A comparative study of the impact of FACTS devices on the voltage stability in the power systems

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Abstract. Over the past few decades, demand for electricity has increased significantly, whereas expansions in power generation and transmission have been severely restricted due to resource constraints and environmental constraints. As a result, most transmission lines were heavily loaded, and efficiency of the power system became a limiting factor for transmitting electrical power. It is considered a major and demanding problem to establish a secure and stable operation of the electricity networks. Because of its significance, the voltage stability of the power systems has received considerable attention from researchers. Therefore, this paper sheds light on a substantial number of the adopted techniques, including STATCOM and SVC devices to achieve this purpose. A case study was deemed to be an IEEE bus-14 device. To simulate this analysis, a MATLAB package has been utilized. The simulation results showed that by using these methods, the voltage stability of the related system is considerably improved.

1. Introduction
The growing demand for electricity and power transferability among utilities has consolidated apprehensions about voltage security of the power system. Voltage collapse has been considered responsible for a lot of main turbulences. Accordingly, a number of researchers attempted to comprehend voltage phenomena. Most of these researchers focused on voltage stability under steady-state conditions [1]. Undeniably, many researchers have projected voltage stability index depending on load flow analysis. A specific issue that is being investigated in such studies is that the Jacobian matrix of a Newton-Raphson method becomes a singular at the steady-state voltage stability limit. Therefore, load flow solutions close to the critical point are exposed to divergence. Hence, accuracy computation algorithms have been employed to vanquish mathematical instability. A bus liability in the electrical network relies on the reactive power provided by the power system. Different abnormal conditions contribute to emerging voltage instability, including disruption and load demand proliferation, which cause a considerable decline in the voltage profile of the power system. Once the power system reaches the voltage collapse or the critical loading point, reactive and real power losses escalate promptly. Hence, the reactive power support has to be sufficient to meet the system requirement. Instability of the system voltage can contribute to decreasing reactive power and voltage of the proposed system [2]. This situation could be noticed by plotting power transmitted against voltage at the receiving end, which is called PV curve. Maximum load ability of the system that can be met before approaching the nose point is termed system margin. An increase in the power transferred leads to decreasing the voltage at the receiving end. This ultimately results in the vulnerable point and reactive power minimization in the power supply which leads to voltage collapse. In order to preserve the power network from collapse, the reactive power load must be reduced by adding supplemental...
reactive power near to voltage collapse point. In this regard, a variety of techniques have been used to avoid voltage collapse, including load shedding, reactive power compensation and distributed generations [3]. In this paper, FACTS devices such as STATCOM and SVC are used to enhance the voltage stability.

1. FACTS devices overview

Flexible AC Transmission Systems (FACTS) such as the Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC) are commonly used in power networks because of their ability to provide dynamic power flow control. Additionally, FACTS devices have several benefits for the power systems including voltage stability enhancement, power transfer improvement, power losses reduction, compensation of reactive power and boost system security [4] [5]. Therefore, the use of these devices had become an essential part in power systems, especially wind farms [6]. This section will discuss clearly the models and the work of several main types of fact devices which are STATCOM and SVC.

1.1. SVC Devices

SVC is classed as one of the most popular FACTS devices in terms of the installation in the world grids. This is because it is characterized by its ability to adjust reactive power to enhance system voltage [4]. In fact, it absorbs surplus reactive power, leading to decreasing bus voltage where it is installed. Otherwise, in the case of reactive power shortage, it works as a capacitor to provide the reactive power required in the system to elevate voltage magnitude. It is worth mentioning that there are two key structures of SVC, which are a fixed capacitor (FC) coupled with the thyristor controlled reactor (TCR), and thyristor switched capacitor (TSC) with the thyristor controlled reactor (TCR), as illustrated in figures 1 and 2. The TSC can lessen standby power losses. But, from steady-state view, this should be analogous to the fixed capacitor-thyristor controlled reactor (FC-TCR) [7]. The FC-TCR is utilized for SVC analysis in this paper. SVC comprises of a well-regulated shunt reactor as well as shunt capacitor. SVC susceptance is adjusted by regulating thyristor firing from 90 to 180, regarding SVC voltage [8]. By presumptuous, controller voltage is equivalent to a bus voltage then applying a Fourier series analysis on the waveform of the inductor current, the TCR at the base frequency can be taken to work as a variable inductance (Xv) [9] [10].

\[ X_v = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \]  

(1)

Where:

- \( X_L \) denotes the reactance that is caused by the fundamental frequency in the absence of thyristor control.
- \( \alpha \) refers to the firing angle of thyristor

The controller equivalent impedance (Xe) can be formulated as presented in Equation (2) below:

\[ X_e = X_c \frac{\pi/r_x}{\sin 2\alpha - 2\alpha + \pi(2 - 1/r_x)} \]  

(2)

Where: \( r_x = \frac{X_c}{X_L} \)
1.1.2. STATCOM Device. SATCOM is a shunt compensator FACTS device that is represented by synchronous voltage sources, which are similar to a synchronous machine with the exception of a rotational section. The basic structure of STATCOM is illustrated in figure 3. It produces a balanced collection of the sinusoidal voltages at the base frequency coupled with promptly governable amplitude as well as the phase angle. A STATCOM is composed of the voltage source converter that transforms the DC voltage to the AC voltage to recompense the required active and reactive powers in a system. A STATCOM supplies superior terminal characteristics compared to SVC which provides lessening terminal characteristics at low voltage [9].

