PSCAD Modeling of One-Cycle Control VAR

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Abstract

Voltage support has been a common problem utilities have faced for many years and although there exists many solutions, the advent of renewable energy devices and electric vehicles make the problem of voltage support an even greater challenge today. The increasing use of electronic devices by consumers also increases the magnitude of dealing with voltage support. A promising new solution to voltage support is seen in One Cycle Control, a new control method that uses a nonlinear feedback technique on power electronics to produce high quality sine waves with fast dynamic response. This control paradigm is seen in its application to a voltage support device known as STATCOM. This project aims to model the One Cycle Control method applied to a STATCOM device, known as OCC-VAR in PSCAD. However, stability issues in One Cycle Control can prevent the device from producing desirable results.

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1 Introduction

Low voltage is a common problem faced amongst utilities today. Low voltage can be characterized as either a voltage sag or undervoltage. According to IEEE Standard 1159-2009, a voltage sag is defined as a decrease to between 0.1 and 0.9 p.u. in root mean square (rms) voltage at the power frequency for durations of 0.5 cycle to 1 minute [1]. Although they have always been present in power systems, it is only recently when customers have become aware of their inconvenience [2]. Undervoltage however, is characterized as a decrease in rms voltage less than 0.9 pu for a duration longer than 1 minute [1].

The problem with low voltage can be seen in the power equation: $P = VI$. For a constant power, a lower voltage leads to a higher current in order to satisfy the above equation. This high current can lead to a variety of problems such as performance and reliability issues, damaged equipment, or part or all of the power system going offline. Since high current is usually an indicator of a fault, relays and circuit breaker devices will set off, leading to parts of the system going offline in an effort to shed load. Continual load shedding can lead to a voltage collapse however, and cause system blackouts. Continuous voltage sags and undervoltage conditions can lead to blackouts as well. Voltage sags are caused by switching operations associated with a temporary disconnection of supply, the flow of inrush currents associated with the starting of motor loads, or the flow of fault currents [3]. Continuous operating voltages in a power system are kept typically within ±5% of the nominal voltage levels for power transmission and sometimes a slightly wider range for distribution. Standards generally provide for equipment to be able to operate correctly within the range of ±10%. It is vital that voltage do not fall too far below these lower limits for any significant period of time because, in general, reactive current demand increases as the voltage falls. The increase in reactive demand causes the voltage to fall further

and the system tends towards complete collapse [4]. Blackouts of course, must be avoided since much of modern life depends on electricity.

Low voltage is also a problem with the continuing interconnections of bulk power systems, brought about by economic and environmental pressures, has led to an increasingly complex system that must operate ever closer to the limits of stability [5]. Although overloading problems can be reduced by building new transmission lines, resistance from environmental advocates as well as financial concerns and land rights prevent utilities from doing so. Nuclear and fossil fuel generation could be used to help offset overloading, however due to economic and political reasons, no nuclear power reactors have been ordered since 1978, and three reactors have been decommissioned [6].

To accommodate the growing energy demands, more generation needs to be provided. However, due to environmental resistance groups and the movement for more environmentally friendly energy, energy suppliers have been looking at renewable energy sources in the recent years such as solar, wind, hydro, co-generation, etc. The renewable energy sources, which have been expected to be a promising alternative energy source, can bring new challenges when it is connected to the power grid. However, the generated power from renewable energy source is always fluctuating due to the environmental condition. In the same way, wind power injection into an electric grid affects the power quality due to the fluctuation nature of the wind and the comparatively new types of its generators. The integration of wind energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability, and power quality problems [7].

As seen, the huge involvement of renewable energy sources in the past few years has made the power system even more complex than it already is. The unreliable nature of these alternative sources of generation can contribute to the low voltage problems faced by utilities. It can also cause transient or power quality issues that may significantly affect the system as well. The increasing use of electric

vehicles and consumer electronics will also add to the electricity demand that is often a cause of low voltage. Utilities have many challenges to deal with in the coming years.

2 Background

2.1 Existing Methods

Various solutions have been used to deal with the problem of low voltage. One of the most common, and perhaps the cheapest, is the shunt capacitor. Since power systems tend to be naturally inductive, they consume reactive power which leads to voltage drops. Supplying reactive power with a shunt capacitor will lead to a voltage rise as this decreases the overall reactive power consumed by the system, as shown in Figure 2-1.

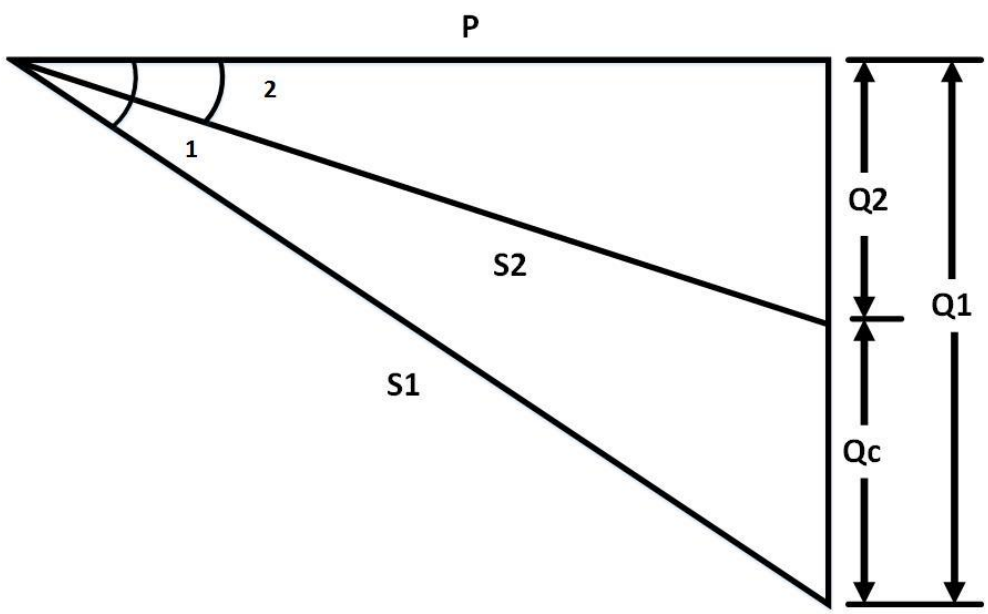

Figure 2-1: Effect of Adding Shunt Capacitor

Q_{r1} represents the reactive power consumed by the system before the capacitor is added. Q_C is the reactive power amount supplied by the capacitor and Q_{r2} represents the overall reactive power consumed by the system once the shunt capacitor is added.

Shunt capacitors are available in two types: fixed and switched. Fixed capacitors, as their name suggests, are at a set value and thus can only provide a certain amount of reactive power at any given time. For a more flexible solution, switched capacitors are used, which can provide a variable amount of VAR since it can switch on more or less amounts of reactive power. However, since it is switching capacitor banks of set values, it is not precise as some other voltage support methods. A bigger problem however, is the transients caused by switching on and off the capacitors. Although this is considered normal and generally not a problem for utilities, for sensitive customers with low voltages this can cause the transients to be magnified and cause tripping of adjustable speed drives [8].

Another method used for voltage control is the static VAR compensator (SVC). The SVC is part of power electronics devices known as Flexible AC Transmission system (FACTS). A SVC consists of capacitor or reactor banks with at least one being switched by thyristors. Typically they are thyristor-controlled reactor (TCR) based. To achieve continuous leading or lagging reactive power regulation, they are used in conjunction with fixed capacitors or thyristor-switched capacitors (TSC). The phase angle is modulated for the thyristors to provide smoother control and flexibility of the switching devices. An example of a SVC is shown in Figure 2-2.

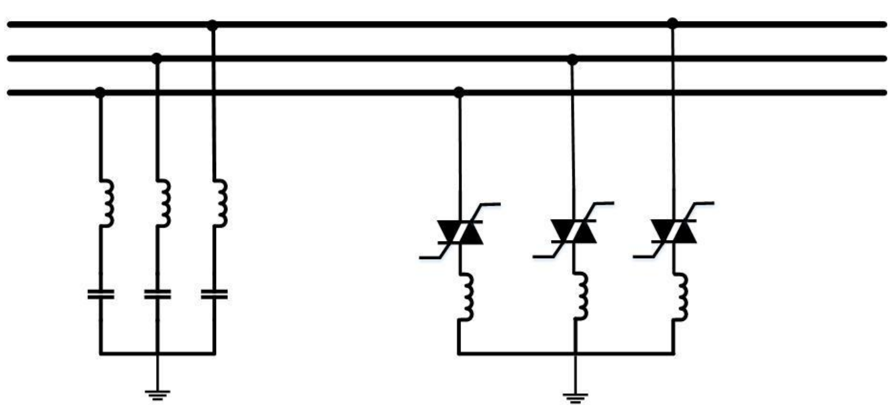

Figure 2-2: Static VAR Compensator with TCR and Fixed Capacitors

Due to the chopped reactive load of using thyristors, this creates harmonics in the system, which requires filters, adding to the reactive power themselves since they are capacitive. In addition, the response time is limited by the inherent time delay in thyristor gating control [9].

Another device used for voltage support is the synchronous condenser. It is essentially a synchronous machine without any load, which is controlled by a voltage regulator to be either underexcited or overexcited, which in turn affects the power factor. A one line diagram of a synchronous condenser is shown in Figure 2-3.

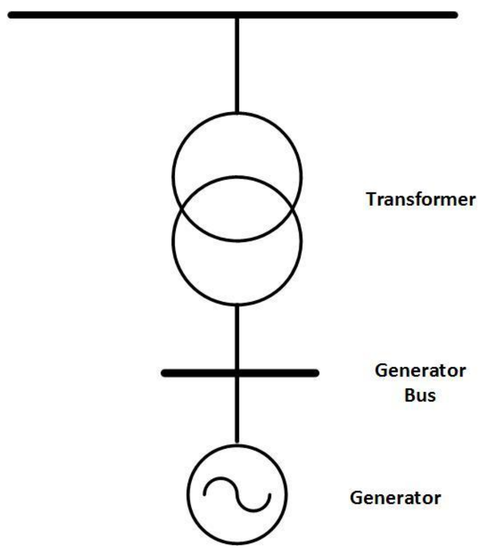

Figure 2-3: Synchronous Condenser

Because of its more mechanical nature and it being a more traditional technology, it is more understood and does not produce harmonics like the SVC. Since it is more understood, it is seen to be more robust and has high overload capability and can provide good reactive power support under low voltage conditions. However, they can include a higher level of losses, mechanical wear (meaning more maintenance), and slower response times compared to that of power electronic solutions such as the SVC [10].

The Static Synchronous Compensator (STATCOM), also known as Static Synchronous Condenser (STATCON), is another method for voltage support. Like the SVC, it is a member of the FACTS family of

power electronics devices. It is based on a voltage-sourced converter (VSC) to mimic a synchronous condenser [10]. It consists of a voltage source behind a reactance, as shown in Figure 2-4.

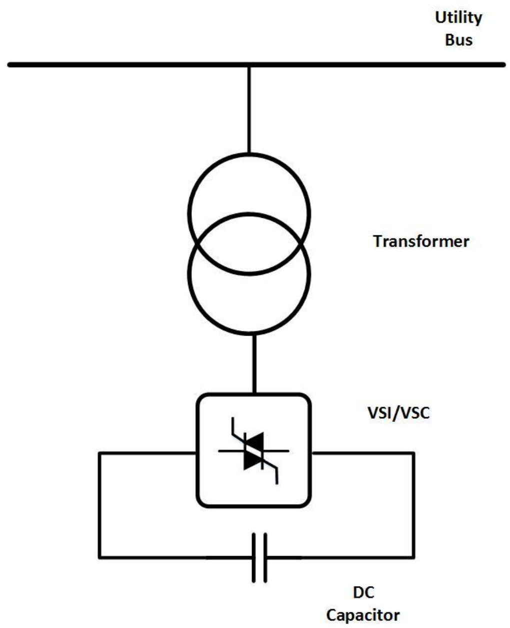

Figure 2-4: STATCOM One Line

Compared to SVC, STATCOM offers many advantages. It offers better compensating capability, faster response, less harmonics and smaller physical size [11]. It also has the ability to maintain full capacitive output current at low system voltage, making it more effective than SVC in improving the transient stability. Its dynamic performance also far exceeds other VAR compensators as it has an overall system response time of 10ms or less [12]. A problem with STATCOM however, is that it is blocked during extreme voltage sags, when it may be needed most [10].

