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Voltage Control and Dynamic Performance of Power Transmission Using Static VAR Compensator

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Abstract

The power demand, in the recent years, has increased substantially while the expansion of power generation and transmission has been severely limited due to environmental restrictions and limited resources. As aneffect, some transmission lines are heavily loaded and the system stability and voltage becomes a limiting factor for power transfer. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, studies reveal that FACTS controllers could be employed to enhance voltage profile in the network in addition to their function of power flow control in the network.

This paper presents how static var compensator (SVC) can be utilized to control transmission system dynamic performance for system disturbance and effectively regulate system voltage. Static var compensator (SVC) is basically a shunt connected static var generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power variables, typically, the control variable is the system bus voltage. Voltage control and the increase in system load abilityarethe main applications of SVC in this paper. Firstly, to design a controller for SVC devices on a transmission line, a single machine infinite bus (SMIB) is modeled. A state space model is developed in the MATLAB/SIMULINK to show the improvement in the dynamic performance of the system.

Keywords: Voltage Control, FACTS, static var compensator, SMIB,dynamic performance.

1. Introduction

Flexible AC transmission systems (FACTS) have gained a great interest during the last few years, due to recent advances in power electronics. FACTS devices have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, and transfer capability enhancement. As supplementary functions, damping the inter-area modes and enhancing power system stability using FACTS controllers have been extensively studied and investigated [1].

The increase in the loading of the transmission lines sometimes can lead to voltage collapse due to the shortage of reactive power delivered at the load centers [2]. This is due to the increased consumption of reactive power in the transmission network and the characteristics of the network.

Various FACTS controllers like SVC, STATCOM, IPFC, UPFC etc are used today in electrical power network depending upon its application.The main focus of this paper is the application of static var compensator (SVC) to solve voltage regulation and improve system dynamic performance. SVC is a thyristor based controller that provides rapid voltage control to support electrical power transmission voltages during any system disturbance.It is an important matching device in the network designed to improve the power factor closer to unity. If the power system's is capacitive (leading) the SVC will use reactors to consume VAR's from the system, lowering the system voltage to the reference. Under inductive (lagging) loading conditions, the capacitor banks are automatically switched in, thus maintaining the system voltage to the reference.

2. Literature Review

In this section, published literature from international electrical engineering groups such as theInstitute of Electrical and Electronics Engineers (IEEE), were reviewed with important relevant subjects related to voltagecontrol, var compensation, and static var compensators briefly discussed and identified.

2.1 History and Background of SVCs

Static var compensators, regarded as the first FACTS controllers, have been used in NorthAmerican transmission systems since late 1977 in western Nebraska [3]. The aforementioned transmission SVC device was installed to provide "automatic, continuous voltage control."Since then, there are a lot of transmission SVCs commissioned around the world, andmany transmission SVCs applied in North America. The term "transmission systemSVC" is used because SVCs are also applied at the distribution level to compensate for localvoltage fluctuation problems due to industrial load operation [4].

The heart of the SVC is an ac power semi-conductor switch commonly known as the"thyristor valve" that is used in principle to replace mechanical switches to achieve rapid,repetitive, and in some cases continuous control of the effective shunt susceptance at a specificlocation in a transmission system by a set of inductors and capacitors [5.] For example, the fixed capacitor (FC) in parallel with a thyristor-controlled reactor (TCR), the valve continuously and "smoothly" controls the reactor to achieve a "netsusceptance" that is varied to maintain the transmission system voltage to a desired value orrange.

The overall steady-state characteristics of the SVC are described in the form of a volt-current(VI) curve, as illustrated in the following sections. An automatic voltage regulator with a transferfunction of [K * 1/(1+sTp)] is often used.Reference [5] provides an excellent application-oriented and often referenced book byDr. Hingorani and Dr. Gyugyi that "emphasizes physical explanations of the principlesinvolved in FACTS applications.