The steady state equation can be expressed as presented below [10] [13]. However, both studies in [8] and [9] have a limitation anchored on the distributed generation units being supposed to be dispatchable resources and located at peak demand.

$$V_{dc} = \frac{P}{C V_{dc}^2} - \frac{V_{dc}}{R_{dc} C} - \frac{R(p^2 + Q^2)}{C V_{dc}^2}$$  \hspace{1cm} (3)

The power injection at the load bus can be formulated as following [10] [13]:

$$P = V^2 G - K V_{dc} V G \cos(\theta - \alpha) - K V_{dc} V B \sin(\theta - \alpha)$$ \hspace{1cm} (4)

$$Q = -V^2 B + K V_{dc} V B \cos(\theta - \alpha) - K V_{dc} V G \sin(\theta - \alpha)$$ \hspace{1cm} (5)
Where:

- G: STATCOM conductance
- B: STATCOM susceptance

**Figure 3.** Basic structure of a STATCOM device [14]

2. Simulation and results

The IEEE-14 bus system was employed for studying voltage stability. The proposed system encompasses 5 generators including one slack bus, 11 load buses in addition to 20 transmission lines. PSAT toolbox, which is defined as a power system analysis tool that has several features such as power flow and continuation load flow, has been performed on the IEEE-14 bus system to appraise voltage stability of the system. The performance of IEEE-14 bus system with application of SVC and STATCOM under different loading scenarios is studied. A PQ model is employed for system loads, while the generators limits are disregarded. The assessment of voltage stability is executed from a secure and stable operation point; after that, the loads are increased by λ until reaching a critical point.

\[
\begin{align*}
P_l &= P_{l_0} (1 + \lambda) \\
Q_l &= Q_{l_0} (1 + \lambda)
\end{align*}
\]

Where \(P_{l_0}\) and \(Q_{l_0}\) Indicate active and reactive loads under normal circumstances, while \(P_l\) and \(Q_l\) new active and reactive loads arising from a rise in load by \(\lambda\) factor. The simulation findings of the continuation power flow that are presented in figure 4 demonstrate that 4,5,9, and 14 load buses are the vulnerable buses in the proposed network. Figures 5 and 6 illustrates the voltage profile and PV curve of IEEE 14 bus system without FACTS devices. It is noticed that voltage profile of some load buses is not within the acceptable level (-5% to 5%). This system is approaching a collapse point, where the Jacobian matrix of the system became singular at scaling factor \(\lambda = 2.198\). Based on figures 5 and 6, it has been found that the 14th is a critical bus which requires reactive power support to restore the system to the normal case. Table 1 illustrates the voltage profile of the projected system under normal and critical scenarios.
Table 1. Voltage profile of the IEEE-14 bus system

| Voltage | Base | Critical Point |
|---------|------|----------------|
| V1      | 1.06 | 1.06           |
| V2      | 1.045| 1.045          |
| V3      | 1.03 | 1.01           |
| V4      | 0.935| 0.673          |
| V5      | 0.945| 0.655          |
| V6      | 1.01 | 1.03           |
| V7      | 0.967| 0.781          |
| V8      | 1.09 | 1.09           |
| V9      | 0.939| 0.687          |
| V10     | 0.936| 0.710          |
| V11     | 0.965| 0.875          |
| V12     | 0.978| 0.975          |
| V13     | 0.976| 0.926          |
| V14     | 0.924| 0.641          |

Figure 4. Voltage profile of IEEE 14 bus system at the normal condition.

Figure 5. Voltage profile of the IEEE 14 bus system at the critical conditions
2.1. STATCOM Installation

Based on voltage collapse analysis, it is found that bus 14th of the proposed system is targeted as an appropriate site for installing STATCOM device. The parameters of STATCOM are shown in table 2. The results exhibit that the voltage profile is improved for the entire system and the maximum loading factor is increased up to 2.3706 at the present of STATCOM. It is noticed that the maximum loading factor does not escalate rather than this value when STATCOM is placed at other buses that are not regarded as vulnerable buses in the system. The improved voltage profile and the proposed system's new maximum load rate are shown in the figures 7 and 8.

| STATCOM parameters             | Value           |
|-------------------------------|-----------------|
| Power                         | 1 P.U           |
| Max & Min current             | (1.2 and -0.6) P.U |
| Regulator gain (Kr) (P.U/P.U) | 5               |

Figure 6. PV curve at the Normal case.

