Investigation of the Effects of FACTS Devices on the Voltage Stability of Power Systems

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***Abstract*—In parallel with the technological advances, the electrical power demand is constantly increasing and this makes the voltage stability difficult for the electrical power systems. At this point, FACTS (Flexible AC Transmission System) devices come into prominence in order to provide the voltage stability and increase the power transfer capacity. In this study, the most critical buses are determined by making the continuous power flow analysis on the IEEE 14-bus power system. Then, the FACTS devices SVC (static VAr compensator), UPFC (unified power flow controller), STATCOM (static synchronous compensator) and SSSC (static synchronous series compensator) are used to provide the voltage stability. For the cases with/without FACTS devices, the maximum loading limits of the most critical buses are compared by utilizing the bus voltage and bus angle values, and the λ-V curves. In consequene, many comparative assessments are made related to the voltage stability enhancement in power systems.**

Keywords*—Power systems; voltage stability; SVC; UPFC; STATCOM; SSSC

I. INTRODUCTION

Nowadays, the electricity demand is increasing day by day with the technological developments. This increasing energy demand is driving the power systems to work near the boundary of instability region. This condition creates the problem of voltage stability in power systems. The voltage stability is expressed as the ability to maintain the voltages of all buses constant after the power system has been subjected to a disruptive effect on a given initial operating condition [1, 2]. In power systems, the implementation of Flexible AC Transmission System (FACTS) devices is intensively preferred in order to minimize the voltage unstability.

FACTS devices are the power electronic-based equipments. FACTS devices improve the voltage instability in a more rapid and effective manner in the power systems that are expanding and overloaded [3, 4]. FACTS devices can change the parameters such as impedance, voltage and phase angle in a power system [5]. By means of them, the power flow in the overloaded lines is reduced and thus, the low system loss is occurred with respect to the increasing load demand. In addition, they provide the control possibilities both in the steady-state power flow control and in the dynamic stability control [6, 7].

In the literature, many studies have been made to improve the voltage stability of power systems with the FACTS devices. *Nikouei et. al.* used the SSSC to prevent the voltage drops in power systems and developed a system that does not need to use any filter for quickly responding the voltage drops [8]. *Conka et. al.* examined the effect of thyristor controlled series capacitor (TCSC) on the transient stability of the Slovak power transmission system. The settling time and the size of active power swings were found shorter and smaller with TCSC, respectively [9]. *Musunuri et. al.* compared STATCOM, SVC, SSSC and TCSC in terms of the steady-state voltage stability and the shunt devices provided the best performance for reducing the voltage collapse in comparison to the series compensation [10]. *Vanitha et. al.* improved the fuzzy differential evolution algorithm to solve the multiobjective optimal power flow with FACTS devices. The proposed optimization technique maximized the loadability condition of the power system with minimum installation costs of FACTS devices [11]. *Telang et. al.* applied the voltage stability indices under the load increase scenario and the voltage stability of the entire power system was improved by the properly placed STATCOM [12]. *Dosoglu et. al.* investigated the effects of phase-shifting transformers on the voltage stability of the IEEE 14-bus power system and the maximum loading limits decreased between the phase angles of 10 and 30 degrees [13]. *Valle et. al.* examined the influence of generalized UPFC device on the small signal stability of power systems and enhanced the damping of small oscillations [14]. *Gautam et. al.* determined the optimum location and capability of SVC and TCSC in the power transmission line and the power transfer capability and stability of the IEEE 5-bus power sytem was developed [15]. *Saravanan et. al.* applied the particle swarm optimization technique in IEEE 6-, 30- and 118-bus power systems in order to find the minimum installation cost and the optimum location of FACTS devices. It was observed that UPFC ensured the maximum loadability at high cost, TCSC offered the relatively good loadability with less cost and SVC had the lowest cost but the least loadability [16]. *D. Choudhary.* also showed the the effectiveness of SVC, STATCOM and TCSC in improving voltage magnitude profile, maximum loading point, active and reactive power losses [17].

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In this study, as a base case, a continuous power flow analysis is initially performed on the IEEE 14-bus power system in order to calculate the bus voltage and bus angle values. Later, the maximum loading limits of the most critical buses are analyzed by means of the case studies that connect SVC, UPFC, STATCOM and SSSC devices to the corresponding power system, respectively. As a result, the effects of the mentioned FACTS devices on the power system voltage stability are investigated in detail and it is observed that UPFC comes into prominence as the most effective FACTS device among all case studies.

