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Study of Flexible AC Transmission Systems and Static Var Compensator and Their Behavior on Power and Voltage Control in Transmission Networks

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ABSTRACT

With the increasing complexity of networks, the participation of generators in the production and control of reactive energy has become insufficient. Thus, the network must rely on other compensation sources or means, such as conventional devices (capacitor banks, static inductors) and Flexible AC Transmission Systems (FACTS) devices, which ultimately are at least as often consumers as they are suppliers of reactive energy. The objective of this work is to improve the voltage control through reactive power error compensation with systems FACTS "Static Var Compensator (SVC)" devices. In order to achieve this objective, we focus on in a few types of disturbances: the appearance of a short circuit, and the sudden increase in load. To validate this theoretical study, we carried out several transient stability simulation tests on an SVC coupled with a transmission network using MATLAB programming language and PSAT software on an IEEE model network (05 and 14 nodes) in order to restore the power flows as well as the voltage plane to their normal state after a well-defined disturbance (fault). The results obtained clearly show the essential role that FACTS systems can play in the stability of electrical networks; by compensating for reactive energy, they have enabled an improvement in the voltage regulation.

1. INTRODUCTION

An electrical network is a set of infrastructure for transporting electrical energy from production centers to places of electricity consumption [1]. Industrialization and population growth are the first factors for which the consumption of electrical energy is steadily increasing. Thus, to have a balance between production and consumption, it is at first sight necessary to increase the number of power stations, lines, transformers, etc., which implies an increase in cost and a degradation of the natural environment. This causes the degradation of the behavior of an electrical network.

Assuming that the power balance is guaranteed by the central power generators under the variable power demand, the network components will be exposed to a certain amount of current and voltage stress and will generate losses in the network. The study of power flow plays an important role here as a tool to evaluate these constraints in the steady-state domain [2].

With the complexity of networks, the participation of generators in the production and control of reactive energy has become insufficient [3-5].

Thus, the network must use other sources or rather other means of compensation, such as conventional devices (capacitor batteries, static compensator chokes) and Flexible AC Transmission Systems (FACTS) as vital tools in modern electrical networks, offering advanced control over key parameters such as voltage, impedance, and phase angle. By enabling dynamic management of power flow and enhancing system stability, FACTS technologies help maximize the performance of existing transmission infrastructure without the need for costly physical upgrades.

Among the various types of FACTS devices, the Static Var Compensator (SVC) stands out for its effectiveness in managing reactive power and maintaining voltage stability.

With fast-acting, electronic control, SVCs play a crucial role in improving power quality, supporting renewable integration, and increasing the reliability of both transmission and industrial power systems.

This article examines the function and importance of SVCs within the broader context of modern power system operation. The objective of this work is to improve the voltage stability in electrical power systems introduced by the FACTS concept as a philosophy of total network control [6, 7]. As part of our work, we are interested in a few types of disturbances:

- The appearance of a short circuit.
- The sudden increase in load.

The applications will be illustrated using PSAT [8] software on IEEE networks of 14 and 9 busbars, thus making it possible to analyze the behavior of this network with or without faults and with the integration of FACTS systems (SVC) to overcome the consequences of defects. Then we presented in detail the results of a simulation developed under the MATLAB environment (an application of SVC in electrical networks).

2. MODELING OF SVC

The FACTS shunt devices modeled are static reactive power compensators such as the SVC and other derivatives, Thyristor Controlled Reactor (TCR) and Thyristor Switched Capacitor (TSC) [9]. Although they show worse performance than the static synchronous compensator, they are hardly significant in steady state. Moreover, the simulations are carried out for cases where the voltages are close to the nominal value.

In this situation, the SVC and the STATCOM have similar characteristics [10, 11].

3. MODELING MODEL OF STATIC REACTIVE POWER COMPENSATOR SVC

The SVC device is modeled by a variable shunt y_{SVC} admittance (Figure 1) [12]. Assuming the SVC is lossless, the admittance is therefore purely imaginary:

$$y_{SVC} = jB_{SVC} \tag{1}$$

The susceptance B_{SVC} can be of capacitive or inductive nature in order to supply [13] or to absorb, respectively, reactive power Q_{SVC} (Figure 1(c)).

The values of the SVCs are expressed in the form of reactive power (Q_{SVC}) absorbed at the rated voltage (U_n) [14]. The correspondence with the B_{SVC} susceptance is given by the following relationship [15]:

$$B_{SVC} = -U_n^2\, b_{SVC} = -U_n^2\, \frac{X_C[2(\pi-\alpha)+\sin 2\alpha]-\pi X_L}{\pi X_C X_L} \tag{2}$$

$$Q_{SVC} = -\frac{B^2}{U_n} - B_{SVC} \tag{3}$$

A minus sign indicates that SVC supplies reactive power to the system when it is capacitive, while it consumes it when it is inductive. The variation of the injected reactive power as a function of the voltage is represented in Figure 2 for several compensation values [9].

