

Simulation of FACTS Devices as Reactive Power Compensators and Voltage Controllers in the Smart Grid

Ramadan Elmoudi, University at Buffalo

Ramadan Elmoudi (IEEE Student M'10) received the B.Sc. degree and the M.Sc. degree in electrical engineering in 1996 and 2007 respectively from Misrata Institute of Industry and Academy of Graduate Studies, Tripoli, Libya, respectively. He has over 10 years of industrial experience in National Power Sector beside his work as a developer of automation systems in different disciplines. Currently he is pursuing the Ph.D. degree in electrical engineering in U B (SUNY), Buffalo, NY. His interests are in power systems control, artificial-intelligence (AI) applications in Smart Grids, power electronics for Smart Grids and Advanced Protection and Automation centers

Dr. Ilya Y. Grinberg, Buffalo State College

llya Grinberg graduated from the Lviv Polytechnic Institute (Lviv, Ukraine) with an M.S in E.E. and earned a Ph.D. degree from the Moscow Institute of Civil Engineering (Moscow, Russia). He has more than 30 years of experience in design and consulting in the field of power distribution systems and design automation. He has over 38 published papers. Currently he is professor of engineering technology at SUNY Buffalo State. His interests are in the field of electric power distribution systems analysis, design automation, and systems engineering.

Prof. Mohammed Safiuddin, University at Buffalo, SUNY

B.E. (Electrical) Osmania University, India, MSEE University of Illinois), MBA, Ph.D. UB(SUNY). Junior Engineer, Andhra Pradesh State Electricity Board (India) (1958-59). Westinghouse Electric Corporation, Buffalo, New York (1960-85). Research Professor, Advanced Technology Applications, Electrical Engineering, University at Buffalo (SUNY) (1977-2010). President, STS International, Amherst, NY (1985-present). Technical interests cover static power conversion and optimal control systems applied to industrial processes, energy conservation and energy management. Holds 10 patents in this field and has published numerous technical papers. IEEE Life Fellow. Awarded Roscoe Allen Gold Medal (1957, Osmania University) for excellence in hydraulics. Awarded "IUSD Award of Merit" in 1992 (IEEE-Industry Applications Society). Recognized for meritorious achievement in continuing education by the IEEE-EAB award for the year 2000. Member Pi Mu Epsilon (Mathematics), Beta Gamma Sigma (Business) honor societies, and "Eminent Engineer" member Tau Beta Pi.

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Abstract

This paper provides a modeling platform for students to understand and study power system dynamics using Matlab® and PSCAD/EMTDC® when Flexible AC Transmission Systems (FACTS) devices for reactive power compensation and voltage control are implemented. In this study, a proposed power system's voltage profile has been modeled and analyzed using Matlab® and PSCAD/EMTDC® to determine the optimum parameters for the design of FACTS devices, such as Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC). A tutorial was developed as part of the Smart Grid Control Systems course at SUNY University at Buffalo. This tutorial provides the insight for both undergraduate and graduate students as well as practicing engineers. It helps them to understand FACTS devices design and implementation by highlighting their main characteristics and enhancing performance of the power system they are being integrated with.

Introduction

As an outcome of the deregulation of electric power industry, power transmission operators are now responsible for their own business. Therefore, they must make the best use of their transmission capacity and ensure that transmission losses are minimized¹. Also, any loss of transmission capacity means loss of income for the power transmission operators. Therefore, all actions must be taken to ensure that reactive circulating power does not obstruct available transmission capacity. In addition, energy congestion in critical transmission corridors must be avoided to eliminate the risk of jeopardizing the grid stability, reliability as well as profitability of business operations. Moreover, to offer the greatest flexibility, transmission operators must ensure the maximum safe operating margins to allow power injection and tapping from its buses without endangering stable operation. Thus, the successes of transmission operation depend on offering the maximum available transmission capacity (ATC) on their transmission lines. It is apparent that in developing the smart grid realm, transmission operators have a greater responsibility to make their networks more flexible. Advancements in power-electronics technology now offer new fast, controllable FACTS controllers to assure this required flexibility. The subject matter is an integration of classic power systems, power electronics, control theory and programing among others and is quite complicated for understanding by students and engineers who have no previous exposure to this field. During development and implementation of Control Systems for Smart Grid course it was decided to develop and present a tutorial to assist electrical engineering students and professionals in achieving deeper understanding and obtaining practical skills related to FACTS devices in order to meet the power flow control challenges.