II. FACTS DEVICES

IEEE describes FACTS devices as; a system and a static device consisting of power electronic components for controlling one or more transmission line parameters to increase controllability and power transmission in power systems [18, 19]. FACTS devices provide the stability of power systems by means of suitable compensation of series impedances, currents, voltages and active-reactive powers of the lines in a power system [20]. FACTS devices have two main functions in power systems [21]: First one is to increase the power transfer capacity of the transmission line in a power system. Second one is to perform the power flow control of the designated transmission lines. SVC, UPFC, STATCOM and SSSC FACTS devices used in this study are described below.

A. SVC (Static VAr Compensator)

The SVC is a FACTS device that shunts transmission lines. The main function of it is to inject a capacitive or inductive current according to the system state of the bus to which it is connected [22]. It provides to control the system voltage within the defined values by controlling the reactive power drawn from the line in power systems. The most common types of it are the fixed capacitor-thyristor controlled reactor (FC-TCR) and the thyristor-switched capacitor (TSC). The general structure of SVC is shown in Figure 1.

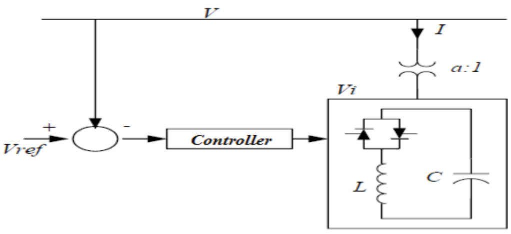

Fig. 1. The general structure of SVC [22]

B. UPFC (Unified Power Flow Controller)

The UPFC is one of the most effective FACTS devices for power systems [23]. It performs the active control and the dynamic compensation of transmission lines in power systems. Figure 2 shows the general structure of UPFC. It consists of the combination of a STATCOM and a SSSC. Here, Converters 1 and 2 represent the STATCOM and SSSC, respectively. In this case, the active power of the system works as an AC-to-AC power converter that allows the bi-directional power flow between STATCOM and SSSC connection. In addition, STATCOM and SSSC devices can independently generate or consump reactive power [24, 25].

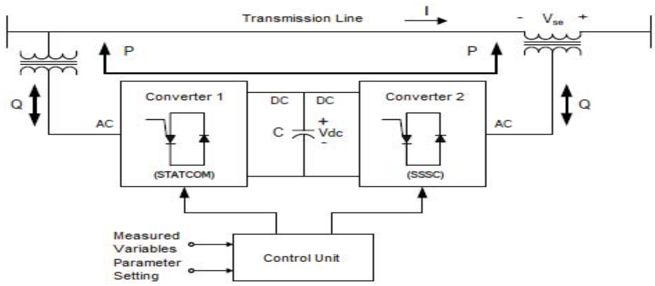

Fig. 2. The general structure of UPFC [24]

C. STATCOM (Static Synchronous Compensator)

STATCOMs are the FACTS devices that are shunted to transmission lines. The STATCOM device consists of a connection transformer, a converter and a direct current capacitor [26]. Here, V and V_o are the system's AC voltage and the output voltage of STATCOM, respectively. In order to improve the bus voltage to which it is connected, it may supply the reactive power to transmission lines or it may consume the reactive power from transmission lines [27, 28]. The general structure of STATCOM is shown in Figure 3.

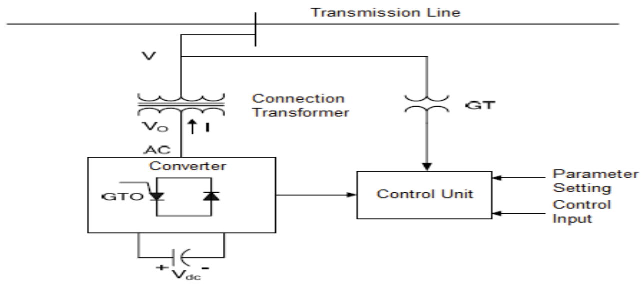

Fig. 3. The general structure of STATCOM [29, 30]

D. SSSC (Static Synchronous Series Compensator)

The SSSCs are the FACTS devices that are connected in series to the transmission line in a power system. The SSSC generates a three-phase balanced voltage with the phase angle of 90 degrees to the line current, whose amplitude and angle can be quickly changed by the power electronic components. The active and reactive power control is possible with the SSSC. A small DC capacitor is sufficient for the reactive power control. The SSSC can operate as a series capacitor or reactor depending on the effect of the voltage applied to the transmission line. The transmitted active power increases in the capacitive operating states, while it decreases in the same manner in the inductive operating states [31]. Figure 4 shows the general structure of SSSC.