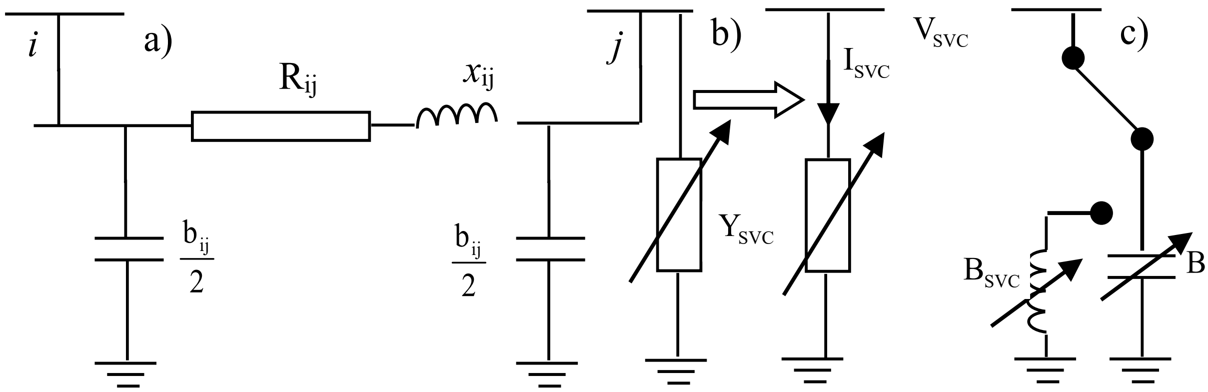

Figure 1. Modeling of SVC: a) SVC placed in node j, b) Symbol, c) SVC model

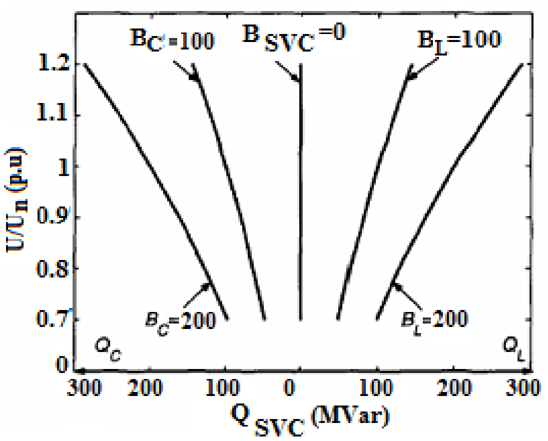

Figure 2. Variation of reactive power by an SVC as a function of nodal voltage

3.1 SVC location

FACTS installations are usually located at existing substations. However, both cases are considered, namely when the SVC is placed in a node and when it is located in the middle of the line [16-18].

3.1.1 SVC placed in a network node

When connected to network nodes, SVCs are typically placed where there are large or highly varying loads [19, 20]. They can also be positioned at nodes where the generator fails to supply or absorb enough reactive power to maintain the desired voltage level. When an SVC is present at node *i*, only the element of the nodal admittance matrix is modified.

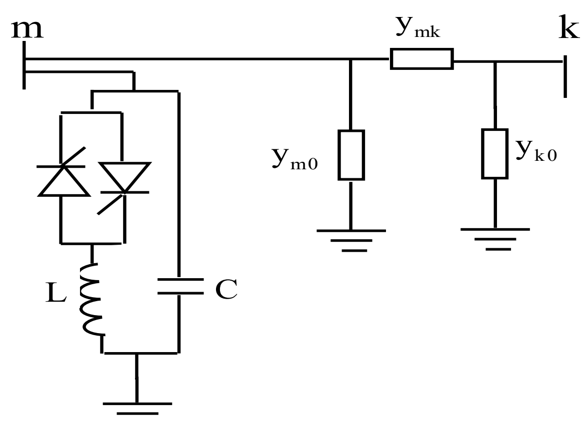

Figure 3. SVC inserting in a line

For an SVC connected to a busbar m of a line section represented by the quadrupole (y_{m0}, y_{mk}, y_{k0}) as shown in Figure 3, the contribution of the SVC [21, 22] to the new admittance matrix concerns the shunt element. This results in the admittance matrix for the line.

$$Y_{new}^{line} = \begin{pmatrix} Y_{mk} + Y_{m0} + Y_{SVC} & -Y_{mk} \\ -Y_{mk} & Y_{mk} + Y_{k0} \end{pmatrix} \quad (4)$$

$$Y_{SVC} = \mathrm{j}\frac{1}{X_L X_C}\left[X_L - \frac{X_C}{\pi}(2(\pi - \alpha) + \sin 2\alpha)\right] \quad (5)$$

$$X_{SVC}(\alpha) = \mathrm{j}\frac{\pi X_L}{(2(\pi-\alpha)+\sin 2\alpha)-\pi(X_L/X_C)} \quad (6)$$

3.1.2 SVC placed at the middle of a line

When the static compensator is inserted in the middle of a line, the line is divided into two identical sections [23]. The SVC is connected to the additional bus "t" as shown in Figure 4.