Reactive power is an important, but not an easy, concept to understand in electrical power systems. Reactive power compensation is considered as a powerful tool for optimizing the power flow on transmission networks. Inadequate reactive power leads to voltage collapses and has been a major cause of several recent major power outages worldwide¹. Reactive power compensation can be provided by using FACTS devices, which are power electronics-based devices that control and regulate the power flow within the power system. They are capable to reroute power through the optimum available paths regardless of the dynamics of the power system. Clear understanding of the principles of FACTS devices and how they affect the behavior of the power system becomes easier after grasping the fundamentals of designing primary building blocks of all thyristor based FACTS devices. Since the process of developing and implementing FACTS devices is quite complicated, the use of power systems modeling tools becomes obvious to facilitate the learning process in this field. Two available software packages, Matlab \mathbb{B}^2 and PSCAD/EMTC \mathbb{B}^3 where chosen to be used in the tutorial and simulation. Matlab® uses a high-level language and an interactive environment for numerical computation, visualization, and programming. Using Matlab®, electrical engineering students can analyze data, develop algorithms, and create models and applications. In the tutorial, Matlab® is used to study the voltage profile dynamics of a proposed power system with varying load profile. Besides that, the PSCAD/EMTC® provides vast possibilities in power system simulation. It contains a comprehensive library of system models ranging from simple passive elements and control functions, to complex electric machines and FACTS devices. In order to understand the dynamics of a power system in the presence of FACTS devices, modeling and simulation approach allows students to appreciate the value of these devices and their role in enhancing the

power system performance for different scenarios and case studies. Moreover, when the students grasp the concept of FACTS devices, they will be able to use PSCAD/EMTC models to build their own designs in order to solve complex compensation and voltage control problems.

Power System Configuration

In order to appreciate the role of FACTS devices, a power system should be specified and its voltage profile analyzed. The representative power system, as shown in Fig. 1, consists of:

- Power source step up transformer combination with rated voltage of 230 KV at 60 Hz.
- 300 Km (168.4 miles) high voltage transmission line⁴ with impedance $Z_{line} = (7.5 + j86.71)\Omega$
- Dynamic load with a lagging power factor that changes within well-known limits.



Figure 1. Single- line diagram of the specified power system configuration.



Figure 2. Power system's voltage profile at different loading and power factors

Voltage Profile Study of the Specified Power System

The voltage profile is studied at the receiving end of the transmission line, i.e. the bus where the load is connected to the transmission line. The load is dynamic with a varying profile within the limits between 20 to 140 MVA, while the power factor is also changing from unity down to 0.4 lagging. Matlab® is used for simulation of the given power system and for analysis of the voltage profile at the receiving end during load variations. Figure 2 illustrates the voltage profile of such a system. It is obvious that when the load increases the voltage drops. The red line in Fig. 2 shows the minimum standard acceptable voltage limit of 0.95 pu of the rated voltage (or 95% of 230 KV in our case). Therefore the voltage must not drop below this limit. Otherwise, the system will have a voltage quality issue and unacceptable performance. Figure 2 illustrates that

the voltage profile of the given power system under different loading conditions has undesirable performance in most cases. Only at 20 MVA load at power factor greater than 0.9 lagging, voltage is acceptable and lies within limits. This means that the loading capability of the system cannot exceed 20 MVA. Therefore, corrective measures should be taken to address this problem.

Shunt Compensation

One remedy to such a problem is using a shunt compensation at the receiving end. That is, by connecting a shunt capacitor to the load, required reactive power is supplied localy and the power source would not have to provide reactive power to the load. Transmission line is also relieved from transmitting reactive power to the load. Consequently, the system in Fig. 1 is amended as depicted in Fig. 3. The value of the capacitor changes as the reactive power demand varies; the maximum reactive power demand is about 42.15 MVAr as shown in Fig. 4. Therefore, the maximum capacitance value has to be about 15 μ F as illustrated in Fig. 5.



Figure 3. Single-line diagram for the shunt compensated system



Figure 4. Load reactive power demand



Figure 5. Compensator capacitance variation with reactive power demand.

