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Original scientific paper

IMPROVING PERFORMANCE OF TRANSMISSION NETWORKS USING FACTS THROUGH CONTINUATION POWER FLOW METHOD

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Abstract. *Over the past 50 years, modern electrical systems have become more complex, as they overrun the geographical boundaries of neighboring countries. The problem is that the power system faces many challenges, because it is exposed to difficult operating conditions. The phenomenon of voltage instability is the most frequent phenomenon, and this can lead to the collapse of the power system. To avoid power outages in the system (especially in blackout situations), the power system must be analyzed in order to maintain voltage stability in the expected difficult operating conditions. The main objective is to determine the maximum load capacity of the system and the causes of voltage instability. The voltage instability problem is related to the nature of nonlinear loads, so different load characteristics must be taken into consideration when analyzing voltage stability.*

This study aims to discover the maximum load capacity required by using the continuous power flow method (CPF) in the studied network. Then, the performance of this network using a Flexible Alternating Current Transmission System (FACTS) will be utilized. FACTS systems present a promising solution in improving the voltage stability by improving the power transmission capacity and controllability of the parameters of the existing power networks. This study will be conducted on a reference network platform under normal working conditions, then installation of one of the FACTS systems will show its effect on improving voltage stability. The continuous power flow method will be used to find PV curves, which in turn will help to determine the conditions of maximum loading while maintaining stability, and identify the bus bar with the smallest voltage, on which the flexible AC systems will be installed. The software environment MATLAB/PSAT will be used for modeling and simulation.

Key words: *Voltage stability, Continuation Power Flow (CPF), maximum load conditions, Flexible Alternating Current Transmission System (FACTS), Thyristor-Controlled Series Capacitor (TCSC)*

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1. INTRODUCTION

Power systems face a lot of challenges, because the energy demand is increasing drastically nowadays. Due to that, the generated power will be increased. There are various ways of increasing power generation. Power must reach the end consumers through the existing transmission lines, and/or new transmission line should be built. In any case, the loading capacity of the existing transmission lines will increase. If these transmission lines are overloaded, the problem of voltage stability will appear [1]. The voltage profile of the system transmission lines will be affected, and as a result, the power losses will increase. The use of Flexible Alternating Current Transmission Systems (FACTS) systems in specific locations of the system will solve most of the previous problems in important power transmission lines [1]. FACTS devices will improve: loading capacity of transmission lines voltage levels and reduce power losses under normal operating conditions and during the occurrence of faults.

FACTS devices depend on sophisticated power electronic elements, which help control the power flow in transmission lines. These systems can be connected in series or in parallel to important transmission lines. Through it, this reactive and active power could be controlled [1].

Continuous power flow method is considered one of the best methods used for load flow analysis [1, 2, 3]. Studies have confirmed that this method is effective for studying voltage stability in the transmission system. The CPF is characterized by reduced execution time and computation burden, in addition to accuracy and ease of implementation. This method has been applied to the IEEE 11-bus system.

In this paper, the following systems - SVC, TCSC and UPFC will be connected on a specific bus-bar in the studied transmission system in order to improve the voltage stability in it. The Continuation Power Flow (CPF) method will be used to study the impact of previous systems on the transmission system other studies did not use CPF method to improve the stability if transmission networks in the presence of FACTS systems.

The CPF method uses the step method in prediction and correction, therefore, the Jacobian matrix is not considered a mono matrix. The principle of this method is to locate the weakest transmission line, where one of the flexible alternating current systems will be connected. Then, an analytical study will be implemented to compare the performance of the network before and after adding the aforementioned system [1, 3, 4, 5].

2. VOLTAGE STABILITY

Voltage stability is defined as the ability of the power system to maintain the voltage of all buses within acceptable values during normal conditions or after the occurrence of a disturbance. The system is subjected to voltage instability when overloading occurs. The parameters of the system will change and the voltage will drop rapidly. In this case, the automatic control units would be unable to control the system changes and suppress them accordingly. It may take several seconds or even (10-20) minutes to suppress the changes in the voltage. If the disturbance keeps occurring, the voltage then becomes unstable, which would lead to a collapse in the voltage of generators and transmission lines. In other words, the main reason behind the instability of the power system is that the system is unable to meet the demand for reactive power [3, 4, 5, 12, 13].

3. P-V CURVES

The P-V curves express the changes in voltage when the reactive power of the load has changed. These curves are the result of the implementation of load flows at different levels of uniformly distributed loads combined with the constant power factor. When the number of system branches increases, the time required to find these curves will also increase because the time required to calculate the load flow will definitely increase. The P-V curves provide the index of voltage stability of a network as well as the voltage collapse point. Voltage stability analysis provides transmission limits through the study of P-V curves. Moreover, these curves give the results of the entire system and determine the disturbances which have an impact on the system blackout or emergencies [3, 4, 5, 6, 7, 12, 13].

4. CONTINUATION POWER FLOW (CPF) METHOD

The CPF method consists of the following steps:

1 – Run load flow emergencies [3, 4, 5, 6, 7, 12, 13]:
The principle of continuous load flow is to trace the solutions of a nonlinear system through the steps of prediction and correction, considering the nonlinear equations.

$$F(\delta, V, \lambda) = 0 \tag{1}$$

where λ is the load factor, and the value of λ is between $0 \leq \lambda \leq \lambda_{\text{critical}}$. The following equations give the conventional load flow for a bus *i*.

$$\begin{aligned} P_{Gi} - P_{Li} - P_{Ti} &= 0 \\ Q_{Gi} - Q_{Li} - Q_{Ti} &= 0 \end{aligned} \tag{2}$$

where P_{Gi} , Q_{Gi} are the active and reactive generated power, respectively. P_{Li} , Q_{Li} are the active and reactive power of loads. P_{Ti}, Q_{Ti} are the net power injected into the bus *i*. Therefore, the net power equations are given as follow:

$$\begin{aligned} Q_{Ti} &= \sum_{j=1}^{n} |V_i| \times |V_j| \times |Y_{ij}| \times \sin(\delta_i - \delta_j - \delta_{ij}) \\ P_{Ti} &= \sum_{j=1}^{n} |V_i| \times |V_j| \times |Y_{ij}| \times \cos(\delta_i - \delta_j - \delta_{ij} \end{aligned} \tag{3}$$

