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Article

Improving Power Quality Using D-STATCOM with Capacitor as Energy Storage System

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Abstract: Power electronics are used more frequently to raise awareness of power quality which must be considered when designing modern power systems for effective operation and continuous power supply to various load centers. Otherwise, it will be hazardous for residential and commercial customers, reducing the production of their work due to faults and equipment damage. Electronic technology known as Flexible AC Transmission System (FACTS) may improve power stability to make the electric power system efficient. Oscillation damping in the Power system is still a big concern for operating a safe and dependable power system. The static synchronous compressor (STATCOM) is connected to assist power networks with poor power quality and voltage regulation. Although there are several uses, voltage stability is the most frequently used. An average model of the D-STATCOM control approach is presented in this work to improve the transmission of power quality flow and voltage stability in electric power systems. An increase in system voltage stability, reactive power flow control for different loads, and dynamic response of STATCOM are the primary goals of this research work.

Keywords: Energy Storage System, Flexible AC Transmission System, Harmonics, STATCOM, Voltage Stability

1. Introduction

1.1. Background and Motivation

Voltage, current fluctuations, and generator rotor dynamic oscillations may disrupt the electrical grid. When the power transfer exceeds the transmission strength, electromechanical oscillations frequently have large peak values and poor damping [1]. Stability, voltage, and frequency control may be significantly enhanced in electromechanical oscillations if control mechanisms are available and suitably constructed. Due to this discovery, it is possible to improve the safety and reliability of connected power systems [2]. FACTS (Flexible AC Transmission Systems), on the other hand, is an alternative approach to increasing power system performance. The network operators are concerned about power quality, especially if FACTS devices are installed in the utility grid. Rated frequency refers to preserving sinusoidal voltage and current waveforms. The unnecessary voltage drop will increase source-side losses and, as a result, cause a line outage because the system will be under more strain trying to transmit the fictitious power. Therefore, reactive power adjustment is the most important for better transient response [3]. The approaches utilized for compensation are FACTS devices, which are used for controllability and have come under more importance in recent years. The fundamental objective of these devices is to provide the quick reactive or inductive power needed at that time [4]. An AC transmission system that can change one or more features is called a FACTS (voltage, phase angle, and impedance). These devices may help transient voltage and frequency regulation at critical network nodes by dampening electromechanical oscillations [5]. STATCOM is designed and implemented to minimize voltage and attenuate power system oscillations by controlling reactive power. There are no bulk energy storage devices in the STATCOM; therefore, when the VSI is turned off, the DC capacitor can't compensate for active power losses. Reactive and actual power compensation may be added to STATCOM's power control by connecting the DC capacitor to an energy storage device like a battery. Accelerated synchronous generator operation is one way to lower the frequency of active power flow oscillations [6]. The block diagram of the static synchronous compensator is shown in Fig. 1.

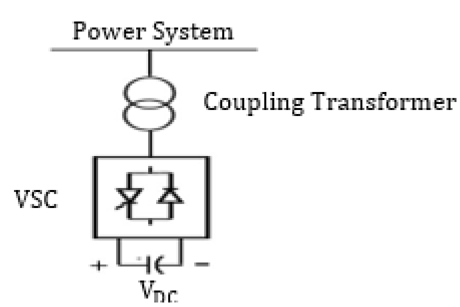


Figure 1. Block diagram of the static synchronous compensator.

Shunt transformers link the voltage source converter to a utility bus. $\boldsymbol{V_{AC}}$ is the bus voltage. $\boldsymbol{I_{AC}}$ is the injected current of STATCOM. $\boldsymbol{V_{OUT}}$ is the output voltage of VSC. $\boldsymbol{V_{DC}}$ and $\boldsymbol{I_{DC}}$ are the DC voltage and current of capacitor side. $\boldsymbol{V_S}$ is the output voltage of STATCOM. From Fig. 2, it is clear that if the $\boldsymbol{V_S}$ is greater than $\boldsymbol{V_{AC}}$, the current direction will be from STATCOM to the AC system and vice versa [7].

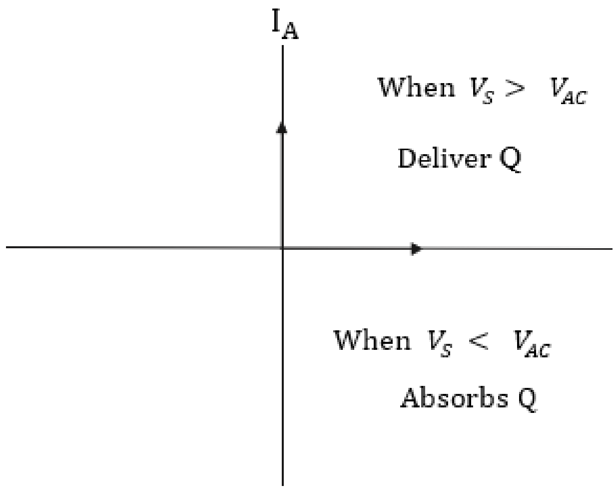


Figure 2. STATCOM power exchange.