2.2 Voltage Control and Dynamic Performance

References [6,7] provide in-depth and comprehensive explanations and application examplesassociated with voltage stability and system stability and control. These references discuss how and when SVC application can:

(1) Effectively improve voltage control and dynamic performance

(2) A cost-effective solution

The influence on voltage control capabilities of reactive compensation devices such asmechanically-switched capacitors (MSC), SVC, voltage-source converters (STATCOM), andthyristor controlled series capacitors (TCSC) are compared in [8]. This IEEE paper comparesthe ability of the aforementioned devices to influence the transient voltage stability of atransmission system, and their ability to maintain security under contingency conditions. SVCswith "smooth" control can solve transient voltage stability and regulation problems that cannotbe solved by MSCs due to the limitations of switching speed and switching frequency of MSC.However, MSC can be economically used together with SVCs to provide a static var system forvoltage control.

The mentioned references also discuss how reactive compensation such as SVC is often applied inor around load centers (with remote generation) where the system connecting the load center tothe generation source can become relatively weak under certain contingency conditions leadingto voltage control or collapse problems.

The CIGRE report [9] discusses the results of an electric utility survey on thepractices that utilities use for transmission operational planning studies with respect to voltagelimits and reactive margins to ensure adequate system security and reliability. This reportoutlines the general process that utilities use to determine system voltage limits and reactivepower margins required to prevent voltage collapse (for example) for different system conditionssuch as peak and light loading, and contingency outages of transmission lines and/or generators.System and device modeling is also discussed in this report.

3. Mathematical Modeling

The extent of the modeling of the SVC and the power system is depended on the nature of the power system studies to be performed. SVCs are used primarily in power system for voltage control as either an end in itself or a means of achieving other objectives such as system stabilization [10].

3.1 Basic Arrangement

The SVC provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high speed thyristor switching/controlled reactive devices [11]. An SVC is typically made up of following major components:

1. Coupling Transformer
2. Thyristor valves
3. Reactors
4. Capacitors

In general, the two thyristor valve controlled/switched concepts used with SVCs are the thyristor-controlled reactor (TCR) and the thyristor switched capacitor (TSC). The TSC provides step response and the TCR provides a smooth or continuously variable susceptance.

Figure 1 illustrates a TCR/FCincluding the operating process concept. The control objective of the SVC is to maintain the desired voltage at the high voltage bus. In steady state, the SVC will provide some steady state control of the voltage to maintain it highest voltage bus at the predefined level. If the bus voltage begins to fall below its set point range, the SVC will inject reactive power Q_{net}into the system (within its control limit) from the fixed capacitors and from thyristor switched capacitors, thereby increasing the bus voltage back to its desired voltage level. If the bus voltage increases, the SVC will absorb reactive power from the system by connecting the reactors to the system.

3.2 SVC V-I Characteristics

The steady state and dynamic characteristics of the SVC describe the variation of SVC bus voltagewith SVC current or reactive power. SVC can be operated in two different modes:

1. Voltage regulation mode
2. Var control mode

In this paper, I will be analyzing the SVC characteristics in voltage regulation mode. When the SVC is operating in voltage regulation mode, it implements the VI characteristics as shown in figure-2.

As long as the SVC susceptance B stays within maximum and minimum susceptance values imposed by the total reactive power of the capacitor banks (Bcmax) and reactor banks (Blmax), the voltage is regulated at the referencevoltage. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output) and the V-I characteristics has the slope Xs.

3.2.1 Voltage Regulation Mode

The Voltage control action of the SVC in the linear (voltage regulation mode) range is described as: $Vsvc = Vref + XsIsvc$

Where,

V_{SVC} = SVC positive sequence Voltage

V_{ref} = Reference voltage at the terminals of the SVC duringthe floating condition, when the SVC is neither absorbing nor generatingany reactive power.

X_S= Slope or Current Droop is defined as the ratio of voltage-magnitude change to current-magnitude change over the linear-controlled range of the compensator.