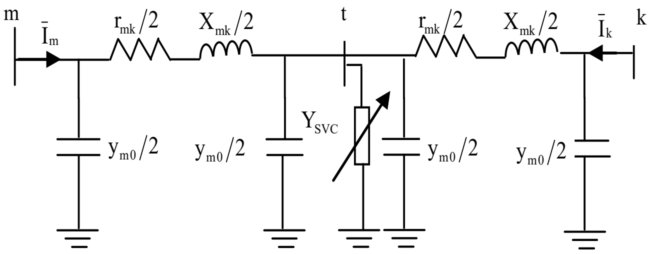

Figure 4. SVC placed at the middle of a line

In order to account for this new bus, an additional row and column must be added to the nodal admittance matrix.

To avoid having to change the number of buses in the network and therefore the size of the admittance matrix, a star-delta transformation allows the system to be reduced by removing the "t" bus and calculating the parameters of an equivalent line. Figure 5 illustrates the steps required to obtain this equivalent line.

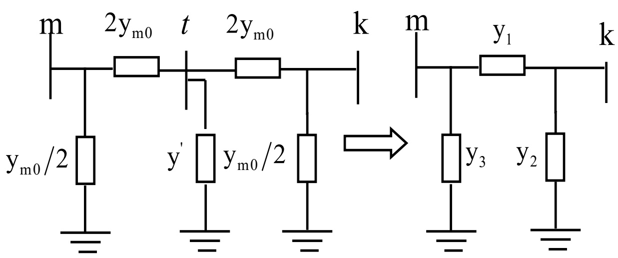

Figure 5. Y-Δ transformation

$$\begin{cases} Y_1 = \dfrac{4Y_{mk}^2}{4Y_{mk} + Y_{SVC} + \dfrac{Y_{m0}}{2} + \dfrac{Y_{k0}}{2}} \\ Y_2 = \dfrac{Y_{mk}(2Y_{SVC} + Y_{m0} + Y_{k0})}{4Y_{mk} + Y_{SVC} + \dfrac{Y_{m0}}{2} + \dfrac{Y_{k0}}{2}} + \dfrac{Y_{m0}}{2} \\ Y_3 = \dfrac{Y_{mk}(2Y_{SVC} + Y_{m0} + Y_{k0})}{4Y_{mk} + Y_{SVC} + \dfrac{Y_{m0}}{2} + \dfrac{Y_{k0}}{2}} + \dfrac{Y_{k0}}{2} \end{cases} \quad (7)$$

All elements of the admittance matrix of a row with an SVC in its middle are modified, such as

$$Y_{new}^{line} = \begin{pmatrix} Y_{mm} & Y_{mk} \\ Y_{km} & Y_{kk} \end{pmatrix} \quad (8)$$

4. MODELING APPLICATIONS AND CALCULATION RESULTS

In order to complete the theoretical work, we propose in this one some applications. As a result, we will first carry out our applications on the standard IEEE14-node network by implementing PSAT software (power system analysis toolbox) [8] written in MATLAB language. Next, we will implement an application on a standard IEEE05-node network, utilizing the MATLAB environment to calculate the power distribution.

4.1 Study of an IEEE network with 14 nodes

It corresponds to a balanced three-phase aerial network of 14 nodes where the power and frequency bases of the network are 100 MVA and 50 Hz. It contains two generators, sixteen transmission lines, eleven loads, three synchronous compensators, and a static capacitor as shown in Figure 6.

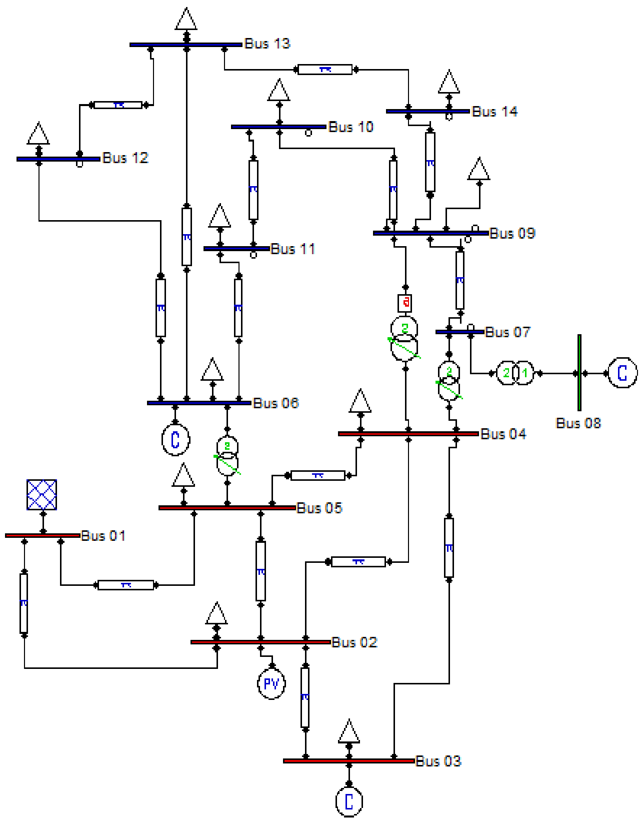

Figure 6. Diagram of the 14-node IEEE

4.1.1 FACTS system effect (SVC) on faulty network

In this study, we will visualize the effect that the installation of the FACTS system (SVC) can have on the power flow and voltage profile.