The conventional control method for VSCs is known as Sinusoidal Pulse Width Modulation (SPWM). SPWM is used since it produces harmonics at much frequencies than the fundamental frequency, making it easier to filter [13]. SPWM uses a reference sine wave with the desired frequency and compares it to a carrier triangle wave. When the triangle wave is greater than the sine wave, the switch is turned off. When the sine wave is greater than the triangle wave, the switch is turned on. The

control method can be used for bipolar switching or unipolar switching, with the former shown below in Figure 2-5.

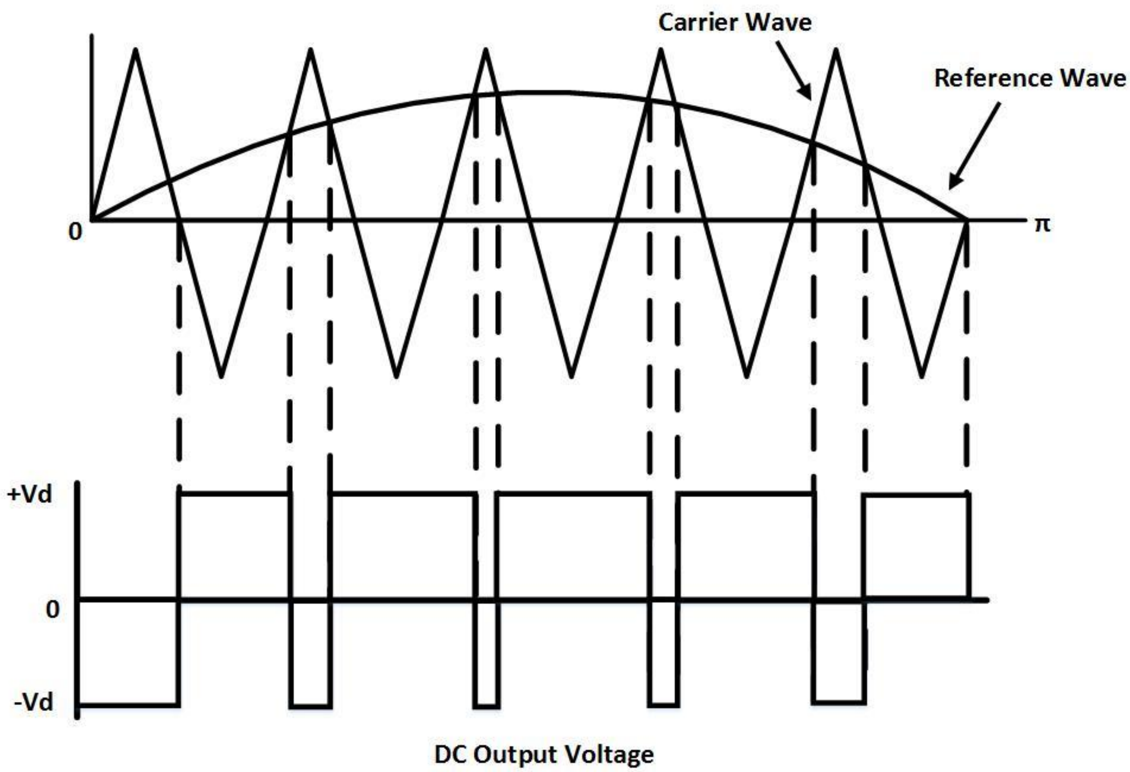

Figure 2-5: Sinusoidal Pulse Width Modulation with Bipolar Switching

In this case, the sine wave controls the duty ratio of the upper switch in a branch of a VSC, which has a complementary duty ratio to the bottom switch. Thus, when the upper switch is off, the bottom switch is on, as seen in Figure 2-5.

Two modulation variables are used to control the output voltage. The first is the frequency modulation ratio $m_f = \frac{f_s}{f_1}$, where f_s is the frequency of the carrier wave and f_1 is the frequency of the sine wave and also the fundamental frequency of the desired output voltage. This ratio determines the harmonic spectrum for a certain degree of control and for a given modulation pattern [14]. The other modulation variable is $m_a = \frac{V_{control}}{V_{triangle}}$, where $V_{control}$ is the peak amplitude of the sine wave and $V_{triangle}$ is

the peak amplitude of the carrier wave. Depending on the value of m_a, will determine what region the inverter is operating in. For $0 \le m_a \le 1$, linear modulation occurs which is desired, since the output voltage varies linearly with m_a and the DC voltage [13]. This is seen in the equation for the fundamental frequency of the output voltage for a full bridge configuration: $V_1(t) = \frac{V_{control}}{V_{triangle}} V_{dc} sin\omega_1 t = m_a V_{dc} sin\omega_1 t$. When m_a passes this value, the voltage amplitude is no longer a linear function of m_a. When m_a is increased even further, it reaches the saturation region and the output voltage becomes a square wave and is independent of the value of m_a [13].

This project will analyze the abilities of a new voltage support device that uses power electronics known as One Cycle Control (OCC). Because OCC itself refers to a control method rather than a specific device, OCC can be applied to different power electronics devices and have them perform better than if they were controlled by methods such as SPWM. The device that will be modeled in this project is known as OCC-VAR, which is OCC applied to a STATCOM device.

3 Design Requirements

The goal of this project is to create a simple simulation model in PSCAD that shows the functionality of OCC-VAR. The OCC simulation model will be tested on a three phase system that is representative of a utility along with a load. The capabilities of the device that the model is trying to emulate are:

- maintains the voltage at nominal levels
- produces leading reactive power during a voltage sag
- produces lagging reactive power during a voltage swell
- performs the above abilities with one-cycle response

Furthermore, this model will be implemented using Power Systems Computer Aided Design (PSCAD). The graphical user interface of the system allows for ease of use compared to programming

tools such as MATLAB or OpenDSS. Its integration of power electronic, digital, and power systems devices also makes it a desired tool over other graphical tools such as Simulink.

This model can be used as an analytical and evaluation tool for understanding the characteristics of OCC-VAR. Though it is a simple model, it should be easily modifiable to integrate into simulation and testing with models of actual utility systems.

4 Design

4.1 Introduction to One-Cycle Control

Before OCC and its application to voltage support can be explained, more detail on OCC itself must be explained first. OCC is the term used to describe a nonlinear control technique invented by Dr. Slobodan Cuk and Dr. Keyue Smedley [15]. Because switches are nonlinear systems, the idea is that a pulsed nonlinear control should provide faster dynamic response and reject input perturbations better than linear control since the nonlinear control matches the system [16].

Although the OCC technique can be implemented under constant-frequency, constant on-time, constant-off time, or variable (adjustable time on and time off) switches, constant-frequency is most commonly used [17]. The basic idea of OCC can be seen in Figure 4-1 below for a constant frequency switch.

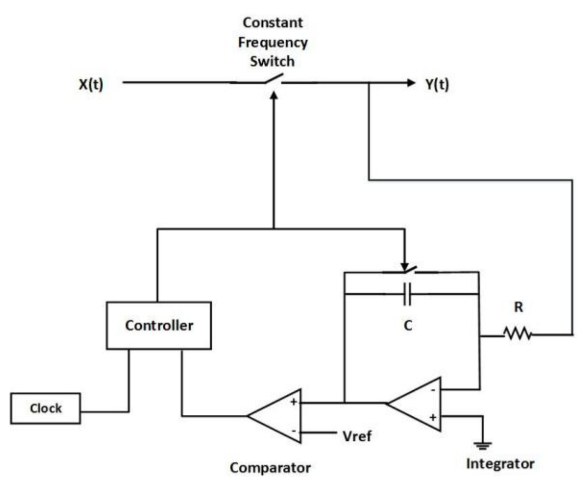

Figure 4-1: One-Cycle Controlled Constant Frequency Switch

An input signal x(t) is passed through a switch and has an output y(t). The average value of y(t) is obtained by integrating y(t). This integrated value is then compared with a reference. As soon as the integrated value reaches the reference, the comparator sends a signal to the controller, which turns the

switch off and resets the integrator to zero. The theory and importance behind this will be explained in the next section.

4.2 One-Cycle Control Theory

From [18]:

A switch is defined as operating under a function k(t):

$$k(t) = \begin{cases} 1, & 0 < t < T_{on} \\ 0, & T_{on} < t < T_s \end{cases} \quad \text{Eq. 3-1}$$

If the switch stays on for duration T_{on} and stays off for duration T_{off}, then its duty cycle is defined by $d = \frac{T_{on}}{T_s}$, which is modulated by the control signal $v_{ref}(t)$. The switch chops up the input signal x(t) to produce an output y(t) with the same frequency and pulse width as k(t), with x(t) as the envelope of y(t) as seen in Figure 4-2.

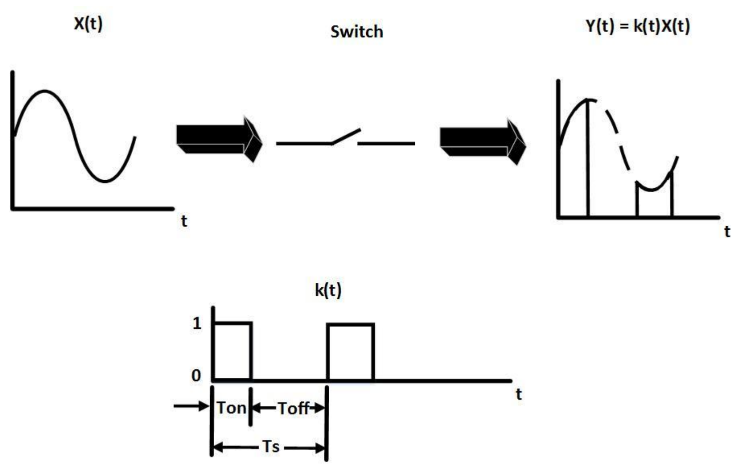

Figure 4-2: Switch Input, Output and Switch Signal

Assuming that the switch frequency f_s is much higher than the frequency bandwidth of x(t) or $v_{ref}(t)$, the effective output value y(t) is equal to the average value over a switch cycle:

$$y(t) = \frac{1}{T_s}\int_0^{T_s} x(t)dt \approx x(t)\frac{1}{T_s}\int_0^{T_{on}} dt = x(t)d(t) = x(t)v_{ref}(t) \quad \text{Eq. 3-2}$$

Thus, the output signal y(t) is a product of the input signal x(t) and the control $v_{ref}(t)$ making the switch nonlinear. If the control signal is constant, for example $v_{ref}(t) = D$, then the output becomes Dx(t), as is the case in digital signal processing. For power processing applications, x(t) usually represents the power, while $v_{ref}(t)$ is the signal to be amplified. Ideally, the input power x(t) is constant, but in reality there are perturbations causing disturbances to the output y(t) also.

If the switch duty ratio is modulated such that in each cycle the integration of the chopped waveform at the switch output is exactly equal to the integration of the control signal, i.e.:

$$\int_0^{T_{on}} x(t)dt = \int_0^{T_s} v_{ref}(t)dt \qquad \text{Eq. 3-3}$$

Then the output signal becomes instantaneously controlled within one cycle:

$$y(t) = \frac{1}{T_s}\int_0^{T_{on}} x(t)dt = \frac{1}{T_s}\int_0^{T_s} v_{ref}(t)dt = v_{ref}(t) \qquad \text{Eq. 3-4}$$

Since the switching frequency f_s, is much higher than the time-varying reference voltage, the reference can be seen as constant in one period, thus simplifying the above equation to:

$$y(t) = v_{ref} \qquad \text{Eq. 3-5}$$

Thus, the switch is able to reject any input disturbances since it does not depend on x(t) and is able to linearly pass v_{ref}, turning a non-linear switch into a linear switch.