Thus slope $X_S$is given by $Xs = \frac{\Delta V}{\Delta I}$

ISVC = SVC reactive current (I>0 indicated an inductive current)

3.2.2 Var Control Mode

In the var control mode, the SVC is operating as a fixed susceptance device. It absorbs or injects a fixed amount of reactive power into the system. The following equations govern the var control mode:

When SVC is fully inductive,$V = \frac{I}{Blmax}$

Where, Blmax= Maximum inductive susceptance

When SVC is fully capacitive,$V = \frac{-I}{Bcmax}$

Where, Bcmax= Maximum capacitive susceptance

3.3 SVC Dynamic Responses

The SVC is operating in voltage regulation mode; its response speed to a change of system voltage depends on the voltage regulator gains (proportional gains Kp and integral gain Ki), the droop reactance Xs, and the system strength (short circuit level).

For an integral type voltage regulator (Kp=0), if the voltage measurement time constant Tm and the average time delay Td due to valve firing are neglected, the closed loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:$Tc = \frac{1}{Ki(Xs+Xn)}$

Where,

Tc= Closed loop time constant

Ki =Proportional gain of the voltage regulator

Xs= Sloop reactance

Xn = Equivalent power system reactance

The above equation demonstrates that you obtain faster response speed when the regulator gain is increased or when the system short circuit level decreases (higher Xn values). If you take into account the time delays due to voltage measurement system and valve firing, you obtain an oscillatory response and, eventually, instability with too weak a system or too large a regulator gain.

3.4 SVC Control Systems

The control system of an SVC has four main components as shown in the figure-3:

1. Voltage Measurement System
2. Voltage regulator
3. Distribution unit
4. Synchronizing Pulse generator

- A measuring system measures the positive sequence of the system voltage to be controlled, shown in the figure-4.
- A voltage regulator uses the voltage error (difference between the measured voltage Vm and the reference voltage Vref) to determine the SVC susceptance B needed to keep the system voltage constant, as shown in the figure-5. Voltage regulator uses a PI regulator to regulate primary voltage at the reference voltage. A voltage droop is incorporated in the voltage regulation to obtain V-I characteristics.
- A distribution unit determines the TSCs (and eventually TSRs) that must be switched in and out, and computes the firing angle ‘alpha’ of the TCRs. Distribution unit uses the primary susceptance Bsvc computed by the voltage regulator to determine the TCR firing angle ‘alpha’ and switching of the Thyristor switched capacitor. The firing angle ‘alpha’ as a function of the TCR susceptance if given by

$$Btcr = \frac{2(\pi - \alpha) + \sin(2\alpha)}{\pi}$$

  - A synchronizing system using a Phase Locked Loop (PLL) synchronized on the secondary voltage and a pulse generator that send appropriate pulses to the thyristor. The pulse generator uses the firing angle ‘alpha’ and the thyristor switched capacitor status from the distribution unit to generate pulses.

4. Method of Analysis

In this project, the performance of the SVC is analyzed in voltage regulation mode. A three phase programmable voltage source is used to model the varying system voltage and observe the SVC performance.The system of Hlawga generating station is modeled in this project. The single line diagram of the system is as shown in the figure-6:The system voltage is 11kV and the compensator is connected to the system trough 3 x 47.5 MVA, 33 kV step up transformer. On the secondary side, a three phase wye connected capacitor bank rated 50Mvars is paralleled with the delta connected TCR. A static var compensator is used to regulate the voltage on a 33kV bus at Hlawga generating station.

When the system voltage is low, the SVC generates reactive power (SVC Capacitive). When the system voltage is high, the SVC absorbs reactive power (SVC inductive). The SVC is rated +50Mvar capacitive to -25Mvar inductive.The SVC static and dynamic characteristics are modeled at the system fundamental frequency.

5. Program and Model

In order to analyze the above mentioned network, a model is created in the MATLAB/SIMULINK environment as shown in the figure-7.