STATCOM is shown as a variable voltage source behind a reactance. As a result, the STATCOM has a compact design since the capacitor banks and shunt reactors are not required to produce and consume reactive power [8]. The equivalent circuit of the VSC-based STATCOM is illustrated in Fig. 3.

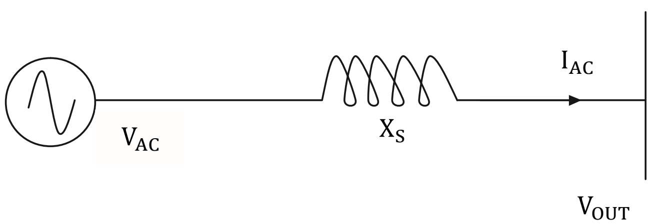


Figure 3. Equivalent circuit of the STATCOM.

The Actual power entering the converter covers switching losses and charges the DC capacitor to an appropriate DC voltage level. Each switching cycle involves the charging and discharging of the capacitor. However, the average capacitor voltage is constant in a steady state [9].

Switching losses are supplied by the total available power from the AC system in a steady state. The size of the DC capacitor and the actual power losses from switching determines how much True power the STATCOM can deliver or consume. The quantity of Actual power transmission is similarly limited since the DC capacitor and losses are also minor. As a result, at its line terminals, the output current of STATCOM must be roughly positive 90° to the AC system voltage [10].

The following equation can be used to express the equivalent reactive power exchanged.

$$Q = (V_S^2 - V_S V_{AC} Cos\alpha)/X \quad (1)$$

where 'α' is the angle that exists between V_S and V_{AC}

The following equation calculates the True power exchange between the VSC and the AC system.

$$P = (V_S V_{AC} Sin\alpha)/X \quad (2)$$

Reactive power control is used to reduce or eliminate voltage sags and flickers; when STATCOM is connected to an Energy Storage System (ESS), Supplementary Damping Controllers (SDCs) may be utilized to damper voltage and power oscillations in tie-lines or decrease their peak values during transient occurrences in BESS (Battery Energy Storage System). Because of this management activity, the stability margins of linked power systems are expanded, and the quality of system load power is improved [11]. It is required to make some form of compensation to fulfil standards for power quality. A few years ago, passive filters like capacitor banks were used on the distribution side to reduce the issue of power quality. With the aid of power conditioning equipment, research is moving quickly to minimize concerns about the quality of the electricity. DVR, STATCOM, and UPQC are power conditioning equipment. The increasing hazards of faulty lines imperil secure operation and consistent supply. Depending on the kind of device, FACTS devices have various degrees of ability to change power flows and voltages. A suitable fast response compensator is always needed if the load's reactive power varies rapidly. Such compensating devices, which are members of the FACTS family, are the SVC, TCSC, etc. Improving the voltage profile is the primary goal of using shunt compensation of the reactive power in the power network. The presence of FATCS devices enhances the circuit's reactive power [11].

The results of the completed simulation of FACTS reveal an improvement in the voltage profile. FACTS technology creates unique possibilities for managing power and increasing the capacity of existing, new, and upgraded lines that might be used. A second-generation FACTS device called the UPFC allows for independent regulation of Actual and Reactive power while enhancing supply quality and dependability [12]. Three significant factors considerably impact how much power flows across a transmission line.

1. Magnitude of bus voltage (V)
2. Transmission line impedance (Z)
3. Phase angle of bus (θ)

Devices made by FACTS can regulate one or multiple parameters to enhance the performance of systems because numerous FACTS controllers have been installed and are functioning together in expansive and expanding power system networks, which clearly shows the operating characteristics of power systems, including voltage profile, oscillations damping, network management and security, etc., have been greatly improved. FACTS devices have quick and precise responses since they are made with solid-state controllers. FACTS devices like STATCOM will be utilized in this research work to enhance the quality of power by monitoring and controlling the voltage profile of the system [13].

1.2. Literature Review

FACTS family includes different devices that control reactive power to enhance power quality. Each device has significance over others. Static Var Compensator (SVC) is a combination of a Thyristor Controlled Reactor (TCR) and a Thyristor Switch Capacitor (TSC) to improve power quality by limiting the system's harmonic distortion and reactive power. They mentioned the TCR and TSC and their combination with a passive filter for controlling the power system's reactive power and current harmonics. Additional filters are required as nonlinear loads increase in any power system. As a result, this is helpful for power systems with nonlinear loads. Successful compensation was made using TSC-TCR, adjusted to the rising load, and a power factor close to unity. The benefits of the TSC-TCR combination are that it can continuously control reactive power and practically no transients. Also, control and operation are Flexible. However, the generation of harmonics will be less due to the controlled reactor, which is small compared to the total controlled power. SVC has fewer losses and low cost, but compared with STATCOM, SVC has a slower and larger response. Also, Real-world power sources like batteries, fuel cells, etc., may readily be connected to STATCOMs. STATCOM can keep the system voltage under control and prevent a voltage drop. STATCOMs are shunt-connected Solid-State Devices (SSD). To withstand the disruptions, STATCOMs are strategically installed in the power system due to their smaller size and fast flicker compensation [14].

