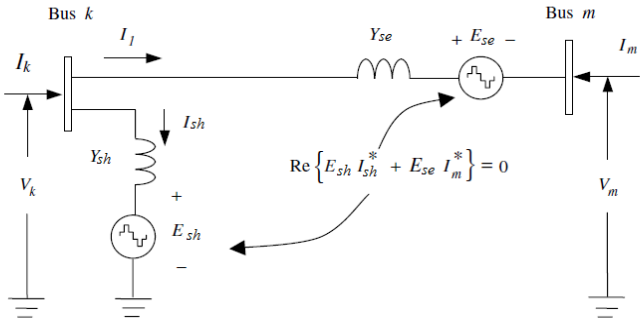



Fig-3 Equivalent circuit based on solid-state voltage sources[8].

The UPFC voltage sources are:

$$E_{se} = V_{se}(\cos\theta_{se} + j\sin\theta_{se}) \quad (1)$$

$$E_{sh} = V_{sh}(\cos\theta_{sh} + j\sin\theta_{sh}) \quad (2)$$

where $V_{sh}$ and $\theta_{sh}$ are the controllable magnitude ($V_{shmin} \leq V_{sh} \leq V_{shmax}$) and phase angle($0 \leq \theta_{sh} \leq 2\Pi$) of the voltage source representing the shunt converter. The magnitude $V_{se}$ and phase angle $\theta_{cR}$ of the voltage source representing the series converter are controlled between limits ($V_{semin} \leq V_{se} \leq V_{semax}$) and ($0 \leq \theta_{se} \leq 2\Pi$), respectively. The phase angle of the series-injected voltage determines the mode of power flow control. If $\theta_{se}$ is in phase with the nodal voltage angle $\theta_k$, the UPFC regulates the terminal voltage. If $\theta_{se}$ is in quadature with respect to $\theta_k$, it controls active power flow, acting as a phase shifter. If $\theta_{se}$ is in quadrature with the line current angle then it controls active power flow, acting as a variable series compensator. At any other value of $\theta_{se}$, the UPFC operates as a combination of voltage regulator, variable series compensator, and phase shifter. The magnitude of the series-injected voltage determines the amount of power flow to be controlled[8].

## IV. AVAILABLE TRANSFER CAPABILITY

Available Transfer Capability (ATC) is the measurement of the transfer capability remaining in the physical transmission network for further commercial activity, over and above already committed uses. The reasoning behind the development of ATC is based on several principles developed by the North American Electric Reliability Council's (NERC) [9]. ATC must recognize time-variant power flow conditions and the effects of simultaneous transfers/parallel path flow from reliability Viewpoint. The electric utilities' ATC strategy must include flexibility in allowing for different transfer capabilities over time and reasonably capture these capabilities in a time variant posting[10]. ATC calculations must be dependent on the points of electric power injection, the directions of transfers across the network and the points of delivery. In short, ATC can be defined as, [9]

ATC = TTC – CBM – TRM – "EXISTING TC"

Where, TTC represents total transfer capability. The amount of power that can be transferred over the interconnected transmission network in a reliable manner while meeting a specific set of pre-and post-contingency system conditions. This capacity is defined by the worst contingency for the defined point-to-point path and the thermal, voltage and/or stability limits of the path. CBM represents capacity benefit margin[11]. The amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements. TRM represents transmission reliability margin[11]. The amount of transmission transfer capability needed to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

## V. VOLTAGE STABILITY

As power systems become more complex and heavily loaded, voltage collapse becomes an increasingly serious problem. Voltage collapse has already occurred in real-world electric power systems. Fortunately, practical analytical tools will soon be making their ways from researchers to system designers and operators [12]. A large, nonlinear, interconnected power network can exhibit very complex dynamic phenomena when the system is disturbed from a steady-state operating condition. To complicate things even more, power systems are becoming more heavily loaded as the demand for electric power rises, while economic and environmental concerns capacity. Under these stressful operating conditions, we are encountering a new instability problem called voltage collapse, which has led to blackouts in electric utilities around the world. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse [13].

Voltage collapse[14] phenomena in power systems have become one of the important concerns in the power industry over the last two decades, as this has been the major reason for several major blackouts that have occurred throughout the world including the recent Northeast Power outage in North America in August 2003. Point of collapse method and continuation method are used for voltage collapse studies [13]. Of these two techniques, continuation power flow (CPF) method is used for voltage analysis. These techniquesinvolve the identification of the system equilibrium points or voltage collapse points where the related power flow Jacobian becomes singular [11]. Usually, placing adequate reactive power support at the "weakest bus" enhances static voltage stability margins. The weakest bus is defined as the bus, which is nearest to experiencing a voltage collapse. Equivalently, the weakest bus is one that has a large ratio of differential change in voltage to differential change in load ($\partial V/\partial P$total). Changes in voltage at each bus for a given change in system load are available from the tangent vector, which can be readily obtained from the predictor steps in the CPF process[12]. In addition to the above method, the weakest bus could be obtained by looking at right eigenvectors associated with the smallest eigen value as well. Each FACTS device has different characteristics; some of them may be problematic as far as the static voltage stability is concerned. Therefore, it is important to study their behaviors in order to use them effectively.