A three phase programmable voltage source is used to vary the system voltage and observe the SVC performance. The system short circuit MVA is 500MVA.The SVC is connected through a transformer of 11/33kV, 3 x 47.5MVA rating and a constant load of 10MW is also connected to the secondary side of the transformer.The SVC control system model has the following main components as discussed earlier.

5.1 Voltage Measurement Unit Model:This unit measures the positive sequence voltage of the network. And this is represented by the figure-8.

5.2 Voltage Regulator Unit Model:The Voltage measurement module takes the reference voltage and the measured positive sequence voltage of the system and calculates the Susceptance of the network. The voltage regulator block uses PI controller as depicted in the figure-9.

The voltage regulator is used with the following control parameters:

Ki = 200, Kp = 0, Xs = 0.03 (Droop), Xn = 0.0667 (System eq. reactance)

5.3 Distribution Unit Model:This unit determines the TCS to be switched on/off and calculates the firing angle of the TCR according to the following equation and represented by the figure-10.

$$Btcr = \frac{2(\pi - \alpha) + \sin(2\alpha)}{\pi}$$

5.4 Firing Unit Model:This unit provides the pulses to the thyristor units. This pulse generator sends appropriate pulses to the TCR and TSC.

6. Analysis of Results

A three phase programmable voltage source is used to vary the system voltage, the voltage is successively decreased to 0.97pu at t = 0.1s, increased to 1.03pu at t = 0.4s and finally returned to nominal voltage to nominal voltage to 1.0pu at t=1.0s.

When we start the simulation and observe the SVC dynamic response to voltage steps on the scope. Scope B shows the actual positive-sequence susceptance B1 and the control signal output B of the voltage regulator.The plot obtained is depicted in the figure-11.

- Scope 2 shows the actual system positive sequence voltage V1 and output Vm of the SVC measurement system. And its plot is shown in the figure-12.
- Scope 3 shows the reactive power injected by the SVC to the system, as depicted by the figure-13.

7. Conclusion

This project has demonstrated that modern transmission static var compensators can be effectively applied in power transmission systems to solve the problems of poor dynamic performance and voltage regulation. Transmission SVCs and other FACTS controllers will continue to be applied with more frequency as their benefits make the network more “flexible”.

Since SVC is a proven FACTS controller, it is likely that utilities will continue to use the SVC’s ability to resolve voltage regulation and voltage stability problems. The performance of SVC voltage control is dependent on many factors such as effect of network resonance, transformer saturation and voltage distortion. In some cases, transmission SVCs also provides an environmentally-friendly alternative to the installation of costly and often un-popular new transmission lines.Dynamic performance and voltage control analyses will continue to be a very important process to identify system problems and demonstrate the effectiveness of possible solutions.

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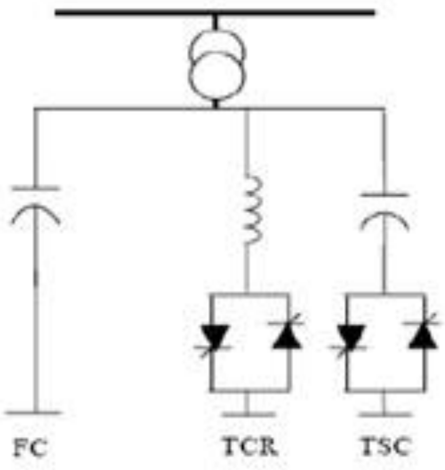


