Modelling and Control of STATCOM in Power System under Fault Conditions

Simranpreet Singh

M.Tech Scholar, Electrical Engineering Department,
Yamuna Institute of Engineering & Technology, Yamunanagar, Haryana, India

ABSTRACT

This paper deals with compensation of frequently time-variable loads by means of 24 pulse STATCOM controllers. An different faults are considered as a heavily distributing load. The STATCOM system was used to ensure good power quality at the point of common coupling. For analysis of the system performance, the PSCAD/EMTDC programme was applied. Simulation models of the load and two types of STATCOM controllers, 12-pulse and 24-pulse, are discussed in the paper. A MATLAB/Simulink model of a measurement block is also proposed for power quality assessment. Some results of simulation are presented, which show the compensation effectiveness.

KEYWORDS: Carrier-based pulse width modulation (CBPWM), Cascaded H-bridge inverter, power factor (PF) correction, reactive power (VAR) compensation, static synchronous compensator (STATCOM)

I.   INTRODUCTION

Power quality and efficiency issues arising from unmanaged power flow, which include low power factor (PF), voltage collapse, unbalance, excessive harmonics, transients and oscillations, have been a major concern in power transmission and distribution systems. Reactive loads, which naturally possess low PF, draw excessive reactive power (VAR) restricting the maximum active power transfer and moreover, adding losses to the power transmission and distribution systems [1]. Furthermore, voltage variations or disturbances such as voltage sags/swells, which is caused by low PF loads, hard switching, lightning, and sudden increase/decrease in the loading conditions, will challenge the tolerance level of electrical equipment in terms of stability and reliability [2]. Therefore, it is essential to improve the voltage stability of power system networks under both contingency and normal operating conditions. This led to the development of flexible ac transmission system controllers such as VAR compensators to enhance neighboring utilities and regions with more economical and reliable exchange of power. The rapid development of the power electronics industry has opened up opportunities for improving the operation and the management of power system networks [3]. The conventional voltage-source inverter (VSI)-based static VAR compensators such as STATCOM has been the most effective solution for providing VAR compensation due to its ability to compensate for a wider range of VAR in fraction of cycle [3]. Multilevel inverters have recently shown their ability to alleviate problems associated with the conventional two-level inverters and therefore have received an extensive research in recent years. There are various different topologies of multilevel inverters that have been proposed and studied in the open literature [4]. Among these, the multilevel cascaded H-bridge inverter (MCHI) has been an attractive topology for STATCOM due to their modularization, extensibility, control simplicity, high-quality output [5]–[7], and its ability to provide negative sequence current compensation [8]. This topology connects several H-bridge inverter modules in series to produce the desired multilevel output waveform. On the other hand, the choice of modulation technique plays an important role in the STATCOM control system as it has a

high impact on its compensation objectives, transient as well as steady-state performances. Therefore, several pulse width modulation (PWM) strategies have been investigated, proposed, and documented in the literature including carrier-based PWM (CB-PWM) [9]–[11], multilevel space vector modulation (SVM) [12]–[16], and selective harmonic elimination PWM (SHE-PWM) [17]–[22]. Furthermore, various control strategies of different inverter topologies-based STATCOM have been developed to obtain decoupling control for solving typical problems [23]–[41]. For instance, a selective harmonic control-based passivity theory incorporated with P-controller was presented in [23] to achieve VAR, unbalance, and harmonic compensations under distorted and unbalanced operating conditions. Although the control loop consists of second-order low-pass filters to reduce the effects of signal distortion, the proposed controller still offers fast tracking o the command values (i.e., 5 cycles to reach steady state) and compensation of delay inherent to the digital implementation. However, this was accomplished with high-switching frequency (i.e., 10 kHz) to attain the desired current loop bandwidth. Moreover, when it was compared with PI-controller, the distortion of residual source current due to the 5th, 7th, and 13th harmonics generated by the load was only marginally reduced. Another control scheme with fixed modulation index (MI) and variable dc capacitor voltage levels was presented in [24] to provide VAR compensation and voltage regulation. When MI was fixed for both capacitive and inductive operating modes, low total harmonic distortion (THD) was achieved without utilizing the harmonic elimination technique and with a switching frequency of about 2 kHz. However, this led to poor dynamic performance, where it took approximately 10 fundamental cycles to restore the grid voltage back to a unity and then reach steady state. In [25], the authors claimed that a traditional PI-controller with constant parameters may not be robust enough due to the variations of system parameters. Thus, a fuzzy-PI-based direct output-voltage control scheme with immunity capability of uncertainties in the STATCOM system was introduced to simultaneously regulate the voltages at the point of common coupling (PCC) as well as dc-link voltage, forcing the system to return back