## VI. ATC-CONTINUATION METHOD

One way to compute transfer capability with a software model is called continuation. From the solved base case, power flow solutions are sought for increasing amounts of transfer in the specified direction [11]. The quantity of the transfer is a scalar parameter, which can be varied in the model. The amount of transfer is gradually increased from the base case until a binding limit is encountered [15]. This continuation process requires a series of power system solutions to be solved and tested for limits

[15]. The transfer capability is the change in the amount of transfer from the base case transfer at the limiting point. Continuation can be simply done as a series of load flow calculations for increasing amounts of transfers [16]. However, when convergence could be poor such as the case for transfers approaching voltage instability, methods that allow the transfer parameter to become a dependent variable of the model are the most successful [11].
Continuation Power Flow (CPF) is a method for finding the maximum value of a scalar parameter in a linear function of changes in injections at a set of buses in a power flow problem[15]. Originally introduced for determining maximum loadability, CPF is adaptable, without change in principle, for other applications, including ATC. The CPF algorithm effectively increases the controlling parameter in discrete steps and solves the resulting power flow problem at each step[11,16]. The procedure is continued until a given condition or physical limit preventing further increase is reached[11,17]. Because of solution difficulty and the need for the Jacobean matrix at each step, the Newton power flow algorithm is used. CPF yields solution even at voltage collapse points. Therefore CPF has four important elements: predictor, step length control, parameterization strategy and corrector[11].

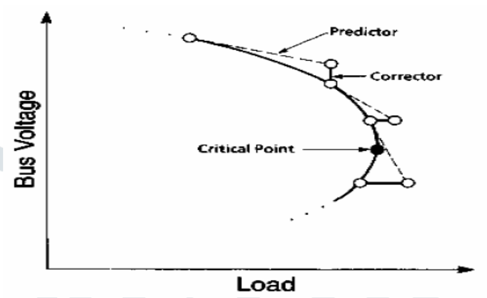


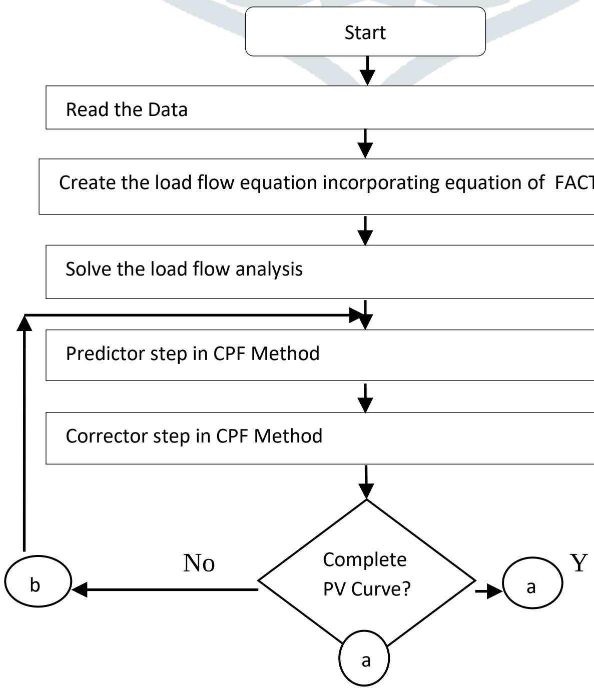

Figure 4: The predictor – corrector scheme[11,15]

A. *Predictor and Step Length Control*

The predictor with step length control provides an initial estimate of the state variables for power flow solution for the next step increase in transfer power[11,15]. Without a good starting approximation for each step, the power flow algorithm will fail to converge or converges to an extraneous solution.

B. *Corrector and Parameterization*

The corrector is a slightly modified Newton power flow algorithm in which the Jacobian matrix is augmented. Because the number of state variables for power flow solution is unchanged, it is necessary, at each step of CPF, to select and assign a value to one variable[11,15]. This is called local parameterization. The selection and assigned value are made by CPF.