2 – Expected Step:
The step size depends on the direction of the tangent at the previous solution point. Equation (4) gives the tangent [3, 4, 5, 5, 7].

$$dF(\delta, V, \lambda) = 0 \tag{4}$$

By applying the partial differentiation of equation (4), equation (5) is given as follow.

$$\frac{\partial F}{\partial \delta}(\partial \delta) + \frac{\partial F}{\partial V}(\partial V) + \frac{\partial F}{\partial \lambda}(\partial \lambda) = 0 \tag{5}$$

Therefore, the matrix is given by equation (6), where the right side of equation(6) represents tangent vector *t*.

$$[(\frac{\partial F}{\partial \delta})(\frac{\partial F}{\partial V})(\frac{\partial F}{\partial \lambda})]\begin{bmatrix}\partial\delta\\ \partial V\\ \partial\lambda\end{bmatrix}=0 \tag{6}$$

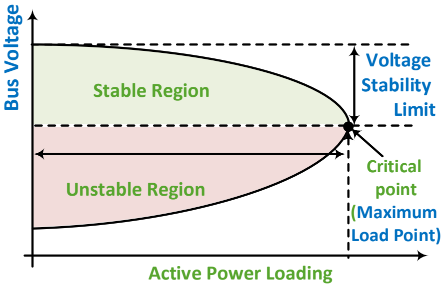


Fig. 1 P-V characteristic [2, 7]

$$\begin{bmatrix}(\frac{\partial F}{\partial \delta})(\frac{\partial F}{\partial V})(\frac{\partial F}{\partial \lambda})\\ Z_k\end{bmatrix}[t]=\begin{bmatrix}0\\ \pm 1\end{bmatrix}=0 \tag{7}$$

The row vector is equal zero and the K^{th} element is equal 1.

$$[t]=\begin{bmatrix}d\delta\\ dV\\ d\lambda\end{bmatrix} \tag{8}$$

The tangent vector t is defined in equation (9).

$$[t]=\begin{bmatrix}(\frac{\partial F}{\partial \delta})(\frac{\partial F}{\partial V})(\frac{\partial F}{\partial \lambda})\\ Z_k\end{bmatrix}^{-1}\begin{bmatrix}0\\ \pm 1\end{bmatrix} \tag{9}$$

By solving the equations, we find:

$$\begin{bmatrix}\delta^*\\ V^*\\ \lambda^*\end{bmatrix}=\begin{bmatrix}\delta\\ V\\ \lambda\end{bmatrix}+\sigma\begin{bmatrix}d\delta\\ dV\\ d\lambda\end{bmatrix} \tag{10}$$

3 – Correction Step:

The correction step comes after choosing the size of the prediction step for the tangent vector [3, 4, 5, 6, 7].

$$\begin{gathered}\sigma\begin{bmatrix}d\delta\\ dV\\ d\lambda\end{bmatrix}\\ x\in R^{2n_1+n_2+1}\\ or\quad x\in R^{2n_1-N_g-N_s}\end{gathered} \tag{11}$$

where n_1, n_2 the number of buses in series and n is the total number of buses in the system. N_g is the PV generated buses and N_s is the number of infinite buses [3, 4, 5, 6, 7].

The extended equation is an equation from group of equations to determine the status of the variables.

$$x_k = \mu \tag{12}$$

Therefore, the equation resulting from a group of equations is given by (13) [3, 4, 5, 6, 7].

$$\begin{bmatrix} F(x) \\ x_k - \mu \end{bmatrix} = [0] \tag{13}$$

Figure 2 shows the scheme of the calculation method in the CPF algorithm [10].

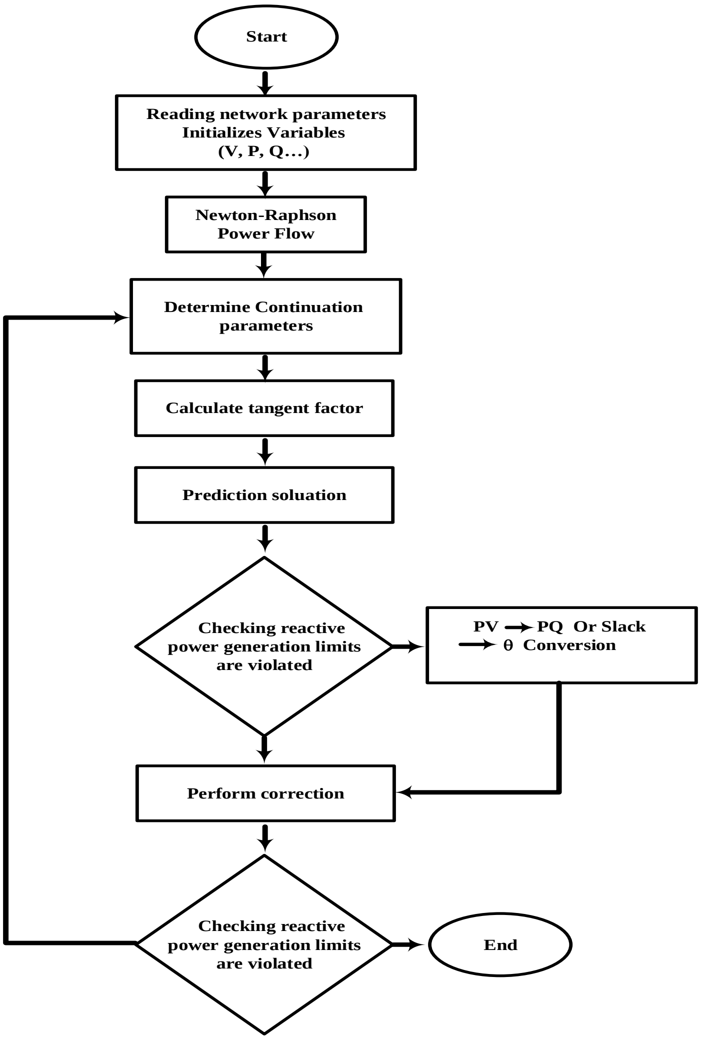


Fig. 2 Flow chart of calculation method used in the CPF algorithm [10]

5. TYPE OF FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS (FACTS) [1]

FACTS controllers are normally connected in series or parallel to the transmission lines. These controllers enhance the power transfer capability of the existing transmission lines. They also improve the voltage stability of the transmission system. When subjected to external disturbances, these controllers help the power system to regain its normal state. Effective reactive power management is done using these controllers in transmission system [1, 11].