to steady-state value faster than the PI-controller. However, the design process of fuzzy controller involves defining complicated rules and factors that relate the input variables to the output model properties while offering only moderate improvement of compensating performance over the conventional PI-controllers. Fukuda and Imamura [26] presented the PSI regulator (i.e., combination of PI with S (sinusoidal) regulators) to provide control of a VSI regardless of using any coordinate transformations. However, the controller's parameters (i.e., gain parameters) were not specifically defined and moreover, details on the modulation technique as well as the employment of switching frequencies are not discussed. A self-tuning PIcontroller using particle swarm optimization (PSO) algorithm was extended to the STATCOM aiming to achieve satisfactory dynamic response under balanced load [27]. When compared with the formal fuzzy approach, the PSO method does not require inference rules to obtain the controller gains, instead, it requires an evaluation function, which attained by the Runge– Kutta numerical method to specify the performance of the control system in real-time applications. Nevertheless, these two approaches involve complex formulations which increase the computational burden of digital signal processor. Furthermore, a modified "icosφ" control algorithm which was based on the extraction of the fundamental load current and source voltage using second order low-pass filter was applied to a three-level inverter [28]. However, the delays caused by these filters limit the bandwidth of the regulator control loops, hence, deteriorating the dynamic performance of the controller. This has been further confirmed by Pilawa-podgurski et al. [29], where the authors claimed that transient performance of an inverter is determined by the delay around the control loop and the switching frequency of the inverter. In [30], an automatic gain controller was proposed to reduce the influence of the high source impedance and mitigate the effect of the inherent phase-locked loop (PLL) delay, which is the source of the oscillations exhibited by the STATCOM under different loading conditions. The method was further utilized in [31] to reduce the effect of the PLL delay. However, overshoots in STATCOM current (i.e., three times higher than the rated current) still occur during the changes in loading condition, causing the need of higher rating power components as well as threatening the system stability due to poor transient response (i.e., 15 cycles to reach steady state) [32]. Another reactive current compensator-based direct current control method using triangle carrier wave was proposed in [33]. Despite the precise and fast tracking current performance achieved by this method, an oscillation of the measured STATCOM current was still observed, which can potentially cause voltage instability in weak power systems. Purcell and Acarnley [34] presented a strategy that increases the control update frequency (i.e., allowing the inverter to switch earlier) to achieve reduction in the steady-state current ripple. Nevertheless, the strategy requires higher inverter switching frequency (i.e., 36 kHz) to improve the transient performance and moreover, requiring more computation efforts compared to the classical decoupling controllers to attain higher resolution timing of switching events. A hybrid PWM scheme was reported in [35] to achieve good THD performances during the steady-state operation (i.e., provided by the SHE-PWM technique with low switching frequency) and effective suppression of the transient resonance during a load step change (i.e., attained by the SVM technique with high switching frequency), respectively. However, the transition between the two modulation techniques during a load step change led to large peak transient oscillations and resonances in the ac waveforms.

II. STATCOM BASIC OPERATION

STATCOM (Static Synchronous Compensator) or known as ASVG (Advanced Static VAR Generator) is a solid-state voltage source inverter that is coupled with a transformer and connected to a transmission line. H. Akagi, Y. Kanazawa et al. described the basic working principle of STATCOM in [2]. STATCOM injects an almost sinusoidal current, of variable magnitude, at the point of connection. It is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network Emilio F. Couto et al. explained this in[3]. The function of a STATCOM model is based on how it's regulating the reactive current flow through it. This property is useful for regulating the line voltage.
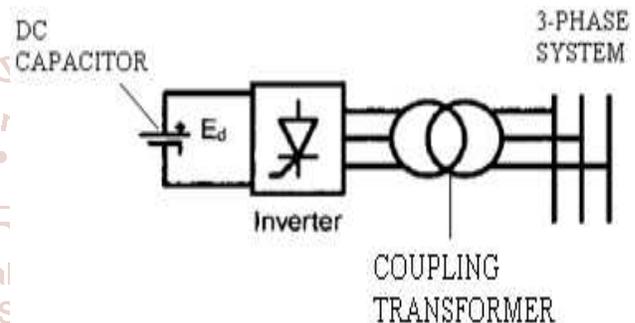
Figure 1 Schematic configuration of STATCOM diagram