4.3 One-Cycle Control Buck Converter

In order to demonstrate OCC's capability, its application to a buck converter will be examined. First, the derivation for a buck converter transfer function will be analyzed. A standard buck converter is

shown in Figure 4-3.

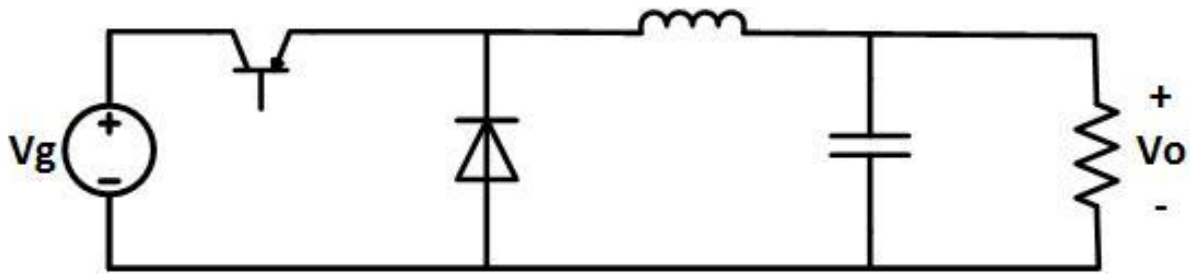

Figure 4-3: Standard Buck Converter Configuration

The buck converter transfer function is derived from volt second balance, which states that in steady-state, the average voltage across an inductor is equal to zero (which is why it appears as a short in DC). When the switch is on, the diode's anode is less positive than the cathode so the diode is reverse biased and current flows from the source to the load, charging the inductor. Assuming the switch is ideal and has no voltage drop, the voltage across the inductor when the switch is on $v_{Lon} = v_s - v_o$, where v_s is the source voltage and v_o is the output voltage. When the switch is off, the source is disconnected from the circuit and the diode becomes forward biased. The inductor will then discharge so current flows in the direction that the diode will permit. Assuming the diode is ideal and there is no voltage drop, the voltage across the inductor with the switch off is $v_{Loff} = 0 - v_o = -v_o$. Since $t_{on} = DT$ and $t_{off} = (1-D)T$, then by volt second balance:

$$\int_0^T V_L dt = \int_0^{DT} v_L dt + \int_{DT}^T v_L dt = 0 \quad \text{Eq. 3-6}$$

$$v_{Lon} t_{on} + v_{Loff} t_{off} = 0 \quad \text{Eq. 3-7}$$

$$(v_s - v_o)DT - v_o(1-D)T = 0 \quad \text{Eq. 3-8}$$

Solving for v_o results in the transfer function for a buck converter:

$$v_o = Dv_s \quad \text{Eq. 3-9}$$

As the name implies, the average output voltage of a buck converter is lower than the input voltage, as seen in the above equation. Another method of looking at the transfer function is by using the explanation seen in section 4.1. The switch with duty cycle D chops up the input voltage v_s so that the output at the diode voltage $v_d = Dv_s$. The inductor and capacitor at the output act as a lowpass filter that send the DC value of the diode voltage to the output thus, $v_d = v_o = Dv_s$.

4.4 Conventional Feedback for Buck Converter

To see the advantages that OCC has to offer, it will be compared with conventional feedback. The conventional feedback method is shown below in Figure 4-4.

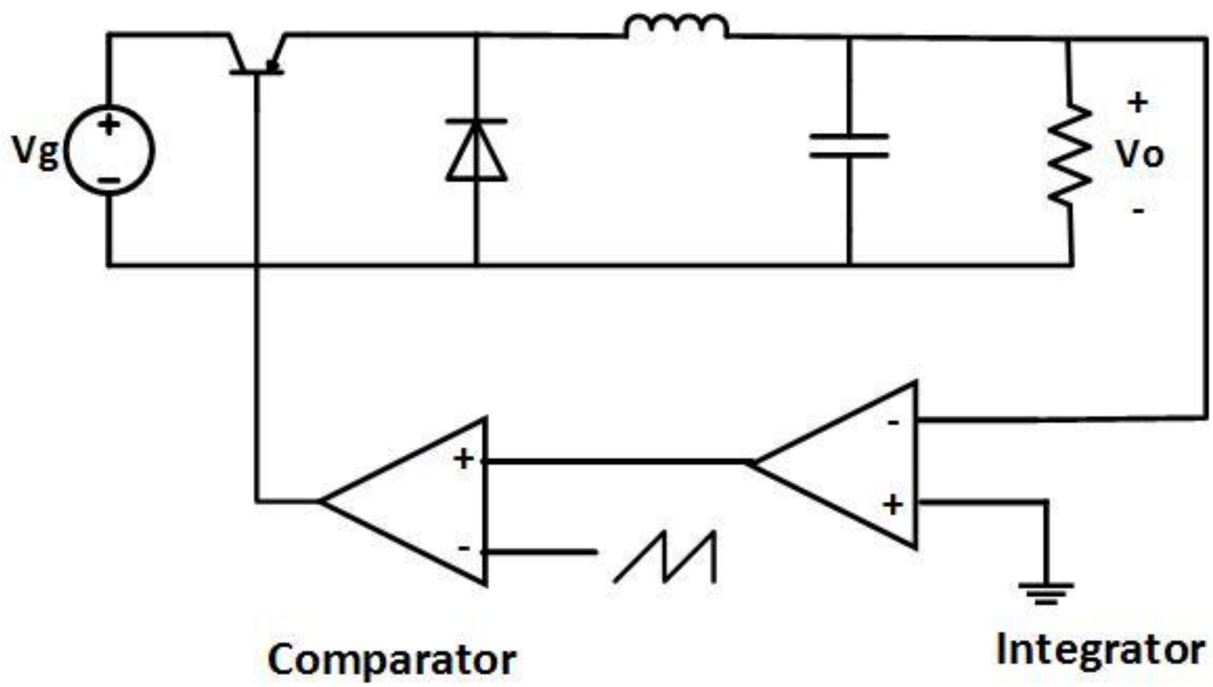

Figure 4-4: Conventional Control for Buck Converter

The output voltage of the buck converter is measured then subtracted with some reference voltage (inverting the measured value) and then amplified and compared with a sawtooth wave. The comparator determines the duty cycle of the switch; when the inverted output voltage is greater than the sawtooth wave, the switch is on. When the sawtooth function has a greater value than the inverted

output voltage, the switch is off. When the output voltage is constant (no input perturbations), the duty cycle stays constant, as seen in Figure 4-5.

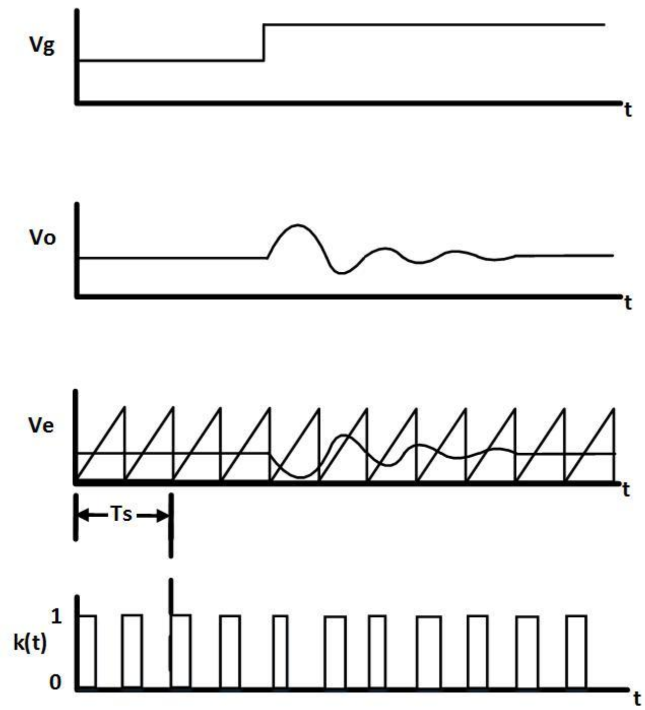

Figure 4-5: Conventional Feedback Waveforms: Vg is the source voltage, Vo is the output voltage, Ve is the inverted output voltage, and k(t) is switch waveforms

When the input receives a disturbance, a step up disturbance in the case of Figure 4-5, this is reflected in the inverted output voltage and affects the duty cycle accordingly. The step up perturbation will cause the switch to decrease its on time, however the switch overcompensates and it takes several cycles for the output voltage to reach the desired value, as seen in Figure 4-5.

The OCC control method is designed to overcome the slow response seen in conventional feedback. OCC applied to a buck converter can be seen in Figure 4-6.

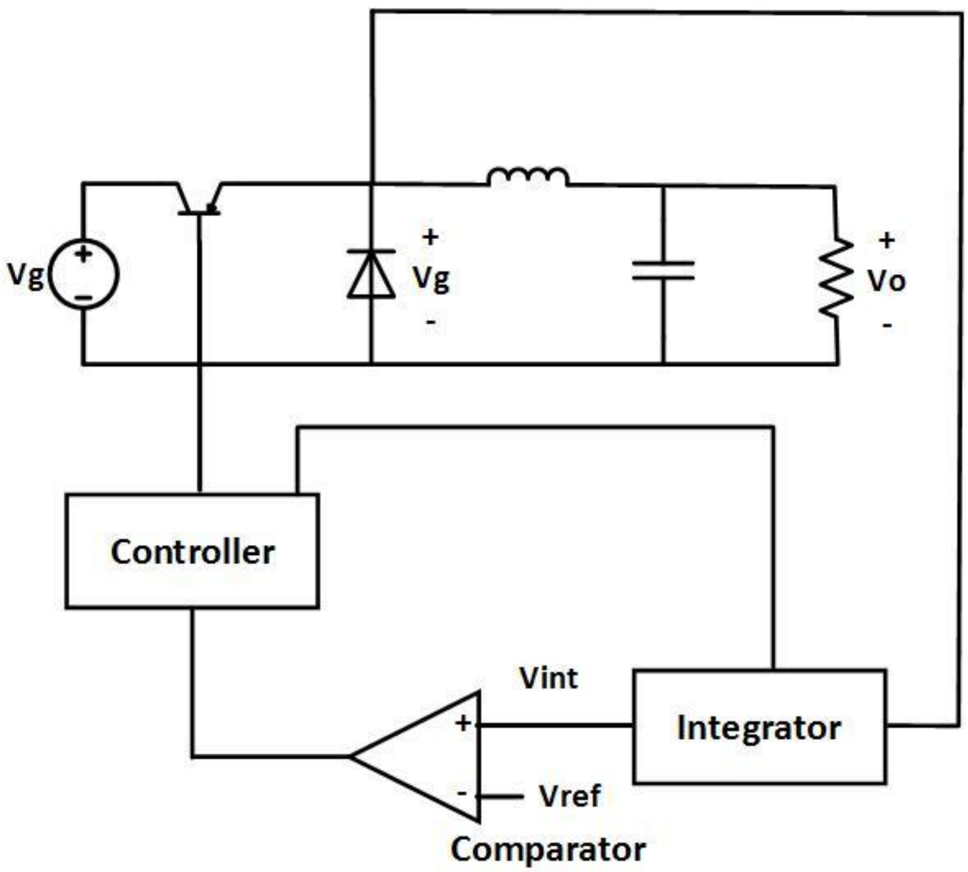

Figure 4-6: Buck Converter with One-Cycle Control

Since the average voltage across the inductor is zero, the average voltage across the diode is equal to the average output voltage. The idea is that, if the average diode voltage can be controlled, then so can the average output voltage. This is where OCC comes into effect. By integrating the instantaneous diode voltage, which is the switch output, this will obtain the average diode voltage. This integrated voltage is then compared with a control reference, in this case the desired output voltage. As soon as the integrated value reaches the reference value, the comparator sends a signal to a controller to turn off the switch and reset the integrator. The controller keeps the switching at a constant frequency to simultaneously send signals to the switch and integrator.