The series compensation results in the improvement of the maximum power transmission capacity of the line. The net effect is a lower load angle for a given power transmission level and, therefore, a higher-stability margin. The reactive-power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive-power compensation is adjusted proportionately. Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions [1, 11].

Application of series capacitors in a long line constitutes placing a lumped impedance at a point. Therefore, the following factors need careful evaluation:

- The voltage magnitude across the capacitor banks (insulation).
- The fault currents at the terminals of a capacitor bank.
- The placement of shunt reactors in relation to the series capacitors (resonant over-voltages).
- The number of capacitor banks and their location on a long line (voltage profile).

While, shunt devices may be connected permanently or through a switch. Shunt reactors compensate for the line capacitance, and because they control over-voltages at no loads and light loads, they are often connected permanently to the line, not to the bus [1, 11].

Shunt capacitors are used to increase the power-transfer capacity and to compensate for the reactive-voltage drop in the line. The application of shunt capacitors requires careful system design. The circuit breakers connecting shunt capacitors should withstand high-charging in-rush currents and also, upon disconnection, should withstand more than 2-pu voltages, because the capacitors are then left charged for a significant period until they are discharged through a large time-constant discharge circuit. Also, the addition of shunt capacitors creates higher-frequency–resonant circuits and can therefore lead to harmonic over-voltages on some system buses [1, 11].

So, FACTS systems can be classified into three main groups:

- Series control systems (like TCSC),
- Shunt Control Systems (like SVC),
- Shunt-series composite control systems (like UPFC) [1, 11].

5.1. Thyristor-Controlled Series Capacitor (TCSC)

Thyristor-Controlled Series Capacitor (TCSC) is one of the FACTS types, consisting of a capacitor connected as in parallel with the reactance which is controlled by a thyristor, as shown in Figure 3. Additionally, Figure 3 shows the installation of the arrester discharger made of metal oxide to avoid the occurrence of over voltage across the unit. The series connection of several TCSC units is used to meet the total required compensation, as observed in Figure 4 [8, 9, 11, 12].

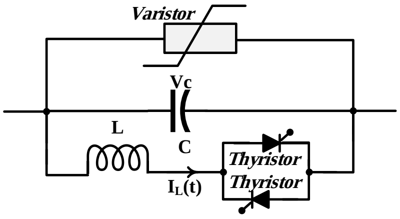


Fig. 3 Power circuit of TCSC compensator

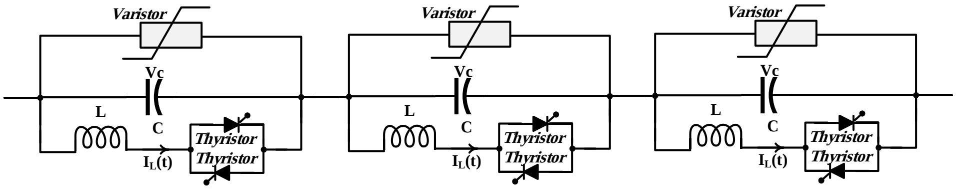


Fig. 4 Series connected TCSC compensators

5.2. Static Var Compensator

The SVC is an advanced technology that is widely used for transmission applications for several purposes. The primary purpose is usually rapid control of voltage at weak points in the network. Worldwide, there is a steady increase in the number of installations. The IEEE-definition of an SVC is as follows: "Static Var Compensator (SVC): A shunt-connected static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage) [8, 9, 11, 12, 13].

SVC is an umbrella term for several devices. The SVC devices discussed in the following sections are the TCR (Thyristor Controlled reactor), FC (Fixed Capacitor) and TSC (Thyristor Switched Capacitor). The components of an SVC may include: transformers between the high voltage network bus and medium voltage bus where the power electronic equipment is connected, a fixed (usually air-core) reactor of inductance L and a bidirectional thyristor. The thyristors are fired symmetrically in an angle Î± in a controlled range of 90° to nearly 180°, with respect to the capacitor voltage. The TSC is often used in order to decrease standby losses. Figure. 5 shows a common structure of SVC [8, 9, 11, 12, 3].

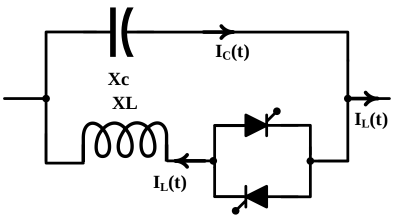


Fig. 5 Common structure of SVC

5.3. Unified Power Flow Controllers

The Unified power flow controller (UPFC) is one of FACTS, which is combined of series and shunt FACTS. It consists of two voltage source converters (VSCs), the two VSCs are connected to common DC capacitor bank. The first unit of UPFC is a Static Compensator (STATCOM), which is connected VSC via parallel transformer, then to the DC bus. The second unit is a Static Synchronous Series Compensator (SSSC). It is also connected to the VSC via series transformer, the to the DC bus. The UPFC provides the control capabilities in power flow and instantaneously satisfy the power flow regulation requirements (see Figure 6).

The major control techniques are as follows [8, 9, 11, 12, 18]:

- Reactive shunt compensation or bus voltage regulation;
- Reactive series compensation or line impedance compensation [8, 9, 12, 18].