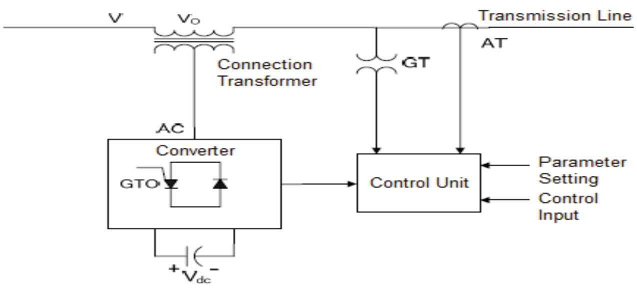

Fig. 4. The general structure of SSSC [31]

III. Case Study and Simulation Results

In this study, the IEEE 14-bus power system is used by means of the Power System Analysis Toolbox (PSAT) of MATLAB [32]. In this power system, firstly, the most critical buses are determined according to the bus voltage and bus angle values by making the continuous power flow analysis. As a result, the buses numbered as 4, 5, 9 and 14 are determined as the most critical buses. It should be noted that the bus 14 among the buses 4, 5, 9 and 14 Using the PSAT, bus voltages, bus angles and λ-V (Maximum loading limit-Bus voltage) curves of the buses 4, 5, 9 and 14 are compared both for the base case (without FACTS devices) and for the case after connecting FACTS devices (SVC, UPFC, STATCOM and SSSC). Figure 5 illustrates the general scheme of IEEE 14-bus power system [10].

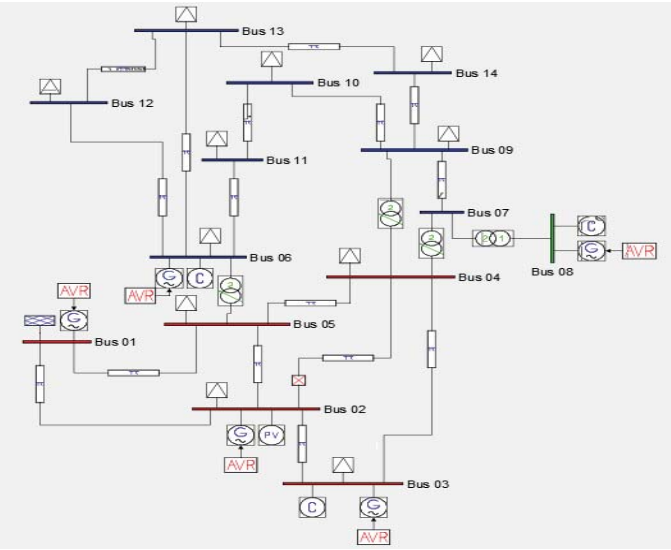

Fig. 5. The general scheme of IEEE 14-bus power system

A. *The Base Case*

The voltage and angle values of all buses for the continuous power flow analysis performed in the base case are given in Table I. The maximum voltage drops are occurred in the buses 4, 5, 9 and 14. Figures 6(a) and 6(b) illustrate the bus voltage and bus angle values. In addition, the maximum loading limit λ is computed as 2.8236 in the base case. The λ-V curves of the buses 4, 5, 9 and 14 are depicted in Figure 6(c).