Unified Power Flow Control (UPFC) separately controls the true and phantom power and step-like variations in power quality. Where actual and phantom power regulation is desired, UPFC can be connected to a bus. When there is a serious fault, FACTS devices increase voltage. When there is a fault, they provide reactive power. In addition to enhancing supply reliability and quality, UPFC offers separate control of useful and non-useful power. Two types of transmission lines exist. Transmission systems use a single circuit and a double circuit. UPFC is the most flexible and sophisticated power electronic equipment for regulation and power flow optimization in electrical power transmission networks. It presents significant potential benefits for the transmission line's static and dynamic performance but poses significant design difficulties for the power electronics and power system. Control and safety of this modern instrument are of the greatest priority as the UPFC advances from an idea to the full-scale implementation of a power system. The primary transmission lines are the greatest location for UPFC to reduce loss. There are two ways to reduce the loss: first, boosting transition power on lines with low impedance and then lowering transmission power on lines with high impedance. The UPFC control is designed to provide for current control, true and phantom power, and voltage. Additionally, it can lower the system's harmonics and raise total harmonic distortion. The overall reliability of the controller is affected due to the presence of the capacitor. The UPFC has high voltage stability and reliability, but compared to STATCOM, UPFC has a high cost, high transmission capacity, and complex circuit design [15].

Voltage Source Converter (VSC) serves as the foundation for the Static Synchronous Series Compensator (SSSC). At the fundamental frequency, the SSSC injects a balanced set of voltages at 90° behind or ahead of the line current. Thus, the series capacitive or inductive compensation offered by SSSC can be regulated. Because there are no forbidden regions in SSSC, inductive to capacitive series compensation can be switched, and vice versa. The SSSC can interchange actual power with the power system if a storage source is available. It is implemented for managing power flow with a proper setup of control. It has dual magnitude nodes for its reactive compensator, which are constant reactance mode and constant quadrature voltage mode. It has better controllability of power flow and power oscillation damping, gives a signal on system failure safeguard, and increases the life of equipment; also, it requires a coupling transformer. STATCOM has Lower Total Harmonic Distortion (THD) than SSSC, small volumetric dimensions, and a small rating [16].

The thyristor control series capacitor (TCSC) is a common FACTS controller that enables quick and continuous regulation of transmission line reactance. Transmission lines are linked in series with the TCSC. A regulated reactive power source with shunt connections is STATCOM. With fast adjustable amplitude and phase angle, A balanced set of three-phase sinusoidal voltages are generated by STATCOM at the fundamental frequency. The system's voltage stability, small signal stability, and transient stability are all improved by TCSC and STATCOM's dynamic solid performance. STATCOM returns to a steady state more quickly than TCSC. It is evident that compared to the installation of TCSC, a higher level of damping may be achieved by installing STATCOM [17].

Interline Power Flow Control (IPFC), is a more efficient and versatile form of FACTS device. It can simultaneously control the flow of useful and non-useful power in the transmission lines. It is a new FACTS controller member designed for managing power flow and compensation in multi-line transmission systems. IPFC is the most recent FACTS Device implemented to control power flow over more than one transmission lines. It is made up of two dc-to-ac converters placed back-to-back, known as SSSC, and therefore, it utilizes series coupling transformers to link in series to dual transmission lines. The converters' dc terminals are connected via a shared dc connection. It switches off the system for excessive voltage, current, and harmonics. Compared to other FACTS devices, the IPFC's better damping characteristics can always be attributed to a genuine power flow controller. Compared to IPFC, STATCOM is more affordable and has the simplest design [18].

Magnetically-Controlled Shunt Reactors (MCSRs) are used to compensate for phantom power and maintain voltage levels in HV electric networks rated for voltage levels 36–750 kV. Inductive reactance is used by the MCSR (static shunt-style device) to provide smooth regulation. A capacitor bank, which may be permanently connected or employ mechanical or thyristor switching, may be present in parallel with a series-connected reactance and thyristor valve. The combination is referred to as SVC. MCSR is less complex for high-power applications. The expense of installing MCSR is high. Since a few years ago, researchers have also concentrated on protecting MCR faults, which are capable of controlling the active and reactive power flow in the transmission line at the same time. It is a new member of the FACTS controller, which was conceived for the compensation and power flow management of multi-line transmission systems. The most powerful and versatile FACTS device is the Interline Power Flow Controller (IPFC). It is capable of controlling the active and reactive power flow in the transmission line at the same time. It is a new member of the FACTS controller, which was conceived for the compensation and power flow management of multi-line transmission systems [19].

1.3. Contribution

Considering the significant advancements achieved, however, none of them indicated or improved power quality using the STATCOM averaged model. Power quality may be enhanced with a variety of FACTS devices, and voltage stability enhancement is also necessary to a large extent. Also, fast response, economic conditions, and accuracy of results should be kept in mind while using FACTS devices.

