Three-level inverter based STATCOM

1 Introduction

Reactive compensation has been used extensively in the power industry in order to provide voltage regulation, improve transient stability and aid in power system oscillation damping [1]-[5]. Switched capacitors and inductors have been replaced by static var compensators (SVCs) and recently, due to the advent of high power, self-commutated switches, static compensators (STATCOM) are showing great promise and could be a favorable alternative to SVCs of similar rating. Present installations in North America have exceeded 100 MVARs [6], [7] and with the restrictions on rights-of-way, improved low-sag conductors, and increased interconnections between power systems, reactive compensation requirements will definitely increase. Much of this void will likely be filled by larger fast-acting STATCOM.

1.1 Principles of reactive compensation

The fundamentals of reactive power compensation and the associated benefits will be introduced briefly here. For a more rigorous and in-depth treatment, readers are referred to many of the good references on the subject [1]-[13]. For self-commutated system using either gate turn-off thyristors (GTO) or insulated gate bipolar transistors, reactive compensation can be thought of as the connection of a ideal voltage source, either in shunt, with the goal of injecting reactive current, i_q or in series, in order to control directly the line current, i_c (Fig. 1.1). This strategy is possible with self-commutated valves since they possess the added degree of freedom to control the angle between the injected voltage and the voltage of the system.

Only the case of shunt compensation will be considered here, where the injected voltage is connected to the system via a coupling inductance, which is usually the leakage reactance of the coupling transformer. The connection is usually made at approximately the midpoint of the transmission line but connection near the load is also possible. The converter used to generate the voltage is a self-regulated inverter, where the dc bus voltage is controlled by introducing a slight phase shift between the output voltage and the voltage at the point of common coupling (PCC). This is most commonly referred to as a static compensator (STATCOM).

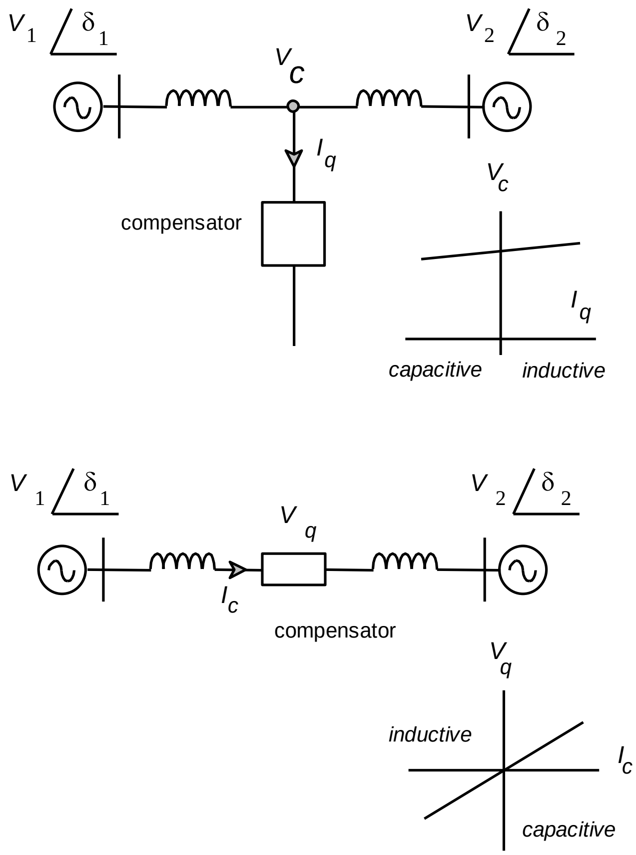


Fig. 1.1. Principles of var compensation in transmission systems. (a) Shunt compensation. (b) Series compensation.

The simplified representation of a self-commutated synchronous rectifier is shown in Fig. 1.2. The angle and magnitude of the fundamental current, *I* depend on the relative angle and magnitude of the fundamental output voltage generated by the rectifier. In this way, the rectifier is able to control independently both the real and reactive components of the current. The line reactance acts as a low pass filter in order to eliminate the harmonics which are generated by the pulse-width modulation (PWM), such that the filtered current is near-sinuisoidal.

In the case of a STATCOM, the line reactance is typically the leakage reactance of the coupling transformer and the load on the dc side is typically absent. The injected voltage is usually in phase with the source voltage and the amount of reactive power injected or absorbed in controlled by varying the magnitude of the voltage. In order to account for losses in the switches and the transformer, a small phase shift is introduced in order to regulate the dc voltage. The STATCOM topology and the associated phasor diagram can be used to understand the basis for the control of the reactive current, i_q (Fig. 1.3).

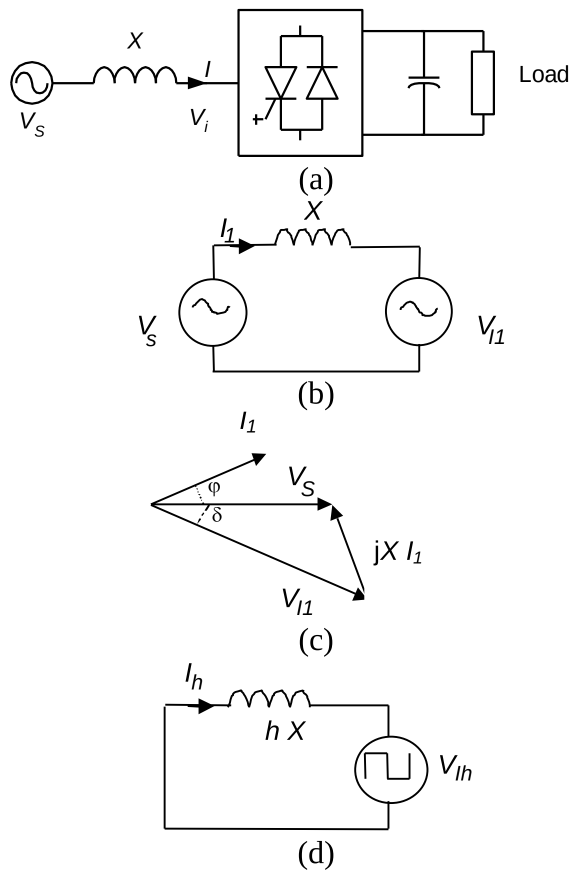


Fig. 1.2. Operation of a self commutated synchronous rectifier. (a) Schematic diagram (b) Equivalent circuit for fundamental frequency operation. (c) Phasor diagram for fundamental frequency operation. Leading power factor. (d) Equivalent circuit for switching frequency components. Line reactance and synchronous reactance are lumped.

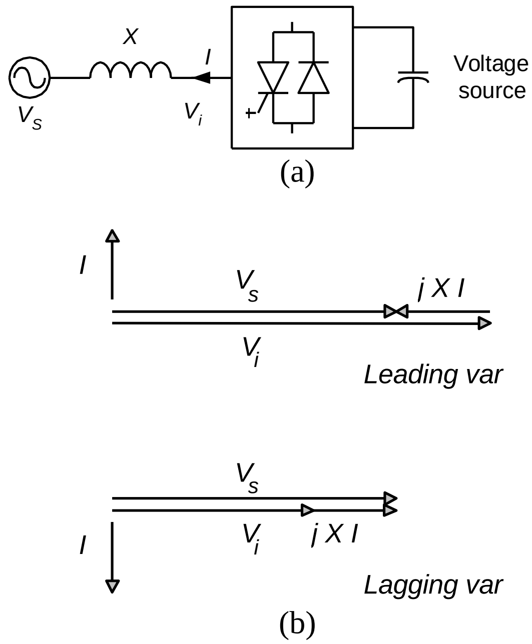


Fig. 1.3. Static compensator (STATCOM) based on the principle of synchronous voltage sources. (a) Power circuit configuration based on a voltage source converter. (b) Operation with leading and lagging var injection.

The steady-state operation of the STATCOM can be represented by the reactive injections as a function of the reference voltage at the PCC. Each of the lines have a small slope, known as the droop characteristic, whereby the reference voltage is slightly less at maximum leading reactive current and slightly greater at maximum lagging reactive current. Typically, the variation in the reference voltage is 3%.

The droop characteristic is used for the following reasons [1]:

(i) The linear operating region of the compensator can be extended

(ii) Strictly defined voltage reference can result in a poorly defined operating point and resulting oscillations.

(iii) The slope leads to favorable compensation sharing by numerous regulation devices which are connected at various points in the system.

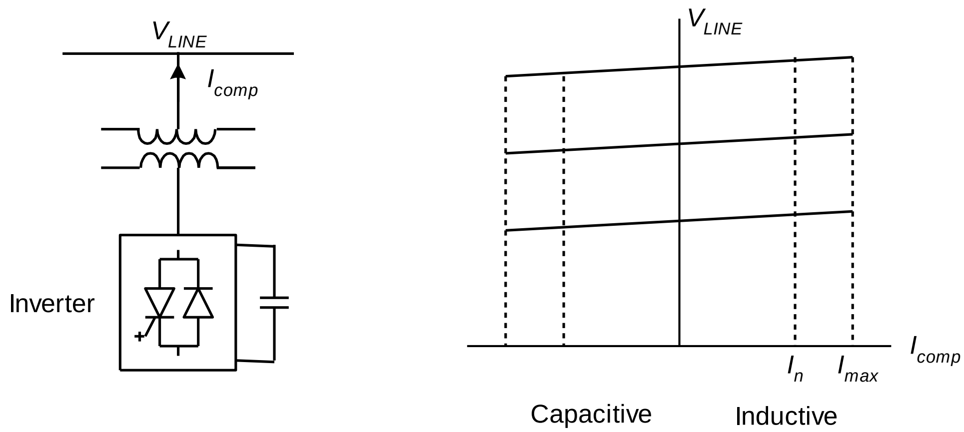


Fig. 1.4. Static Compensator (STATCOM).

1.2 STACOM Control Principles

Usually, the STATCOM control consists of an outer regulation loop which sets the reference reactive current based upon the aforementioned droop equation and an inner current loop which sets the inverter output voltage in order to achieve the desired current (Fig. 1.5). A separate loop determines the phase shift in order to regulate the dc voltage. Other elements of the control include a phase-locked loop to provide synchronization with the ac system and the measurement and filtering of the positive sequence component of the voltage along with the instantaneous reactive current.

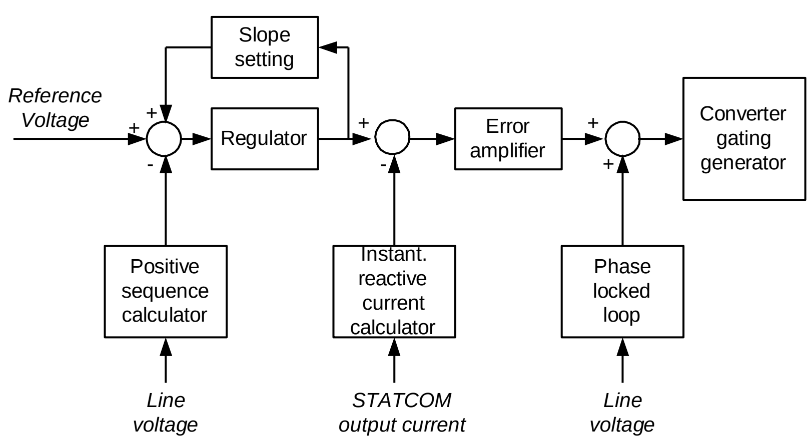


Fig. 1.5. Typical STATCOM control system configuration (TVA).

Auxiliary control signals may be added along with the positive sequence component of the voltage such as the deviation of the system frequency, Δf or the change in the power flow along the line, ΔP, which can be used to help provide power oscillation damping [1],[4]. However, the basic control scheme remains unchanged and the primary goal of voltage regulation already leads to additional damping and therefore the addition of either of the supplemental signals may or may not be necessary.

1.3 Role of static compensators

STATCOM and other compensators enable the regulation of the voltage at the PCC, although the amount of regulation depends very much on the installed capacity and the power system under consideration. With a ideal voltage regulator installed at the midpoint of a line, i.e. one without limits, the maximum amount of real power transmitted effectively doubles [1],[2]. Secondary benefits are also realized resulting from the voltage regulation ability. The main advantages associated with STATCOM are listed below:

(i) Regulation of ac voltage
(ii) Doubling of P_{max} for ideal compensator
(iii) Transient stability improvement
(iv) Power oscillation damping

These characteristics are inherently linked, resulting from the fast-acting nature of the STATCOM and its ability to inject rated current even at deep voltage sags (unlike SVCs, whose i_q limits depend very strongly upon the voltage at the PCC). The goals of this study are to first represent a three-level inverter based STATCOM in EMTP-RV and secondly, to demonstrate the desirable characteristics that the STATCOM possesses by performing various systems studies. The following sections present the design and representation of the STATCOM followed by some simulation results which illustrate how the STATCOM can be used to aid in system performance.

2 STATCOM modeling

This section details the modeling of a three-level based inverter in EMTP-RV with emphasis on the design and the representation of the system within the software. The basic control structure as laid out in the previous section is explained in detail and the design procedure is documented. First, the models of the various components are presented. Particularly at high power levels, low switching frequencies are used in order to minimize switching losses. Therefore, a three-level inverter is modeled which enables an effective doubling of the switching frequency compared with a two-level design. This allows for a reduction of one-half of the switching frequency while maintaining the same harmonic content.

2.1 Three level inverter

The three-level topology was first introduced in the late 1970's [15] and possesses the advantage that it has the same waveform quality as a two-level inverter converter operating at twice the switching frequency. The three level voltage source converter differs from conventional voltage source converters in that it has four self-commutated switches in each leg instead of the traditional two. In addition to having anti-parallel diodes across each switch, the converter also has a diode between the midpoint of the upper and lower arms and the neutral point (Fig. 2.1). This design enables the converter to switch not only between the upper and lower dc voltages but it allows the output to be zero as well. Using this feature and a modification of the gating pulse generation, a better voltage waveform can be produced for the same switching frequency. This makes it an attractive option for high power applications where switching losses is a major concern.