TABLE I. The Continuous Power Flow Analysis Results in the Base Case

Bus No	Bus Voltage (p.u.)	Bus Angle (rad)
1	1.06	0
2	1.045	-0.671260933
3	1.01	-1.560352433
4	0.67810746	-1.291448337
5	0.659688679	-1.101364957
6	1.07	-1.943176314
7	0.781416671	-1.71210907
8	1.09	-1.71210907
9	0.683254067	-1.931876171
10	0.708582656	-1.970675096
11	0.868994253	-1.963738847
12	0.975025172	-2.012396091
13	0.92345597	-2.012584447
14	0.670460317	-2.114731041

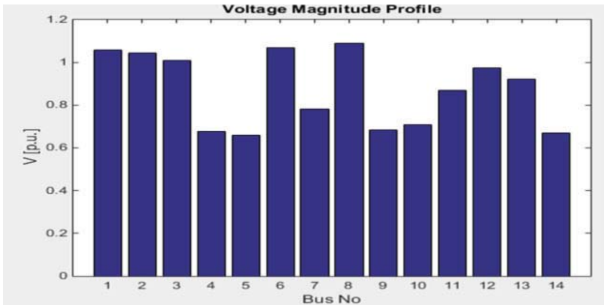

Fig. 6(a). The bus voltage values in the base case

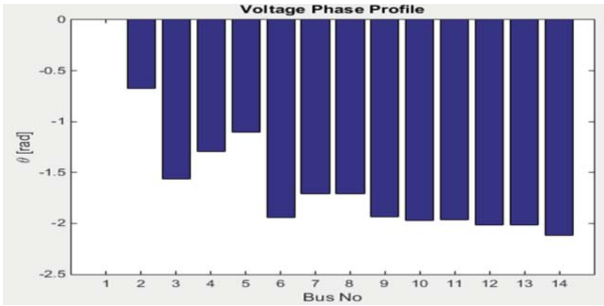

Fig. 6(b). The bus angle values in the base case

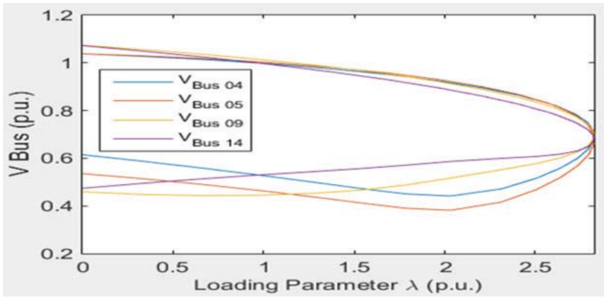

Fig. 6(c). The λ-V curves of the buses 4, 5, 9 and 14 in the base case (λ=2.8236)

B. *The Case After Connecting SVC*

In this case, the SVC device is installed in the bus 14. The voltage and angle values of all buses for the continuous power flow analysis performed in the case after connecting SVC are given in Table II. Figures 7(a) and 7(b) show the bus voltage and bus angle values. It is seen that the bus voltage and bus angle values are improved in comparing with the base case. Also, the maximum loading limit λ is calculated as 2.8981 in the case after connecting SVC. The λ-V curves of the buses 4, 5, 9 and 14 are presented in Figure 7(c).

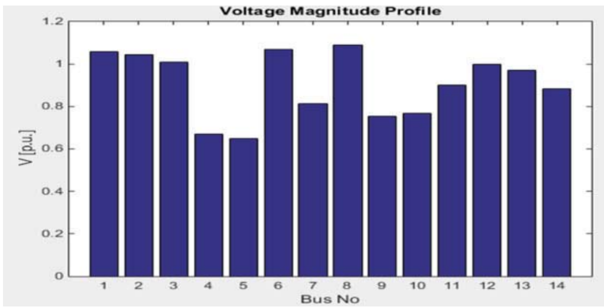

Fig. 7(a). The bus voltages in the case after connecting SVC

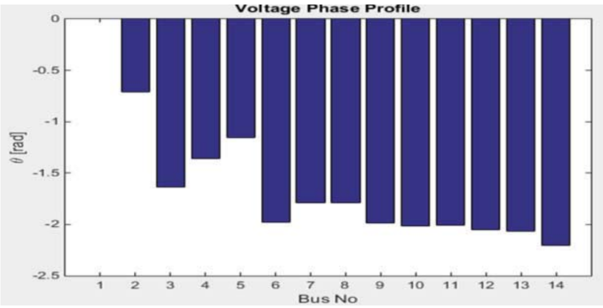

Fig. 7(b). The bus angles in the case after connecting SVC

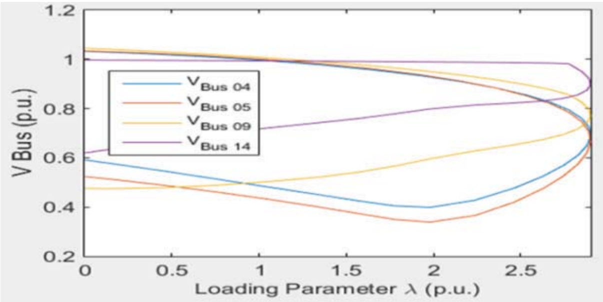

Fig. 7(c). The λ-V curves of the buses 4, 5, 9 and 14 in the case after connecting SVC (λ=2.8981)