Keeping the control reference constant will keep the average diode voltage and thus the output voltage constant. Any fluctuations of the source will affect the slope of integration, but since the integrated value will not exceed the reference due to the comparator and controller, the output voltage will stay constant. For instance, in Figure 4-7 a setup disturbance is seen at the input. This is shown to affect the integrated value since it now reaches the reference value faster, but since the switch is turned off at the instant the integrated value reaches the reference, the output voltage is not overcompensated. Since the integration value reaches the reference at a quicker rate, this lowers the duty cycle of the switch to accommodate the higher input voltage.

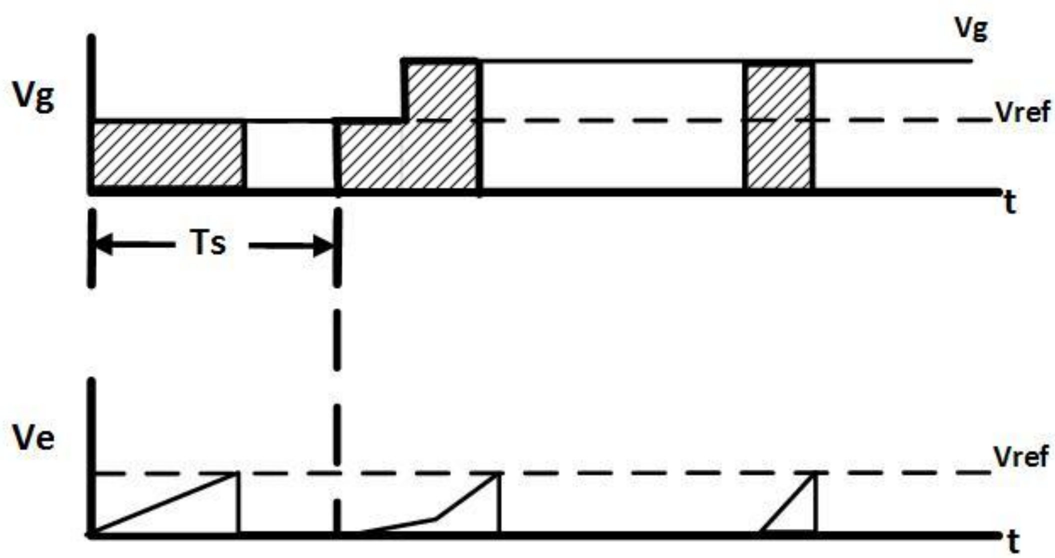

Figure 4-7: One-Cycle Control Buck Converter with Input Perturbation

As seen, the input perturbation is rejected within one cycle, which is where the technology obtains its name. It is this fast dynamic response that makes this control method a promising solution to the challenges that engineers face. The integration value will also follow the reference even if it is varying, as seen in Figure 4-8.

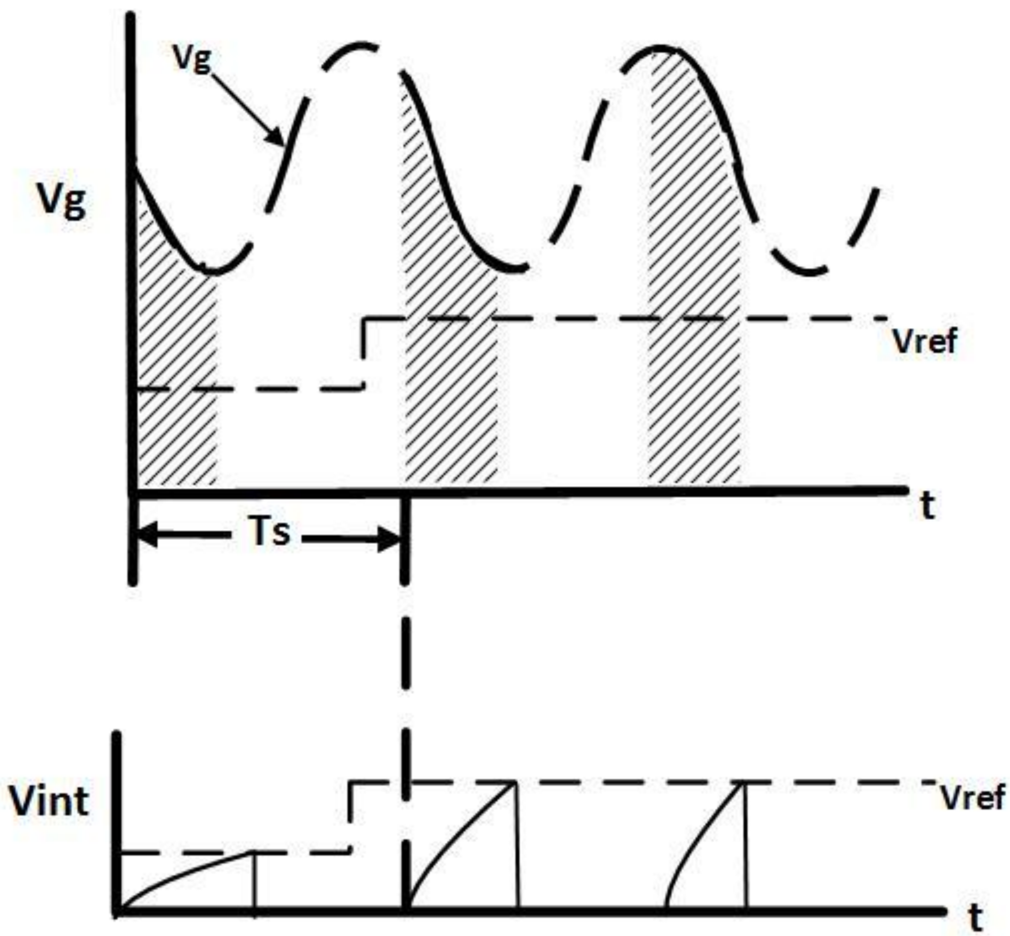

Figure 4-8: OCC Buck with Sinusoidal Input and Step Up Reference

Since the reference is adjusted, the integrated voltage will reach the reference at a different time so the duty cycle will adjust accordingly. For the case in Figure 3-8, the reference voltage is increased, meaning a higher output voltage is desired. This causes the integrated voltage to take a longer time to reach the reference value, so the duty cycle will be larger and the switch will conduct for a longer time. As seen in both **Error! Reference source not found.**

and Figure 4-9, the integrated value will follow the control reference even with a varying input. Of more interest in Figure 4-9 is how the reference is characterized by a sinusoidal waveform, showing that OCC can be used to produce AC waveforms.

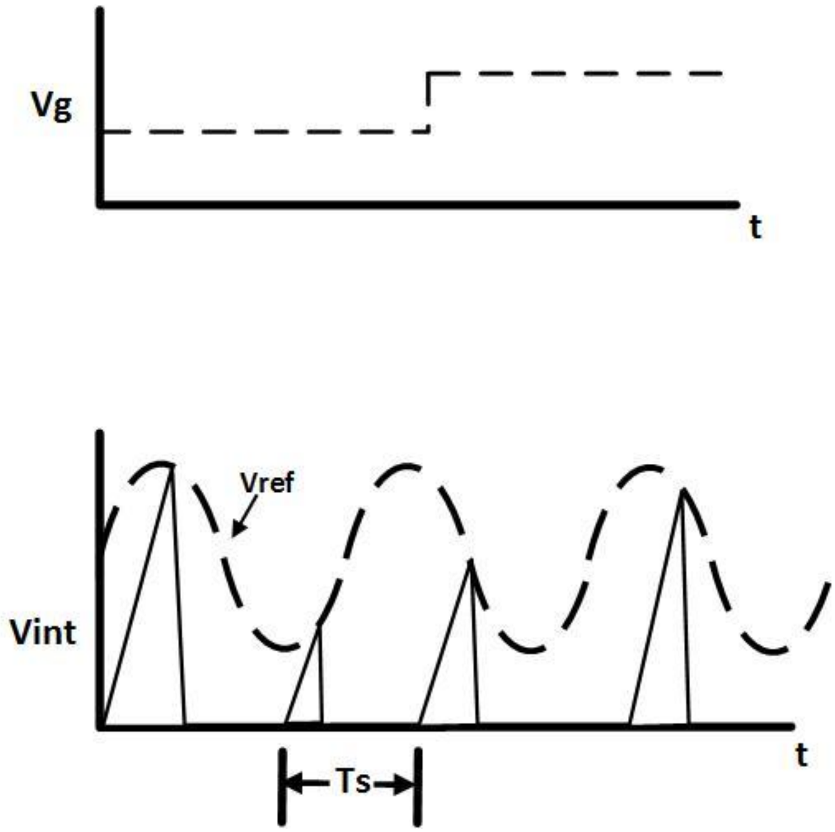

Figure 4-9: OCC Buck with Variable Reference and Input Disturbance

4.5 One-Cycle Control Application to Three Phase Systems

OCC and its uses in voltage support will be examined in its application to three phase systems. Flexible AC Transmission System (FACTS) is defined as “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability” [19]. Many of these FACTS devices use voltage-

source converters as seen in Figure 4-10.

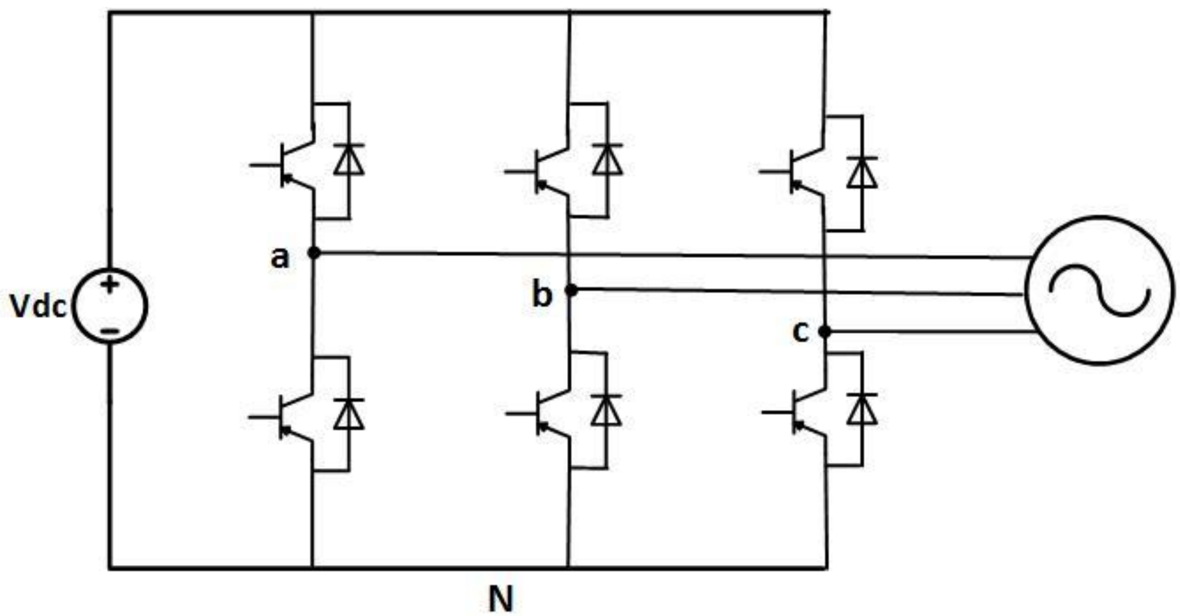

Figure 4-10: Voltage-Source Converter: Inverter with a DC Voltage with One Polarity

As seen in the figure above, each of the phases has two switches each with an antiparallel diode. This configuration allows for the DC voltage to stay at one polarity though the DC current can change direction because of the antiparallel diodes.

As seen in [20], this inverter can be used in many applications, such as: an active power filter (APF) for harmonics suppression in nonlinear loads, power factor corrected (PFC) rectifiers which are for load side harmonic and reactive power correction, and STATCOM for voltage

stability. The different diagrams and waveforms of these devices can be seen in Figure 4-11.