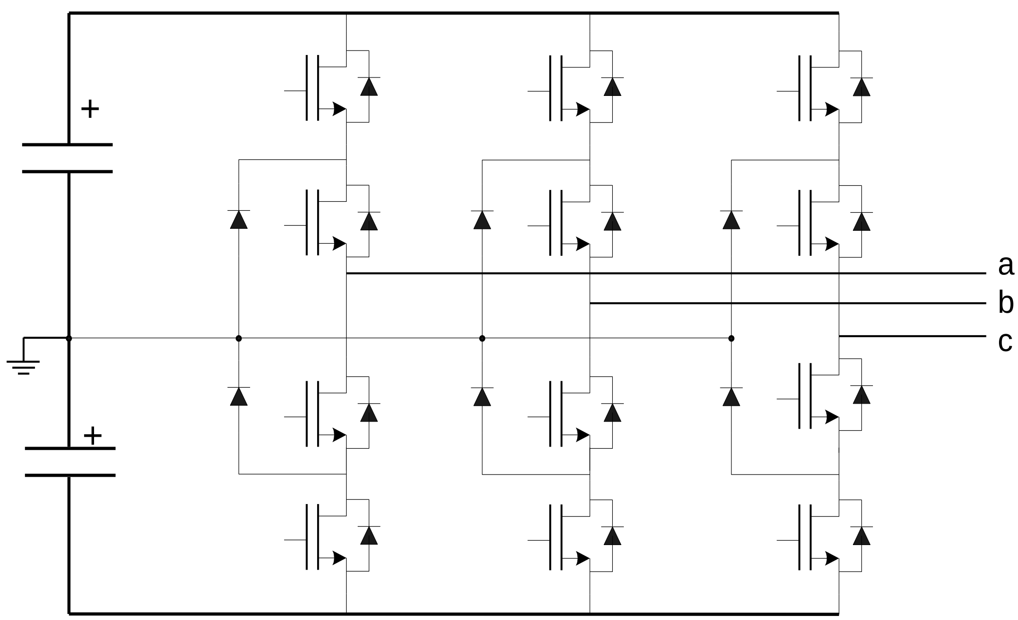


Fig. 2.1 Three-level voltage source converter

2.1.1 Advantages and disadvantages

As mentioned, an effective doubling of the switching frequency makes this topology useful for high power applications namely, motor drives, uninterruptible power supplies (UPS), and synchronous compensators such as STATCOM. However, the arrangement leads to various technical challenges that do not occur with the conventional type of inverter. Firstly, the generation of the three level inverter PWM waveforms is somewhat different since it requires four gating signals instead of simply two. Various methods have been developed which use modified PWM, as well as more complicated methods utilizing space-vector modulation [16]-[19]. Another of the difficulties that has been identified is neutral point potential unbalance which invariably results whereby the voltages across the upper and lower capacitors can differ significantly. This issue must be considered in the generation of the gating signals in order to prevent undesirable operating characteristics.

2.1.2 Three-level converter model

The three level converter was constructed in ETMP-RV using an IGBT switch model. The IGBT switch model was developed starting from the ideal switch model. A nonlinear diode placed in series with the switch ensures conduction of current in only one direction. The antiparallel diode was modeled using the nonlinear diode as well. A snubber circuit was also placed in parallel with the switch in order to complete the IGBT representation (Fig. 2.2). In order to prevent problems in calculation of the steady-state initialization, a large resistance is placed across the terminals of the ideal switches which are initially open. This does not change anything in terms of the behavior of the IGBT, it is used only to facilitate steady-state initialization. A small inductance which serves as a current limiter can be placed between the dc bus and the switch terminals. This aids in convergence of the nonlinear diode model as well as models the connection.

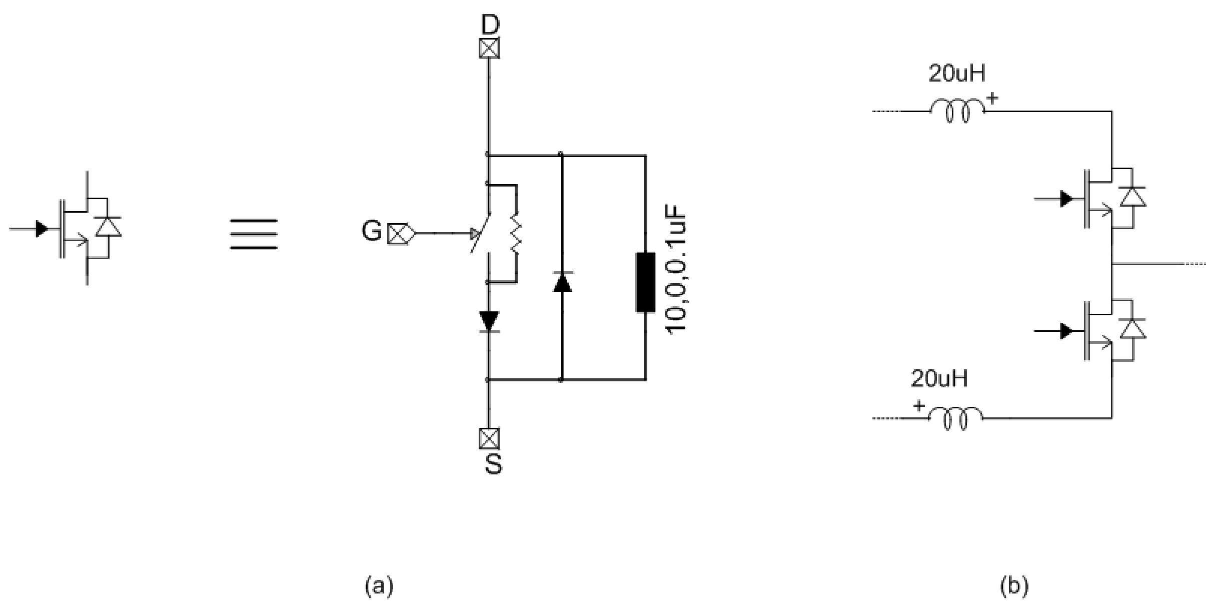


Fig. 2.2 EMTP-RV representation of the insulated gate bipolar transistor (a) IGBT model (snubber 10 Ω, 0.1µF) (b) current limiting inductance connection to dc bus (resistance in parallel with inductance).

Next, the developed model of the IGBT was used to construct the three-level inverter (Fig. 2.3) The neutral point clamp diodes were modeled again using the same nonlinear diode model. The diode model, which differs from the ideal diode model, is simply a nonlinear resistance which emulates the diode characteristic. This enables simultaneous switching of current to the diode branch once the upper IGBT in a branch is switched off. Addition of power pins at each of the terminals and reduction into a subcircuit completes the design.

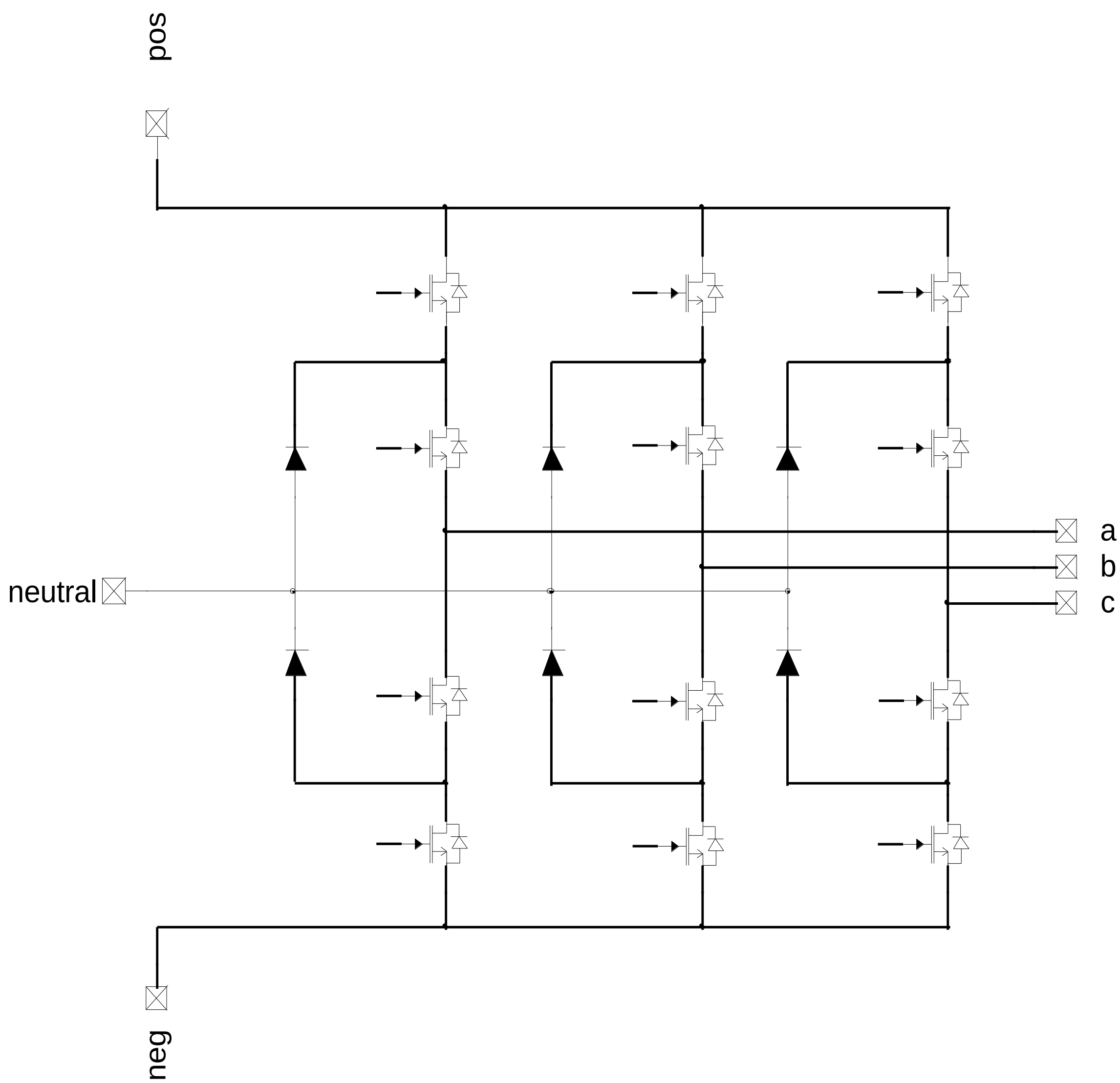


Fig. 2.3 EMTP-RV model of a three phase, three-level voltage source inverter

2.1.3 Three level modulation principle

Although there exist many complicated modulation schemes for three level VSCs, a modified PWM scheme was implemented here for its simplicity. The algorithm follows from conventional SPWM and although it is more simplified by nature, its performance does not differ significantly from more in depth schemes. The PWM generation produces 4 gating signals, one for each IGBT in a given leg. The four combinations of switching logic and the resulting output voltages are given below in Table 1. From the Table, the generation of the four PWM signals using triangular carriers can be determined.

Table 2.1: Switching logic and output voltages for a three level converter

SU1	SU2	SL1	SL2	V_{out}
0	0	1	1	$-V_d/2$
0	1	1	0	0
1	1	0	0	$V_d/2$

The PWM signals are produced using two triangular signals: starting from a conventional triangular carrier, two different offsets of opposite sign are added to the triangular waveform to give the required carriers. Then, the two new carrier signals are compared with the reference voltage waveform and the output as well as its inverse are used for the various gating signals. In order to deduce which outputs correspond to which gating signals one simply refers to Table 2.1. The figures of the reference voltage, the triangular carrier and the desired output voltages are given below (Fig. 2.4).

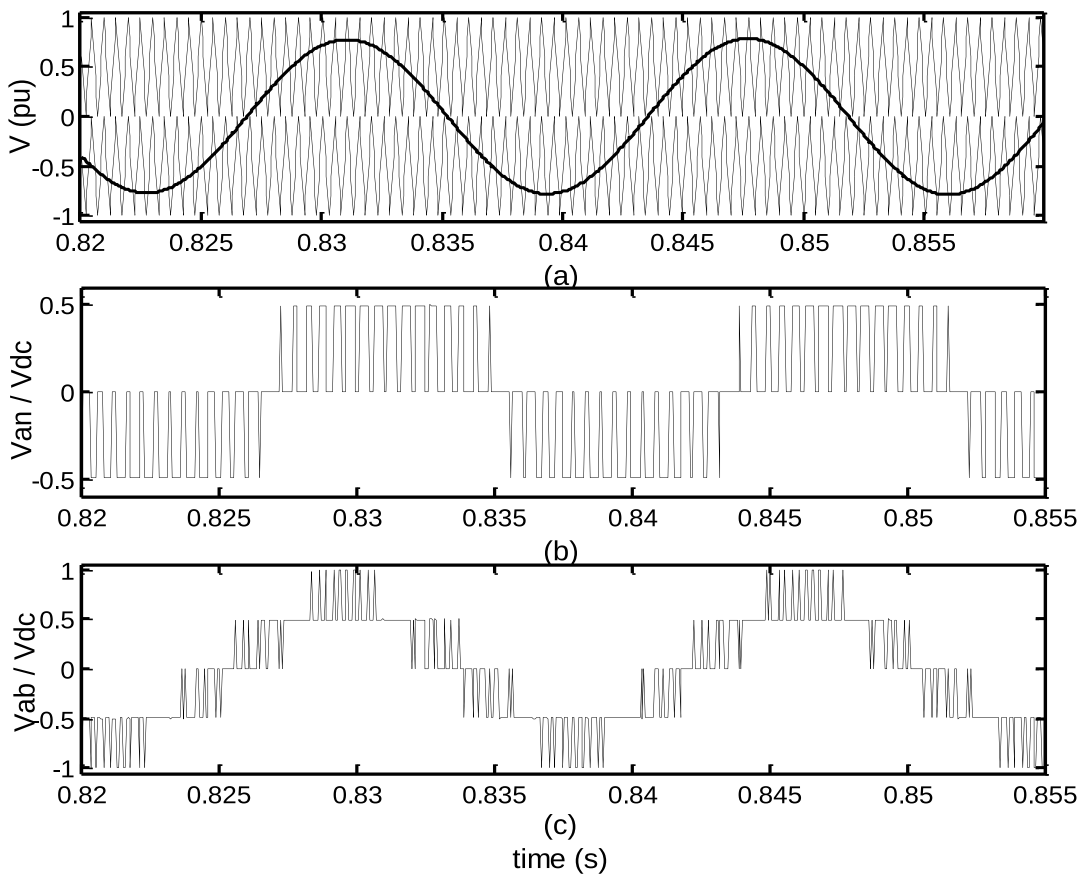


Fig. 2.4 (a) Reference voltage with triangular carriers (b) three level output line to ground voltage and (c) line to line voltage

The theory of the three level PWM generation is then reproduced in EMTP-RV using various blocks from the control library. First the triangular signal is produced to which the various offsets are added. Since EMTP does not possess a triangular waveform block one was created using the desired switching frequency, f_s, and combinations of various control blocks (Fig. 2.5). The first f [u] block performs a simple calculation in order to extract the decimal component of f_s * t which is then limited between the range 0 and 1. In order to understand the idea, consider the simple example of a switching frequency of 2 kHz and t = 17 ms. The output of the first f[u] block becomes:

$$f[u]_1 = 2000(16.25x10^{-3}) - Trunc(2000(16.25x10^{-3})) = 32.5 - 32 = 0.5 \qquad (2.1)$$

The output of the first block is then evaluated by the two f[u] blocks which follow, which are simply linear functions as shown. The final component of the waveform generation is the comparator signal which selects the linear waveform corresponding to the solid line in the figure. In this way, a triangular waveform is synthesized which can be used for various types of modulation used in the control of power electronics, including SPWM, dc chopper circuits, and three-level modulation. Synchronization of the triangular waveform with the modulating signal has not been done but through modification of the scheme to incorporate a phase shift this could be accomplished.