Figure 1: SVC Configuration

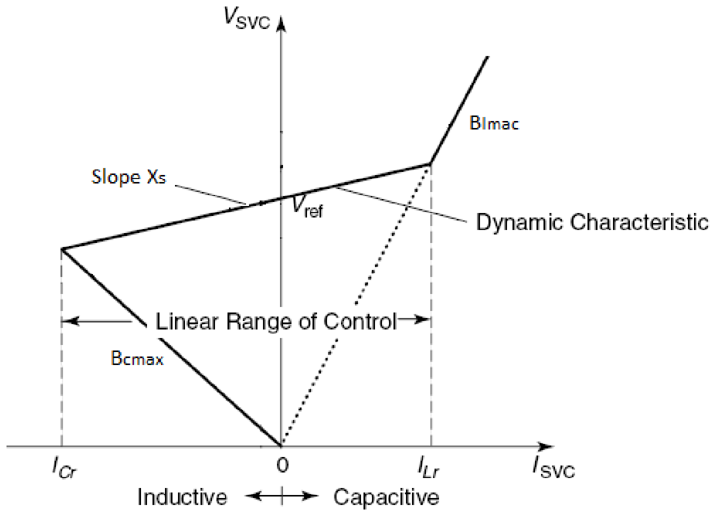


Figure 2: SVC VI Characteristics

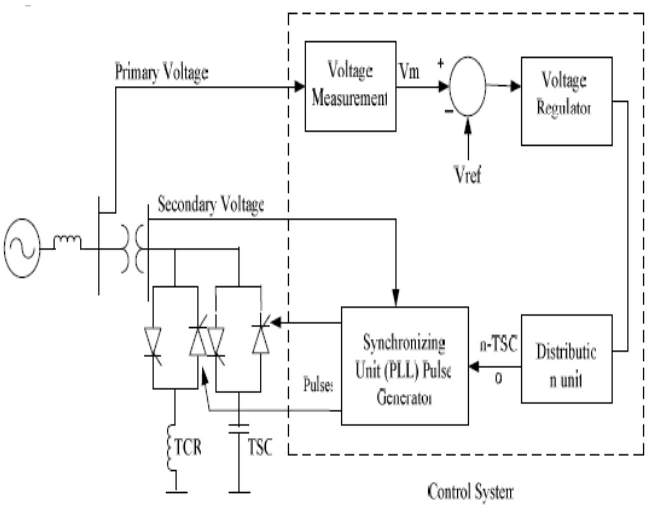


Figure 3: Control system of an SVC.

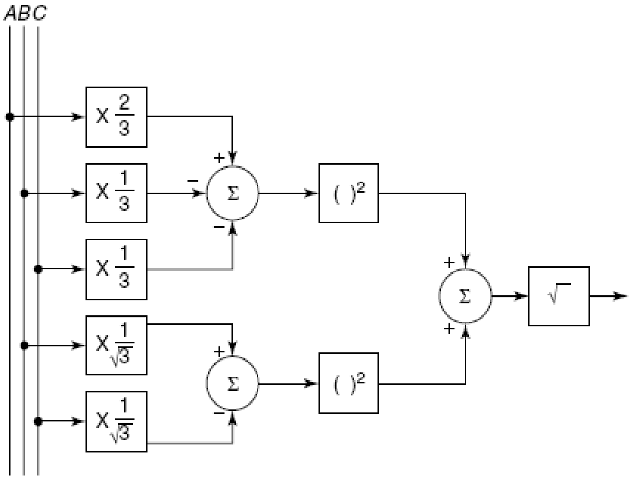


Figure 4: Measuring system of SVC.