TABLE II. THE CONTINUOUS POWER FLOW ANALYSIS RESULTS IN THE CASE AFTER CONNECTING SVC

Bus No	Bus Voltage (p.u.)	Bus Angle (rad)
1	1.06	0
2	1.045	-0.6655
3	1.01	-1.5476
4	0.70873	-1.2744
5	0.69144	-1.0833
6	1.07	-1.8306
7	0.83753	-1.6636
8	1.09	-1.6636
9	0.78125	-1.8469
10	0.79253	-1.8765
11	0.91208	-1.8602
12	1.0027	-1.9029
13	0.9769	-1.9178
14	0.90862	-2.2057

C. The Case After Connecting UPFC

In this case, the UPFC device is installed between the lines 13 and 14. The voltage and angle values of all buses for the continuous power flow analysis performed in the case after connecting UPFC are given in Table III.

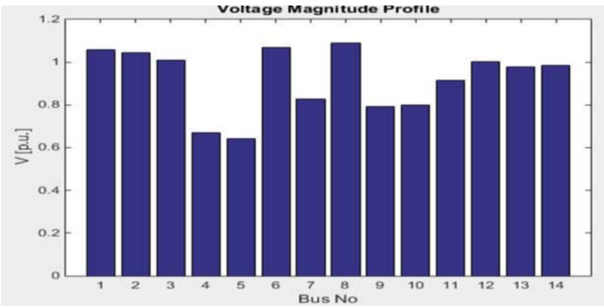

Fig. 8(a). The bus voltage values in the case after connecting UPFC

Figures 8(a) and 8(b) illustrate the bus voltage and bus angle values. Similarly, it is observed that the bus voltage and bus angle values are improved in comparison to the base case. Also, the maximum loading limit λ is computed as 2.919 in the case after connecting UPFC. The λ-V curves of the buses 4, 5, 9 and 14 are depicted in Figure 8(c).

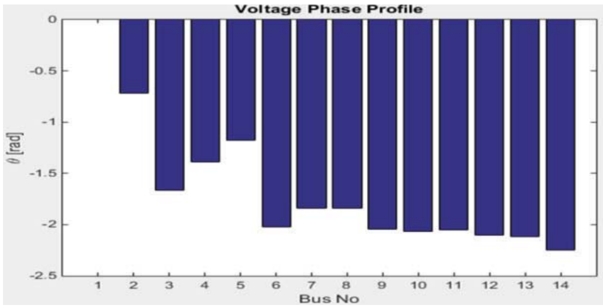

Fig. 8(b). The bus angle values in the case after connecting UPFC

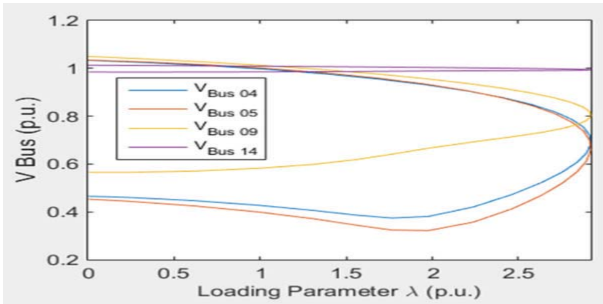

Fig. 8(c). The λ-V curves of the buses 4, 5, 9 and 14 in the case after connecting UPFC (λ=2.919)

TABLE III. THE CONTINUOUS POWER FLOW ANALYSIS RESULTS IN THE CASE AFTER CONNECTING UPFC

Bus No	Bus Voltage (p.u.)	Bus Angle (rad)
1	1.06	0
2	1.045	-0.67785
3	1.01	-1.5724
4	0.70724	-1.2977
5	0.6845	-1.1048
6	1.07	-1.8786
7	0.84777	-1.7152
8	1.09	-1.7152
9	0.80954	-1.9069
10	0.81661	-1.9305
11	0.9244	-1.9113
12	1.0034	-1.9538
13	0.97778	-1.9718
14	0.98754	-2.1028

D. The Case After Connecting STATCOM

In this case, the STATCOM device is installed in the bus 14. The voltage and angle values of all buses for the continuous power flow analysis performed in the case after connecting STATCOM are given in Table IV. Figures 9(a) and 9(b) show the bus voltage and bus angle values. Similarly, it is seen that the bus voltage and bus angle values are improved in comparing with the base case. Also, the maximum loading limit λ is calculated as 2.9061 in the case after connecting STATCOM. The λ-V curves of the buses 4, 5, 9 and 14 are presented in Figure 9(c).