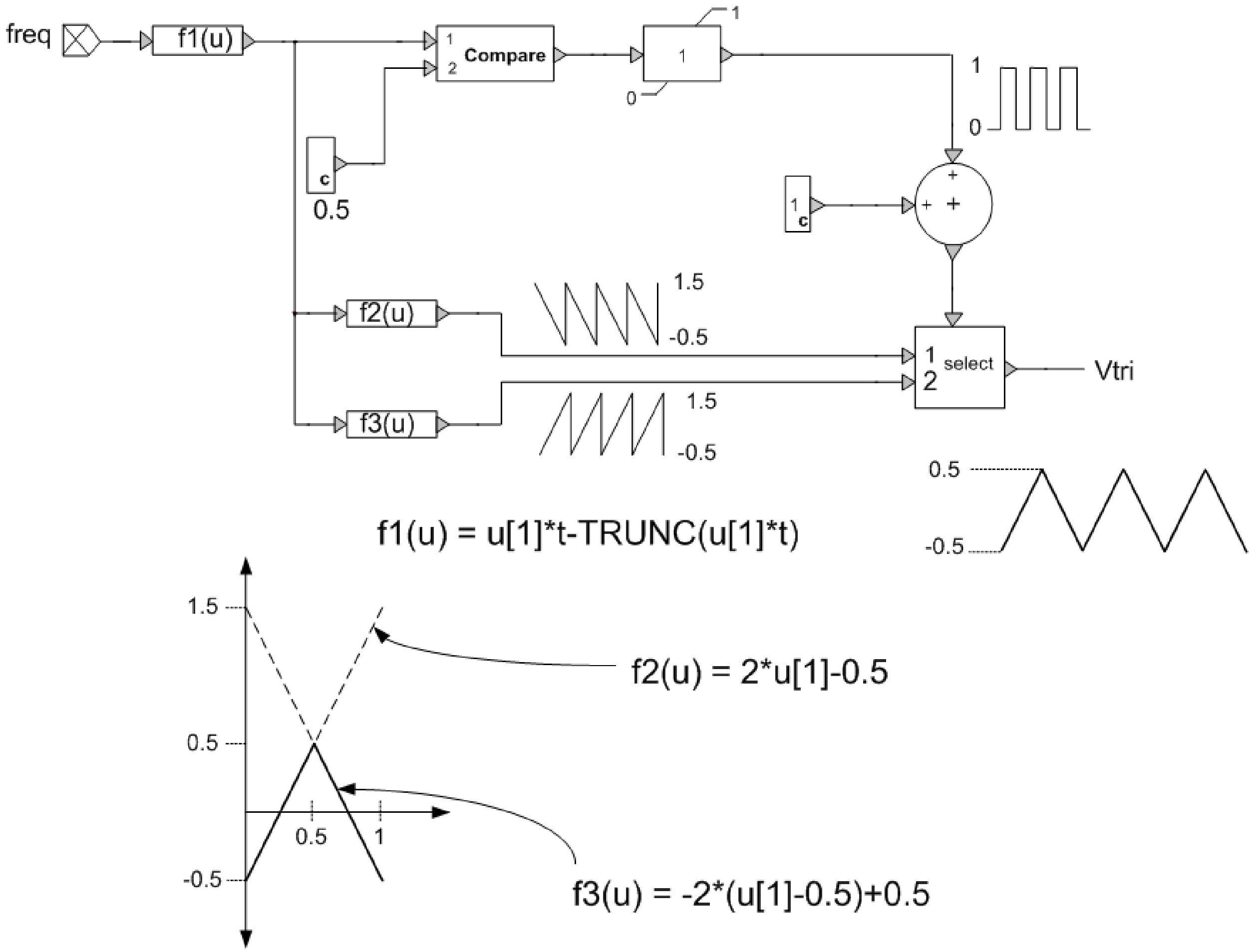


Fig. 2.5 Generation of triangular waveform

In order to utilize the triangular waveform for three phase modulation, offsets of 0.5 and -0.5 are added to produce the two required modulating signals. Following the comparison of the new triangular signals with the reference voltage, the gating signals are selected from the various inputs. The entire representation of the three level modulation for one inverter leg is shown in Fig. 2.6. Note that this block alone does not complete the modulation of the three level inverter since it does not take into account the neutral point balancing problem.

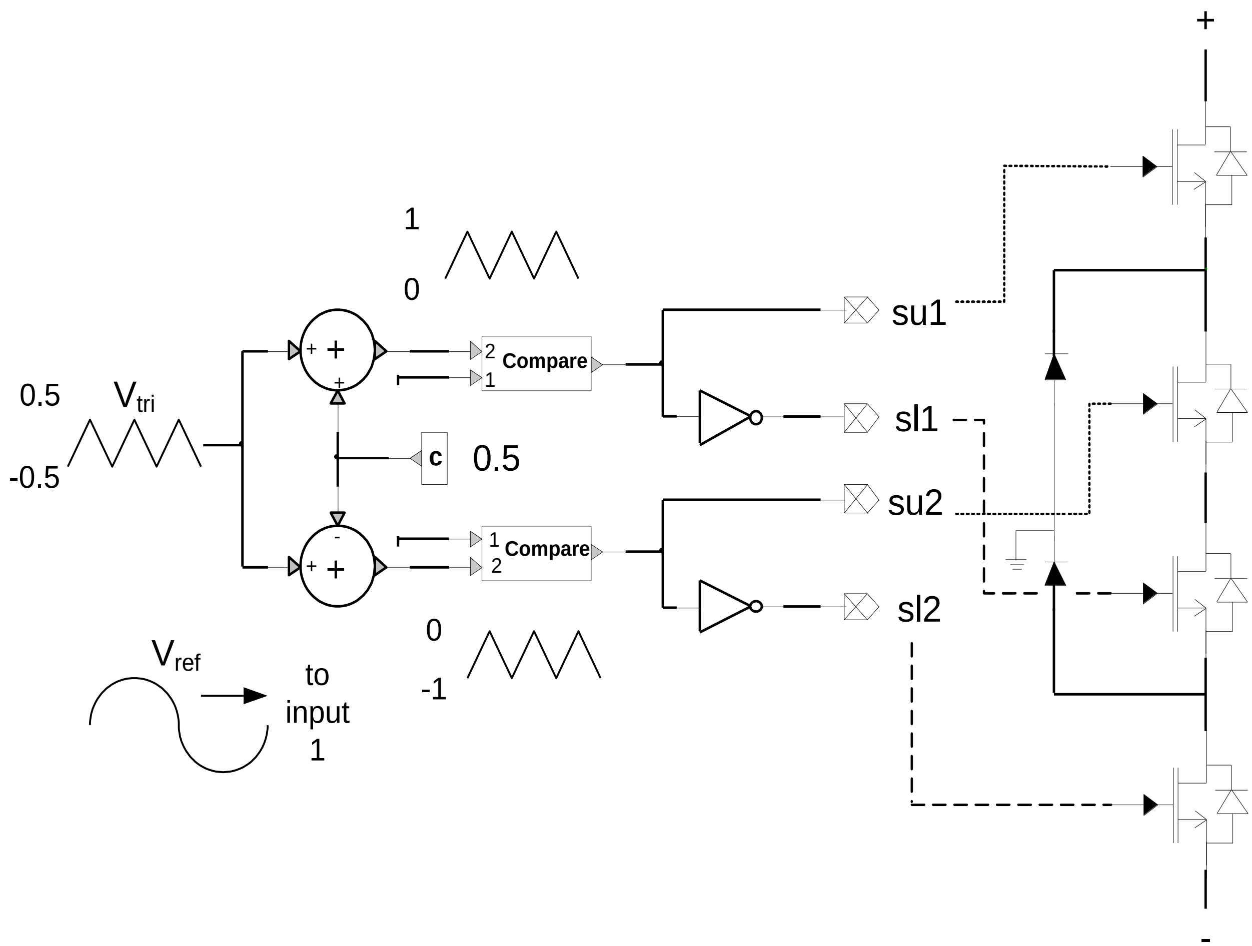
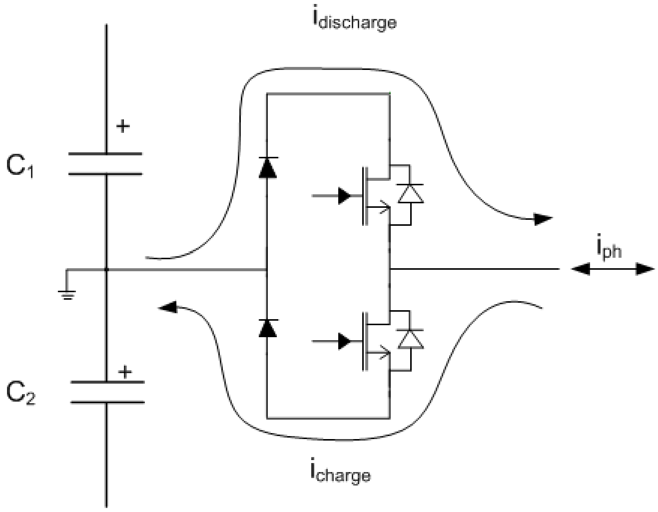


Fig. 2.6 Generation of three level PWM signals

2.1.4 Dc voltage unbalance control

The neutral point unbalance is a problem which results in three level inverter when the neutral point is connected to charging current for longer periods than to discharging currents (or vice-versa). Although the dc voltage regulator works properly, the inequality between charging and discharging neutral point current results in an unbalance between the dc voltage across the upper and lower capacitors. This is an undesirable characteristic since even if the converter is properly modulated the resulting output waveform becomes asymmetric about the x-axis and consequently, similar distortion results in the line currents. Therefore, it is imperative that a neutral point balancing algorithm be used in order to limit the unbalance to a small margin, for instance 1-2 %.

There exist various algorithms for neutral point balancing including control of neutral point connection [19], space-vector modulation techniques [18], and control of the negative sequence power for higher level converters [11]. In this case, the neutral point connection time is controlled since the PWM scheme is easily modified and the concept is relatively straightforward. In order to understand the principle let us consider the case of how the neutral point potential is charge or discharged. As previously mentioned, the neutral point potential changes when it is connected to the one of the phases. This results when the uppermost and lowermost switches are not on. The two innermost switches are gated and the neutral point diodes are forced to conduct. The direction of the current in the corresponding leg determines whether the neutral point potential increases or decreases (Fig. 2.7).



i_{ph}	ΔV_{C1}	ΔV_{C2}	$\Delta(V_{C1}-V_{C2})$
Charge	< 0	> 0	< 0
Discharge	> 0	< 0	> 0

Fig. 2.7 Neutral point connection and resulting change in capacitor voltages

In order counteract a neutral point potential unbalance, the neutral point connection of the phase which will contribute further to the imbalance is omitted. This is done by utilizing traditional two-level modulation for that phase only. Since neutral point unbalance does not occur with large frequency for a 1% tolerance band and due to the fact that only one phase is modulated using two level PWM, there is not a significant reduction in the effective switching frequency. To summarize, the redefined modulation scheme, taking into account neutral point balancing consists of the following:

(i) Identify whether neutral point unbalance exist by comparing the upper and lower capacitor voltages,
(ii) If not, modulate according to three level theory presented above
(iii) If unbalance exists, first identify the phase current which will contribute further to the unbalance
(iv) Modulate that phase using two-level modulation, the other two are modulated using the three level theory.

This is method is realized continuously, therefore if the unbalance is eliminated or if the phase current which contributes to the unbalance changes, the control responds accordingly. The implementation of the balancing algorithm is shown in Fig. 2.8.

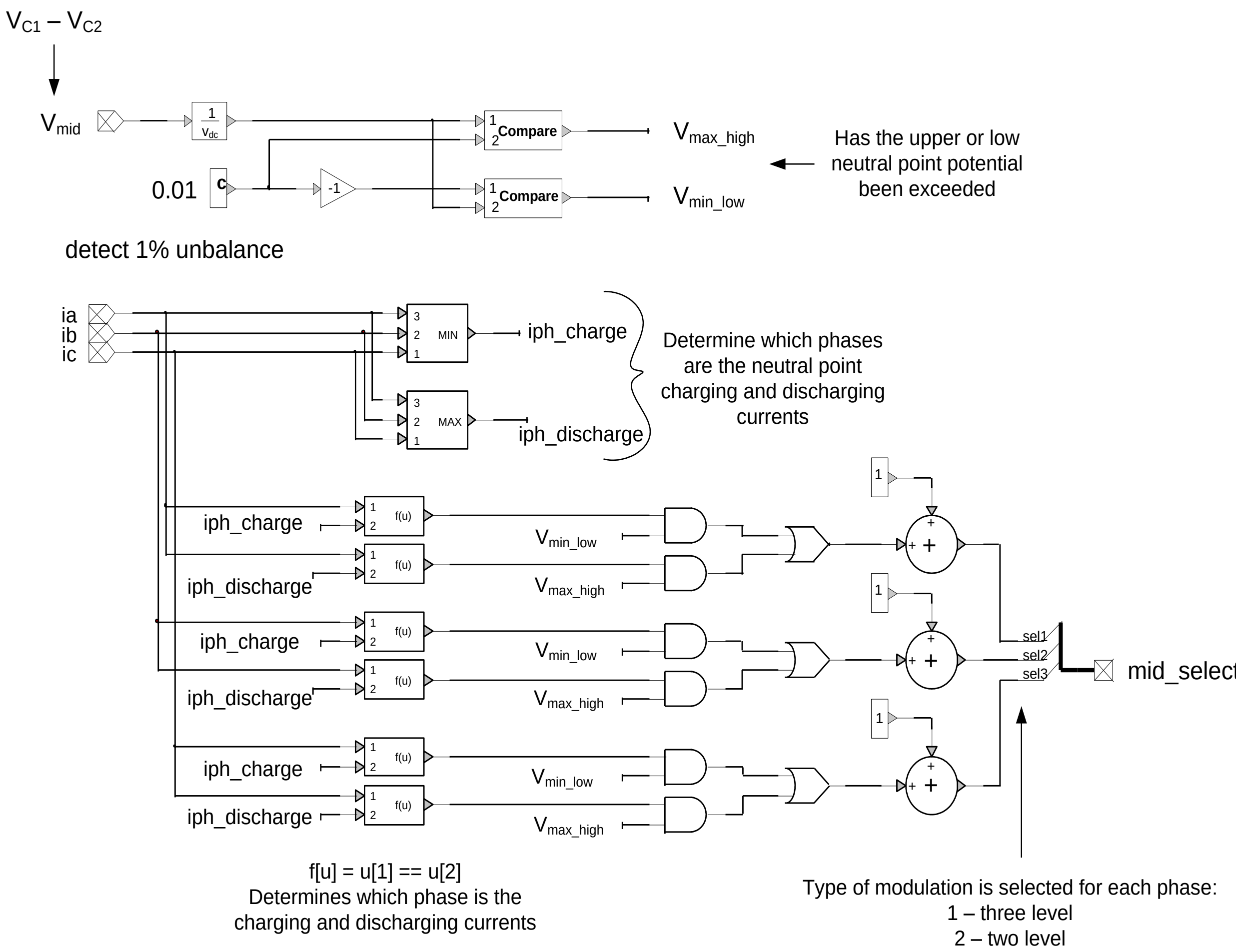


Fig. 2.8 Neutral point unbalance detection and control

2.2 STATCOM system

The complete three level converter based STATCOM was constructed using the converter block, two dc capacitors, and a 13.2/500 kV step-up transformer used to match the voltage of the STATCOM with that of the substation voltage (Fig. 2.9). The 10% leakage inductance of the transformer serves as the coupling inductance, enabling control of reactive power to and from the STATCOM. A model of the inductor with high frequency losses has been incorporated between the dc bus and the converter. This models the interconnection but also aids in convergence of the nonlinear diode. Default values may be changed, however, large changes may require retuning of some of the control parameters.