Figure 7. Voltage profile of IEEE 14 bus system at the critical condition with STATCOM at 14th
2.2. SVC Installation

In this case, STATCOM has been removed and SVC device is installed at the 14th bus which denotes the vulnerable bus in the proposed grid. After that, the simulation process is repeated to comprehend the influence of SVC on the power system stability as compared to STATCOM. The SVC parameters are shown in table 3. It is noticed that the power system voltage profile is enhanced and Maximum Loading Factor (MLF) is enlarged to 2.302, which is lower than the STATCOM installation scenario, as shown in figure 9 and 10.

Table 3. SVC parameters

| SVC parameters | Value          |
|----------------|----------------|
| Reference Voltage | 1.00 P.U     |
| Power           | 1 P.U         |
| BC              | (1.0 and -1.0) P.U |
| Regulator gain Kr (P.U/P.U) | 100          |

Figure 8. PV curve for IEEE bus system with STATCOM at 14th

Figure 9. Voltage profile of IEEE 14 bus system at the critical condition with SVC at 14th
2.3. Comparison between STATCOM and SVC Devices

Voltage profile of the IEEE-14 bus network under several scenarios including normal, STATCOM and SVC cases are illustrated in table 4 below. It is noticed that the voltage profile of the system, especially at the 14th bus, is improved considerably with the installation of the STATCOM and SVC devices at this bus. With light load condition, the voltage profile of the 14th bus is analogous when using STATCOM or SVC. In this scenario, both devices function in the linear zone of the V-I characteristics. However, while the load is enlarged, the voltage profile of the 14th with the application of STATCOM is better than the SVC. In the highest loading level, the voltage magnitude of 14th reaches 0.976 with STATCOM and approaches up to 0.951 with SVC. This is because, despite that the STATCOM and SVC carry out the same function, but when the system voltages become less than the normal level, the STATCOM will inject reactive power more than the SVC. Because, in the SVC, the generated maximum capacitive power is proportional to the square of the system voltage, while in the STATCOM, the generated maximum capacitive power is decreasing linearly with the system voltage. This ability of the STATCOM to generate more reactive power is considered as an important advantage over the SVC. In addition, the STATCOM response is faster than the SVC, because thyristor firing delay in the STATCOM is less than that in the SVC, which is 4ms for the SVC.

Table 4. Voltage profile of the IEEE-14 bus system

| Bus no. | Normal case | Critical point | STATCOM | SVC |
|---------|-------------|----------------|---------|-----|
| 1       | 1.06        | 1.06           | 1.06    | 1.06|
| 2       | 1.045       | 1.045          | 1.045   | 1.045|
| 3       | 1.03        | 1.01           | 1.01    | 1.01|
| 4       | 0.9352      | 0.673          | 0.983   | 0.950|
| 5       | 0.9458      | 0.655          | 0.981   | 0.956|
| 6       | 1.01        | 1.03           | 1.03    | 1.03|
| 7       | 0.9678      | 0.781          | 1.02    | 1.019|
| 8       | 1.09        | 1.09           | 1.09    | 1.09|
| 9       | 0.939       | 0.687          | 0.984   | 0.973|
| 10      | 0.936       | 0.710          | 0.977   | 0.972|
| 11      | 0.9653      | 0.875          | 1.025   | 1.022|
| 12      | 0.9783      | 0.975          | 1.044   | 1.003|
| 13      | 0.9765      | 0.926          | 1.012   | 0.998|
| 14      | 0.9245      | 0.641          | 0.976   | 0.951|
In Figure 11, the voltage profiles of all the network buses with STATCOM and SVC devices are shown. It is observed that with the application of FACTS controllers, all buses become within an acceptable voltage range. It is clear that the STATCOM and SVC systems have a significant impact on the PV curve, improving the critical point by generating nose point by moving out of the PV curve. Based on Figures 11 and 12, the STATCOM system provides all buses with a much better voltage profile compared to the SVC device. This is because, the STATCOM has the ability to generate more reactive power than the SVC. In the IEEE-14 bus system, STATCOM is placed at the weakest bus, then, the reactive power provided by this bus provides the system with a significant voltage profile. STATCOM provides reactive energy on the 14th bus, which improves the IEEE-14 bus system's voltage profile.

3. Conclusion
A brief overview of FACTS tools like STATCOM and SVC is discussed in this paper. Two types of FACT devices, STATCOM and SVC, were then introduced to boost the voltage stability of the respective power network. The core purpose of using such strategies is to increase the power network's load capacity and reduce power losses, which can help improve the voltage stability of the power network. Several methods are used to design FACTS devices and incorporate them into power systems. PSAT toolbox, which is an overview of the open source electrical power network, was used to apply
this research. The comparative study was carried out using such FACTS devices on the IEEE-14 bus system to understand the impact of each device on the stability of the power system. The simulation findings on the selected system showed that with the application of STATCOM and SVC devices, the projected system's voltage profile and Maximum Loading Factor (MLF) increased. It is noted that in the case of STATCOM system, the voltage stability enrichment is better than in the case of SVC installation.

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