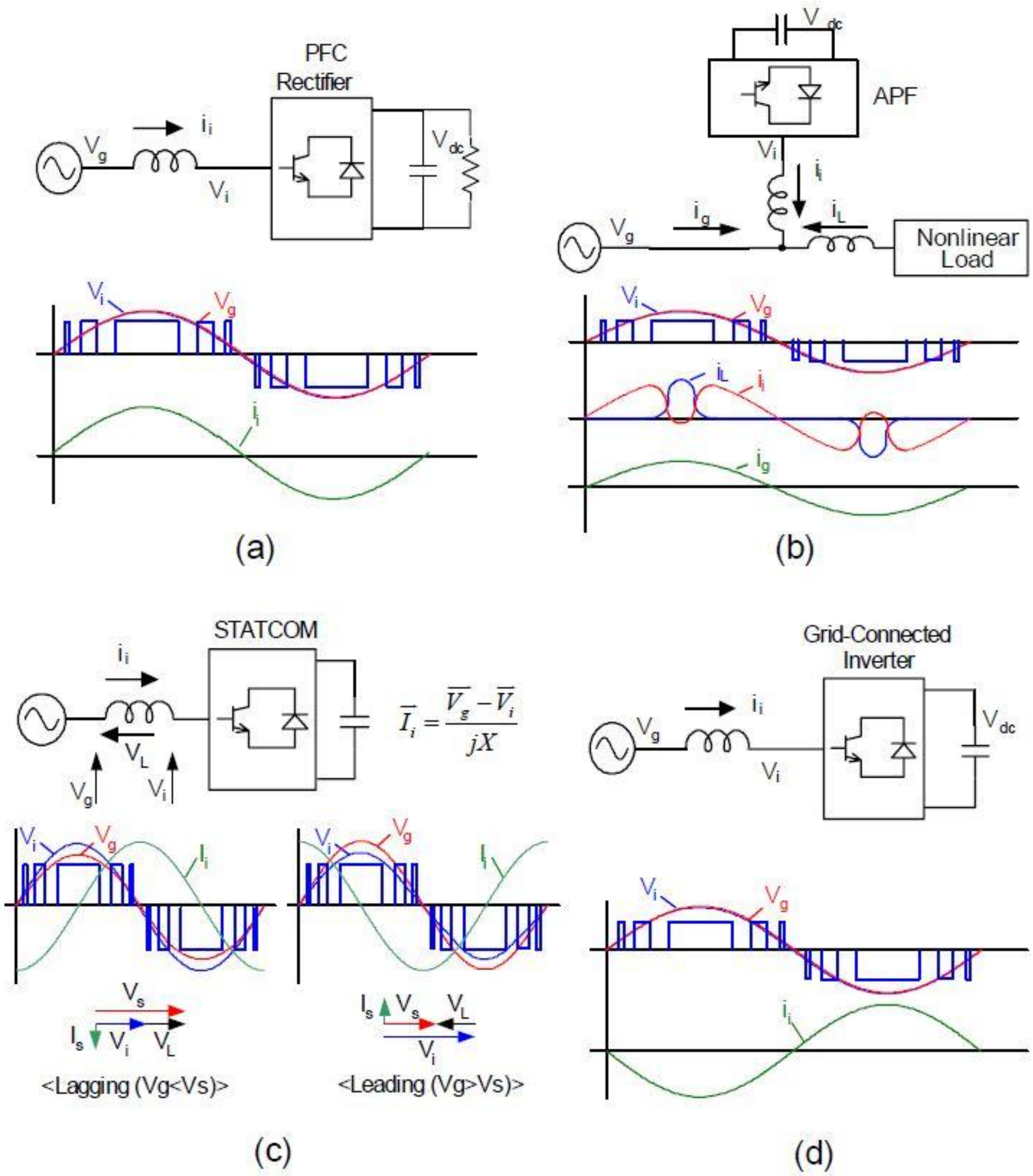

Figure 4-11: Voltage Source Converter Confiugrations as a) Power Factor Correction Rectifier b) Active Power Filter c) STATCOM d) Grid-Connected Inverter as seen in [20]

Though there exists different configurations and control strategies for the above applications, most use DQ conversion and real-time reference current calculation so they require high-speed digital microprocessors and high performance A/D converters, making them expensive, unreliable and

complex. OCC tries to mitigate this problem by acting as an analog computer so it requires simple circuitry and is highly reliable [20].

The control goal for OCC can be derived by looking at the block diagram for a three phase shunt APF with a unified constant integration (UCI) OCC controller in Figure 4-12.

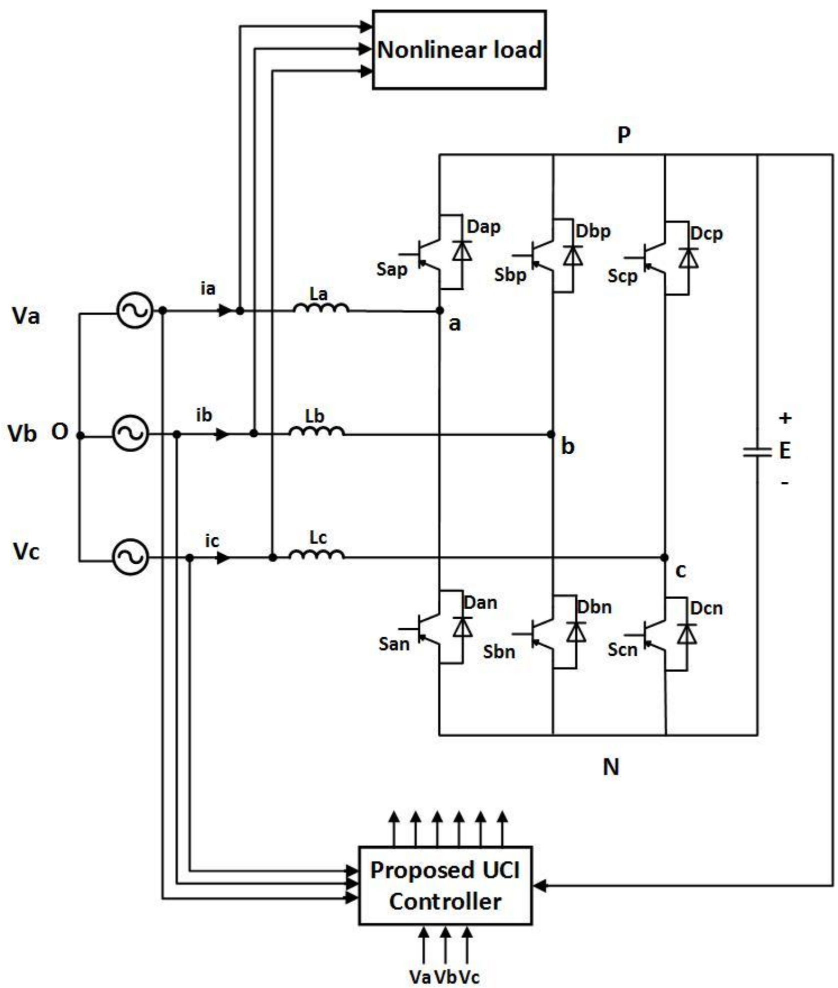

Figure 4-12: Three-Phase Shunt APF with UCI Controller

The driver signals to the switches are complementary, so for instance, the duty cycles for switches S_{an} and S_{ap} are d_{an} and $(1-d_{an})$, respectively. Because the APF requires bi-directional energy flow between the source and the voltage source converter, it is four quadrant operated and therefore always in continuous conduction mode [21]. Because the inverter is operated in CCM, the average node voltages for nodes A, B and C in Figure 4-12 with respect to node N are:

$$V_{AN} = (1 - d_{an})E \qquad \text{Eq. 3-10}$$

$$V_{BN} = (1 - d_{bn})E \qquad \text{Eq. 3-11}$$

$$V_{CN} = (1 - d_{cn})E \qquad \text{Eq. 3-12}$$

Where $d_{an,}$ d_{bn} , and d_{cn} refer to the duty cycles of the bottom switches and E is the DC voltage. With the above equations, Figure 4-12 can then be simplified to the model shown in Figure 4-13.

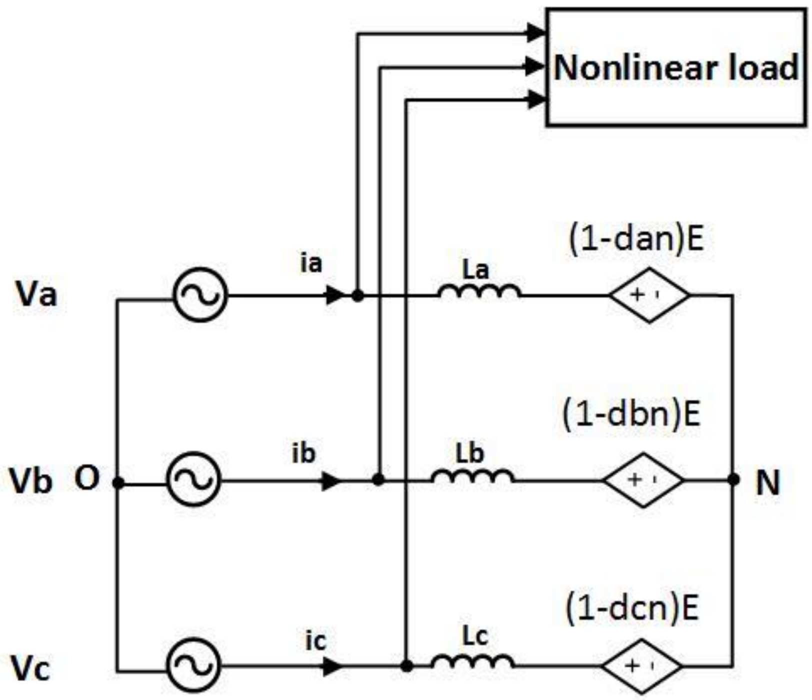

Figure 4-13: Switching Cycle Average Model for APF

Assuming that a three phase system is balanced, the phase voltages can be represented by

$$v_a = \sqrt{2}V_i \sin(wt) \qquad \text{Eq. 3-13}$$

$$v_b = \sqrt{2}V_i \sin(wt - 120^{\circ}) \quad \text{Eq. 3-14}$$

$$v_c = \sqrt{2}V_i \sin(wt - 240^{\circ}) \quad \text{Eq. 3-15}$$

The average vector voltage at nodes A, B and C with respect to node O inFigure 4-13 is equal to the phase vector voltages minus the voltage drop across the inductors L_a, L_b, and L_c:

$$v_{AO} = v_a - jwL_a i_{La} \qquad \text{Eq. 3-16}$$

$$v_{BO} = v_b - jwL_b i_{Lb} \qquad \text{Eq. 3-17}$$

$$v_{CO} = v_c - jwL_c i_{Lc} \qquad \text{Eq. 3-18}$$

Since the inductors are operating at switching frequency and the impedances are very small for the system frequency of 50Hz or 60Hz, the voltage drops across the inductors can be neglected, thus:

$$v_{AO} \approx v_a \qquad \text{Eq. 3-19}$$

$$v_{BO} \approx v_b \qquad \text{Eq. 3-20}$$

$$v_{CO} \approx v_c \qquad \text{Eq. 3-21}$$

Equating Eq. 3-22 through Eq. 3-24 to Eq. 3-13 through Eq. 3-15:

$$v_{AO} \approx v_a = \sqrt{2}V_i \sin(wt) \qquad \text{Eq. 3-22}$$

$$v_{BO} \approx v_b = \sqrt{2}V_i \sin(wt - 120^{\circ}) \qquad \text{Eq. 3-23}$$

$$v_{CO} \approx v_c = \sqrt{2}V_i \sin(wt - 240^{\circ}) \qquad \text{Eq. 3-24}$$

Where V_i is the single phase RMS voltage. The voltages at nodes A, B and C with reference to point O can be expressed as:

$$v_{AO} = v_{AN} + v_{NO} \qquad \text{Eq. 3-25}$$

$$v_{BO} = v_{BN} + v_{NO} \qquad \text{Eq. 3-26}$$

$$v_{CO} = v_{CN} + v_{NO} \qquad \text{Eq. 3-27}$$

Since the system is balanced, $v_a + v_b + v_c = 0$. Thus $v_{AO} + v_{BO} + v_{CO} = 0$. Combining this equation with Eq. 3-28 through Eq. 3-30 above produces:

$$v_{NO} = \frac{-1}{3}(v_{AN} + v_{BN} + v_{CN}) \qquad \text{Eq. 3-28}$$

Using this Eq. 3-31, along with Eq. 3-28 through Eq. 3-30:

$$v_{AO} = v_{AN} - \frac{1}{3}(v_{AN} + v_{BN} + v_{CN}) \approx v_a \qquad \text{Eq. 3-29}$$

$$v_{BO} = v_{BN} - \frac{1}{3}(v_{AN} + v_{BN} + v_{CN}) \approx v_b \qquad \text{Eq. 3-30}$$

$$v_{CO} = v_{CN} - \frac{1}{3}(v_{AN} + v_{BN} + v_{CN}) \approx v_c \qquad \textbf{Eq. 3-31}$$

This can be written in matrix form as:

$$\begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} = \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \qquad \textbf{Eq. 3-32}$$

Combining Eq. 3-35 with Eq. 3-10 through Eq. 3-12, the above matrix equation can express the relationship between duty ratios, input voltage and output voltage:

$$\begin{bmatrix} -\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & -\frac{2}{3} & -\frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & -\frac{2}{3} \end{bmatrix} \begin{bmatrix} d_{an} \\ d_{bn} \\ d_{cn} \end{bmatrix} E = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \textbf{Eq. 3-33}$$

This matrix is singular, so there are an infinite number of solutions, meaning many different solutions can be implemented. According to the method in [21], one of the switches is set to be zero or one, so that the other two duty ratios can be solved. For instance, in a three phase system divided into six different regions that are separated by sixty degrees as seen in Figure 4-14, the duty ratio for the

bottom switch d_{bn} is set to one since phase B has the lowest voltage during this region.