The STATCOM is controlled using measurements of the voltage on the high side of the transformer and the line currents between the converter output and the transformer. In addition, measurement of the voltages across the capacitors is required for neutral point balancing and dc voltage regulation. The details of the control, the principles of which have been outlined in the introduction, will be presented in the following section.

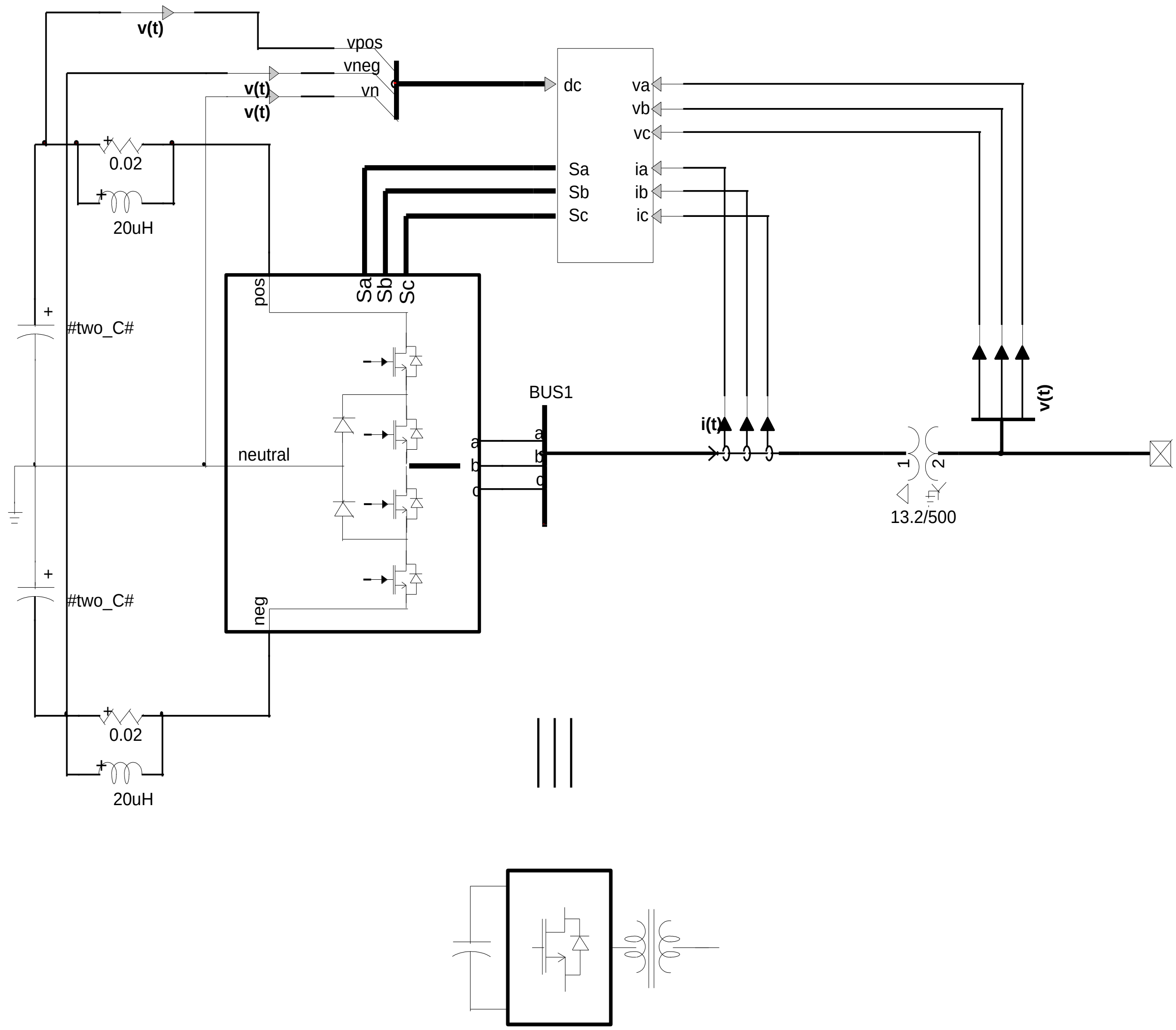


Fig. 2.9 STATCOM representation in EMTP-RV with three level converter, control, dc capacitors and coupling transformer.

3 STATCOM control

The STATCOM control is made up of numerous blocks which together, realize its function. Processing of the various signals in the form of synchronization, filtering, and various transformations are done first. The reactive power control is divided into two parts: generation of the reactive power reference for voltage regulation and power system oscillation damping and the inner reactive current control which sets the magnitude of the converter output voltage in order to achieve the desired reference. The regulation of the dc voltage is performed separately, however, interacts with the converter output voltage by introducing a slight phase shift in order to supply the desired real power to maintain the dc voltage. The specifics of the design and implementation of these control blocks will now be presented. The various characteristics and benefits of the STATCOM are then demonstrated.

3.1 Synchronization and signal processing

In order to properly control the STATCOM, various signals must first be processed and the necessary information is extracted. One of the most important features is the synchronization of the control with the ac voltage at the PCC using a phase locked loop (PLL). This is necessary in order to properly transform the three phase line currents into the correct d and q components. The voltages and currents are filtered in order to extract the fundamental component, eliminating the harmonics which arise from the PWM switching and other components which may be due to other devices in the network.

3.1.1 Phase-locked loop

The PLL used is one of many possible designs and is used to extract the phase angle of the voltage at the PCC as well as the frequency of the same voltage. The PLL design follows that presented in [20] and [21] and using the *a* phase voltage in order to obtain the angle. The frequency of each phase is measured and the average is used in the calculation of the supplemental control signal, Δf, which can be used to enhance power system oscillation damping. Note the block design could be modified in order to calculate the angles of each phase and use an average from the three phases. This could be of importance when looking at the response of the system under voltage imbalances and various asymmetrical faults, namely single line to ground faults on the *a* phase. The block diagram of the PLL structure is shown below in Fig. 3.1. Due to the Δ - Y arrangement of the transformer a 30˚ phase shift must be added to the output of the PLL. This signal is then utilized in the various transformations and reverse transformation which follow.

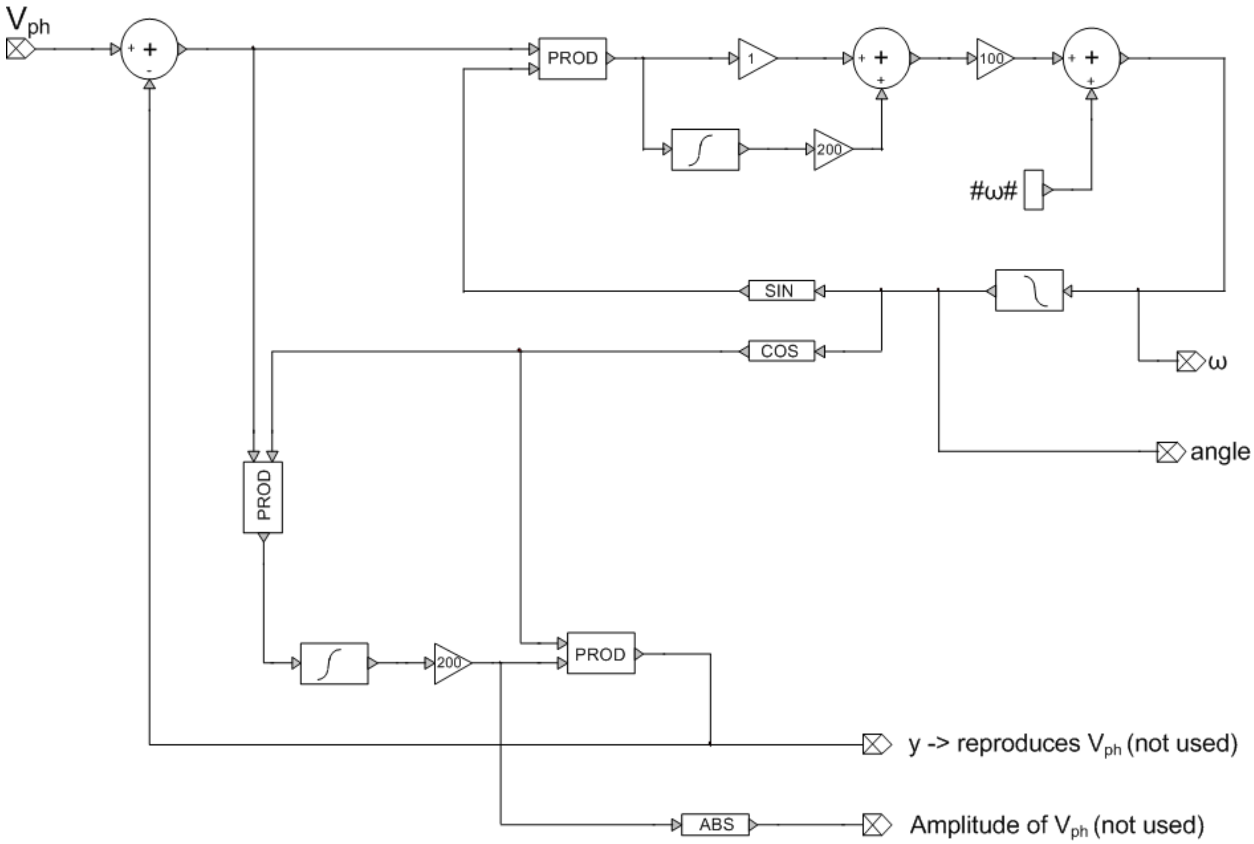


Fig. 3.1 Phase locked-loop for extraction of voltage angle and frequency.

3.1.2 Voltage transformation

For regulation of the ac voltage, it is necessary to determine the magnitude of the voltage at the PCC which is used in the feedback control for generation of the reactive current reference. This is done using a transformation as described in [11]. The transformation consists of an abc to $\gamma\delta 0$ frame (synchronously rotating frame), followed by a transformation to the positive sequence components (Fig. 3.2). Following the generation of the control signals, reverse transformation back to abc quantities provides the modulating signals which are then passed to the three level modulation scheme which was discussed in the previous section. The transformation possesses an interesting advantage in that one is able to implement alternate control loops to account for unbalances in the voltages, as outlined in detail in [11].

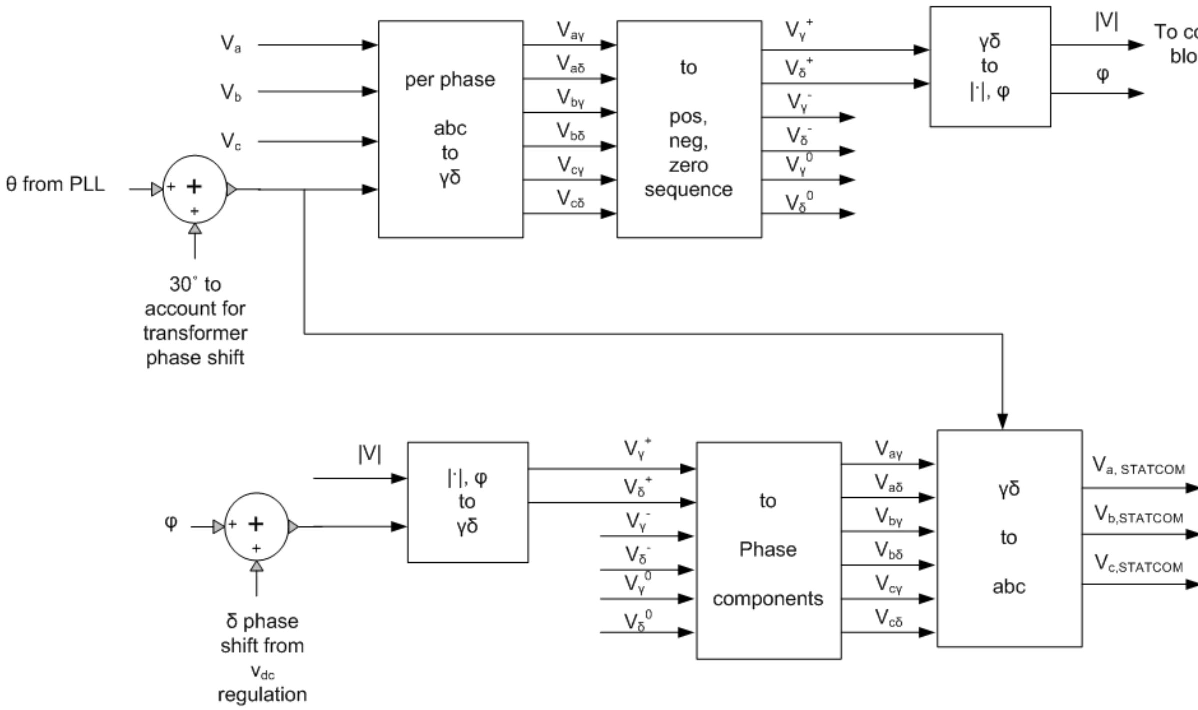


Fig. 3.2 Voltage transformation and reverse transformation for positive sequence component

3.1.3 Current transformation

Processing of the line currents on the low side of the transformation is required in order to extract the reactive component, i_q, which is used as the feedback variable in the current control algorithm. Following bandpass filtering of the three measured currents, they are transformed to the synchronously rotating frame using the angle (PLL output adjusted to take into account transformer phase shift) based upon the transformation matrix:

$$\begin{pmatrix} i_\gamma \\ i_\delta \\ i_0 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta & \cos\left(\theta - 2\pi/3\right) & \cos\left(\theta + 2\pi/3\right) \\ -\sin(\theta) & -\sin\left(\theta - 2\pi/3\right) & -\sin\left(\theta + 2\pi/3\right) \\ 1/2 & 1/2 & 1/2 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{3.1}$$

The above matrix is represented in EMTP-RV by modification of the built-in abc-to-dq0 transformation. The built-in function assumes the voltage at the PCC begins with initial phase of 0˚ and also assumes no deviation in the system frequency, both of which are not usually valid and hence the reason for the specification of the transformation angle. However, the built-in block simplifies realization of (3.1), requiring only a slight modification (Fig. 3.3).