Case of a three-phase short-circuit. In this case, the SVC is connected to node 11, with the fault at node 12 being eliminated by opening line 12-13 and line 12-06 by protection devices to isolate it from the network.

5. DISCUSSION OF RESULTS

The results of our calculations, presented in Figure 7 (after SVC installation), are in perfect agreement with those published in Figure 8 (after STATCOM installation), both in terms of speed and amplitude.

From Figures 7-11, the nodes have a voltage profile similar to that of the pre-fault network voltages when the SVC is connected.

The case of Figure 7 (bus 12) is different: the object of the three-phase fault is isolated from the network by the protection circuit breakers. FACTS shunt systems have a corrective contribution to the voltage of a faulty network given the values that are close to the flat value of 1 p.u. displayed during the installation of these devices.

Figures 9-13 illustrate the active and reactive between the buses (lines) for three scenarios: the network without fault, the network with fault, and the network with SVC.

One can also notice from these figures that the installation of SVC has the effect of relieving some overloaded lines when the network is subject to the fault and returning them almost to their initial states before the fault, as shown by the powers in the lines 1, 11, and 14, etc. (Figure 9).

Thus, the improvement in voltage profile due to the integration of SVC influences the reduction of total active and reactive losses (Tables 1-2).

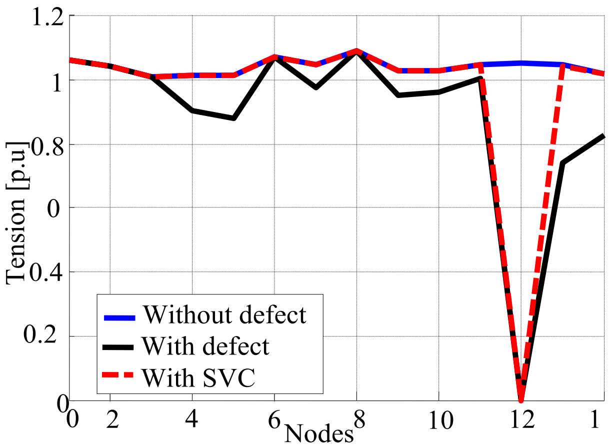

Figure 7. Voltages in each busbar after installation SVC

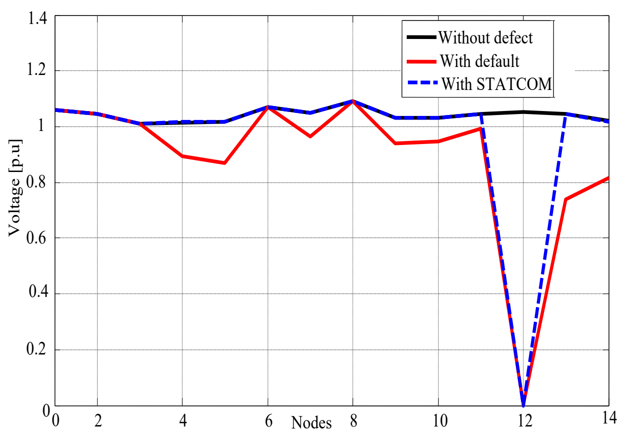

Figure 8. Voltages in each busbar after installation of STATCOM

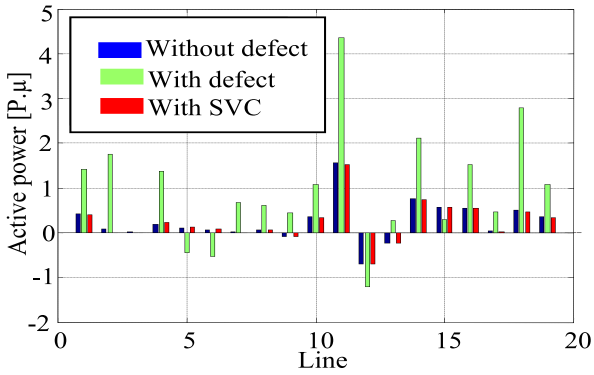

Figure 9. The active powers transiting in the structures of the network

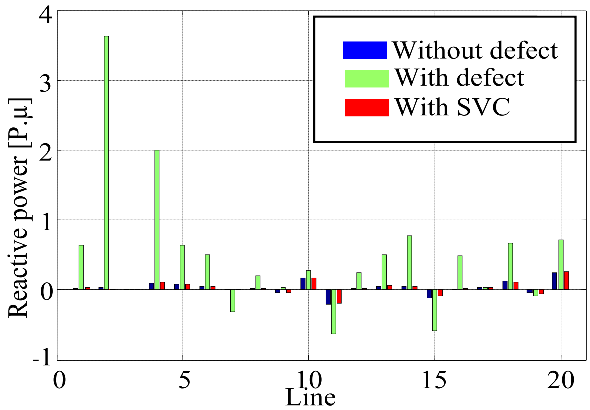

Figure 10. Reactive powers flowing through network structures

Table 1. Active and reactive losses in network structures during a short-circuit

Transmission Line		Without Defect	
		Active Losses	Reactive Losses
2	5	0.00925561	-0.00792088
6	12	0.00082174	0.00171027
12	13	0.00011274	0.000102
6	13	0.00260918	0.0051383
6	11	0.00128391	0.00268867
11	10	0.00052098	0.00121956
9	10	2.6752E-05	7.1063E-05
9	14	0.00073436	0.00156207
14	13	0.00112633	0.00229325
7	9	0	0.01594029
1	2	0.04293563	0.07259631
3	2	0.02318979	0.05144359
3	4	0.00387201	-0.02559454
1	5	0.02783451	0.06177146
5	4	0.00452182	0.00103558
2	4	0.01652612	0.01045123