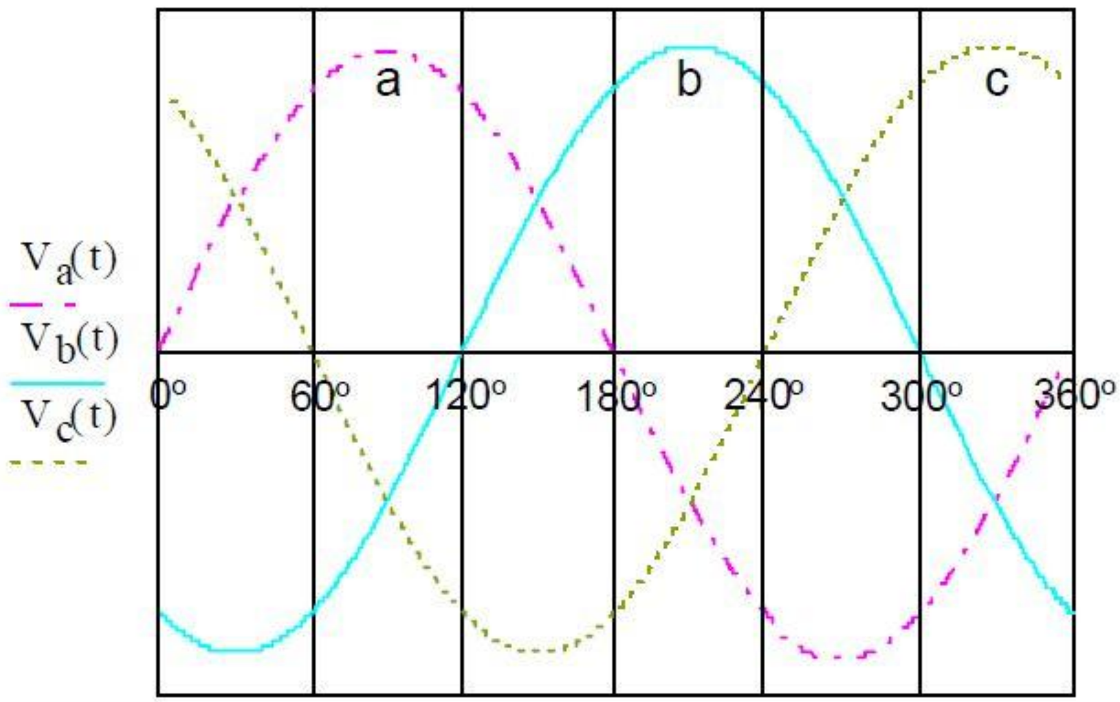

Figure 4-14: Three-Phase Waveforms Divided into Sixty Degrees Regions as seen in [20]

Observing the waveforms in Figure 4-14 one can see that for the regions one, three and five (0˚-60˚, 120˚-180˚, and 240˚-360˚), two of the phases are always higher than the third. Switch T_{in} (i=a,b,c) for the lowest phase is always turned on, and the complementary switch T_{ip} is always off. The duty ratios of the switches T_{ip} and T_{in} in the other legs can be solved for using the matrix above where the duty ratio of one T_{in} is defined by d_p and the duty ratio of the other T_{in} is defined by d_n. A similar observation can be made when examining regions two, four and six (60˚ -120˚, 180˚-240˚, and 300˚-360˚). In these regions, one phase is always higher than the other two so T_{ip} for this phase is always on while the complementary T_{in} is always off. The other switches are controlled by signals in the same way for regions one, three and five. During each of these regions, since the switch in one branch is always on and its complement is always off, the three phase circuit becomes a dual boost equivalent, as seen in Figure 4-15.

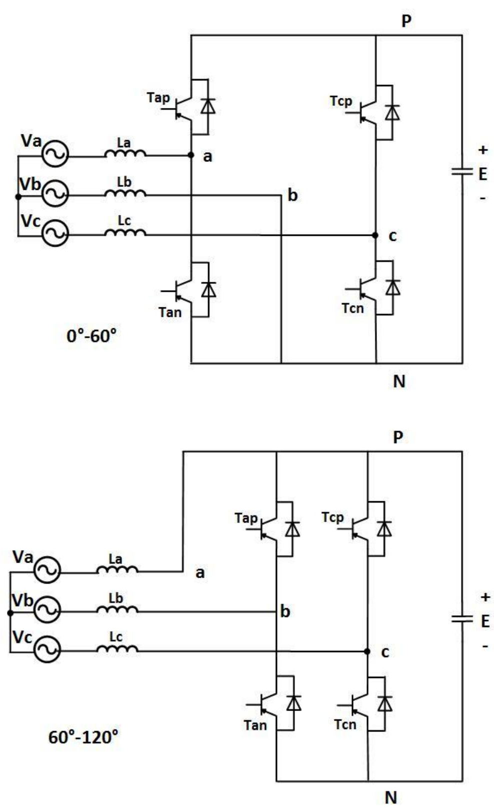

Figure 4-15: Dual Boost Equivalent Circuit for Regions

Referring back to Eq. 3-36, by setting d_{bn} = 1 and setting the matrix to row echelon form, this produces the following equations:

$$\mathbf{1 - d_{an} = \frac{V_c}{E} + \frac{2V_a}{E}} \qquad \text{Eq. 3-34}$$

$$\mathbf{d_{bn} = 1} \qquad \text{Eq. 3-35}$$

$$\mathbf{1 - d_{cn} = \frac{2V_c}{E} + \frac{V_a}{E}} \qquad \text{Eq. 3-36}$$

The control goal for an APF is to achieve unity power factor through the following equations:

$$\mathbf{V_a = R_e i_a} \qquad \text{Eq. 3-37}$$

$$\mathbf{V_b = R_e i_b} \qquad \text{Eq. 3-38}$$

$$\mathbf{V_c = R_e i_c} \qquad \text{Eq. 3-39}$$

where R_e is the equivalent resistance of the load and the VSC. Using these control goal equations and substituting them into Eq. 3-37 while also multiplying the equation by $\frac{R_s}{R_e}E$,

$$\mathbf{\frac{R_s}{R_e}E(1 - d_{an}) = \frac{R_s E}{R_e}\left(\frac{R_e i_c}{E} + \frac{2R_e i_a}{E}\right)} \qquad \text{Eq. 3-40}$$

which can be simplified and expressed as: $V_m(1 - d_{an}) = R_s i_c + 2R_s i_a$, where $V_m = \frac{R_s}{R_e}E$. The same can be done for the Eq. 3-39:

$$\mathbf{\frac{R_s}{R_e}E(1 - d_{cn}) = \frac{R_s E}{R_e}\left(\frac{2R_e i_c}{E} + \frac{R_e i_a}{E}\right)} \qquad \text{Eq. 3-41}$$

to achieve the equation $V_m(1 - d_{an}) = R_s i_c + 2R_s i_a$. These equations can be expressed in matrix form as:

$$\mathbf{V_m \begin{bmatrix} 1 - d_{an} \\ 1 - d_{cn} \end{bmatrix} = R_s \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} i_a \\ i_c \end{bmatrix}} \qquad \text{Eq. 3-42}$$

For a STATCOM system where the goal is to provide reactive current, the key control equation becomes

$$V_m \begin{bmatrix} 1 - d_{an} \\ 1 - d_{cn} \end{bmatrix} = R_s \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} i_a - i_{aref} \\ i_c - i_{cref} \end{bmatrix} \qquad \text{Eq. 3-43}$$

with $d_{bn} = 1$, where i_{aref} and i_{cref} are the reference currents that are 90 degrees out of phase (either leading or lagging) the source voltages. This can be generalized into a generic key control equation for any of the six regions in the three-hundred sixty degree cycle:

$$V_m \begin{bmatrix} 1 - d_p \\ 1 - d_n \end{bmatrix} = R_s \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} i_p - i_{pref} \\ i_n - i_{nref} \end{bmatrix} \qquad \text{Eq. 3-44}$$

where p and n refer to the corresponding phase for the corresponding region.

Referring back to the basic OCC model in Figure 4-6, which is updated in Figure 4-16, the signal v_2 (the switch output) is the integrator input and integrated over time so that it can be compared with signal v_1. Once the two signals are equal to other, the controller turns off the switch and resets the integrator.

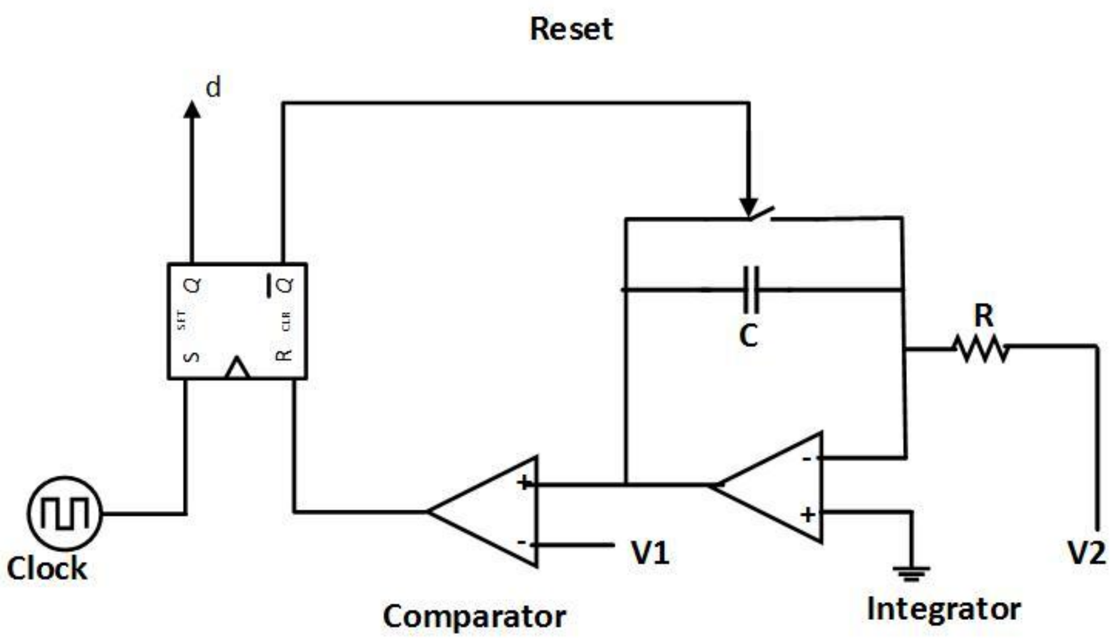

Figure 4-16: Basic One Cycle Control with Constant Frequency

The operation can be expressed in the following equation: $\frac{1}{RC}\int_0^{dT_s} v_2 dt = v_1$, where d is the duty cycle, T_s is the switching period, R is the integrator resistance and C is the integrator capacitance. The duty ratio of the switch is controlled such that the chopped signal of v_2 has an average in each switching cycle that is equal to or proportional to signal v_1. If the integration time constant is chosen to be the same as the switching period, the duty ratio is modulated as $v_2 d = v_1$. Looking at Eq. 3-47, it can be seen that v_2 is the V_m term and v_1 is the right hand side terms of Eq. 3-47 [22]. This can be implemented in Figure 4-17 below.