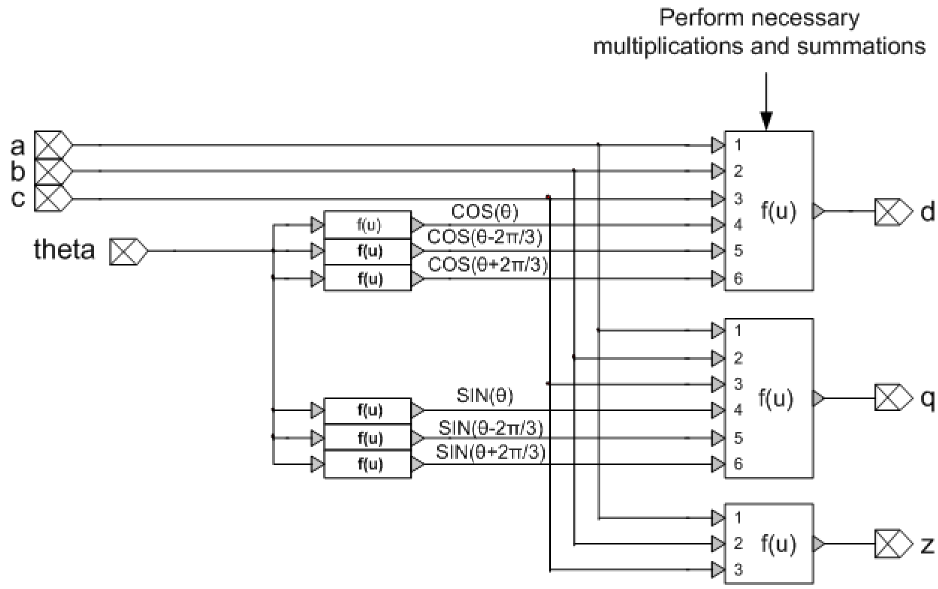


Fig. 3.3 Transformation of abc-to-γδ0 by modification of EMTP-RV abc-to-dq0 block

3.1.4 Filtering

Each of the phase signals is filtered to extract the fundamental frequency component using a band-pass filter which is tuned to fundamental frequency, 60Hz. The filter is a second-order filter with the following transfer function:

$$F(s) = \frac{533s + 5.28x10^{-11}}{s^2 + 533s + 142120} \tag{3.2}$$

The frequency response of the filter is plotted in order to illustrate the gain with frequency (Fig. 3.4). Modification of the response is possible, if desired, following filter design techniques as outlined in various signal processing references, such as [23].

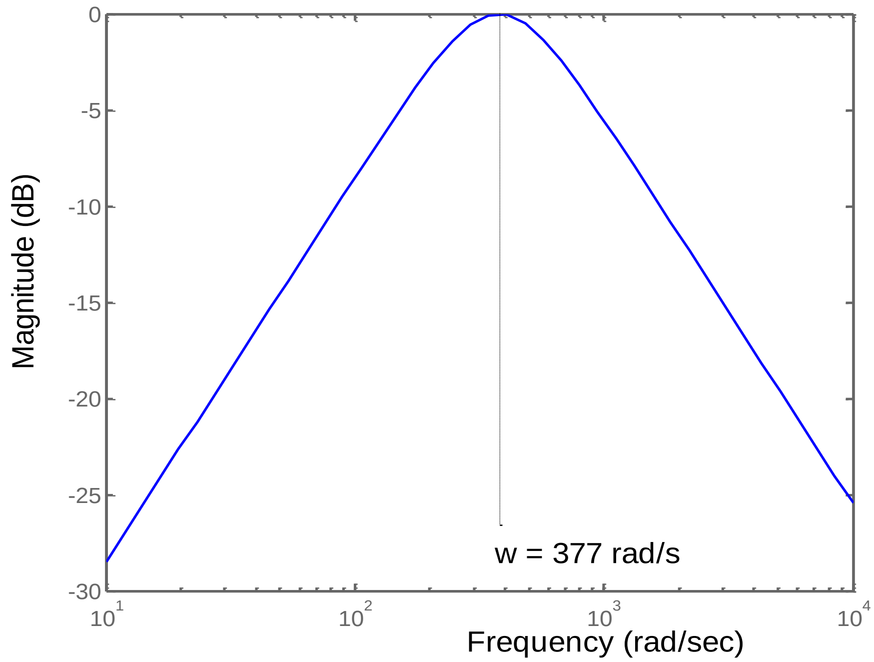


Fig. 3.3 Frequency response of bandpass filter used for filtering of fundamental frequency component

3.2 I_q current control

The inner current control loop consists of a linear feedback controller which sets the magnitude of the converter voltage in order to regulate the reactive power delivered to or absorbed from the system. Comparison of the reference signal with the reactive component of the output of the abc-to-γδ0 current transformation produces the error signal which is passed through a proportional-integral (PI) block to generate the positive sequence STATCOM voltage. The positive sequence voltage is transformed back to abc quantities which are then modulated. By adjusting the magnitude of the STATCOM voltage, the reactive current supplied to the PCC is controlled. Here the principle of reactive current control is revisited, followed by the state-space representation of the system, the method for derivation of the control parameters, and finally the EMTP-RV representation of the control is presented.

3.2.1 Principle of Iq control using voltage magnitude

In order to understand the principle of reactive current control, let us once again consider the two bus system (Fig. 3.4), where V_{st} is the fundamental component of the STATCOM voltage, V_{PCC} is the voltage at the PCC, and X is the leakage inductance of the coupling transformer. Here, the copper losses of the transformer have been neglected as usually the impedance is much smaller than that of the leakage reactance. The real and reactive power flow from the PCC to the STATCOM is given by the following two relationships:

$$P = \frac{V_{PCC} V_{st}}{X} \sin \delta \qquad (3.3)$$

$$Q = \frac{V_{PCC}{}^2 - V_{PCC} V_{st} \cos \delta}{X} \qquad (3.4)$$

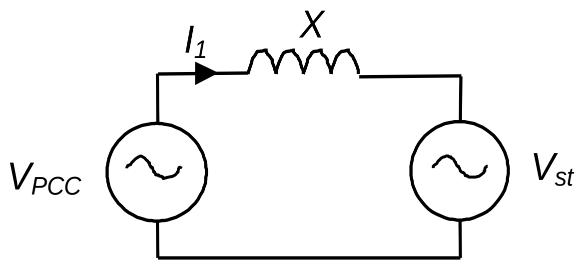


Fig. 3.4 Two-bus system representing the fundamental components of STATCOM system

Then, assuming the angle, δ, between the two voltages is small allows us to re-write (3.3) and (3.4) as follows:

$$P \cong \frac{V_{PCC} V_{st}}{X} \delta \qquad (3.5)$$

$$Q \cong \frac{V_{PCC} (V_{PCC} - V_{st})}{X} \qquad (3.6)$$

One can then see how the reactive current can be controlled by simply adjusting the relative voltage of the fundamental component of the V_{st}. In addition, this has shown that introducing a phase shift between the two voltages allows real power to flow and thus can be used to regulate the dc bus voltage (discussed later). Derivation of the state space model of the real and reactive components of the current can then be used to determine the controller gains.

3.2.2 State space model

The fundamental component of the current, I_1 can be divided into two components, corresponding to that in phase with the V_{PCC} and that in quadrature to the voltage, denoted i_d and i_q, respectively. From Fig. 3.4, the state-space representation of the system can be derived and is given by:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega_o \\ -\omega_o & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_{st,d} \\ v_{st,q} \end{bmatrix} - \frac{1}{L}\begin{bmatrix} |V_{PCC}| \\ 0 \end{bmatrix} \qquad (3.7)$$

Where, R is the lumped losses, L is the leakage inductance, and ω_o is the nominal system frequency. Here the subscripts d and q denote the components in phase with and quadrature to the V_{PCC} space vector, respectively. Consequently, there is no quadrature component contribution from V_{PCC}. For the reactive current control, the input-output transfer function of interest is the response of i_q as a result of the control input $V_{st,d}$. Using MATLAB, the transfer function is determined with the parameters given in Table 3.1 and the Bode plots are obtained (Fig. 3.5).

Table 3.1 Parameters used in state space model and determination of transfer function

R (pu)	L (pu)	ω_0 (rad/s)	V_{PCC} (kV)	S_{base} (MVA)
0.675%	15%	377	13.2	425

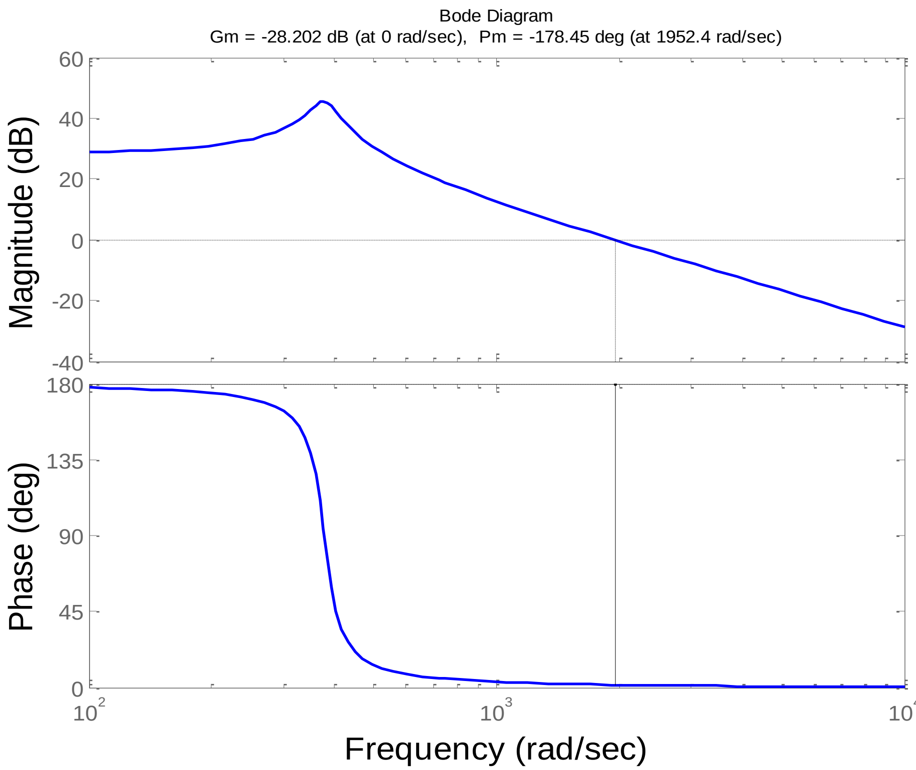


Fig. 3.5 Bode plots of i_q (s) / $V_{st,d}$ (s)

3.2.3 Controller design

The proportional and integral terms of the controller are obtained using standard control theory techniques [22]. The transfer function of the controller is given by:

$$G_{PI}(s) = K_p\left(1 + \frac{K_I}{K_p s}\right) \tag{3.7}$$

First the gain term is derived to satisfy various open-loop criteria, typically a desired phase margin and gain margin are defined and the proportional term is chosen to satisfy these requirements. Then, the integral term is chosen in order to preserve the gain at the crossover frequency, ω_c. This is done by ensuring that:

$$\frac{K_I}{K_P \omega_c} = a << 1 \tag{3.8}$$

Typically *a* in (3.8) is chosen to be 0.1 or less. Following testing of the system, slight retuning of the controllers or redefinition of the gain and phase margin may be required, to account for model inaccuracies due to model uncertainties. The complete current control representation in EMTP-RV is shown below in Fig. 3.6.

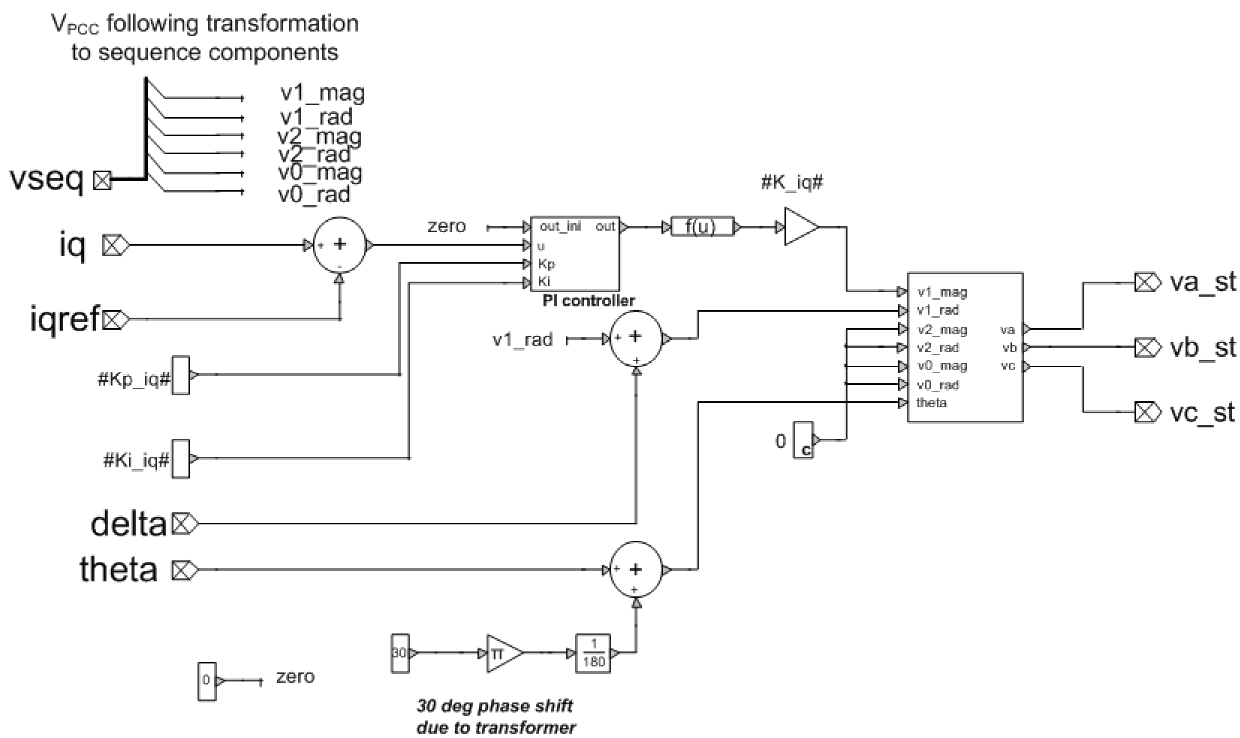


Fig. 3.6 Reactive current control representation in EMTP-RV

3.3 Dc voltage regulation

The principles for the dc voltage regulation were discussed in the previous section. Essentially, the small amount of real power required for regulation of the dc bus voltage is controlled by imposing a small phase shift between the STATCOM voltage and V_{PCC}. This phase shift is determined by the comparison of V_{dc} with its reference followed by a PI block. The phase shift is added to the adjusted PLL angle and is used in the transformation of the STATCOM voltages back to phase quantities. The transfer function is presented below followed by the controller design theory and then representation of the control within EMTP-RV is shown.