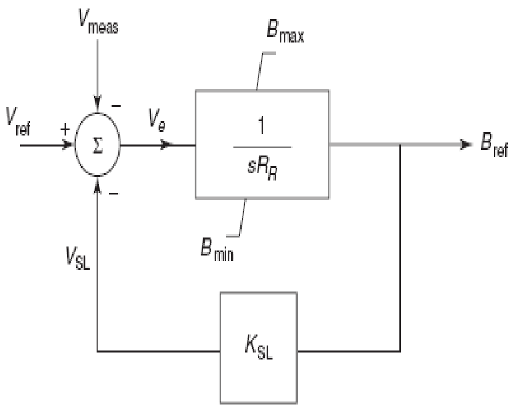


Figure 5: Voltage regulator

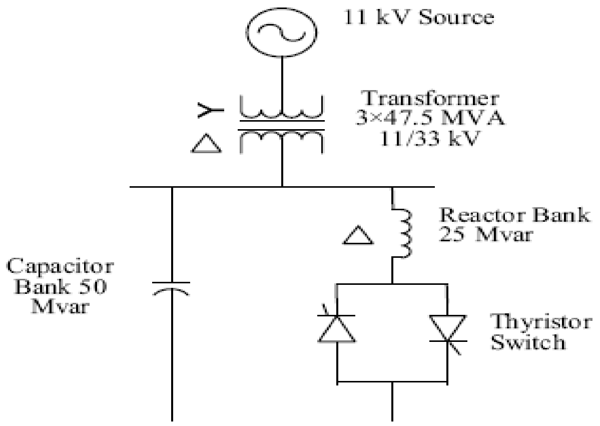


Figure 6: Single line diagram of the system.

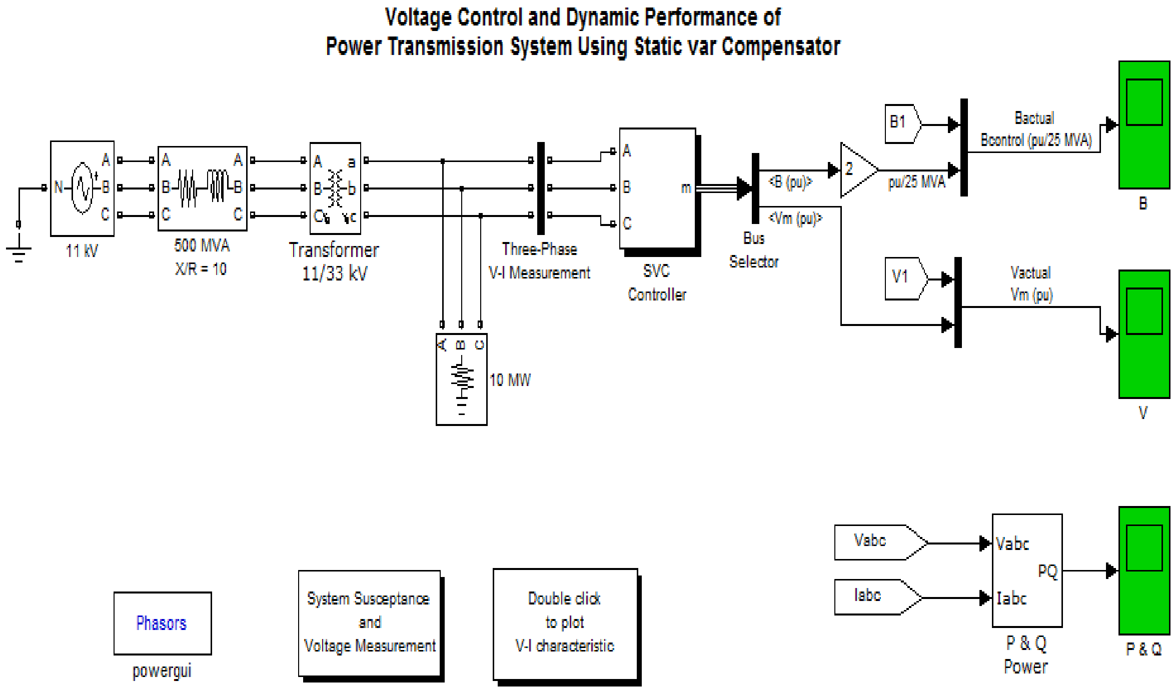


Figure 7: Matlab simulink model.