Figure 6 shows comparison between the voltage profiles of the uncompensated and the shunt compensated power system. It is apparent that the voltage profiles for the compensated system have been improved significantly. However, some loading cases still remain below the minimum limit of 0.95 pu of the rated voltage. This is due to the reactive component of the transmission line itself, which can be compensated using series capacitors.



Figure 6. Voltage profiles for uncompensated and shunt compensated power system



Figure 7. Voltage profiles for uncompensated and shunt compensated power system in 3D

Series Compensation

To address the problem of the voltage drop, as illustrated in Fig. 6, for loadings in the range of 80 MVA to 140 MVA and at power factor values lower than 0.65 lagging, series compensation can be utilized. Therefore, the system is represented in Fig.8, where a series capacitor is added to the impedance of the transmission line. Usually X_C is selected to be within the range of 30% to 70% of the transmission line's inductive reactance¹.



Figure 9. Voltage profile of Series and Shunt compensated system.

Figure 9 illustrates that series compensation alone does not do much to enhance the voltage profile of the power system. However, with shunt compensation it can accomplish the task and bring all the voltage profiles at different loadings above the specified minimum voltage limit, except for 120 and 140 MVA for power factor values greater than 0.85 and 0.73, respectively.

Static VAR Compensator (SVC) Design and Simulation

Referring back to Fig. 8, there are two variable capacitors; one of them is shunt connected to the load bus while the other one is in series with the transmission line. The question now is how these variable capacitors are implemented and integrated with the power system? The SVC is constructed by means of Fixed Capacitor and Thyristor Controlled Reactor (FC-TCR), which is placed in shunt with the load bus as shown in Fig. 10. The firing angles of the TCR are varied for different loading conditions to make the reactive power zero at the source. Manual control is used to set the firing angles for SVC such that it minimizes the reactive power provided from the source and reduces it to a value as close to zero as practical⁵.



Figure 10. Illustration of SVC and the equivalent reactances of its sub-elements

The main building block in most of FACTS devices is the TCR. The TCR comprises a pair of back-to- back thyristors in series with a linear air-core reactor. Control and firing unit is used to vary the firing angle α by which the start of conduction of the thyristor pair is delayed. Variation of the firing angle α changes the effective 60 Hz value of the TCR's inductive reactance jX_{TCR} and this, in turn, changes the net value of the reactance jX_{SVC} of the SVC as a whole. The diagram of Fig.10 illustrates how SVC behaves as a variable reactance in parallel with the composite load. The net reactance of the SVC, jX_{SVC} , can be either inductive or capacitive and its magnitude can be controlled dynamically by controlling the reactance of the TCR branch by means of the thyristor firing angle α .⁵ The inductive reactance jX_{TCR} of the TCR varies between jX_L , and ∞ as the thyristor firing angle α varies from 90° to 180°. The TCR's effective 60 Hz reactance jX_{TRC} is related to the thyristor firing angle α by

$$X_{TCR}(\alpha) = \frac{\pi X_{TCR}}{2(\pi - \alpha) + \sin 2\alpha}$$
(1)

Figure 11 shows the change in the reactance of the TCR as the firing angle varies from 90° to 180° .



Figure 11. TCR reactance change with the change in the firing angle.



Figure 12. Fundamental Characteristics of the SVC's net reactance.

From Fig. 5 the capacitor maximum value has to be 19.3µF; the closest standard capacitor value is 20 µF. Therefore, this will be the value of the capacitor of the SVC, from which the capacitive reactance is $X_C = 132.63 \ \Omega$.

Typically, the 60 Hz inductive reactance X_L of the TCR branch of the SVC is selected such that⁵ $X_L \leq X_C/2$. For our tutorial the value of X_L is selected to be equal 48 Ω , as depicted in Fig. 11, so the inductor of the TCR branch is 0.127 H. Therefore, the SVC impedance is changing with the thyristor firing angle as shown in Fig. 12.