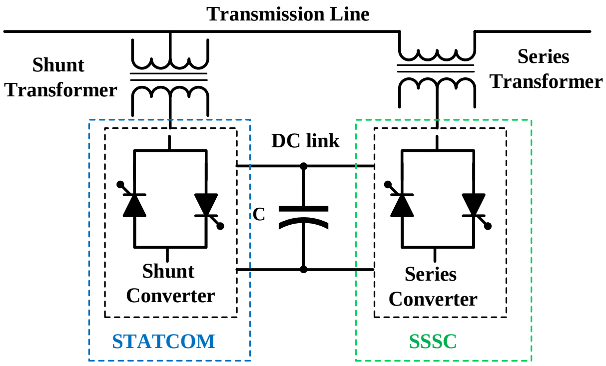


Fig. 6 UPCF block diagram

Between them, the UPFC achieves shunt voltage regulation by injecting an in-phase or anti-phase voltage that varies within the maximum and minimum injection limits. These limits are controlled by the ratings of the shunt converter (see Figure 7) [8, 9, 12, 18].

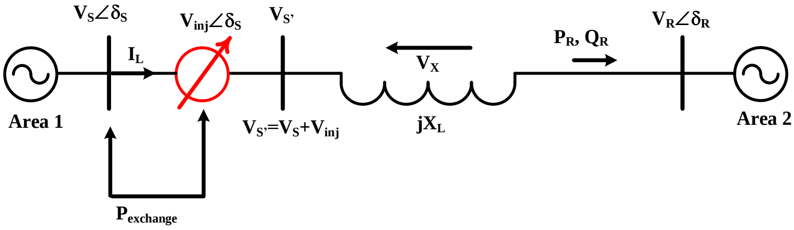


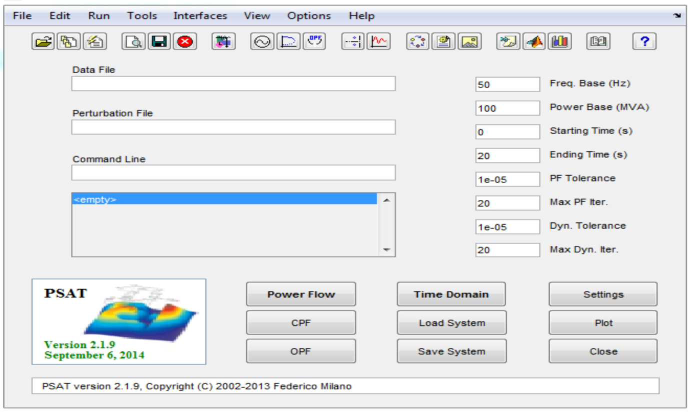
Fig. 7 UPFC voltage injection

6. PRACTICAL STUDY BY USING MATLAB-PSAT SOFTWARE

In this research, MATLAB-PSAT (Power System Analysis Toolbox) is used to model the power system networks. PSAT works within the MATLAB environment and is considered one of the developed software designed to perform static and dynamic analysis of the electrical power systems. It can be used to do the following calculations:

- Load flow,
- Continuous power flow,
- Optimal power flow,
- Continuous power flow,
- Static and transient stability analysis of electrical networks,
- Voltage stability analysis of electrical networks during the static and transient conditions.

Figure 8 shows the Graphical User Interface (GUI) of MATLAB-PSAT which is used to build the electrical power network. The user can add data of the network, build the single line diagrams using the PSAT-Simulink Library whereby the data is saved. After that, the data is uploaded by the information file into the GUI, and the necessary studies pertaining to the networks are then conducted.



<empty>

50 Freq. Base (Hz)
100 Power Base (MVA)
0 Starting Time (s)
20 Ending Time (s)
1e-05 PF Tolerance
20 Max PF Iter.
1e-05 Dyn. Tolerance
20 Max Dyn. Iter.

PSAT version 2.1.9, Copyright (C) 2002-2013 Federico Milano

Fig. 8 User interface of MATLAB-PSAT

7. RESULTS AND DISCUSSION

7.1. Application of the proposed method to a standard IEEE 11-bus system

The IEEE 11-bus system is a standard system often used by power system specialists for conducting research. Figure 9 shows the diagram of the studied network, which consists of 11 buses, and four cylindrical rotor synchronous generators. The voltage level of the generator is 20 kV with a capacity of 900 MVA, while the parameters of all generators remain similar. The system has eight transmission lines, two loads and two capacitors. The frequency is 60 HZ, while the transmission voltage level is 230 kV and the based power is 100 MVA.

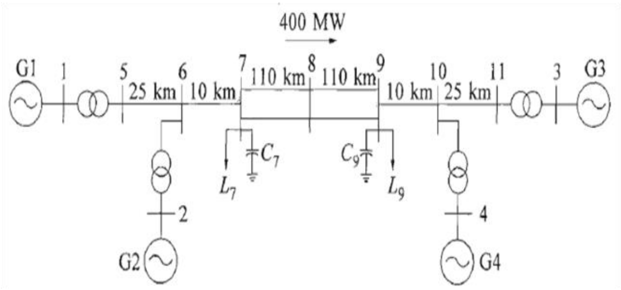


Fig. 9 Diagram of IEEE 11-bus system

7.2. Voltage stability analysis of IEEE 11-bus system utilizing (CPF) method

Load flow analysis is implemented to calculate the voltage of buses and to determine the weakest buses in the network during normal operating conditions. Figure 10 shows the 11-bus system modelled by MATLAB-PSAT.