3.3.1 Transfer function

The input-output transfer function of the change in the dc voltage as a result of the phase shift can be derived using small signal analysis [10]. It is given by:

$$\frac{\Delta V_{dc}(s)}{\Delta\delta(s)} = \frac{3m^2\omega_o L V_{dco}}{CL^2 s^3 + 2RLCs^2 + (\omega_o^{\,2} L^2 C + R^2 C + 3m^2 L)s + 3m^2 R} \tag{3.9}$$

Where m is the modulation index (0.8), V_{dco} = 2.2 pu, is the nominal dc voltage, R is the lumped losses, ω_o is the nominal system frequency, and the remainder of the parameters are as presented previously. The Bode plots can then be obtained for the open-loop system (Fig. 3.7). Similar control techniques as presented in the previous section can be performed in order to obtain the controller parameters.

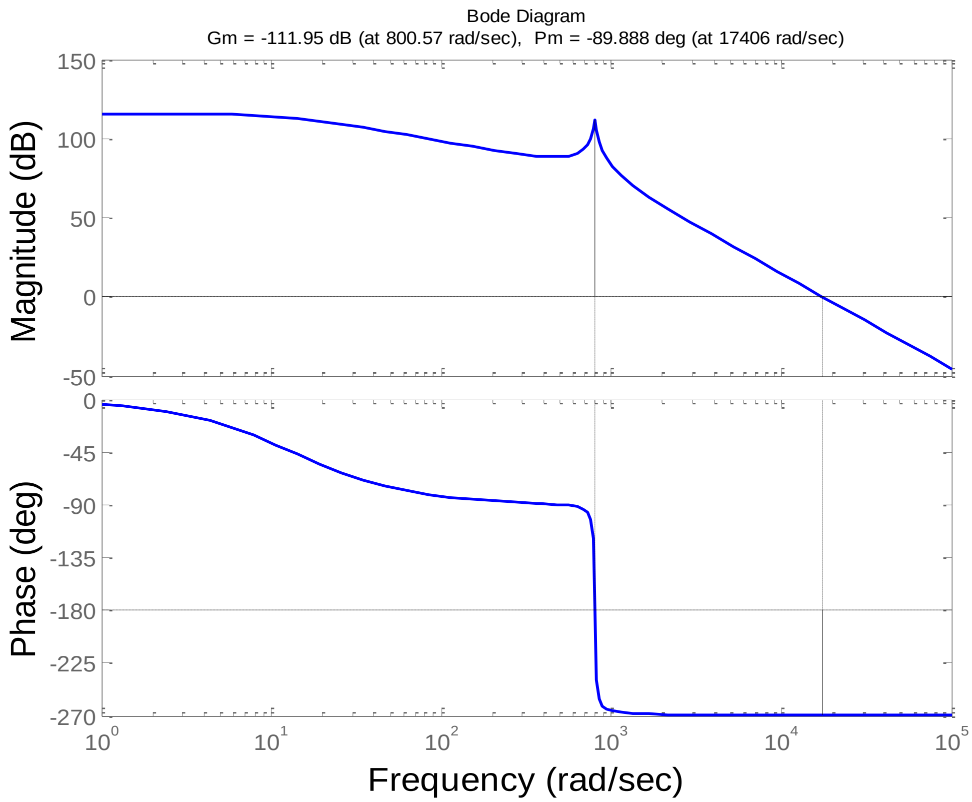


Fig. 3.7 Bode plots of ΔV_{dc} (s) / $\Delta\delta$(s)

3.3.2 Dc voltage regulator

The EMTP-RV representation of the controller is given in Fig. 3.7. Within the control block are contained the controller itself along with the neutral point balancing algorithm which determines the type of modulation scheme for each phase. The dc voltage is calculated using the potential of the positive and negative dc buses and is used as the feedback variable. The phase shift, δ is passed on which is then used in the reverse transformation of the STATCOM voltages as discussed previously. The voltages across the upper and lower capacitors are calculated using the two bus potentials and the neutral potential, and the result is passed on to the neutral point balancing algorithm which sets the modulation type for each phase.

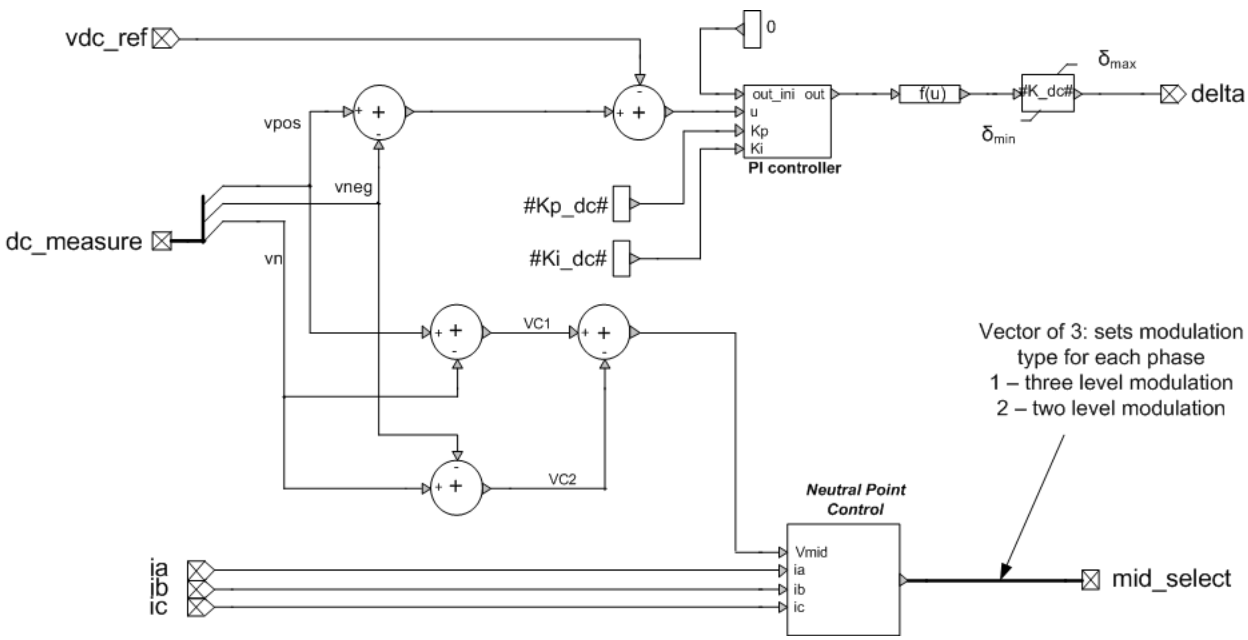


Fig. 3.7 Dc bus control representation in EMTP-RV

3.4 Reactive Compensation control

The generation of the reactive current reference is such that it provides the various improvements of the power system, namely: (i) regulation of the ac voltage at the PCC, (ii) power system oscillation damping, (iii) improved transient stability. As mentioned, the second two result from the proper control of the first, with the exception that power oscillation damping can be enhanced by the addition of a supplemental control signal. For a more detailed analysis of how reactive compensation can contribute to these characteristics, readers are referred to [1]-[5]. The voltage regulation block is presented here and the various components will be discussed. The following section then demonstrates the behavior and the resulting benefits of STATCOM

3.4.1 Droop characteristic

The voltage regulation control utilizes a droop characteristic in order to specify the reference voltage. The benefits of this characteristic were outlined in the introductory section and consist of the following: promote stable operation, prevents the compensator from operating always at its limits, and lends itself to sharing of compensation between different VAr sources. Figure 3.8 shows the droop characteristic where the set point is 1.0 pu and the 3% droop allows the reference voltage to vary between 0.97 pu (maximum leading VArs) to 1.03 (maximum lagging VArs). It is important to note that beyond these limits the reactive current remains at the maximum value unlike SVC’s where the SVC emulates a constant inductance or capacitance. This feature is particularly important for extraordinary circumstances such as symmetrical and asymmetrical faults.

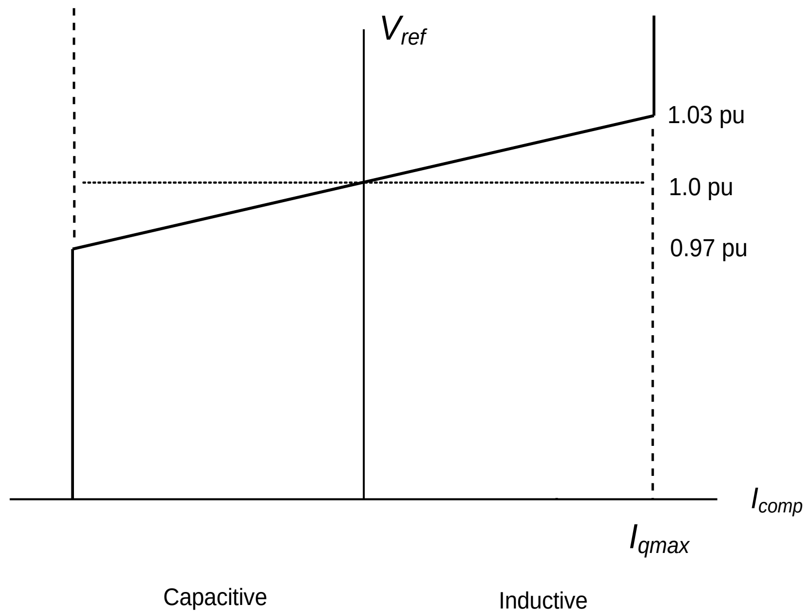


Fig. 3.8 Droop characteristic for a set-point voltage of 1.0 pu and 3% slope

3.4.2 Reactive compensation control block

The reactive compensation control block is given in detail here (Fig. 3.9). The main control consists of a PI compensator which generates the reference reactive current based on the error between the ac system reference and the magnitude of the positive sequence component. The droop characteristic produces the reference voltage based upon the amount of reactive compensation provided and varies from its nominal value (typically 1 pu) to the upper and lower limit which are set by the slope of the line (typically 1-3%). The $\Delta\omega$ signal can be added to the voltage reference in order to realize an increase in the damping of the power system oscillations. Here #iq# is the maximum reactive current, which is defined based upon the STATCOM rating and is calculated within the model mask.

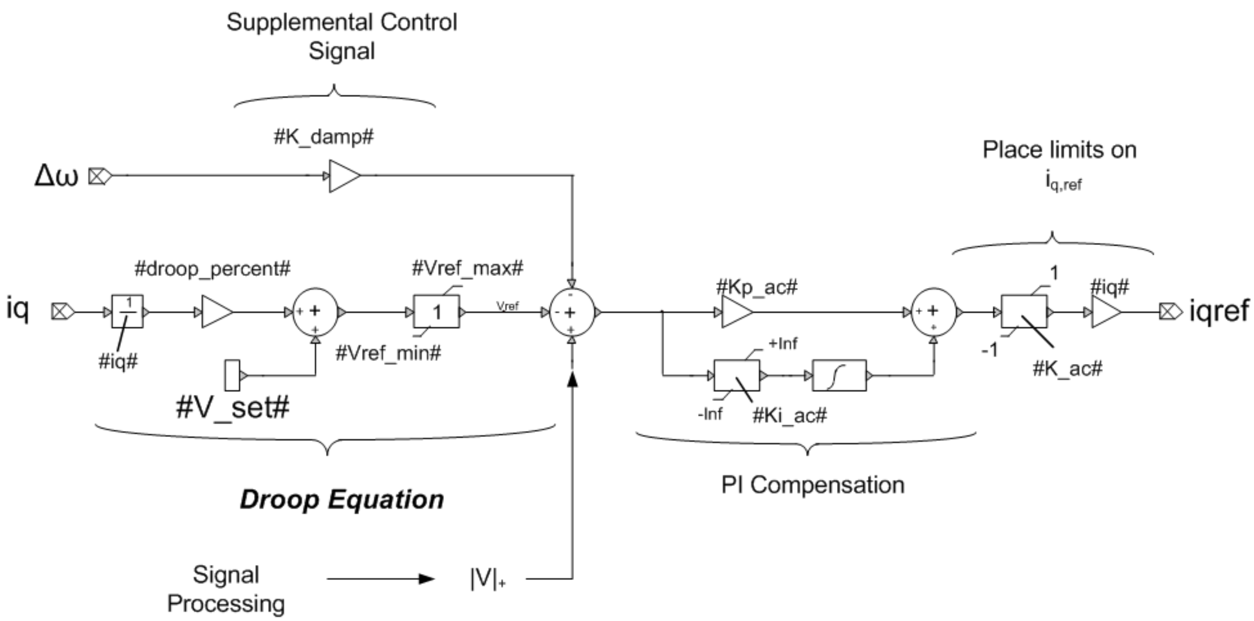


Fig. 3.9 EMTP-RV representation of reactive compensation control block with PI regulator, droop characteristic and supplemental control signal, Δω.

4 STATCOM Characteristics

The operating characteristics of the STATCOM will now be presented. Here, the i_q and v_{dc} control loops are first verified using step changes in the reference signals. Then the ability of the STATCOM to regulate the midpoint voltage of a transmission line and damp electromechanical oscillations is demonstrated. Finally, the response of the system with and without the STATCOM is observed following a 12 cycle, three phase fault.