In addition, Fig. 12 shows that the resonance occurs when the firing angle is equal to 121.8° . Moreover, there are two distinct regions: inductive region and capacitive region. In inductibve region the equivalent circuit of the SVC is a pure inductor. The range of this region spans from $\alpha = 90^{\circ}$ to the resonance angle at $\alpha = 121.8^{\circ}$. On the other hand, the capacitive region extends from the resonance point to $\alpha = 180^{\circ}$. The tutorial considers only the capacitive region of the SVC's characteristics impedance graph. Therefore, the firing angle will be within the range $122.8^{\circ} \le \alpha \le 180^{\circ}$ because the capacitor values at these firing angles will be 0.9394 and 20 µF, respectively, as shown in Fig.13. Thus, the SVC design with these parameters is capable to compensate for most of loadings of the power system represented in the tutorial.



1002(cos-1 0.8) 80+60i
132.79 ² ÷80 220.4148013
132.79²÷60 293.8864017
NMAT.

Figure 14. Calculation of the load components.

Figure 13. SVC Equivalent capacitance value change with variation of the firing angle.

PSCAD is used to simulate the implementation of the SVC for selected loading cases. The load of 100 MVA at power factor 0.8 lagging is selected and the voltage profile is obtained. The load components should be calculated as shown in Fig.14.

The PSCAD models of a single- phase representation of the given power system with integrated SVC are shown in Fig. 15.



Figure 15. PSCAD models of the power system with SVC

A single phase voltage source model is used with parameters as given in Fig. 16a. The SVC is connected to the power system through a circuit breaker (BRK) that closes after 2.5 seconds

from the start of the simulation as shown in Fig. 16b. Thyristor parameters are demonstrated in Fig. 16c. Thyristor firing pulses generation and firing angle control are achieved using the blocks as shown in Fig. 17. A reference signal is fed to the zero detector function block, which will pulse whenever the signal on its input crosses the zero level. The voltage across the load is the reference signal. The output of the zero detector function block is fed to the delay function block. Delay function block holds the signal on its input for a time equal to the desired firing angle, and then it sends the pulse to the gate of the forward thyristor, which is triggered in the positive half of the reference signal. The same is repeated for the backward thyristor, except its pulses are delayed 180° from the forward thyristor triggering pulses as illustrated in Fig. 17.



(a)

Figure 16 Voltage source, timed breaker logic and thyristor parameters



Figure 17. Thyristor firing pulses generation and control (firing pulses at $\alpha = 135^{\circ}$).

After constructing the PSCAD model for the power system with the SVC as shown in Fig. 15, and connecting the blocks of the thyristors firing pulses and control as shown in Fig. 17, the firing angle is set to be about 135° as illustrated in Fig. 13, since at this firing angle the SVC operates in the capacitive region. At this angle the equivalent capacitance value is about 9 μ F, which satisfies the purpose of 100 MVA at 0.8 lagging load compensation. By performing the PSCAD simulation, the load bus voltage profile is represented in Fig. 18.



Figure 18. (a) Load bus voltage profile with and without SVC. (b) The uncompensated load voltage in pu. (c) The compensated load voltage in pu.

From Fig. 18a it is clear that the load voltage profile starts way below the required minimum standard of 0.95 pu. The uncompensated load voltage is about 0.73 pu, which requires compensation to enhance the load voltage profile. Obviously, the SVC boosts the load voltage profile to about 0.9 pu as shown in Fig. 18c. However, this is still below the required 0.95 pu value, although, as mentioned earlier, the SVC has a noticeable role in enhancing the overall power system performance and improves the voltage profile by about 17%.

Figure 19 shows the power system with SVC characteristics waveforms. In this figure the source current is sinusoidal before closing the circuit breaker (prior to the time of 2.5 second). After that the source current waveform is non-sinusoidal due to the effects of SVC. Comprehensive analysis and discussions of these waveforms have been carried in the classroom with students.



Figure 19. The power system with SVC characteristic performance waveforms for: source current, TCR branch current, TCR inductor voltage, SVC capacitor current, and the SVC current.