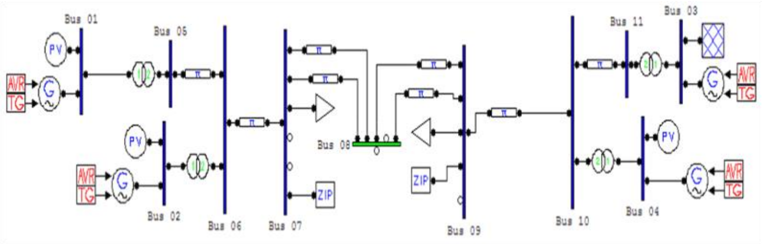


Fig. 10 IEEE 11-bus system modeled by MATLAB-PSAT

The continuation of power flow is analyzed by using MATLAB-PSAT, as explained in Figure 11. The results of 11-bus system are presented in Table 1. Figure 12 presents the voltage of all buses of the studied network calculated by the CPF method.

Table 1 CPF results under normal operating conditions

Bus. Nr.	V [p. u.]	Bus. Nr.	V [p. u.]
1	1.029	6	**0.95987**
2	1.0089	7	**0.93523**
3	1.029	8	**0.90731**
4	1.0086	9	**0.94874**
5	**0.997**	10	0.96691
		11	0.99876

It has been observed in Table 1 and Figure 12 that the critical voltage values in the network are the voltage of Bus 6, Bus7, Bus 8, Bus 9, and Bus10, therefore, these buses are the weakest buses in the network, most subjected to network changes, and the probability of voltage collapse is high compared with the other buses. The software calculates the maximum loading factor of the network. As seen in Figure 8 (from command window in MATLAB), after applying the continuation power flow for the studied network, the maximum loading factor is λ = 1.1481[p. u]. In other words, the network is considered stable before this point. However, the network is found to be unstable, after this point. That is why it is called the maximum loading point.

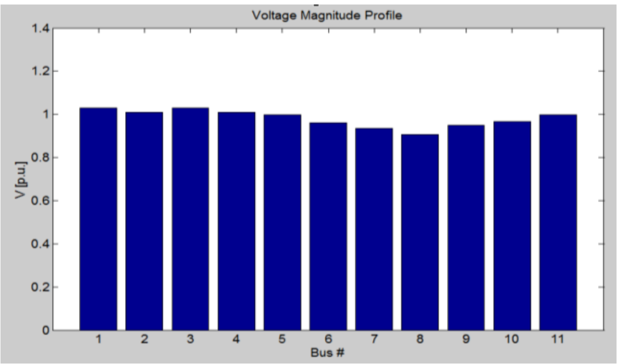
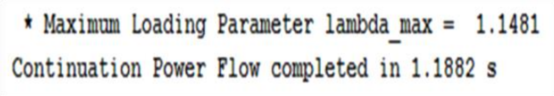