2	5	1.141E-05	0.00126923
6	12	-5.5511E-17	0.05947793
12	13	-5.5511E-17	0.02696423
6	13	6.9389E-18	0.00915092
Transmission Line		With Fault	
		Active Losses	Reactive Losses
2	5	0.13223078	0.37236367
6	12	1.74706905	3.63613811
12	13	1.35618417	1.22702378
6	13	0.34745057	0.68423863
6	11	0.06759087	0.14154373
11	10	0.05996853	0.14037971

9	10	0.02566879	0.06818651
9	14	0.06468913	0.13760244
14	13	0.06044508	0.12306849
7	9	0	0.17212906
1	2	0.34339477	0.98994242
3	2	0.07358563	0.26376249
3	4	0.02719269	0.03794166
1	5	0.2474664	0.97539816
5	4	0.010142	0.0220617
2	4	0.14350705	0.40008214
2	5	0.00159926	0.17789509
6	12	0	2.65225497
12	13	0	0.3589574
6	13	0	0.08982744

Power distribution following a sudden load increase.

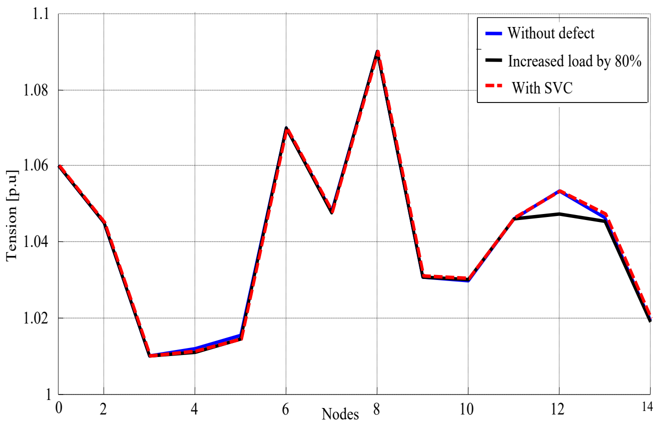

Figure 11. Voltages in each busbar after installation SVC

Table 2. Active and reactive losses in networks according to the increase in load 80%

Transmission Line		Without Defect	
		Active Losses	Reactive Losses
2	5	0.00925561	-0.00792088
6	12	0.00082174	0.00171027
12	13	0.00011274	0.000102
6	13	0.00260918	0.0051383
6	11	0.00128391	0.00268867
11	10	0.00052098	0.00121956
9	10	2.6752E-05	7.1063E-05
9	14	0.00073436	0.00156207
14	13	0.00112633	0.00229325
7	9	0	0.01594029
1	2	0.04293563	0.07259631
3	2	0.02318979	0.05144359
3	4	0.00387201	-0.02559454
1	5	0.02783451	0.06177146
5	4	0.00452182	0.00103558
2	4	0.01652612	0.01045123
2	5	1.141E-05	0.00126923
6	12	-5.5511E-17	0.05947793
12	13	-5.5511E-17	0.02696423
6	13	6.9389E-18	0.00915092
Transmission Line		**With Fault**	
		Active Losses	**Reactive Losses**
2	5	0.010019	-0.00547
6	12	0.001524	0.003173
12	13	2.24E-05	2.02E-05
6	13	0.003098	0.006102
6	11	0.001377	0.002883
11	10	0.000576	0.001348
9	10	2.14E-05	5.69E-05
9	14	0.000762	0.00162
14	13	0.001113	0.002266
7	9	-5.6E-17	0.016007
1	2	0.04493	0.078685
3	2	0.023653	0.053397
3	4	0.00388	-0.02543
1	5	0.029398	0.068393
5	4	0.004213	0.000159
2	4	0.017234	0.012755
2	5	9.32E-06	0.001037
6	12	2.22E-16	0.063118
12	13	0	0.026348
6	13	2.29E-16	0.010094
Transmission Line		**With SVC**	
		Active Losses	**Reactive Losses**
2	5	0.010016	-0.00548
6	12	0.001436	0.002989
12	13	0.000138	0.000125
6	13	0.002895	0.005701
6	11	0.001364	0.002857
11	10	0.000568	0.00133
9	10	2.18E-05	5.79E-05
9	14	0.00075	0.001595
14	13	0.001152	0.002346
7	9	-5.6E-17	0.015953
1	2	0.044922	0.07866
3	2	0.02365	0.053384
3	4	0.003878	-0.02544
1	5	0.029393	0.068371
5	4	0.004214	0.00016
2	4	0.017231	0.012741
2	5	9.2E-06	0.001023
6	12	-2.2E-16	0.063103
12	13	0	0.026353
6	13	4.16E-17	0.010019