Thyristor Controlled Series Compensator (TCSC) Design and Simulation

As mentioned earlier, the SVC does not provide sufficient improvement to the load bus voltage profile for certain loading cases including the case study of 100MVA load at power factor 0.8 lagging. This is due to the transmission line impedance which also can be compensated with the series compensation technique. A fixed capacitor is connected in series with the transmission line to provide the required compensation. However, due to the dynamic loading of the power system a fixed value series capacitor does not fulfill all compensation requirements in a dynamic power system in which the power flow constantly changes. Therefore, the tutorial provides for the TCSC case study of the given power system with above mentioned parameters. The TCSC is designed to provide a compensation in the range of 30% to 70% of the given transmission line inductance. Therefore, the equivalent capacitance values of the TCSC has to change between

101.97 μ F and 43.703 μ F respectively, which corresponds to thyristor firing angles of 180 ° and 118.6° as illustrated in Fig. 21. The TCSC capacitor value is selected to be 102 μ F. The inductor of the TCR branch of the TCSC must be selected such that the resonance occurs outside the control range. The inductor of the TCR branch of the TCSC has a selected value of 50 mH. Matlab® is used to visualize the change of the TCSC impedance with the firing angle as shown in Fig. 20. Noticeably, the resonance occurs when $\alpha = 102.6^{\circ}$, which is outside of the control range.



Figure 20. TCSC reactance change with firing angle



Figure 21. TCSC Equivalent capacitance value change with the change in the firing angle

The PSCAD model of the power system with SVC of Fig. 15 is modified to include the TCSC as shown in Fig. 22.



Figure 22. PSCAD model of the power system with SVC and TCSC

The firing angle of the SVC is kept without change as at $\alpha = 135^{\circ}$. The firing angle of the TCSC is adjusted to provide 70% compensation of the transmission line inductance, for which it becomes $\alpha = 118.6^{\circ}$. The load bus voltage profile is obtained as an outcome of the PSCAD and the results are shown in Fig. 23.



Figure 23. (a) Load bus voltage profile with series and full compensation.

(b) The series compensated load voltage in pu. (c) The fully compensated load voltage in pu. In this case, the load bus voltage profile is improved to about 0.96 pu when the combination of both TCSC and SVC is used. Therefore, the load bus voltage satisfies the standard lower limit of 0.95 pu. Waveforms of the compensated power system are shown in Fig. 24.



Figure 24. The power system with SVC characteristic performance waveforms

Tutorial implementation in the course and students' comments

The tutorial facilitates the learning process of FACTS, one of the advanced and more difficult topics in the field of electric power systems, because different disciplines are involved in this topic, such as power system analysis, power electronics, control systems, and programming. Tutorial focuses on a sample power system configuration. The performance of the load bus voltage profile has been studied and the problem of voltage control has been analyzed. FACTS devices, especially SVC and TCSC, have been proposed to solve the problem of the voltage drop at the load bus. The SVC has been designed and integrated with the given power system. Moreover, the TCSC has also been designed to complement the SVC in order to improve the overall performance of the power system. Students successfully went through learning process to develop a firm understanding of the FACTS devices. They followed the tutorial-based modeling and simulation and were able to develop their own designs to enhance and control performance of power systems assigned to them.

This tutorial has been given to the students in the course EE507 "Smart Grid Control Systems" and some comments are included.

- The tutorial gives us great understanding for the power system dynamics and how its performance can be continuously improved.
- The rule of the thumb is that it is easier to preach than to implement. This was my situation when I started working on analyzing the power system and improving the load bus voltage profile. I got lost in Matlab and PSCAD but this tutorial pointed me directly to my goal.
- I always try to avoid power electronics topics because I have difficulty visualizing the response and behavior of different devices working together. However, PSCAD makes it easy for me to design and implement different power electronics devices with full understanding of what is going on.
- I tried to understand FACTS devices using different books but it was a difficult process because they have treated the topic mathematically without the physical aspects. This tutorial completed the missing piece of the puzzle and solidified my understanding of two of the widely used FACTS devices, SVC and TCSC.

- The tutorial started with the analysis of a very simple power system, then the complexity of the given power system keeps increasing. I do like this sequence of events to solidify my understanding of the problem in hand and suggest the feasible solutions and implement them.
- Using this tutorial increases my performance and reduces the time frame of accomplishing the task. Moreover, I usually go back through the tutorial to fill in any blanks in my understanding.

Future work

Further research and pedagogical aspects to be investigated include but are not limited to:

- Analysis and implementation of three phase TCSC and SVC compensators for an unbalanced power system.
- Power quality issues with respect to the harmonics generated in the presence of FACTS devices and how the remedial solutions can be studied and implemented.
- Active filtering and its interaction with FACTS devices.
- Reliable protection and automatic control for power systems with FACTS devices

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