4.1 Control verification

In order to verify that the control algorithms function properly, the various signals are subjected to step changes in the reference value. The reactive current control, dc voltage regulation, neutral point balancing algorithm are presented below. In addition, the line current and modulating voltage are presented to show the relationship between the reactive current and the modulation index.

4.1.1 Control of reactive current

Here the reactive current reference is subjected to three step changes in order to verify the control: from 0 to 1 pu lagging, from 1 pu lagging to 1 pu leading and from 1 pu leading to 0 pu (Fig. 4.1). As shown below, the reactive current follows the reference signal well.

The line current is plotted for the same operating conditions along with the modulating voltage (Fig. 4.2). As can be noted in the figure, the modulation index varies between approximately 0.6 and 0.9. This is desirable because the converter operates within the linear range and the modulation index does not drop below 0.5 and therefore, the harmonic content is acceptable over the entire range of operation.

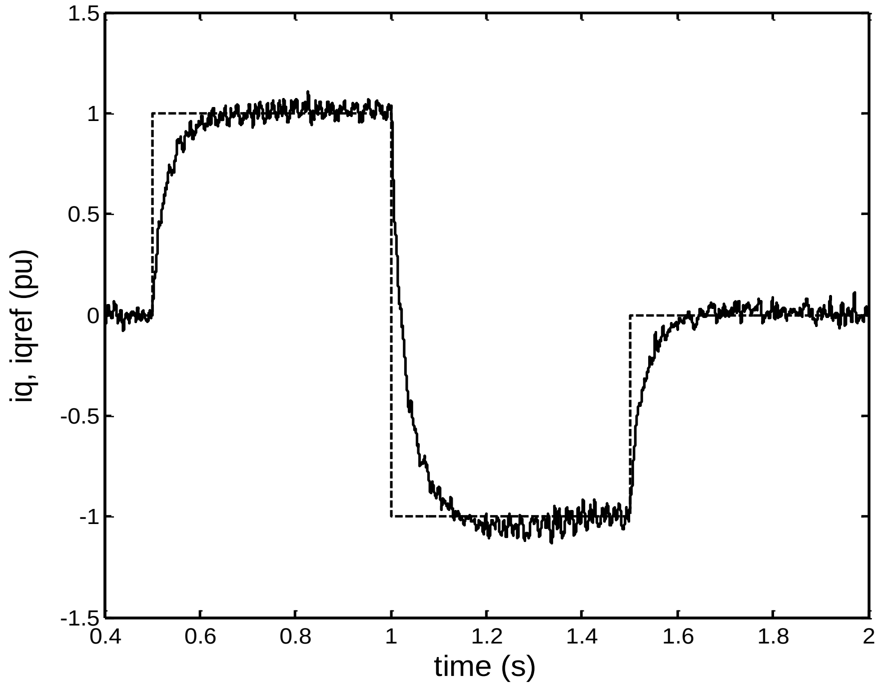


Fig. 4.1 Response of the reactive current i_q to step changes in the reference current

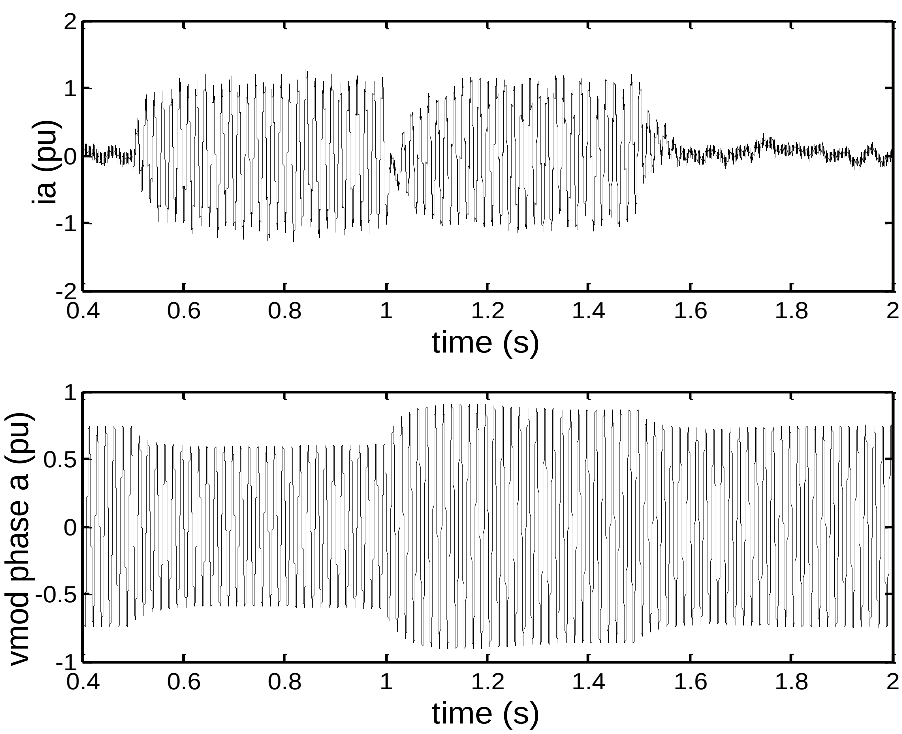


Fig. 4.2 Line current and modulating voltage for the step changes in reactive current ($0.6 < m_a < 0.9$)

4.1.2 Dc bus regulation

The dc bus regulation loop is examined next in order to ensure that the dc voltage is kept within 1% of the reference value and also confirm that the control responds quickly to step changes. This is necessary since the STATCOM must be able to remain operational following fast changes in the dc voltage, for instance following a nearby three phase fault where the STATCOM initially feeds the fault current causing the dc voltage to drop quickly. In addition the neutral point balancing algorithm is tested by setting an initial unbalance of 5% (Fig. 4.3).

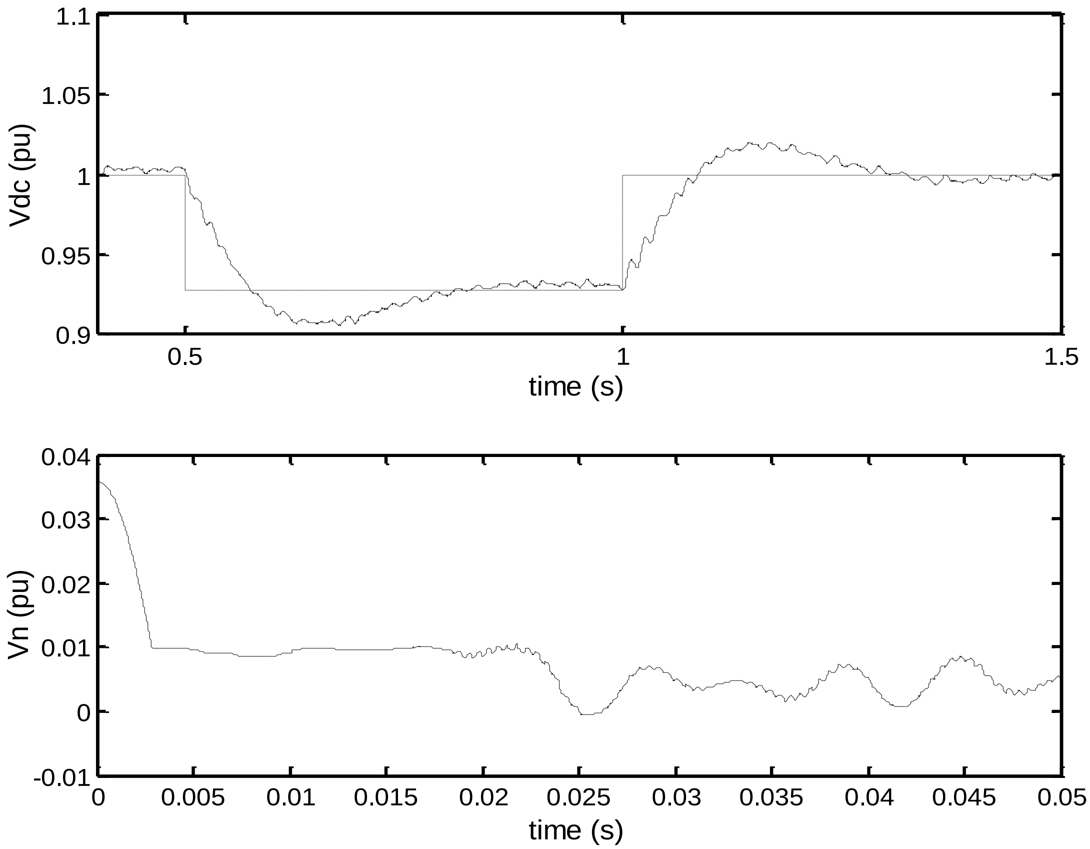


Fig. 4.3 Step change in dc bus voltage, neutral point potential kept within bounds of 1%, V_n set to 5% initially

The STATCOM is subjected to a 7.5% change in the dc voltage reference. The control responds nicely and adjusts the voltage accordingly and returns the voltage to its nominal value following removal of the offset. Also, it can be noted that the neutral point balancing algorithm successfully returns the neutral point potential of 5% to within ±1% of the dc voltage and it remains within the limits thereafter.

4.2 Power System studies

In order to test the impact of the STATCOM on a system, it is connected at the midpoint of a transmission corridor, which connects four synchronous generators to an infinite bus (Fig. 4.4).

The lines include 40% series compensation and approximately 1500 MW is transferred to the infinite bus. The system is used for voltage regulation, power oscillation damping, and transient stability studies.

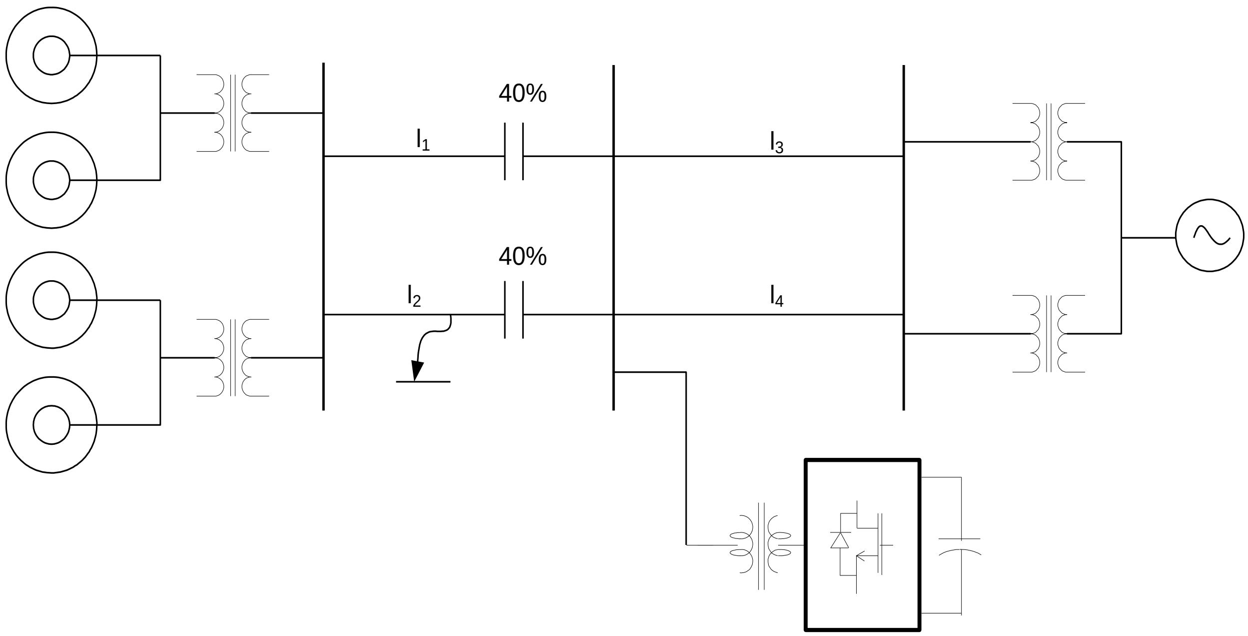


Fig. 4.4 Transmission system for STATCOM system studies

The voltage regulation ability of the STATCOM is demonstrated in the following studies and thus is not presented separately here.

4.2.1 Power system oscillation damping

One of the objectives of this study is to look at the use of a STATCOM for damping of power oscillations resulting from oscillations in the generator speed. Through regulation of the terminal voltage, this goal may be realized without modification to the control design. However, if further damping is required it is possible to add a $\Delta\omega$ component to the control to supply additional damping. Oscillations are artificially produced through the addition of a 1.5 Hz signal to the mechanical input power, sufficient to produce a 10% deviation in the midpoint voltage. The magnitude of the midpoint voltage is presented for the following four cases: no STATCOM, supplemental signal only, voltage regulation only, and both supplemental signal and voltage regulation control (Fig. 4.5). As can be noted, the best results are obtained when both the $\Delta\omega$ and voltage regulation are used. This shows that the STATCOM can improve damping of electromechanical oscillations.