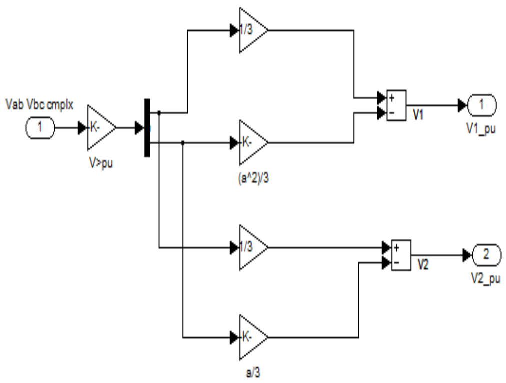


Figure 8: Voltage measurement unit model.

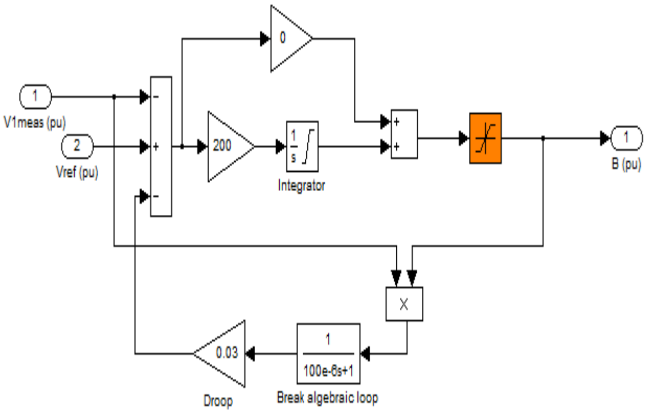
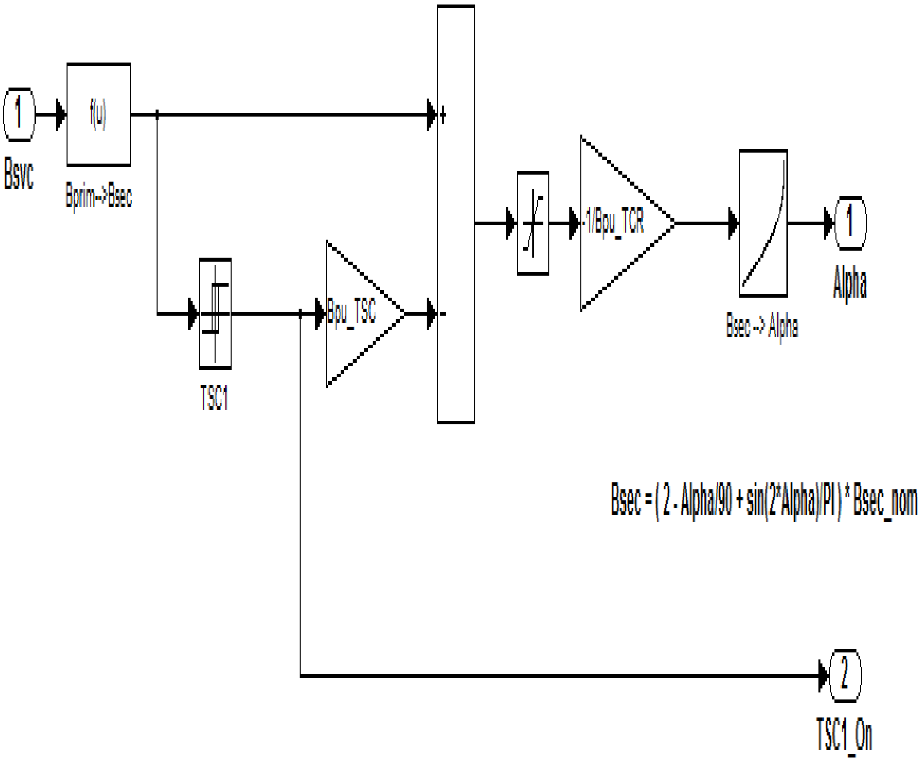