A STATCOM is basically a DC-AC voltage source inverter with an energy storage unit, usually a DC capacitor and operates as a controlled Synchronous Voltage Source (SVS) connected to the line through a coupling transformer as shown in Figure 1.4. The advantages of STATCOM are that its dynamic performance far exceeding other compensator with the response time is less than 10ms [1]. It also can improve transient stability by maintaining full capacitive output current at low voltage system. Edson H. Wantanbe et al described about the principle of control reactive power via STATCOM [8]. It is well known that the amount of type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. When Q is positive, the STATCOM supplies reactive power and when the Q is negative, the STATCOM absorbs reactive power from the system. Reactive power generation was achieved by charging and discharging the energy storage capacitor [8].

The reactive power supplied by the STATCOM is given by this equation.

$$Q = (V_{STATCOM-vs}/ X).V_S$$

Where;

Q = reactive power.

$V_{STATCOM}$ = magnitude of STATCOM output voltage.

V_S = magnitude of system voltage.

X = equivalent impedance between STATCOM and the system

There are two types of STATCOM main circuit configurations, and that is multipulse converter and multilevel converter. In the multi-pulse converter, the 3-phase bridges are connected in parallel on the DC side where the bridges are magnetically coupled through a zigzag transformer, and the transformer is usually arranged to make the bridges appear in series viewed from the AC sides [1].
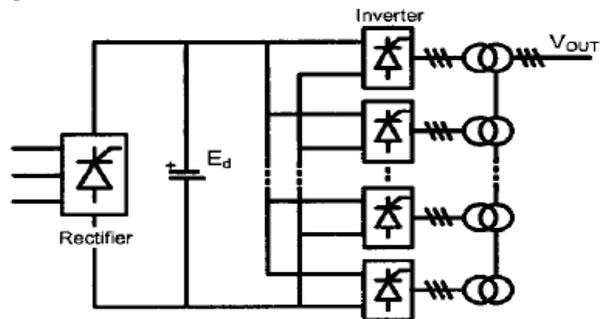
Figure 2- Multi-pulse converter diagram.
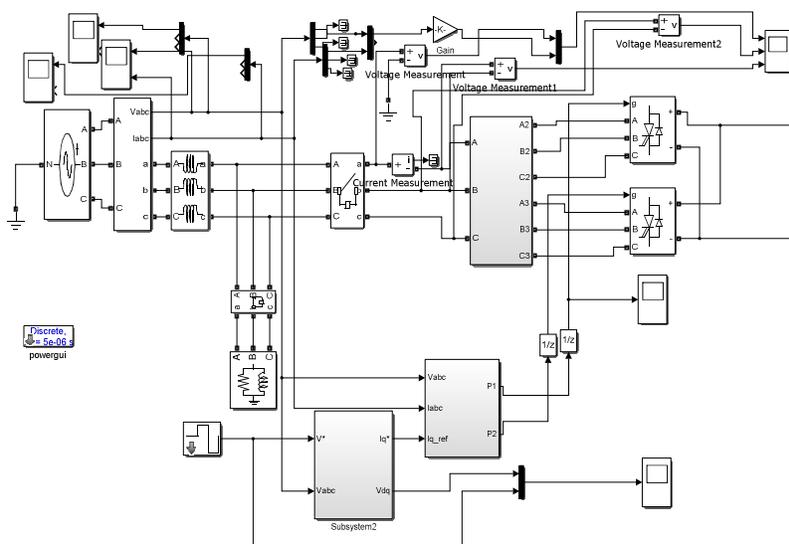
Figure3: 24- PULSE GTO STATCOM
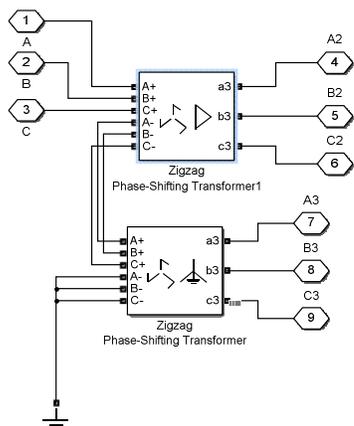
Figure 4- Three-Level Inverter and Zig-Zag Transformer

The STATCOM uses 3-phase 3-level inverter (Fig-2) coupled with four phase shifting transformers introducing phase shift of +/- 15 degrees.