Fig. 11 Voltage of all buses calculated by CPF before adding FACTS



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* Maximum Loading Parameter lambda_max =  1.1481
Continuation Power Flow completed in 1.1882 s
```

Fig. 12 Value of maximum loading factor of the 11-bus system without the compensator

Figure 13 illustrates the P-V curves calculated by CPF method, which provide the maximum loading factors of Bus 5 to Bus11 as a function of the voltage of the network. Moreover, Figure 13 shows the buses which have the critical voltage in the studied network. The critical voltage curves are the lowest among these curves, and Bus 8 is the weakest which has the lowest curve.

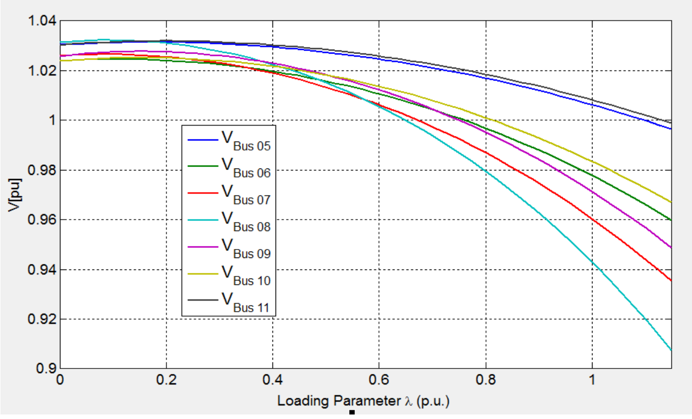


Fig. 13 P-V curves of the 11-bus system before adding FACTS

7.3. Voltage stability analysis of IEEE 11-bus system after adding the Thyristor-Controlled Series Capacitor (TCSC)

A compensator TCSC is connected in series with the transmission line (9-10), as shown in Figure 14.

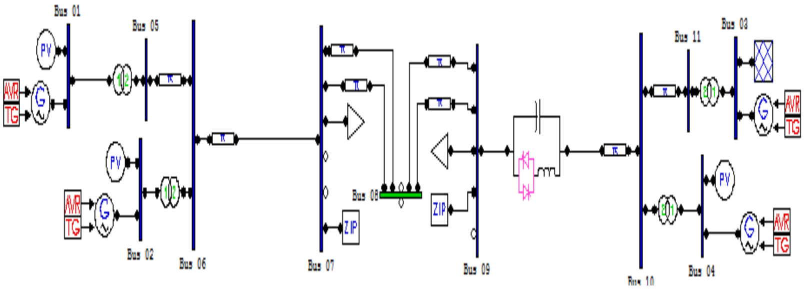
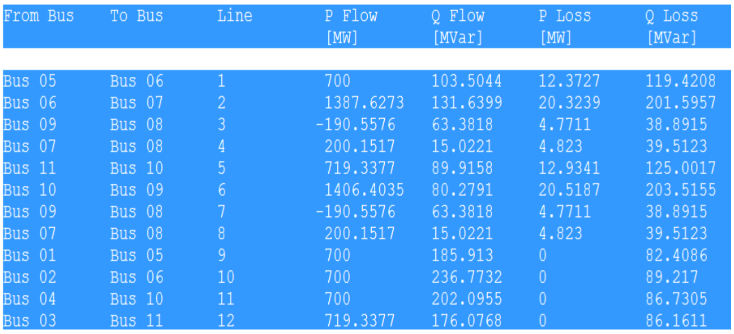


Fig. 14 The studied network after adding the TCSC in series with transmission line (9-10)

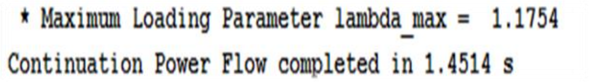
The compensator TCSC is connected in series with the transmission line (9-10), therefore, due to that, Bus 9 and Bus10 were found to be among the weakest buses in the network, as mentioned in Table 1, based on the CPF results. Additionally, this line is considered as one of the network lines, which carries the largest load and has big reactive losses (Table 2).

As observed in Table 2, the active power injected into the line (9-10) is 1406.4035 MW, which has the biggest value. Furthermore, the active and reactive losses are 20.5187 MW and 203.5155 MVAr respectively, while the power losses of this line is bigger than the other transmission lines. The value of the maximum loading factor reflects on the above-mentioned results, where the value is λ = 1.1754 [p. u.] (as indicated in Fig. 15), after adding the compensator TCSC in the line (9-10).

Table 2 Load flow results of the IEEE 11-bus before adding FACTS



From Bus	To Bus	Line	P Flow [MW]	Q Flow [MVar]	P Loss [MW]	Q Loss [MVar]
Bus 05	Bus 06	1	700	103.5044	12.3727	119.4208
Bus 06	Bus 07	2	1387.6273	131.6399	20.3239	201.5957
Bus 09	Bus 08	3	-190.5576	63.3818	4.7711	38.8915
Bus 07	Bus 08	4	200.1517	15.0221	4.823	39.5123
Bus 11	Bus 10	5	719.3377	89.9158	12.9341	125.0017
Bus 10	Bus 09	6	1406.4035	80.2791	20.5187	203.5155
Bus 09	Bus 08	7	-190.5576	63.3818	4.7711	38.8915
Bus 07	Bus 08	8	200.1517	15.0221	4.823	39.5123
Bus 01	Bus 05	9	700	185.913	0	82.4086
Bus 02	Bus 06	10	700	236.7732	0	89.217
Bus 04	Bus 10	11	700	202.0955	0	86.7305
Bus 03	Bus 11	12	719.3377	176.0768	0	86.1611



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 * Maximum Loading Parameter lambda_max =  1.1754
Continuation Power Flow completed in 1.4514 s
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Fig. 15 The value of maximum loading factor of the 11-bus system with TCSC connected in series with the transmission line (9-10)

Fig. 16 presents the values of the maximum loading factor of the studied network with the implementation of TCSC. It was found that the best location to add the compensator TCSC is the line (9-10). In this case, the value of the maximum loading factor λ is the best. Table 3 illustrates the voltage profile of the network from the continuation power flow method after adding the compensator TCSC in series with line (9-10).

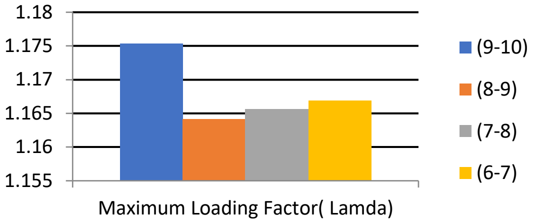


Fig. 16 Value of maximum loading factor with the TCSC connected in different locations

Table 3 Load flow results of the studied system after adding TCSC in series with the transmission line (9-10)

Bus. Nr.	V [p. u.]	Bus. Nr.	V [p. u.]
1	1.028813	6	0.96131
2	1.00841	7	0.938492
3	1.028533	8	0.919863
4	1.007755	9	0.965957
5	0.996724	10	0.967424
		11	0.999152

Fig. 17 provides the P-V curves after adding TCSC in series with line (9-10), where the graph shows improvement on the critical voltage levels compared with the results before adding FACTS. These results are similar to what was presented by the reference [16], that using TCSC compensator in the transmission network, to improve the power transfer capacity and loading factor.

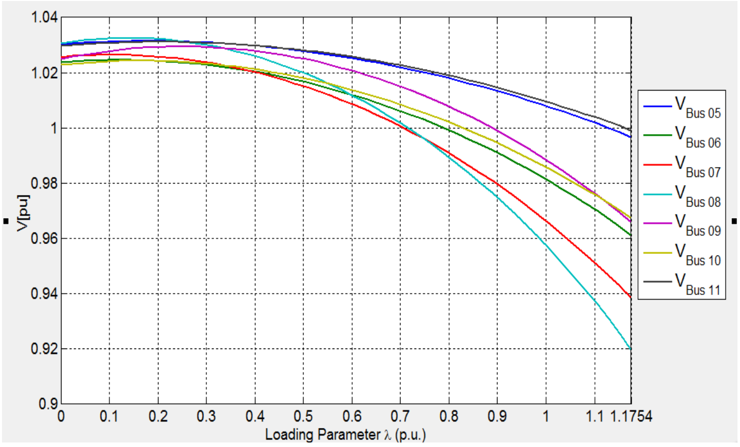


Fig. 17 P-V curves of the 11-bus system after adding TCSC in series with line (9-10)

7.4. Voltage stability analysis of IEEE 11-bus system after adding the Static Variable Compensator (SVC)

A compensator SVC is connected in parallel to busbar-8, as shown in Fig. 18.

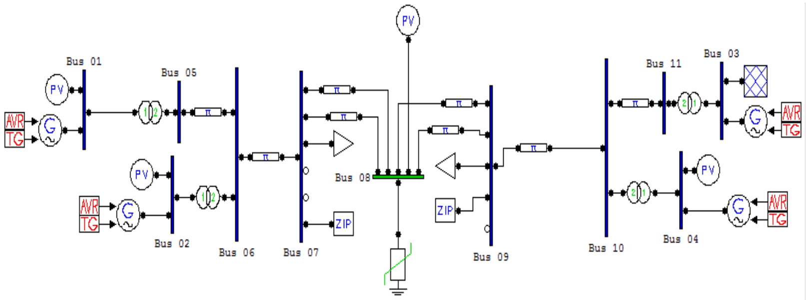
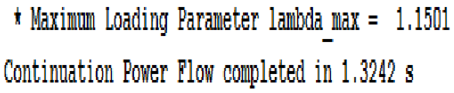


Fig. 18 The studied network, after adding the SVC in parallel at busbar-8

The compensator SVC is connected in parallel at busbar-8, because it is the weak point between the network buses, as mentioned in Table 1. After applying the continuous load flow to the studied network, Table 4 presents the busbar voltages based on the CPF. It is clear that the voltage level of all displayed busbars improved when compared with the first case. Also, it was found that the maximum load capacity of the studied network is that the network load capacity after linking the SVC has improved, it is: λ =1.1501[p. u.] = as shown in Fig.19.

Table 4 Load flow results of the studied system after adding SVC

Bus. Nr.	V [p. u.]	Bus. Nr.	V [p. u.]
1	1.0288	6	0.96945
2	1.0084	7	0.95258
3	1.0291	8	0.96411
4	1.0302	9	0.97936
5	1.0002	10	0.9915
		11	1.009



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* Maximum Loading Parameter lambda_max =  1.1501
Continuation Power Flow completed in 1.3242 s
```