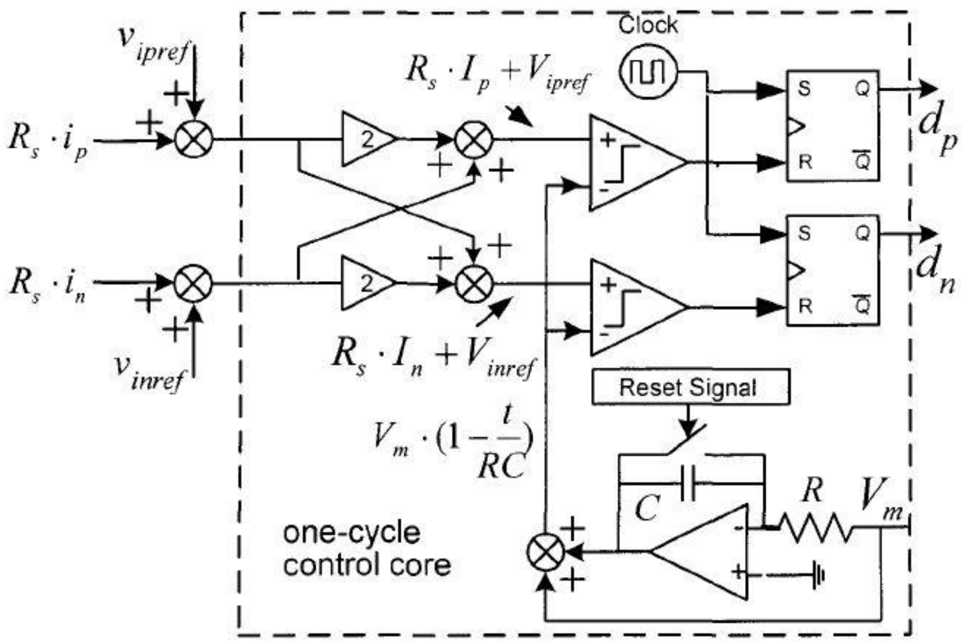

Figure 4-17: One-Cycle Control Core Implementation of Key Control Equation for STATCOM as seen in [22]

The integrator in Figure 4-17 inputs $V_m = \frac{R_s}{R_e}E$, which is the DC voltage processed through a PI controller. The integrator time constant RC is equal to the period. The integrator output is inverted and added with the signal V_m to produce the signal $V_m\left(1 - \frac{t}{RC}\right) = V_m\left(1 - \frac{t}{T}\right) = V_m(1 - d)$, which is the left hand side of Eq. 3-44

and is one of the inputs to the comparators. The sensed currents for the corresponding region are shown on the left of Figure 3-17 and added to reference voltages. They are then processed through some multipliers and summing junctions to produce $R_sI_p + V_{ipref}$ and $R_sI_n + V_{inref}$, which are equal to $2R_s(i_p - i_{pref}) + R_s(i_n - i_{nref})$ and $R_s\left(i_p - i_{pref}\right) + 2R_s(i_n - i_{nref})$, respectively. These are the other inputs to the comparators. The comparators will then determine the duty cycles that will satisfy the control equations.

As seen in Figure 4-15, the circuit converts to a dual boost converter. As shown in Figure 4-18 for region one, the OCC core senses the source currents which are also the inductor currents for the boost converters (note: the diagram is shown for a PFC so there is no reference current being added to the sensed currents).

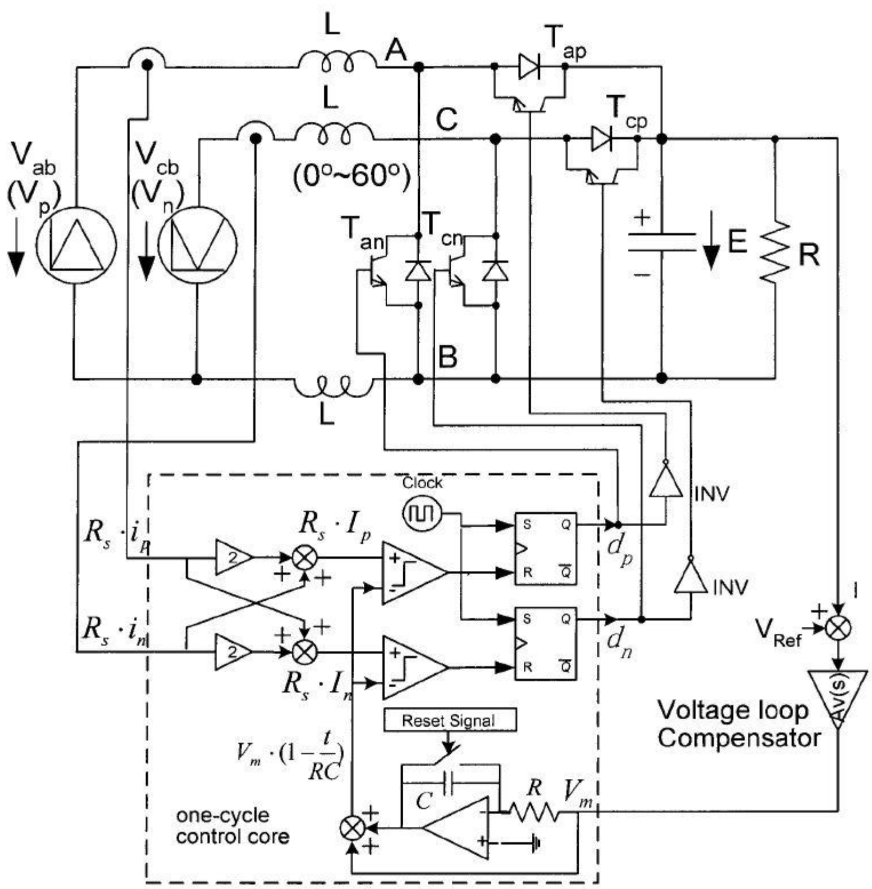

Figure 4-18: Dual Boost Converter Topology for Region 1 as seen in [22]

Since the sensed input currents are also the inductor currents, they have the characteristics of an inductor charging and discharging to produce a triangular waveform, as seen in Figure 4-19.

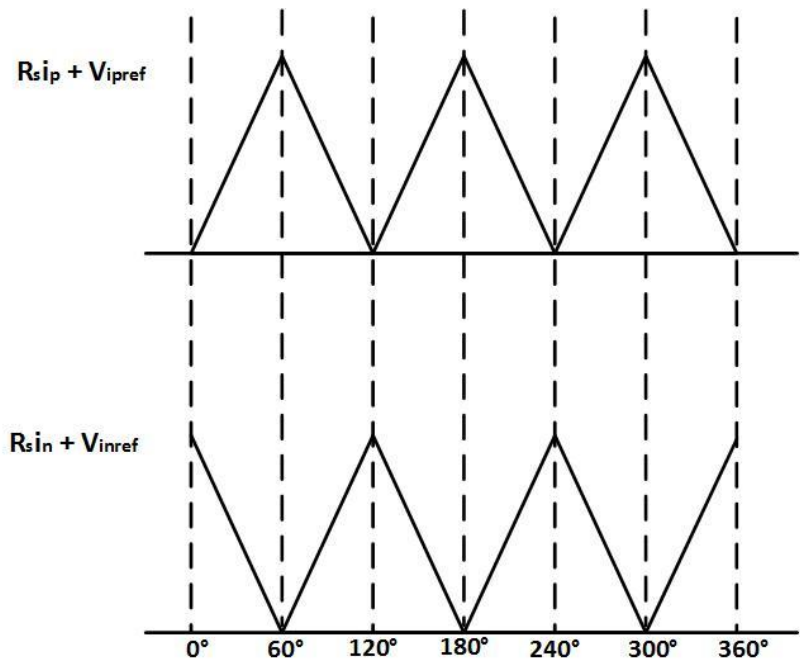

Figure 4-19: Reference Waveforms for Comparator

These waveforms form the reference waveforms, similar to the sinusoidal waveforms used in sinusoidal pulse width modulation (SPWM). These are then compared with the carrier waveform, which is a triangular wave in SPWM but is the sawtooth waveform in OCC. The waveforms of OCC are shown in Figure 4-20.

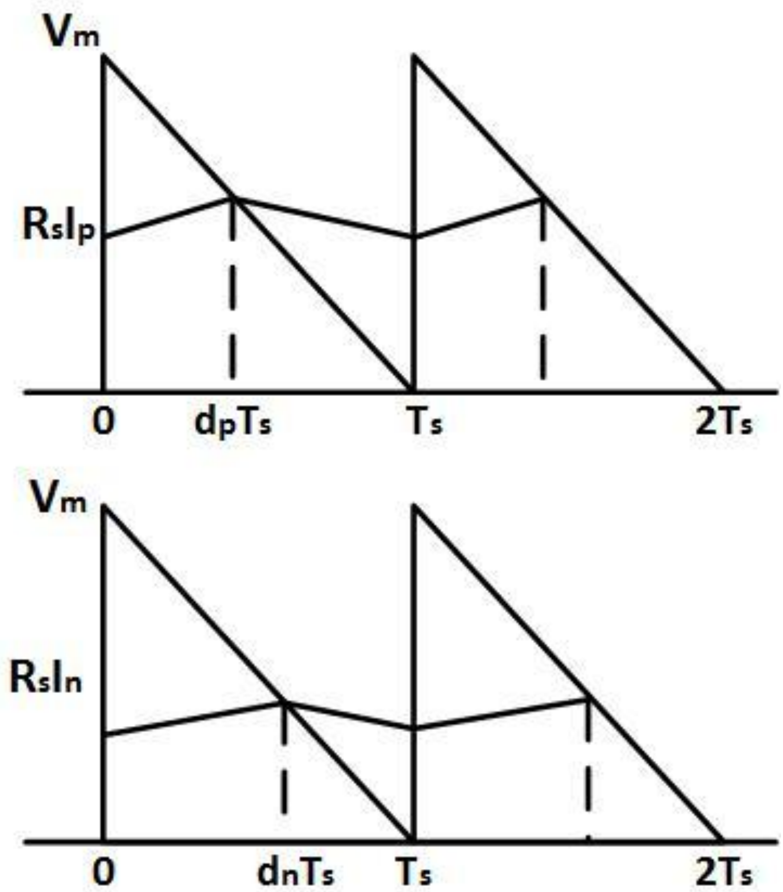

Figure 4-20: One Cycle Control Operation Waveforms

Whenever the reference waveform R_sI_p or R_sI_n is lower than the carrier waveform V_m, the switches with duty cycle d_p or d_n is on (and their complements are off). As soon as the reference value reaches the integrated value, the switches are turned off (and their complements are turned on).

Since the phase corresponding to I_p and I_n is different for each region, a current selector circuit is needed to allow the correct signals to flow through the circuit. The circuit block is shown in Figure 4-21 and is implemented through the use of multiplexers. The multiplexers receive the select signals from the region selection block in Figure 4-21, which is composed of zero crossing detection circuits that determine what region the phase voltages are in. The logic circuit block in Figure 4-21 is switch logic that

determines what driving signals to send to which switches depending on the region. Its logic is based off Table 4-1.