TABLE IV. THE CONTINUOUS POWER FLOW ANALYSIS RESULTS IN THE CASE AFTER CONNECTING STATCOM

Bus No	Bus Voltage (p.u.)	Bus Angle (rad)
1	1.06	0
2	1.045	-0.7037
3	1.01	-1.6281
4	0.68279	-1.3537
5	0.67755	-1.1501
6	1.07	-1.9673
7	0.83045	-1.8012
8	1.09	-1.8012
9	0.79027	-2.0037
10	0.80001	-2.0263
11	0.91565	-2.0028
12	1.00966	-2.0425
13	0.98948	-2.0632
14	0.96916	-2.2262

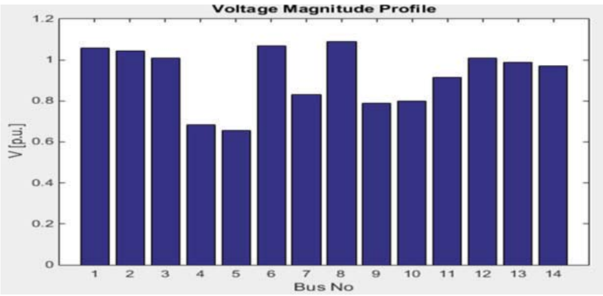

Fig. 9(a). The bus voltage values in the case after connecting STATCOM

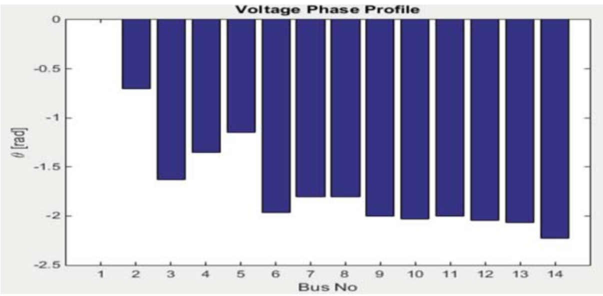

Fig. 9(b). The bus angle values in the case after connecting STATCOM

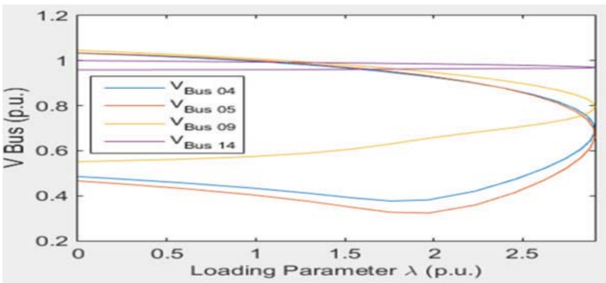

Fig. 9(c). The λ-V curves of the buses 4, 5, 9 and 14 in the case after connecting STATCOM (λ=2.9061)

E. The Case After Connecting SSSC

In this case, the SSSC device is installed between the lines 13 and 14. The voltage and angle values of all buses for the continuous power flow analysis performed in the case after connecting SSSC are given in Table V. Figures 10(a) and 10(b) illustrate the bus voltage and bus angle values. Similarly, it is observed that the bus voltage and bus angle values are improved in comparison to the base case. Also, the maximum loading limit λ is computed as 2.8414 in the case after connecting SSSC. The λ-V curves of the buses 4, 5, 9 and 14 are depicted in Figure 10(c).