The 24-pulse three level inverter consists of zig-zag transformers. The Zigzag Phase-Shifting Transformer block implements a three-phase transformer with a primary

III. MODELLING AND CONTROL

The model (Fig.-3) described in this thesis uses a square-wave, 24-pulse VSC and interconnection transformers for harmonics neutralization. This model represents a three-bus 500 kV system with a 100 Mvar STATCOM regulating voltage.

The internal voltage of the equivalent system connected at B1 can be varied by means of a Three-Phase Programmable Voltage Source block to observe the STATCOM dynamic response to change in system voltage.

The STATCOM consists of a three-level 24pulse inverter and a 30 mF capacitors which acts as a variable DC voltage source. The variable amplitude 60 Hz voltage produced by the inverter is synthesized from the variable DC voltage.

winding connected in a zigzag configuration and a configurable secondary winding. The model uses three single-phase, three- winding transformers. The primary winding connects the windings 1 and 2 of the single-phase transformers in a zigzag configuration. The secondary winding uses the windings 3 of the single phase transformers. The Three-Level Bridge block implements a three-level power converter that consists of one, two, or three arms of power switching devices. Each arm consists of four switching devices along with their antiparallel diodes and two neutral clamping diodes.

The control system task is to increase or decrease the capacitor DC voltage, so that the generated AC voltage has the correct amplitude for the required reactive power. The control system must also keep the AC generated voltage in phase with the system voltage at the STATCOM connection bus to generate or absorb reactive power only. The control system uses the following modules:
➢ PLL (Phase Locked Loop)
➢ Measurement System
➢ Voltage Regulator
➢ Firing Pulses Generator
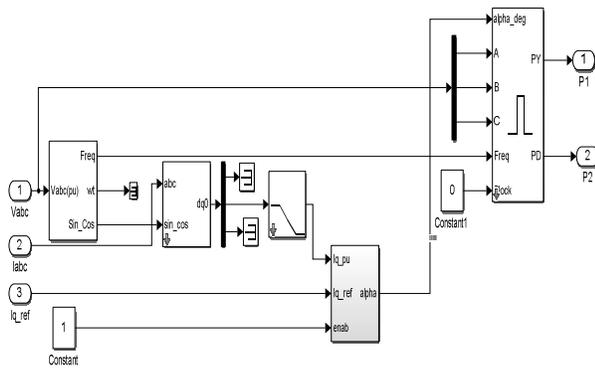
Figure- 5- STATCOM Controller

PLL (Phase Locked Loop)

Phase locked loop synchronizes GTO pulses to the system voltage and provides a reference angle to the measurement system.
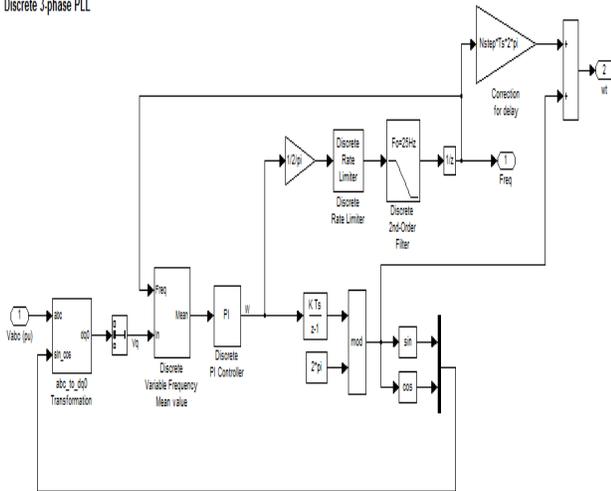
Figure- 6- Phase Locked Loop

Phase-locked loop is a control system that generates an output signal whose phase is related to the phase of an input signal. Fig. 6.4 shows the subsystem of discrete PLL, in this phase wt is generated by line voltages measurements and frequency measurement. First of all abc-dq convertor converts the line voltages in to dq components. Then the reference signal is generated which further used in calculating the phase wt.

IV.   SIMULATION AND RESULTS

Now we will observe the steady state waveforms and STATCOM dynamic response when the system voltage is varied.

Initially the programmable voltage source is set at 1.0 pu, resulting in a 1.0 pu voltage the supply side. As the reference voltage Vref is set to 1.0 pu, the STATCOM is initially floating (zero current). At t=0.22s, voltage is suddenly increased by 3 % (1.03 pu of nominal voltage). The STATCOM reacts by absorbing reactive power to keep voltage at 1.03pu.