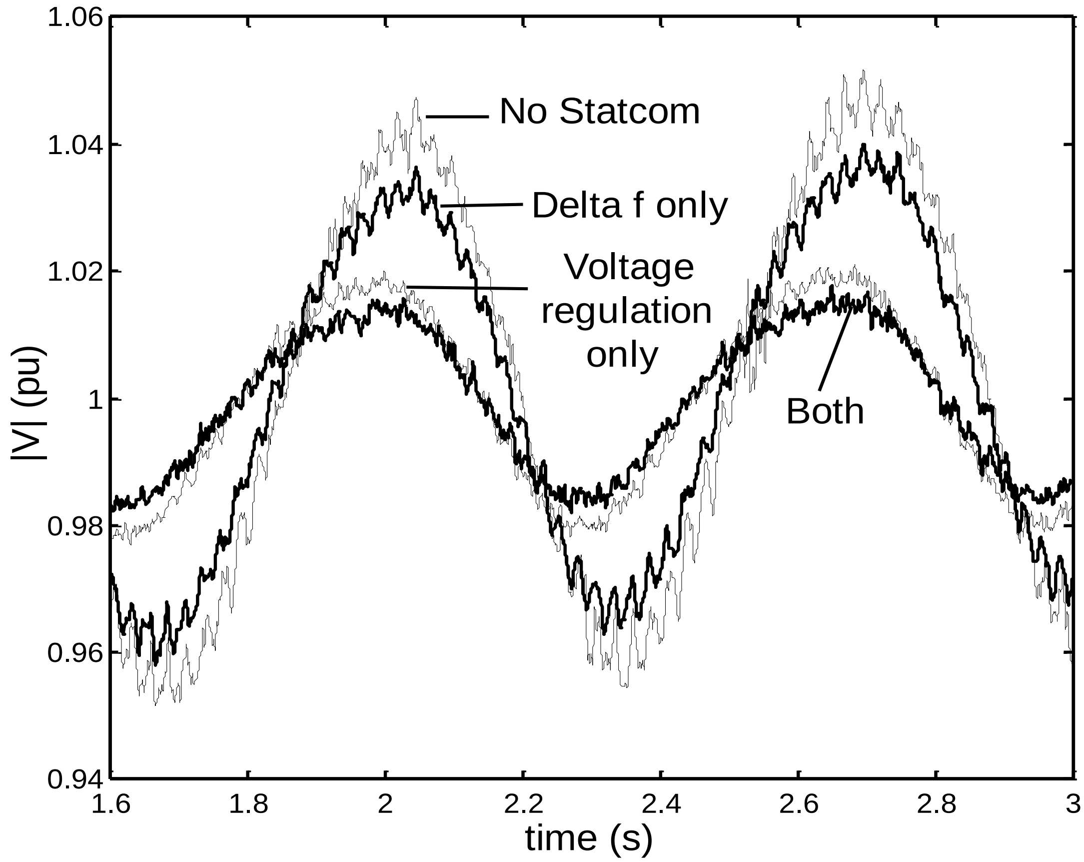


Fig. 4.5 Demonstration of power oscillation damping

4.2.2 Transient stability improvements

The system in Fig. 4.4 is subjected to a 12 cycle, three phase, bolted fault at the midpoint of line l_2, in order to investigate the ability of the STATCOM to improve transient stability. The response is given in Figures 4.6 and 4.7 for the system without and with the STATCOM, respectively. Waveforms of voltage magnitude and load angle show that there is a significant improvement in the transient response following the fault. Without the STATCOM, the system loses synchronism with the infinite bus and the voltage collapses. The STATCOM helps the voltage recover very quickly following the fault and the load angle settles to its steady-state value following some small oscillations. Figure 4.8 presents the voltage response in the two cases together, where the impact of the STATCOM can be clearly noted.

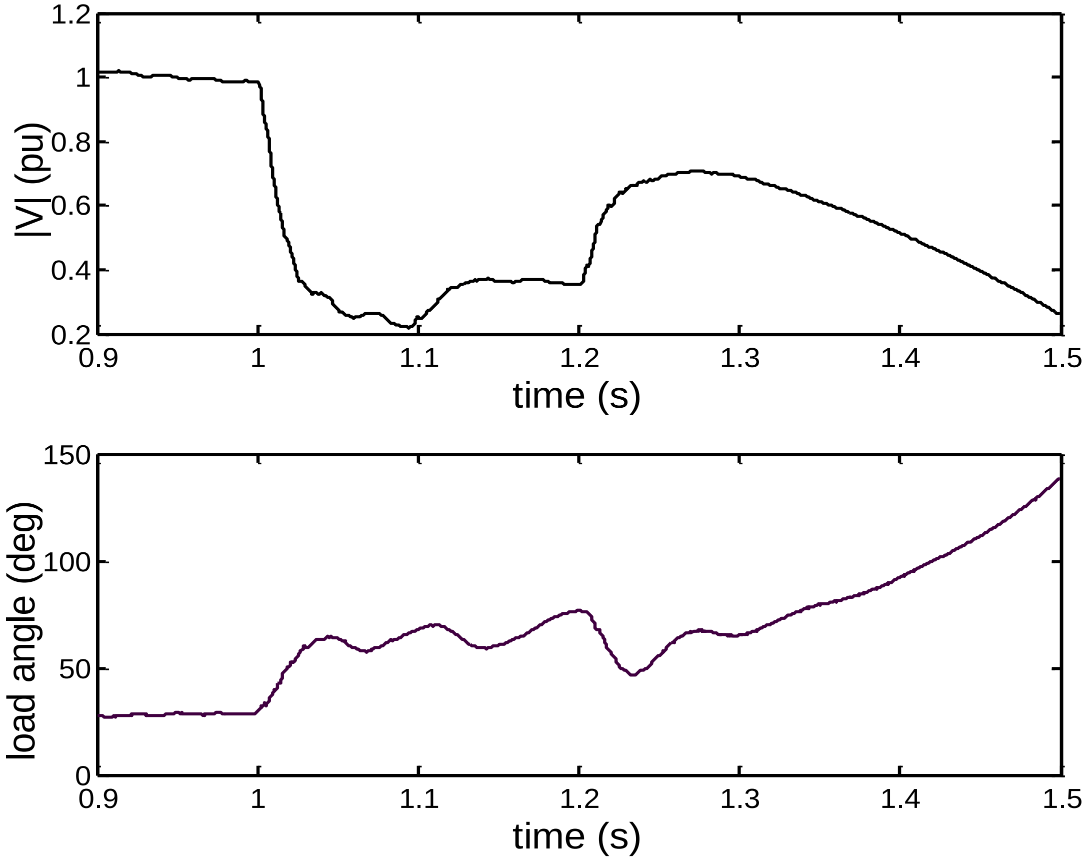


Fig. 4.6 Voltage and load angle response resulting from a 12 cycle three phase fault without STATCOM

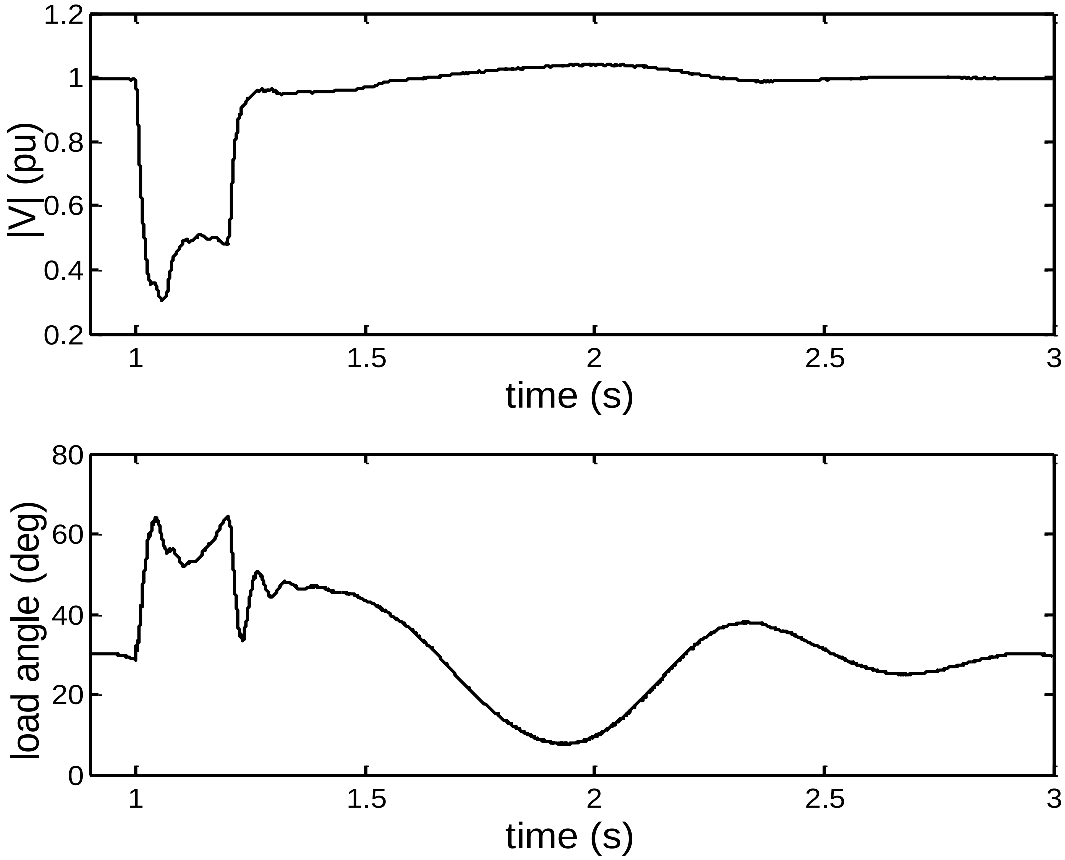


Fig. 4.7 Voltage and load angle response resulting from a 12 cycle three phase fault with STATCOM rated at 0.5 S_{base}

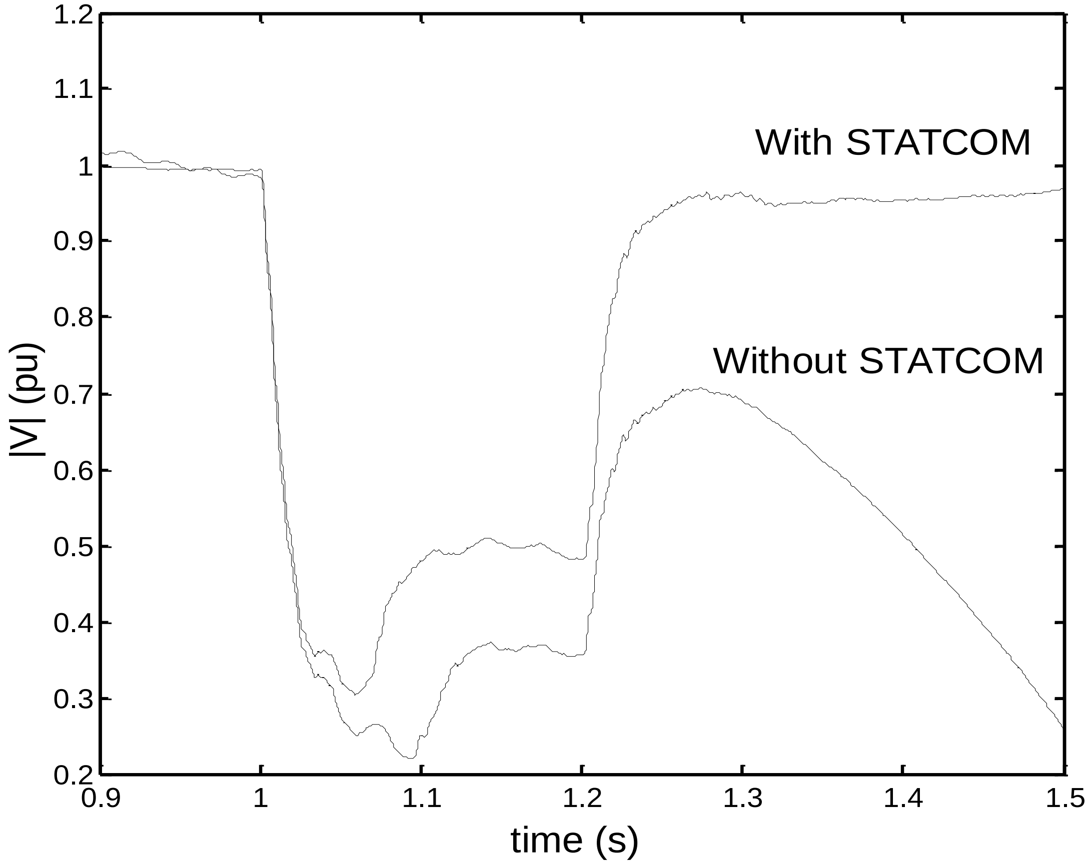


Fig. 4.8 Magnitude of voltage with and without STATCOM

5 Conclusions

The design and theory of a three level inverter based STATCOM has been presented. The realization in EMTP-RV shows that the STATCOM is capable of supplying the reference reactive current, regulating the dc voltage and balancing the neutral point potential. System studies have shown that the STATCOM regulates the ac voltage and enhances electromechanical oscillation damping. The STATCOM responds very well under severe fault conditions and is able to markedly improve the transient stability of the associated transmission system. The complete masked model, submitted along with this final report, allows the user to adjust almost all parameters of the design, thereby making it a useful model for studies with various system configurations and ratings.

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Appendix I - Mask Parameters

STATCOM ratings

statcomMVA = 400	MVA rating
V_pcc=500	High Voltage Level in kV
V_statcom=13.2	Low Voltage Level
V_set=1.00	Voltage setting (HV) in pu
Cdc=100E-03	Dc capacitance
fs=1980	Switching frequency
droop=1	Percentage for the droop characteristic (1-3%)
Freq=60	Nominal system frequency

Within the *rules* section various parameters which are passed into the STATCOM subcircuit are calculated using the STATCOM ratings. As well, the control parameters are defined within. Normally they should be left unchanged but the user may want to make changes in certain cases.

iq=sqrt(2)*statcomMVA*1E06/(V_statcom*1E03*sqrt(3))	rated reactive current
Vdc=V_statcom*2.12*1000	dc voltage reference
Vdc_div2=Vdc/2	
two_C=2*Cdc	
V_statcom_mag=V_statcom*1E03*sqrt(2)/sqrt(3)	magnitude of secondary voltage in volts
droop_percent=droop/100	
Vref_max=1+droop_percent	
Vref_min=1-droop_percent	
w=2*PI*Freq	angular frequency

It is noticed that the changes to the transformer data are automatically transmitted to the transformer appearing at the first subcircuit level of the STATCOM. The transformer has an Exported Mask. The connection between the STATCOM mask and the transformer mask is achieved in the Rules section through the function “set_converter_transfo”. The transformer is located using its specific name “Converter_Transfo”. The user can modify the rules by adding other options, such as changing transformer scope requests or transformer saturation data. Transformer data can be also changed manually by first eliminating the call to “set_converter_transfo” (last line in the Rules section), then clicking OK on the transformer device mask and subsequently canceling the Exported Mask status.

The user must remember that subcircuit content changes are automatically transmitted to all other subcircuits of the same type unless the modified subcircuit is first made unique using the menu Options>Part Type>Make Unique Type.
It is noticed that the last line in the Initial values section of this device is the function call:
make_me_unique();
This statement makes the top level subcircuit of the STATCOM unique as if the Make Unique Type command has been applied manually. After clicking OK on the STATCOM mask the user can modify the top level subcircuit contents, without affecting data for other SVC devices in the given design.

The make_me_unique function has two optional arguments:

- do_mychildren: set to true if the Make Unique Type command must be applied all subcircuit levels of this subcircuit. Default is false.
- my_action_message: set to false to turn off the echo message in the Console window. Default is true.

Control Parameters

For all PI control blocks the parameters are defined referring to the compensator structure:

$$G_{PI}(s) = K_p\left(1 + \frac{K_I}{K_P s}\right)$$

where *K_control_name* = K_p, *Kp_control_name* = 1, and *Ki_control_name* = K_I/K_P

Dc voltage regulator
Ki_dc =15;
Kp_dc =1;
K_dc =0.25;

I_q control parameters
Ki_iq=180;
Kp_iq=1;
K_iq=0.03162;

Ac voltage regulator
Ki_ac=10;
Kp_ac=1;
K_ac=3;

Δω damping constant
K_damp=0.01