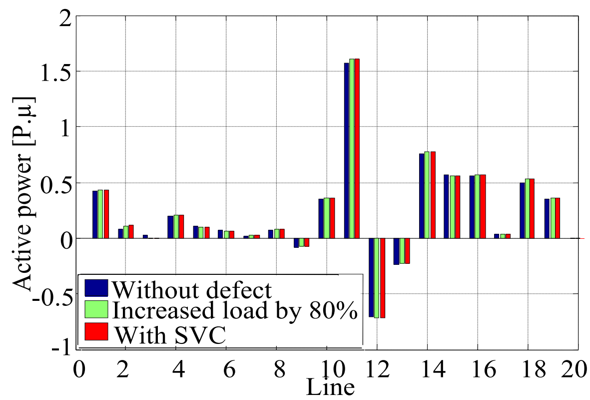

Figure 12. The active powers transiting in the structures of the network

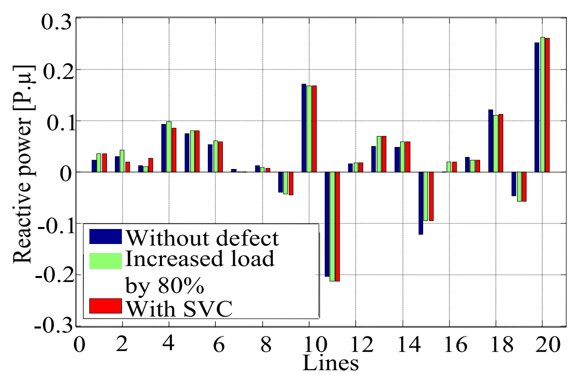

Figure 13. The reactive powers transiting in the structures of the network

6. SIMULATION UNDER THE MATLAB ENVIRONMENT

6.1 Structure of the simulated network

An application on a standard network, an IEEE 05-node test network, consisting of 7 power lines, 2 generators, and 4 loads. First, we present the results of the power flow by the iterative methods of Newton Raphson without an SVC device (Figure 14).

The main parameters of the SVC considered in this study are as follows:

- X_c (pu) = 1.0700,
- X_L (pu)= 0.2880,
- α_{min} (°) = 90,
- α_{max} (°) = 180.

Then we will present the results of the power flow after and before insertion of the SVC device in the network.

6.2 Insertion of the SVC into the network

6.2.1 Inserting an SVC at the beginning of a line

In this case, node 4 is overloaded so as to cause the voltage drop in this node and adjacent ones. The changes affect the active power *P* and reactive power *Q*, which take the values 1.40 pu and 0.40 pu, respectively. This results in a change in the state of the network.

Figures 15-17 show the voltage drops at the load nodes, as well as the increase in total active and reactive power losses in the network following the overload at node 4. An SVC is installed at node 4 to address this issue.