2. Modeling and Simulation

2.1. Modeling of D-STATCOM

Before modeling STATCOM, certain things need to be discussed. As already discussed, STATCOM is a quick-response device that can provide or absorb reactive current; also, it is used for voltage regulation at PCC to the power grid. It comes under the category of FACTS devices. There are three models of STATCOM, which are discussed below:

2.1.1. Detailed Model

The first is a detailed model that accurately describes power electronic IGBT converters. This model has to be divided at a relatively small step (about 5μs) due to the achievement of appropriate accuracy with the 1680 Hz switching frequency. This model is ideal for observing harmonics and the dynamic behavior of control systems over short periods (usually a few hundred milliseconds to a second) [20].

2.1.2. Averaged Model

The typical representation of the Average model, such as the one used here. The IGBT-VSC in this model is modeled as equivalent voltage sources that generate the AC voltage by averaging it over one switching cycle. This model does not represent harmonics, but it does preserve the dynamics that result from the control system and the interaction of the power system. This model enables larger time steps (usually 40μs to 50μs) and, therefore, allows for short-term simulations [21].

2.1.3. Phasor Model

The third type of model is the phasor model, which can be used for simulating over longer periods. The D-STATCOM is not compatible with this model [22].

2.2. Explanation of Averaged Model of FACTS Device (D-STATCOM)

The voltage of a 25 kV distribution network may be controlled using a D-STATCOM. Loads are connected to B3 to get power from feeders (which are 21 km and 2 km, respectively). At B2, for the correction of PF, a shunt capacitor is used. By connecting a 600V load to bus B3 with a 25kV/600V transformer, the system simulates an arc furnace's voltage flicker by absorbing constantly varying currents. The total power is changed between around 1MVA and 5.2MVA by modulating the load current magnitude at a frequency of 5Hz while maintaining a PF of 0.9 (lagging). Changing the load like this will show how well the D-STATCOM can suppress voltage fluctuations.

At B3, voltage is controlled by D-STATCOM, which does this by consuming or producing reactive power as needed. Whereas the voltage generated at the secondary side is in phase with the voltage generated at the primary side, non-useful power is transferred via the leakage reactance of the coupling transformer connected to the STATCOM. In this circumstance, voltage is supplied by a PWM inverter fed by the input voltage.

The D-STATCOM always operates when: The FACTS device (D-STATCOM) behaves like an inductor and absorbs non-useful power when the secondary voltage is less than the voltage of the bus and in contrast, it functions similarly to a capacitor and produces non-useful power: when the secondary voltage is larger than the voltage of the bus.

2.3. Feature of D-STATCOM

The features (used in the model) of D-STATCOM are discussed below:

2.3.1. Coupling Transformer

For coupling the PWM inverter to the power system, a coupling transformer of primary voltage 25KV and secondary voltage 1.25KV is used. The internal voltage of 225 kV is generated by the programmable voltage source.

2.3.2. PWM Inverter with a Voltage Source

On the AC side of this model design, three equivalent voltage sources are used in place of the PWM inverter, with their voltages averaged across one switching frequency cycle (1.68 kHz). As a result, harmonics generated by the inverter are not observable as shown in Fig. 4 . The inverter is shown on the DC side by the current source that is used to charge the DC capacitor (see Fig. 5).