Then, at t=0.42 s the source voltage is decreased to 0.97 pu of its nominal value. The STATCOM reacts by changing its operating point from inductive to capacitive to keep voltage at 0.98 pu. At this point the STATCOM generates reactive power. This change is shown in figure here primary voltage and current that the current is changing from capacitive to inductive in approximately one cycle.

Finally, at t=0.6 s the source voltage is set back to its nominal value and the STATCOM operating point comes back to zero VAR.

Notice that when the STATCOM is operating in inductive mode, the 24-pulse secondary voltage (in pu) generated by inverters is lower than the primary voltage (in pu) and in phase with primary voltage. Current is leading voltage by 90 degree the STATCOM is therefore absorbing reactive power. On the contrary, when the STATCOM is operating capacitive mode, secondary voltage is higher than primary voltage. Current is leading voltage by 90 degree, the STATCOM is therefore generating reactive power.

Finally, if we look inside the Signals and Scopes subsystem we have access to other control signal. When the transient changes on α angle the DC voltage is increased or decreased to vary reactive power. The steady-state value of α (0.5 degrees) is the phase shift required to maintain a small active power flow compensating transformer and converter losses.

RESULTS FOR BALANCED VOLTAGES

Figure 7 shows the phase voltage at the supply side. For the simplicity we have shown only one phase voltage instead of three phase voltages. As it is mentioned previously that the voltage at the programmable voltage source is varied to show the variability in the supply. It can be seen in the figure 7.1 that voltage is variable, at tie 0.22 it is increased and at time 0.42 it is decreased, Again at time 0.6 the voltage is bring back to 1 pu.

Here simulation time is 0.7 seconds and per unit values are taken.
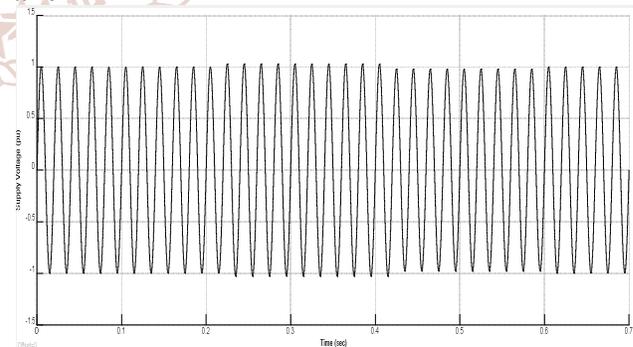
Figure7. Waveform of phase V_a at the supply end

Figure 8 shows the change in the reference value and the d-q axis voltage. As it is mentioned before, the STATCOM is verified under different voltage. This variability is shown in the figure, the d-q axis voltage following the change in voltage.
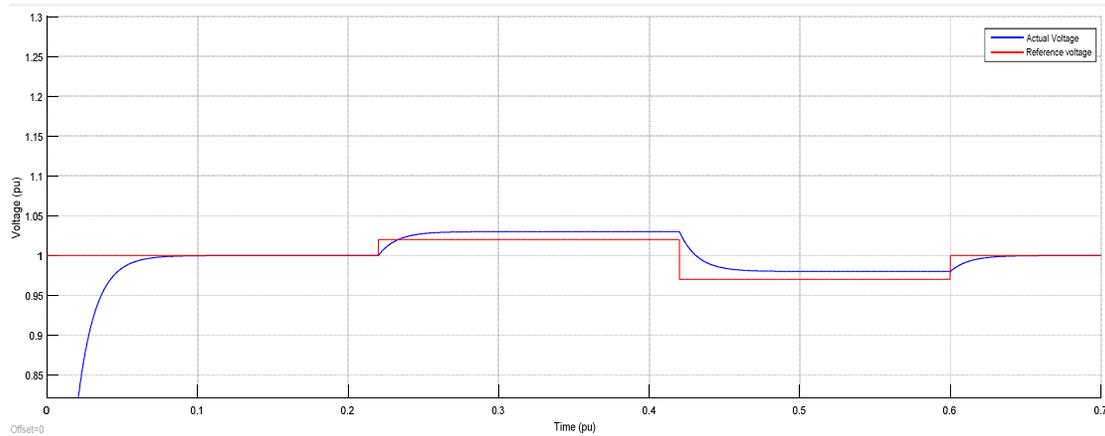
Figure 8 Waveforms of Reference voltage and corresponding actual d-q axis voltage of the system
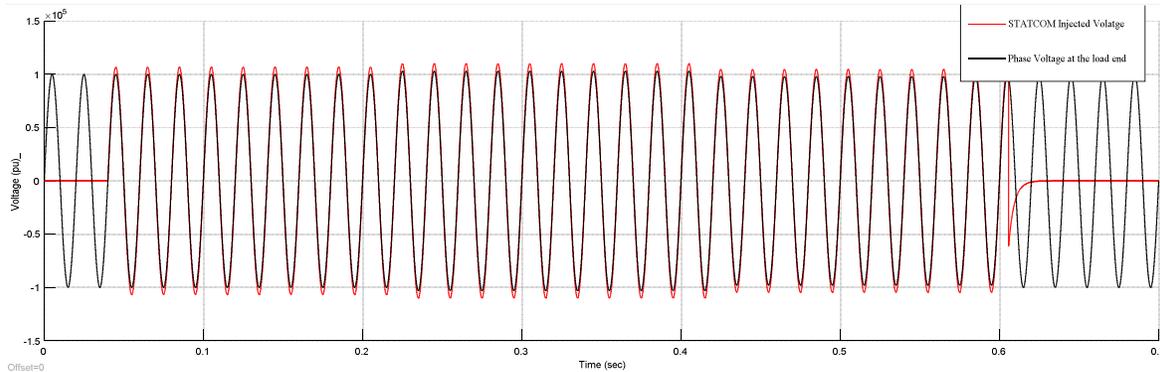
Figure 9 Waveforms of STATCOM voltage and Phase voltage