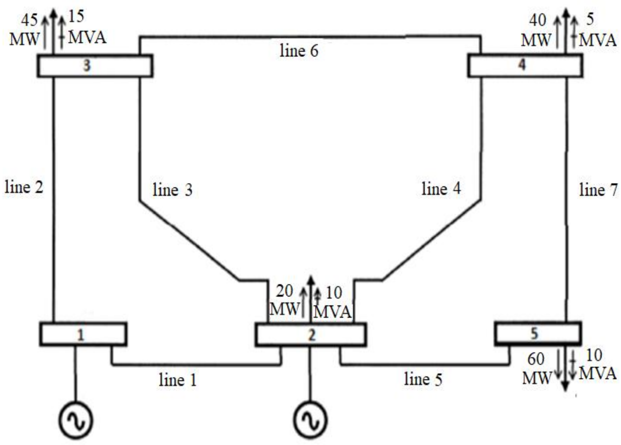

Figure 14. Diagram of the 5-node network

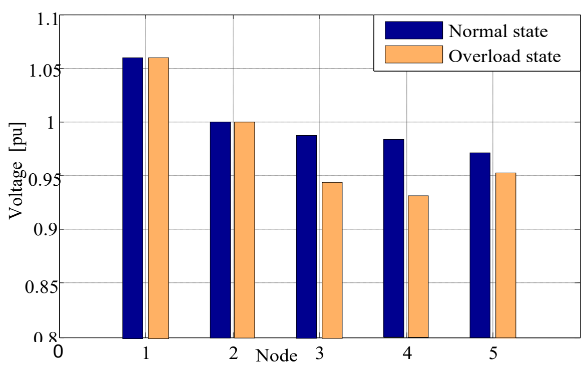

Figure 15. The voltage amplitude in normal state and overload state

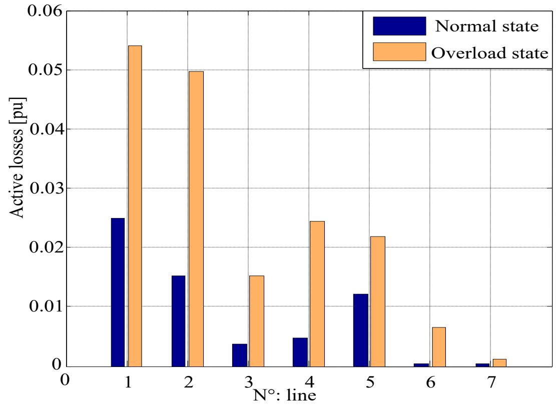

Figure 16. Active losses in the lines

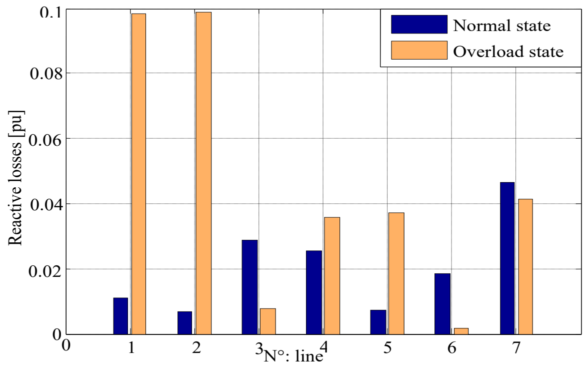

Figure 17. Reactive losses in the lines

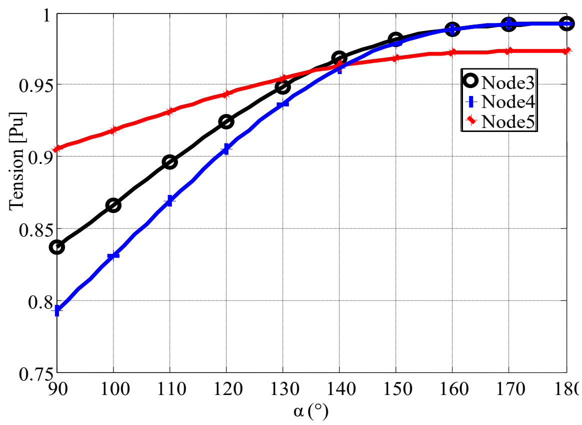

Figure 18. The variation of voltage amplitude as a function of α

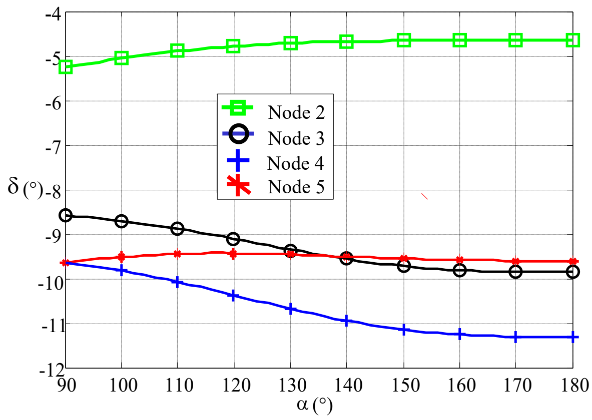

Figure 19. The variation of voltage angle as a function of α

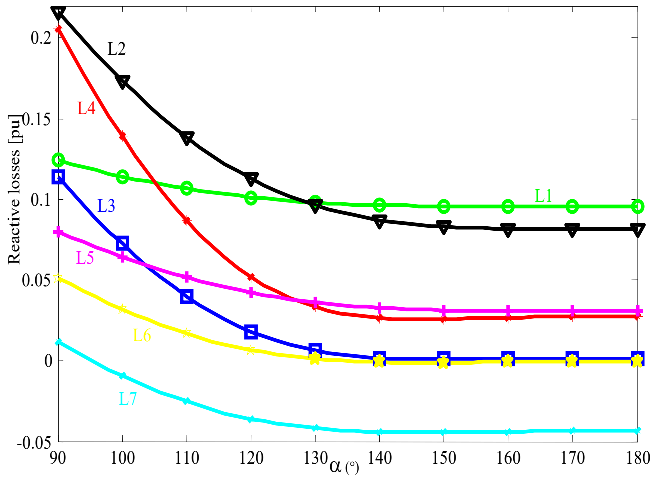

Figure 20. Active losses as a function of α

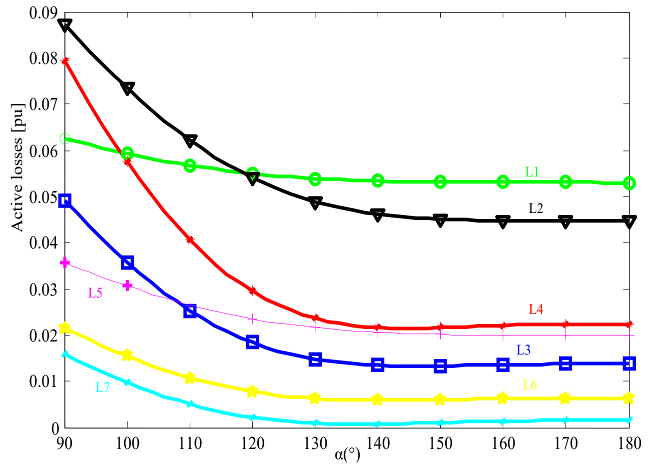

Figure 21. Reactive losses as a function of α

6.2.2 Insertion of an SVC in node 4

The principle is to vary "α" from 90° to 180° to observe the effect of the SVC on the voltages of the nodes and the power losses in the lines.

Figures 18-21 show the influence of the firing angle on the voltage amplitudes and on the powers.

6.3 Discussion and interpretation of results

From an "α" value of 135° (equivalent to QSVC of 0.255 p.u.), the voltages can be compensated (Figure 18). The voltages from this value are within the tolerated limits (+/- 5%). Thus, as in Figures 20 and 21, the SVC fulfills its role of voltage regulator and makes it possible to reduce the losses in the lines. Indeed, the SVC makes it possible to fill, by a local reactivated energy contribution, the consumption at the overload node and, therefore, reduce the reactive energy demand of the generator and the reference node. This naturally makes it possible to reduce the power transmitted through the line (in particular that connected to node 4) and therefore to bounce back the losses.

7. CONCLUSION

In this paper, we addressed the problem of analyzing and quantifying electrical disturbances in power transmission networks, with a particular focus on the flow of active and reactive power and voltage regulation. The aim was to demonstrate the effectiveness of using the PSAT software and the Newton-Raphson method to solve the power flow problem and evaluate the system's performance under various operating conditions.