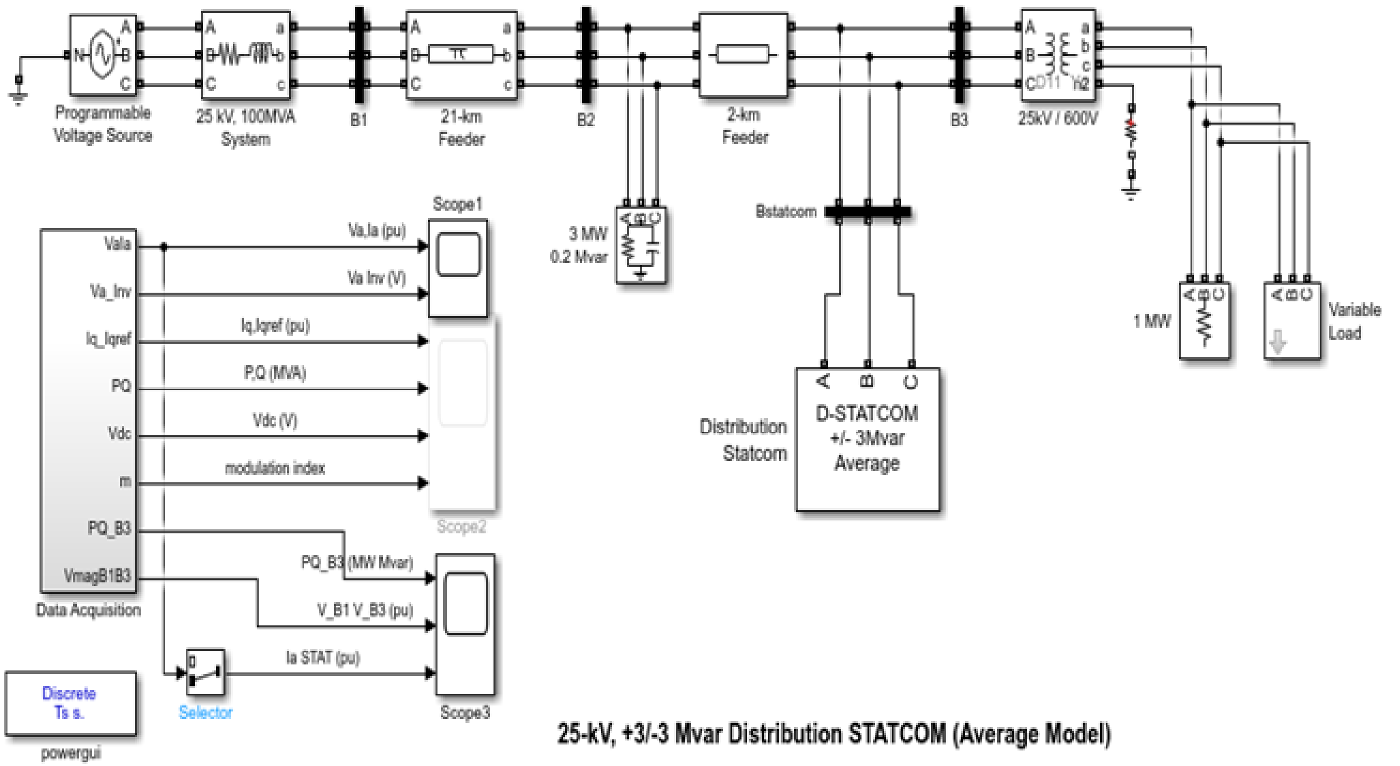


Figure 4. Averaged model of D-STATCOM.

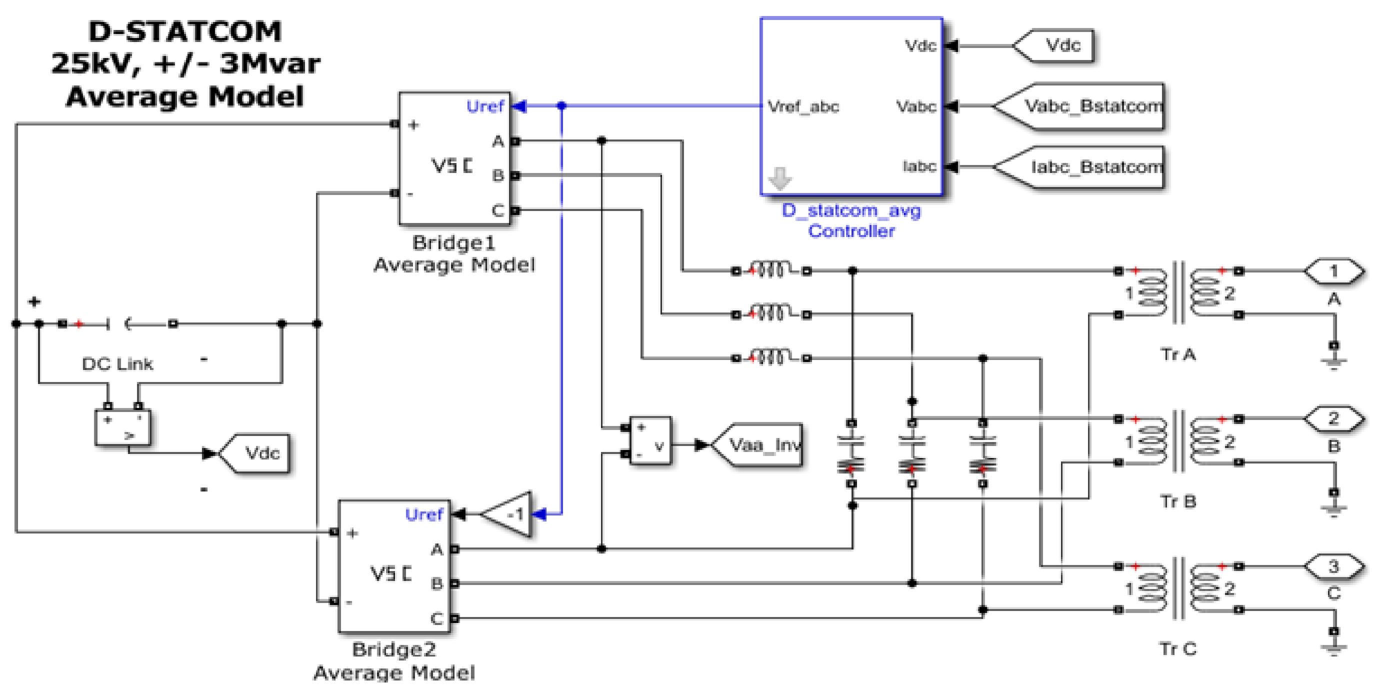


Figure 5. Connection diagram of D-STATCOM in MATLAB Simulink.

$$V_a I_a + V_b I_b + V_c I_c = V_{dc} I_{dc} \tag{3}$$

Now, from the above expression, it is clear that the power at the inverter's AC. inputs is similar to the power DC output.

2.3.3. LC Damped Filters

These are linked with inverters. At 60 Hz, Adding resistance to capacitors in series results in a quality factor of 40.

2.3.4. Capacitor

A 0.01F capacitor that serves as the DC voltage source of the inverter.