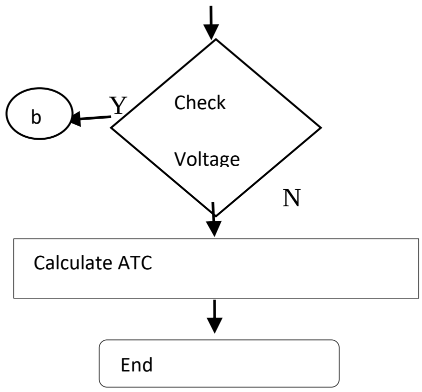



Fig.5:-Flowchart of CPF process with FACTS for ATC Calculation

### VII. RESULTS & DISCUSSION

IEEE 14-bus test system as shown in Fig. 6 is used for voltage stability studies. The test system consists of 5 generators and 11 PQ bus (or load bus).

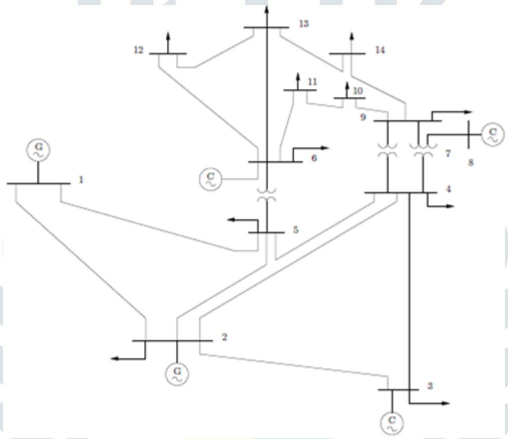


Fig.6:- IEEE 14 bus system

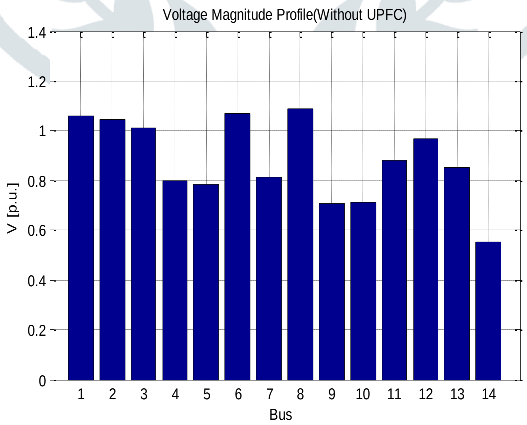



Fig.7:-Voltage magnitude by CPF[Without UPFC]

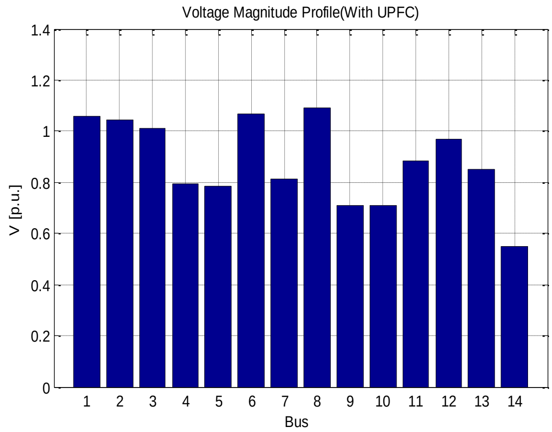



Fig.8:- Voltage Magnitude by CPF[With UPFC]

During ATC enhancement, it is necessary to find out the voltage magnitude (as shown in Fig. 7 & Fig. 8) at each bus so that the security and stability can be maintained. Therefore it is necessary to know the weak bus in the system and with that bus the point at which the voltage collapse (as shown in Fig. 9) can occur, can be obtained.

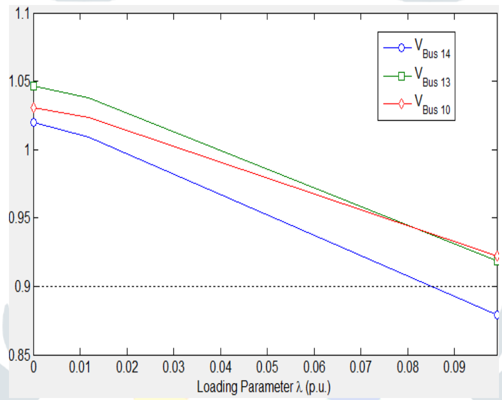



Fig.9:- Voltage collapse [With UPFC]

The result [Table.1] of ATC calculation is a CPF (Continuation Power Flow) routine based method on a Newton Raphson power flow algorithm. The CPF is limited by the Jacobian matrix becoming singular and could not be converged. The amount of CPF processing is reduced using larger steps to find the initial ATC before it is reprocessed again using a smaller step to increase the accuracy.