Figure 9 shows the phase voltage at the load side and corresponding STATCOM voltage injected or absorbed by the STATCOM. The STATCOM is connected to the system from time 0.01 to 0.6 sec. For this time only the STATCOM either injects or absorbed the reactive power to the system.

RESULTS FOR UNBALANCED VOLTAGES
Now we will study the STATCOM waveforms when there is unbalance is produced in the voltage of source. Here we produced the unbalance voltage by changing the parameters of programmable voltage source block.
Here are the various waveforms of the STATCOM under unbalanced voltages.
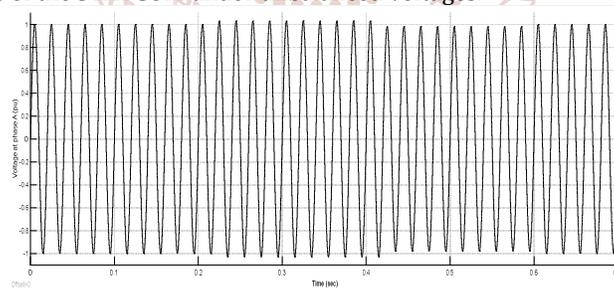
Figure 10 -Waveforms for unbalanced voltages at the supply end.
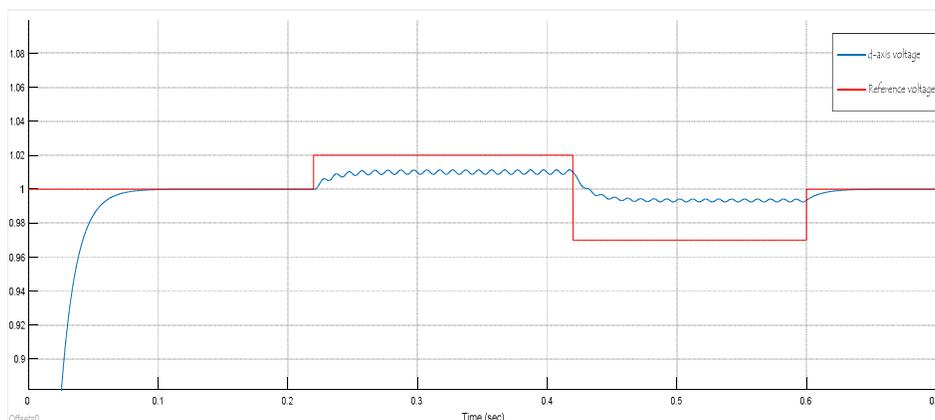
Figure 11 -Waveforms for d axis and reference voltage.

V. CONCLUSIONS

This paper has shown that the STATCOM has good performance in balanced systems, and that in unbalanced systems, double frequency oscillations in the real and reactive instantaneous power and in the dc capacitor voltages. The presence of oscillations in dc capacitor voltage produces a positive sequence 3rd order harmonic voltage and current that cannot be eliminated by ground and delta connections.

In balanced system the STATCOM has a very good performance, allowing compensation of capacitive or inductive reactive power with a fast transient response. However, when there is unbalance in voltages, the STATCOM has its performance diminished.

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