2.3.5. Voltage Regulator

On B3, a voltage regulator is used to regulate the voltage.

2.3.6. Anti-Aliasing Filters

For current and voltage acquisition, anti-aliasing filters are used (see Fig. 6). Also, they are used to minimize the overlapping between waveforms.

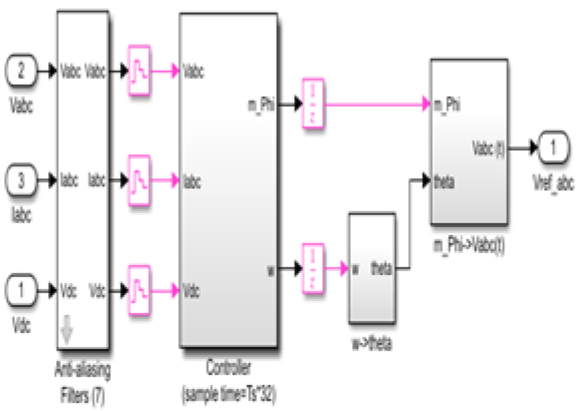


Figure 6. Anti-aliasing filters along with controller of D-STATCOM.

2.4. Functional Module of D-STATCOM

FACTS device (D-STATCOM) controller is made up of some functional modules, which are discussed below:

2.4.1. Phase Locked Loop (PLL)

A PLL is synchronized to the transformer's primary voltage fundamental.

2.4.2. Systems of Measurement

There are two measurement systems; the d-axis and q-axis are the components of voltages and currents. These are computed by the execution of an $abc - dq$ transformation in the synchronous reference defined with $\cos(\omega t)$ and $\sin(\omega t)$, which PLL delivers.

2.4.3. Inner Loop of Current Regulation

Here, two PI controllers (used to compare the system's output signal with their input signal to find out error signal) regulate the currents on $d -$ axes and $q -$ axes. These are the controller's output voltages: Vd and Vq that are required to be generated by the PWM inverter, which is now transformed into phase voltages: Va, Vb, Vc. These phase voltages are utilized in order to produce the PWM voltages. In automatic mode, reference (I_q) is derived from the voltage regulation (outer loop), or in manual mode, a Qref is derived from an imposed reference. Specifically, the DC-link voltage regulator is the source of the I_q reference (see Fig. 7).

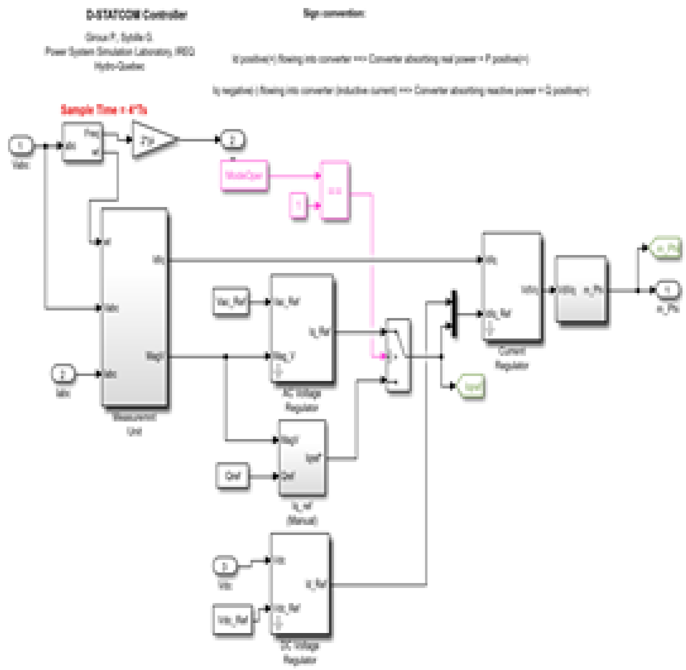


Figure 7: Controller of D-STATCOM.

2.4.4. Outer Loop of Voltage Regulation

The primary voltage is maintained constant by a PI controller in automatic mode at the value specified in the dialogue box of the control system.

2.4.5. DC Voltage Regulator

Its function is to keep Vdc to its significant value as given below:

$$V_{DC} = 2.40 \text{ kV} \tag{4}$$

A 40 μs sampling period is used to divide the electrical circuit. The controller uses a longer sampling period (4 times Ts, or 160 µs).

3. Results and Discussions

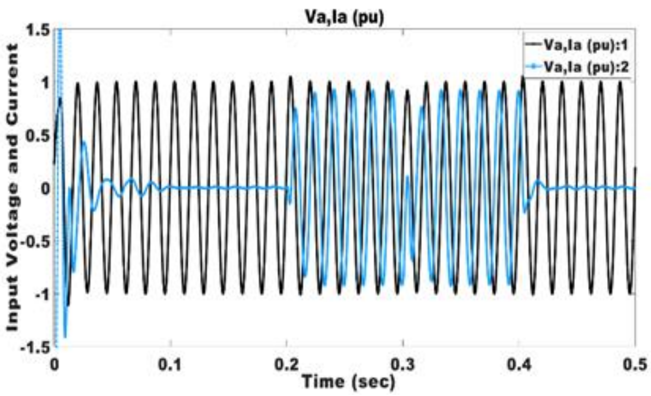
3.1. Dynamic Response

Here, the response of the FACTS device (D-STATCOM) to sudden variations in source voltage will be seen in this demonstration while the variable load is held constant. Verify that the variable load's modulation is not active:

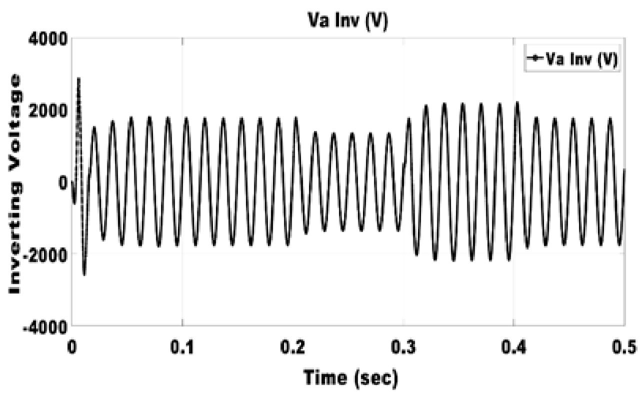
Modulation Timing $[\mathbf{t_{on}}\ \mathbf{t_{off}}] = [\mathbf{0.15}\ \mathbf{1}] * \mathbf{100} >$ Simulation Stop time

The internal voltage (25-kV equivalent) is modulated using a PVS block. Initially, the voltage is set at 1.077 per unit to maintain the initial floating of D-STATCOM ($V = 1$ per unit at B3).

At 0.2sec, 0.3sec, and 0.4sec, three steps are programmed to sequentially increase and reduce the source voltage by 6% and restore it to its original value (1.077 per unit). Now begin with the simulation and observe Scope2 for controller signals and Scope1 for voltage and current of phase A of the connected FACTS device (D-STATCOM). A stable condition is attained after a small transient of around 0.15 seconds (see Fig. 8). At first, the switch is inactive because of the supply voltage, which is too low. It neither delivers any reactive power nor does it receive any from the network [22].



(a) Input voltage and input current.

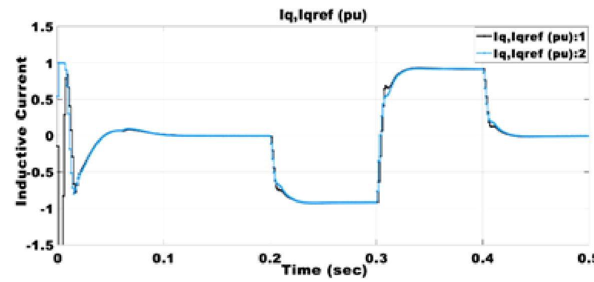


(b) Inverting voltage of D-STATCOM

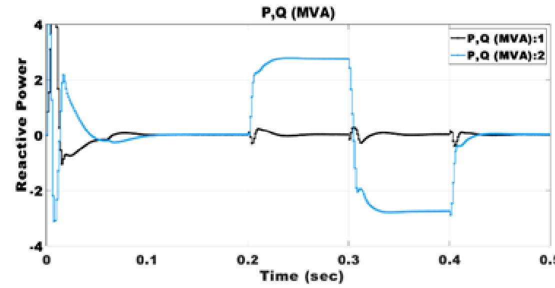
Figure 8. Various profiles of input and output parameters such as voltage and current.

At $t = 0.2sec$, 6% of the source voltage is improved. As a result, by taking non-useful power, the FACTS device (D-STATCOM) can level out voltage (on trace 2 of Scope2 Q=+2.7 MVAR). With $Q = 0$, the value of the source voltage is dropped by 6% at t = 300ms. Keeping voltage at 1 per unit, the D-STATCOM has to provide reactive power. (Reactive power varies from +2.7 to -2.8 MVAR).

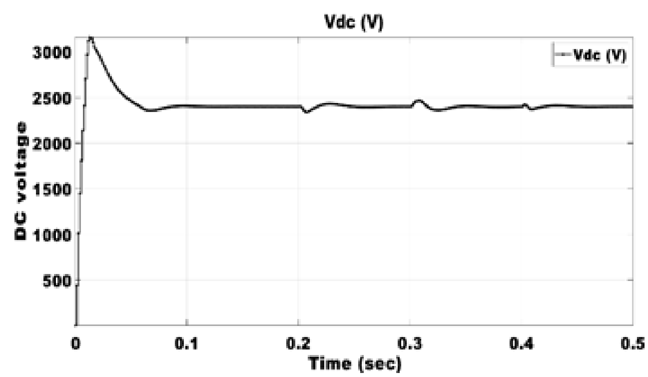
It should be observed on trace 4 of the connected scope 2 rises the change in the operation of the FACTS device (D-STATCOM) from inductive-capacitive causes a rise in the PWM inverter's modulation index from 0.56-0.9, which causes the inverter voltage to increase proportionately. Observing the D-STATCOM current, the reversal of reactive power occurs quite quickly, in around a single cycle, as shown in the magenta signal on trace 1 of Scope 1 in Fig. 9.