Fig. 19 Value of maximum loading factor after connecting SVC

Fig. 20 provides the P-V curves after adding on the SVC, where the graph shows improvements on the critical voltage level compared with the results before adding the FACTS system. So, this result is consistent with the reference [17], since the SVC compensator is capable to improve and maintain the system’s voltage profile within an acceptable limit, and will also reduce power loss, and in effect improve power transfer capability of the system if applied.

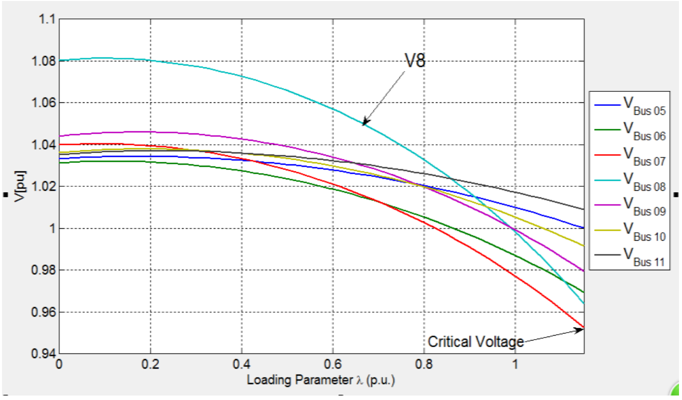


Fig. 20 P-V curves of the 11-bus system after adding SVC

7.5. Voltage stability analysis of IEEE 11-bus system after the addition of the UPFC compensator

The UPFC compensator was connected between the busbars (7-8), as they are the weakest busbars in the studied network, the rated power of UPFC was100 [MVAR]. Figure 21 shows the modeling of the studied network in the presence of UPFC.

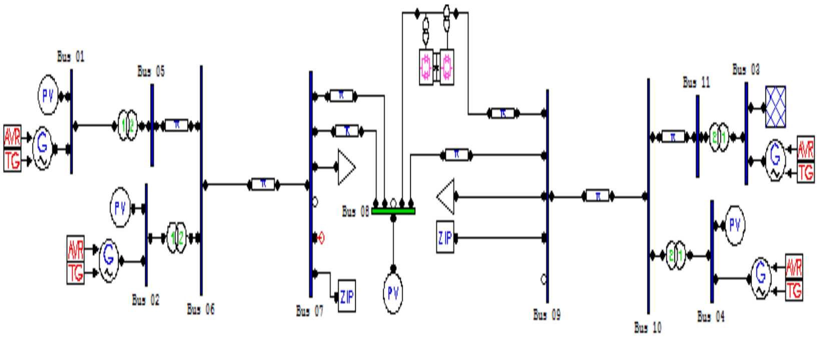


Fig. 21 The studied network after the addition of the UPFC between busbars (7-8)

After applying the continuous load flow to the studied network, Table 5 presents the busbar voltages based on the CPF. It is clear that the voltage level of all busbars was improved when compared with the first case.

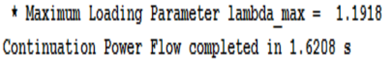
Table 5 Load flow results of the studied system after adding SVC

Bus. Nr.	V [p. u.]	Bus. Nr.	V [p. u.]
1	1.028729	6	0.976393
2	1.008499	7	0.966668
3	1.028578	8	1.018
4	1.008196	9	0.970404
5	1.002375	10	0.978061
		11	1.002686

From this Table (5), the values of the studied network voltage levels, resulting from the continuous load flow method in the presence of UPFC, have been found to be better compared to the previous cases as in Tables (2), (3) and (4). The compensator UPFC points to the best performance in improving the maximum load capacity of the studied network compared with the parallel compensator and the serial compensator, as it controls the volage and reactive power between the two busbars (7, 8). The maximum load capacity becomes λ =1.1918 [p. u.], as shown in Figure (22).

Figure (23) presents the (PV) curves of the IEEE-11 in the presence of UFPC. Thus, the voltage levels become better when compared to the other cases, i.e., the voltage stability margin for the studied network is better, this means that the maximum loading point (or the so-called voltage breakdown point) is better than the other cases, therefore, the system will stay for a long time, when compared to previous compensation cases without the system-collapse.

These results are in agreement with what was provided by the reference [18], that there is an improvement in the real and reactive powers through the transmission line when UPFC is introduced, and combined FACTS system (UPFC) has the advantages like reduced maintenance and ability to control real and reactive powers.