An accurate ATC computation is also very important to the transmission system. If the computed ATC is less than the ATC of the system, the transmission of power will not be efficient economically, if the computed ATC is more than the ATC of the system, the transmission will be operating in a dangerous state and any power increased will stand a chance to collapse the whole system and the result of that is disastrous.

The Table below shows the ATC enhancement with and without UPFC for 15 line out of 20 line because while calculating voltage collapse point the other 5 line are the most critical lines in which the collapse can occur promptly and simultaneously.

Table.1:- ATC calculation at each line with and without UPFC

| Line | Base MW | ATC Without UPFC | ATC With UPFC | TTC |
|---|---|---|---|---|
| Line1-2 | 160 | 78 | 83 | 238 |
| Line 1-5 | 75 | 41 | 45 | 116 |
| Line 2-3 | 76 | 10 | 14 | 86 |
| Line 2-4 | 56 | 15 | 23 | 71 |
| Line 2-5 | 41 | 30 | 33 | 71 |
| Line 4-3 | 21 | 3 | 9 | 24 |
| Line 5-4 | 59 | 7 | 11 | 66 |
| Line 4-7 | 27 | 16 | 19 | 43 |
| Line 4-9 | 16 | 9 | 11 | 25 |
| Line 5-6 | 46 | 19 | 22 | 65 |
| Line 6- | 8 | 25 | 29 | 33 |

| | | | | |
|---|---|---|---|---|
| 11 | | | | |
| Line 6-12 | 8 | 2 | 5 | 10 |
| Line 7-9 | 27 | 16 | 19 | 43 |
| Line 9-10 | 5 | 23 | 24 | 28 |
| Line 11-10 | 5 | 14 | 15 | 19 |

As mentioned earlier, UPFC enables controlling line flow and regulating nodal voltage simultaneously. In order to further escalate the ATC by eliminating the critical voltage of node 14. Comparing the ATC levels, the considerable difference highlights the superior performance of the UPFC on ATC improvement. In this case, with the FACTS control to regulate the voltage and to alleviate the heavy loading burden, the occurrence of a critical situation has been postponed. It can be said that with the ability of flexible power-flow control, FACTS devices can enhance ATC to a great degree. Among them, as the most advanced and versatile FACTS devices with functions of supporting voltage and readjusting line flow simultaneously, UPFC can play an important and unique role in ATC boosting.

From Fig.10, it is observed that using UPFC the ATC is enhanced substantially by almost 7%-18.3% at each bus and thus UPFC can offer an effective and promising solution to boost the usable power-transfer capability, thereby improving transmission services of the present market-based power systems.

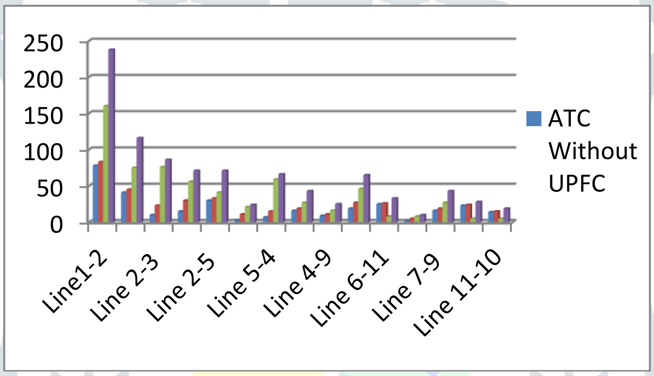



Fig.10:- ATC Enhancement at each line with and without UPFC

## VIII. CONCLUSIONS

ATC Enhancement is an important issue in restructuring the electrical power systems. Based on operating limitations of the transmission system and control capabilities of FACTS technology, technical feasibility of applying FACTS devices to boost ATCs are analyzed and identified.

A CPF-based ATC enhancement is presented to achieve the maximum possible ATC value with FACTS control. With the IEEE 14-bus system as a testing bed, case studies have been conducted using UPFC. The results demonstrated that the use of the UPFC, which enables the balance of line flow and regulate node voltage simultaneously, can enhance the ATC substantially. The considerable difference between the ATC values with and without FACTS control supports FACTS applications for ATC enhancement quantitatively.

In the present paper, the impacts of UPFC on ATC improvement are investigated. The case study has been implemented on a IEEE 14-bus power system. From the numerical results, it can be seen that UPFC increases TTC causing the ATC to improve, and leading to better utilization of transmission grids. Moreover, the results show a maximum 18.3% improvement in ATC by installing UPFC.

Finally, it is to be pointed out that FACTS technology can offer an effective and promising solution to boost the usable power-transfer capability, and also the effect of FACTS devices on ATC enhancement is system dependent, thereby improving transmission services of the present market-based power systems.

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