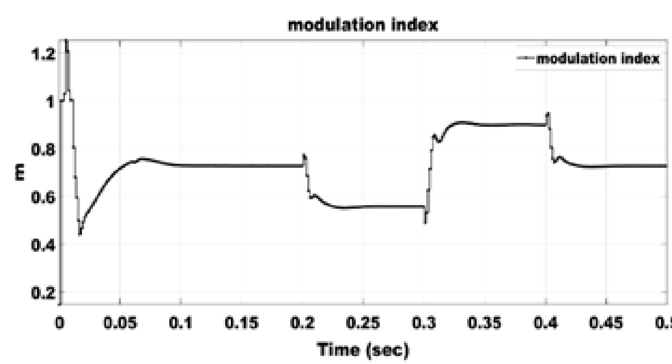
(a) Inductive current.



(b) Reactive power generated by D-STATCOM



(c) DC Voltage in D-STATCOM



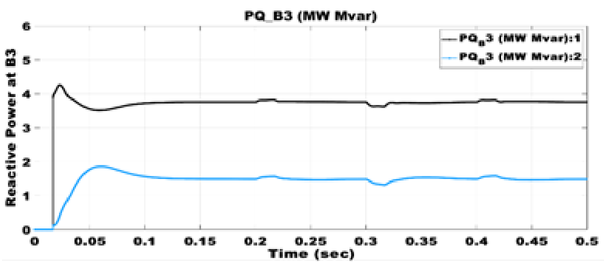
(d) Modulation index in D-STATCOM

Figure 9. Profile of inductive current, reactive power, dc voltage, modulation index in D-STATCOM.

3.2. Reduction of the Voltage Flickering

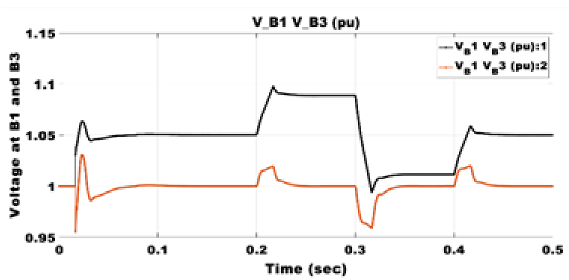
In the following research work, you will examine the FACTS device's (D-STATCOM) capability to reduce voltage flickering by maintaining steady voltage (from a programable voltage source) and activating modulation of the Variable

Load. Keep Changes in the setting from "Time Variation of" to "None" within the Programmable Voltage Source's block menu.

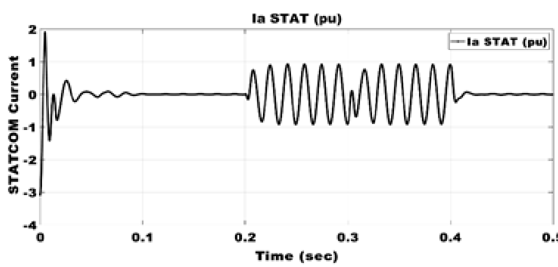


(a)

Reactive power at bus 3.



(b) Voltage at bus 1 and bus 3.



(c) D-STATCOM current.

Figure 10. Profile of Reactive Power, Voltage at Bus 1 and Bus 3, current of D-STATCOM.

Set the Modulation Timing parameter to $[t_{on} t_{off}]$ = [0.150 1] (eliminate the multiplication factor of 100) in the Variable Load block menu last but not least, in the controller of the FACTS device (D-STATCOM), substitute "Q regulation" for "Mode of operation" and also ensure that the $Qref$ is adjusted to 0. The D-STATCOM floats, and voltage is not regulated in this mode.

Now after running the simulation, observe fluctuations of P and Q on trace 1 of B3 and Scope3 in addition, voltages on trace 2 of B1 and B3 in Fig. 10. Now the voltage at B3 fluctuates between the 0.960 per unit and 1.040 per unit which means it is +/- 4% difference in the voltage without the FACTS device (D-STATCOM). Restart simulation by switching the "Mode of operation" setting back to "Voltage regulation" in the controller of the FACTS device (D-STATCOM). At B3, the variation of voltage has been decreased to +/- 0.70%, as seen on Scope 3. On the trace 3 of Scope 3 for compensating the voltage, a reactive current modulated at 5 *Hz* is delivered by the FACTS device (D-STATCOM) and fluctuates within 0.60 per unit capacitive and 0.60 per unit inductive depending on the voltage (low or high) [23].

4. Conclusion

The outcomes of this research work will have a significant effect on consumer load performance and utility loss reduction. As a result of this project, voltage and power quality will be enhanced for the betterment. Instead of building new dams and constructing new transmission lines (the long-term option) to increase the country's power-carrying capacity, the immediate solution is improving the quality of energy sent over the existing grid. In the present project, the terminal voltage is accurately regulated by connecting a STATCOM. By keeping the transmission voltage constant, it improves transient stability. The STATCOM is linked to the transmission line at the distribution side of the network so that the power quality is improved.

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Conflicts of Interest: The authors declare no conflict of interest.

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