TABLE V. THE CONTINUOUS POWER FLOW ANALYSIS RESULTS IN THE CASE AFTER CONNECTING SSSC

Bus No	Bus Voltage (p.u.)	Bus Angle (rad)
1	1.06	0
2	1.045	-0.6991
3	1.01	-1.6245
4	0.68043	-1.3482
5	0.67778	-1.1473
6	1.07	-2.0228
7	0.77355	-1.8168
8	1.09	-1.8168
9	0.68498	-2.0533
10	0.70921	-2.0823
11	0.86855	-2.0567
12	0.96860	-2.0870
13	0.91380	-2.0780
14	0.70258	-2.2561

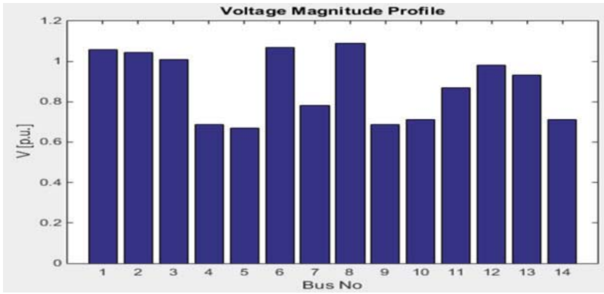

Fig. 10(a). The bus voltage values in the case after connecting SSSC

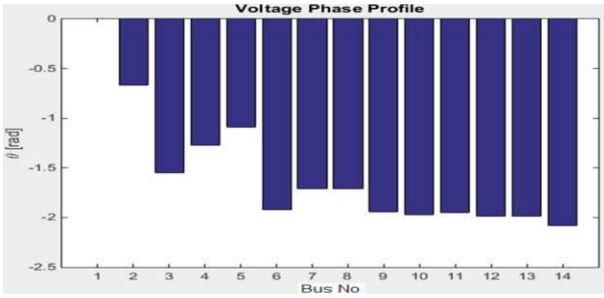

Fig. 10(b). The bus angle values in the case after connecting SSSC

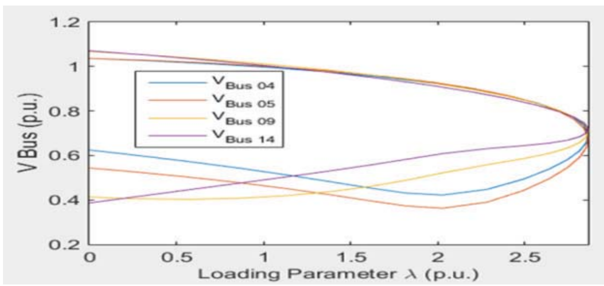

Fig. 10(c). The λ-V curves of the buses 4, 5, 9 and 14 in the case after connecting SSSC (λ=2.8414)

In addition to these evaluations, by means of Table VI, the voltage values of the buses 4, 5, 9 and 14 and the maximum loading limits (λ) are compared considering the cases with/without FACTS devices. As a result, it is obvious that the bus voltage values and the maximum loading limits are improved in the cases with FACTS devices in comparing with the ones without FACTS devices (base case). Besides, it is observed that the best results among the FACTS devices are obtained with the UPFC.

TABLE VI. THE VOLTAGE VALUES OF THE BUSES 4, 5, 9 AND 14 AND THE MAXIMUM LOADING LIMITS

	Base Case	With SVC	With UPFC	With STATCOM	With SSSC
$V_{Bus\ 4}$ (p.u.)	0,6781	0,7087	0,7072	0,6828	0,6804
$V_{Bus\ 5}$ (p.u.)	0,6597	0,6914	0,6845	0,6776	0,6778
$V_{Bus\ 9}$ (p.u.)	0,6833	0,7813	0,8095	0,7903	0,6850
$V_{Bus\ 14}$ (p.u.)	0,6705	0,9086	0,9875	0,9692	0,7026
λ	2,8236	2,8981	2,919	2,9061	2,8414

IV. CONCLUSIONS

In this study, we use the FACTS devices SVC, UPFC, STATCOM and SSSC in the IEEE 14-bus power system in order to analyze the voltage stability. As a result of the analyses conducted, initially, it is seen that the bus voltage values are improved in the cases after connecting FACTS devices, while the ones drop in the base case. Afterwards, it is also found that the maximum loading limits increase with the FACTS devices. Among FACTS devices, the best results are obtained when using the UPFC device. Despite that, the worst results occur when using the SSSC device. In consequence of overall evaluations, FACTS devices provide the voltage stability of power systems and increase the maximum loading limits of power systems. With the further developments in power electronics, more efficient FACTS devices will be employed for achieving more system stability.

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