Our results, supported by a set of carefully designed applications, show that it is indeed possible to model and quantify different types of disturbances in a power transmission system. The simulations clearly illustrate that the PSAT software, combined with the Newton-Raphson power flow algorithm, provides accurate and reliable solutions. The findings demonstrate that both active and reactive power flows are optimized throughout the transmission lines, and that the voltage profiles at the busbars are effectively regulated. This optimization contributes significantly to improving the stability and efficiency of the electrical network.

The implications of this work are notable for both research and industry. By using accessible simulation tools such as PSAT, engineers and researchers can evaluate the impact of various disturbances on power systems and apply corrective measures to maintain grid stability. Additionally, the methodology applied here supports the development of automated and intelligent monitoring systems for modern power networks, especially as renewable energy integration increases the complexity and variability of grid behavior.

However, the study has certain limitations. The simulations were performed under a limited number of scenarios and did not account for dynamic or transient stability effects, which can play a critical role in real-world networks. Furthermore, the use of a steady-state solver like Newton-Raphson does not capture time-domain behavior, which is important in cases of faults or sudden load changes.

For future research, we recommend extending the analysis to include transient and dynamic stability studies, possibly by integrating FACTS devices and renewable energy sources such as wind or solar power. Several studies have highlighted the potential of FACTS controllers in enhancing stability and improving network controllability when combined with optimization techniques [24]. Exploring real-time simulation tools and incorporating larger, more complex network topologies would also enhance the robustness of the findings. Finally, implementing machine learning techniques for predictive analysis and control could open new perspectives for intelligent energy management in smart grids.

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NOMENCLATURE

FACTS	Flexible Alternating Current Transmission Systems
SVC	Static Var Compensator
PSAT	Power System Analysis Toolbox Thermal
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
STATCOM	Static Synchronous Compensator
G	Conductance
B	susceptance
y	admittances between the busbars
x	reactance
r	resistance
Y	admittance matrix
YSVC	SVC admittance
JB	busbars

Greek symbols

α	priming angle, degrees °
β	tension angle, degrees °

Subscripts

i	node i
j	node j
m	SVC location node