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 * Maximum Loading Parameter lambda_max =  1.1918
Continuation Power Flow completed in 1.6208 s
```

Fig. 22 Value of maximum loading factor after connecting UPFC

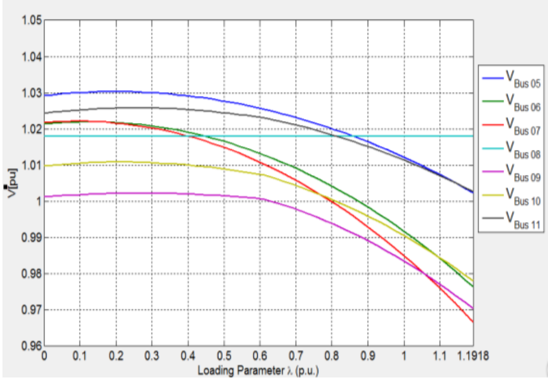

Fig. 23 P-V curves of the 11-bus system after adding the UPFC system

8. CONCLUSION

In this research the continuation power flow method has been used to analyze the possibility of increasing the loading capability of the electrical power systems with the implementation of the FACTS systems (TCSC, SVC, UPFC). This study has applied the IEEE 11-bus system. The research findings include:

1. The CPF has been found to be an effective method in determining the best location to connect the compensators, on the weakest node for the compensators.
2. The study concluded that the implementation of the reactive compensators (series, shunt, or composite) increases the loading capacity of electrical networks, where the loading factor λ of IEEE 11-bus increases: from 1.1481 [p. u.] to 1.1754 [p. u.] in the presence of TCSC, form 1.1481 [p. u.] to 1.150 [p. u.] in the presence of SVC and 1.1481 [p. u.] to 1.1918 [p. u.] in the presence of UPFC.
3. The compensator TCSC is a source of improvement for the performance of the network, this improvement is related to the nature of the network, its loads and line losses.
4. The UFPC compensator shows the best performance among the compensators used in increasing the load capacity of electrical networks, regardless of the nature of the electrical network.
5. The use of different type of compensators (series or shunt), such as SVS &UPFC is recommended so as to be able to compare their performance.

REFERENCES

[1] N. Karuppiah1, S. Muthubalaji, S. Ravivarman, Md. Asif and A. Mandal, "Enhancing the performance of Transmission Lines by FACTS Devices using GSA and BFOA Algorithms", *Int. J. Eng. Techn.*, vol. 7, no. 4.6, pp. 203–208, 2018.

[2] A. Jalali and M. Aldeen, "Novel Continuation Power-flow Algorithm", In Proceedings of the IEEE International Conference on Power System Technology (POWERCON), 2016, p. 16487968.

[3] M. Gudavalli, H. Emulapalli and K. Cherukupall, "Voltage Stability Analysis Using Continuation Power Flow Under Contigency", *J. Theor. Appl. Inf. Technol.*, vol. 99, no. 10, pp. 2373–2383, May 2021.

[4] S. B. Bhaladhare, "Improving Voltage Stability by Using Facts Devices", *IASET: J. Electr. Electron. Eng. (IASET: JEEE)*, vol. 1, no. 1, pp. 1–10, 2016.

[5] S. D. Patel, H. H. Raval and A. G. Patel, "Voltage Stability Analysis of Power System using Continuation Power Flow Method", *Int. J. Technol. Res. Eng.*, vol. 1, no. 9, pp. 763–767, May 2014.

[6] N. Fnaiech, A. Jendoubi and F. Bacha, "Voltage Stability Analysis in Power System Using Continuation Method and PSAT Software", In Proceedings of the 6th international Renewable Energy Congress (IREC), Tunis, 2015, pp. 1–6.

[7] S. Greene, I. Dobson and F. L. Alvarado, "Sensitivity of the loading margin to voltage collapse with respect to arbitrary parameters", *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 262–272, Feb. 1997.

[8] Leonardo L. Grigsby, *Power System Stability and Control*, CRC press, 3rd edition, 2012.

[9] V. Chauhan, B. Singh and J. Bala, "Enhancement of Static Voltage Stability using TCSC and SVC", *Int. J. Sci. Eng. Res.*, vol. 8, no. 4, pp. 127–130, April 2017.

[10] J. M. Teixeira da Silva Marques da Cruz, "Extension of Continuation Power Flow to Incorporate Dispersed Generation", doctor thesis, Lisbon technical University, 2016.

[11] R. Mohan and R. K. Varma, *Thyristor-based FACTS Controllers for Electrical Transmission Systems*, John Wiley & Sons, 2002.

[12] I. G. Adebayo, I. A. Adejumobi and O. S. Olajire, "Power Flow Analysis and Voltage Stability Enhancement Using Thyristor Controlled Series Capacitor (TCSC) Facts Controller", *Int. J. Eng. Adv. Technol. (IJEAT)*, vol. 2, no. 3, pp. 100–104, Feb. 2013.

[13] T. Van Cutsem, "A Method to compute Reactive Power Margins with respect to Voltage Collapse", *IEEE Trans. Power Syst.*, vol. 6, no. 1, pp. 145–156, Feb. 1991.

[14] C. Sharma and M. G. Ganness, "Determination of the Applicability of using Modal Analysis for the Prediction of Voltage Stability", In Proceedings of the IEEE/PES Transmission and Distribution Conference and Exposition, 2008, pp. 1–7.

[15] Y. Zhang, S. Rajagopalan and J. Conto, "Practical Voltage Stability Analysis", In Proceedings of the IEEE PES Power and Energy Society General Meeting, 2010, pp. 1–7.

[16] O. I. Adebisi, I. A. Adejumobi, P. E. Ogunbowale and O. O. Ade-Ikuesan, "Performance Improvement of Power System Networks Using Flexible Alternating Current Transmission Systems Devices: The Nigerian 330 kV Electricity Grid as a Case Study", *LAUTECH J. Eng. Techno.*, vol. 12, no. 2, pp. 46–55, 2018.

[17] S. Kumar, "Implementation of TCSC on a Transmission Line Model to analyze the variation in Power Transfer Capability", *Int. J. Res. (IJR)*, vol. 1, no. 8, pp. 1091–1098, Sept. 2014.

[18] J. P. Sai Kumar Reddy and P. Janga, "Power Flow Improvement in Transmission Line Using UPFC", *Int. J. Electron. Commun. Technol. (IJECT)*, vol. 7, no. 4, pp. 9-12, 2016.