Figure 9: Voltage regulator unit model



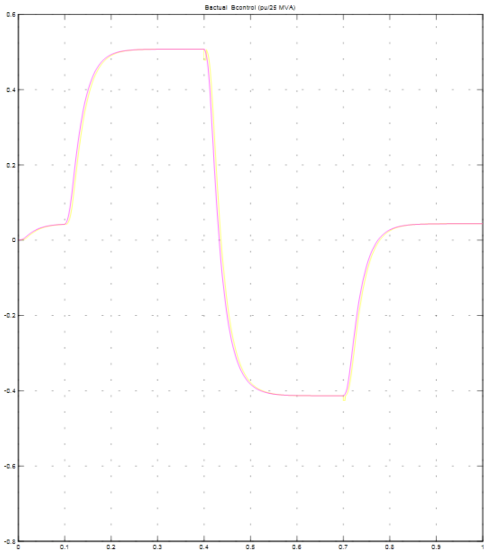


Figure 10: Distribution unit model.

Figure 11: Dynamic response of voltage steps.

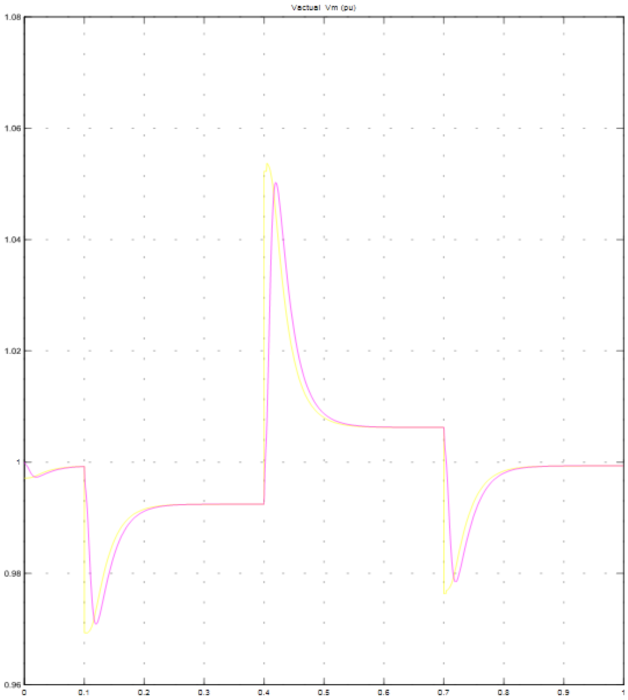


Figure 12: Positive sequence voltage

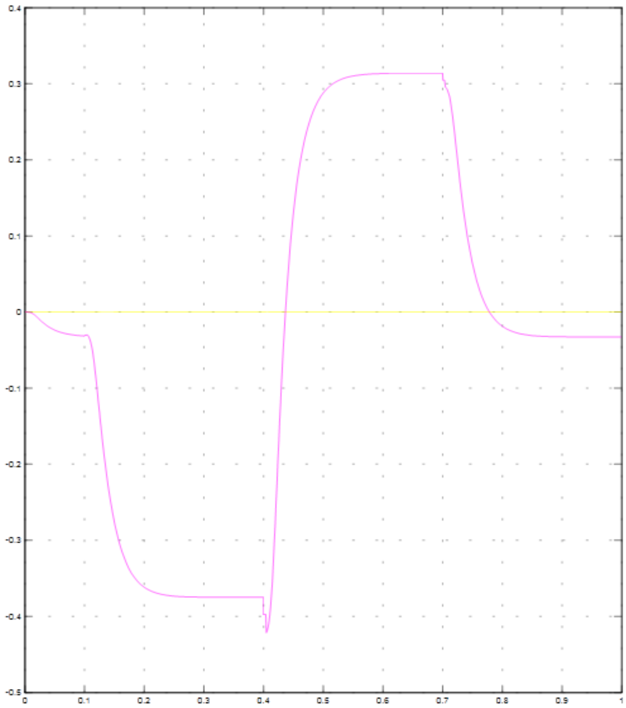


Figure 13: Reactive power injected by SVC