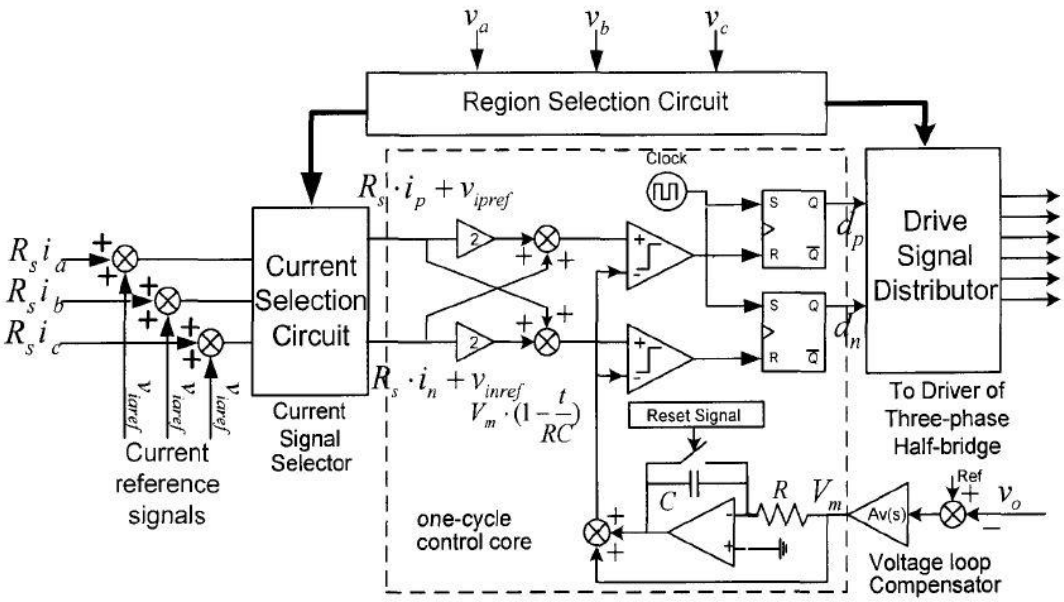

Figure 4-21: One-Cycle Controller for Three-Phase Bridge Inverter as seen in [22]

The table shows the corresponding positive and negative voltages for each region.

Table 4-1: Three-Phase to Two-Phase Transformation for Switching Logic

Region	v_p	v_n	i_p	i_n	d_p	d_n	Q_p	Q_n
0°-60°	v_a	v_c	i_a	i_c	d_{an}	d_{cn}	Q_{an}	Q_{cn}
60°-120°	$-v_b$	$-v_c$	$-i_b$	$-i_c$	d_{bp}	d_{cp}	Q_{bp}	Q_{cp}
120°-180°	v_b	v_a	i_b	i_a	d_{cn}	d_{an}	Q_{cn}	Q_{an}
180°-240°	$-v_c$	$-v_a$	$-i_c$	$-i_a$	d_{cp}	d_{ap}	Q_{cp}	Q_{ap}
240°-300°	v_c	v_b	i_c	i_b	d_{cn}	d_{bn}	Q_{cn}	Q_{bn}
300°-360°	$-v_a$	$-v_b$	$-i_a$	$-i_b$	d_{ap}	d_{bp}	Q_{ap}	Q_{bp}

4.6 PSCAD Modeling

To test the OCC control scheme in PSCAD, a three phase 12.47kV system was used that represented the utility voltage. The magnitude was chosen since it is a typical value for a distribution system. The system is shown below in Figure 4-22.

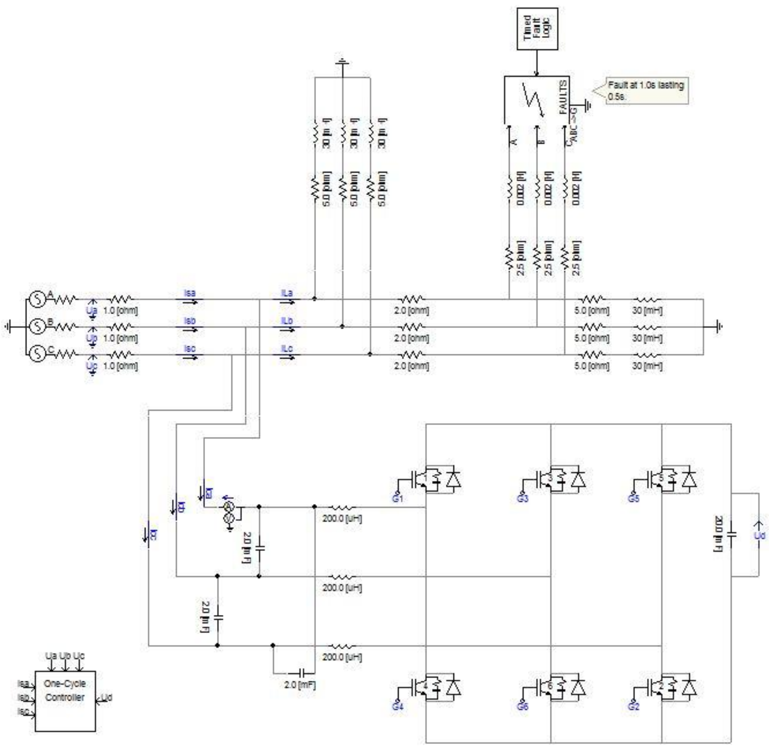

Figure 4-22: Three-Phase PSCAD OCC Model

The utility is connected to inductive loads that cause lagging power factor, as power systems lines are naturally inductive. LC filters are used to smooth the waveforms and mitigate the effects of harmonics. A fault with impedance to mitigate its severity is used to simulate a voltage sag.The OCC-VAR device is then connected in parallel with the load as seen in Figure 4-22. The inverter controlled by OCC is shown connected to the system while the OCC device itself is represented by the OCC block. The OCC block contains the circuitry seen in Figure 4-21.

The region selection circuit in Figure 4-21 consists of zero detection circuits that determine whether a phase voltage is positive or negative. This is implemented in Figure 4-23 using comparators that assign an output value of "1" when the phase voltage is greater than zero and an output value of "0" when the phase voltage is lower than or equal to zero.

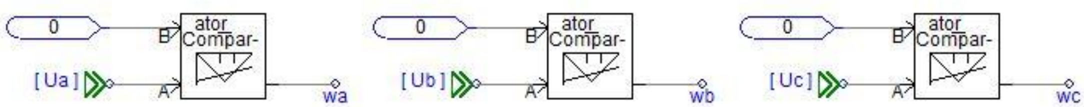

Figure 4-23: Region Selection Circuit

The three comparator outputs, one for each phase, will then determine what region the cycle is in, as seen inTable 4-2. This three-bit code is then used for select signals for other blocks in Figure 4-21. The Y column in the table is used for the arrays that are sent to the multiplexers. Ideally, I(1) and I(8) should never happen, since the phases are never all negative or all positive at the same time, but zero signals are sent if this is the case.

Table 4-2: Region Selection Code and Corresponding Currents

W_a	W_b	W_c	Y	I_p	I_n
0	0	0	I(1)	0	0
0	0	1	I(2)	A_n	B_n
0	1	0	I(3)	C_n	A_n
0	1	1	I(4)	C_p	B_p
1	0	0	I(5)	B_n	C_n
1	0	1	I(6)	A_p	C_p
1	1	0	I(7)	B_p	A_p

1	1	1	I(8)	0	0

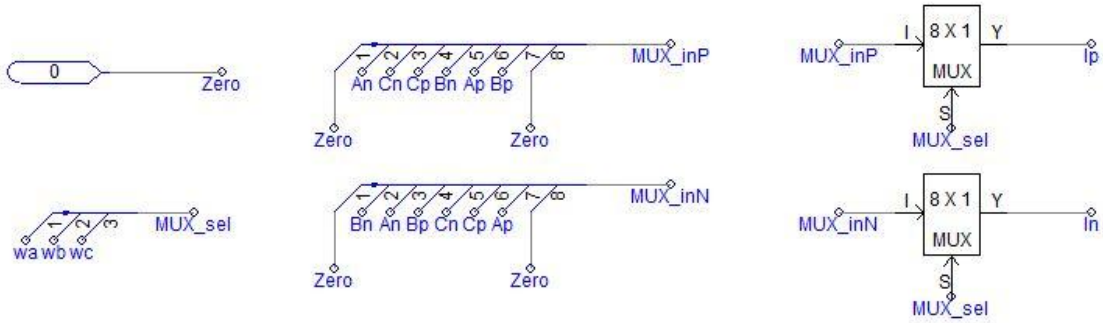

Figure 4-24: Current Selection Circuit

The current selection circuit, shown in Figure 4-24, consists of multiplexers that use the comparator outputs from the region selection circuit as select signals. From the select signal, this will determine what currents will be selected as i_p and i_n as seen in Table 4-1. The signals I_p and I_n are then sent to the OCC-core block in Figure 4-25.

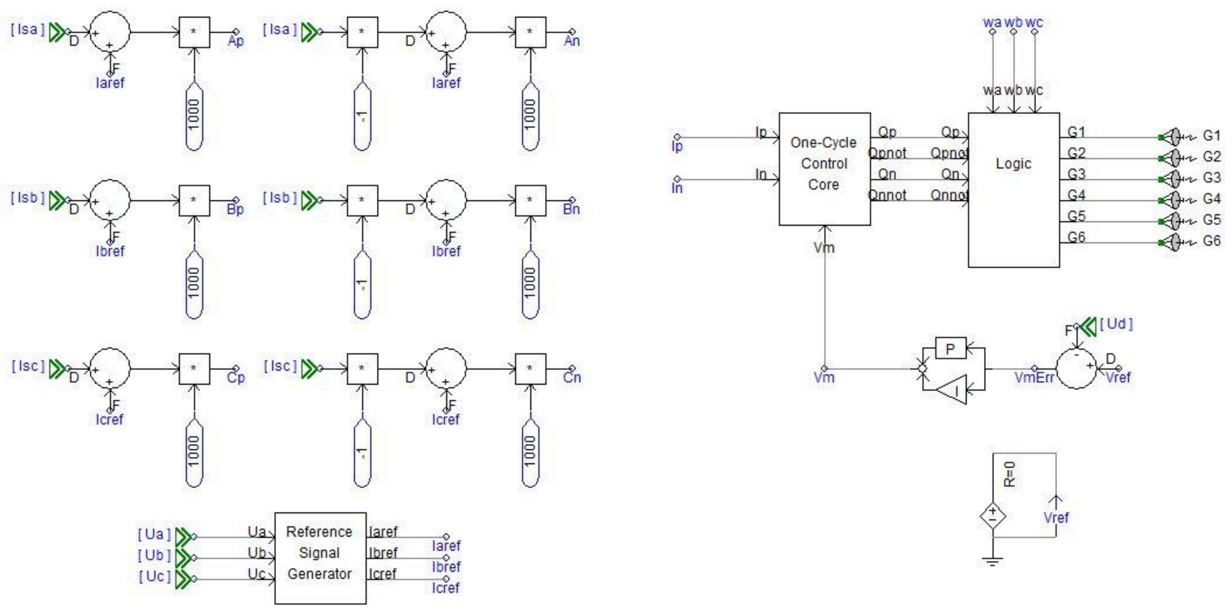

Figure 4-25: PSCAD Implementation of One Cycle Controller Without Region Selection Circuit

Figure 4-25 shows the PSCAD model for Figure 4-21 without the region selection circuit. The sum of the source and reference currents must be multiplied by one thousand in order to keep precise values, as these signals can only be sent as integer values in the arrays to the multiplexers. These values are then converted back into real values by a post divide by one thousand in the One-Cycle Control Core block, as seen later.

The OCC-core block is what is shown in the One-Cycle Control Block in Figure 4-21. Its inputs are i_p, i_n and V_m, where V_m is the sensed DC voltage subtracted from the reference DC voltage and processed through a PI controller, as seen in Figure 4-25. The time constant for the integration in OCC-core is determined by the equation $T_i = \frac{T_s}{2}$, where T_i is the integration time constant and T_s is the switching period. T_s is determined by the clock input to the SR flip-flops, which is also the reset signal to the integrator, shown in Figure 4-26.

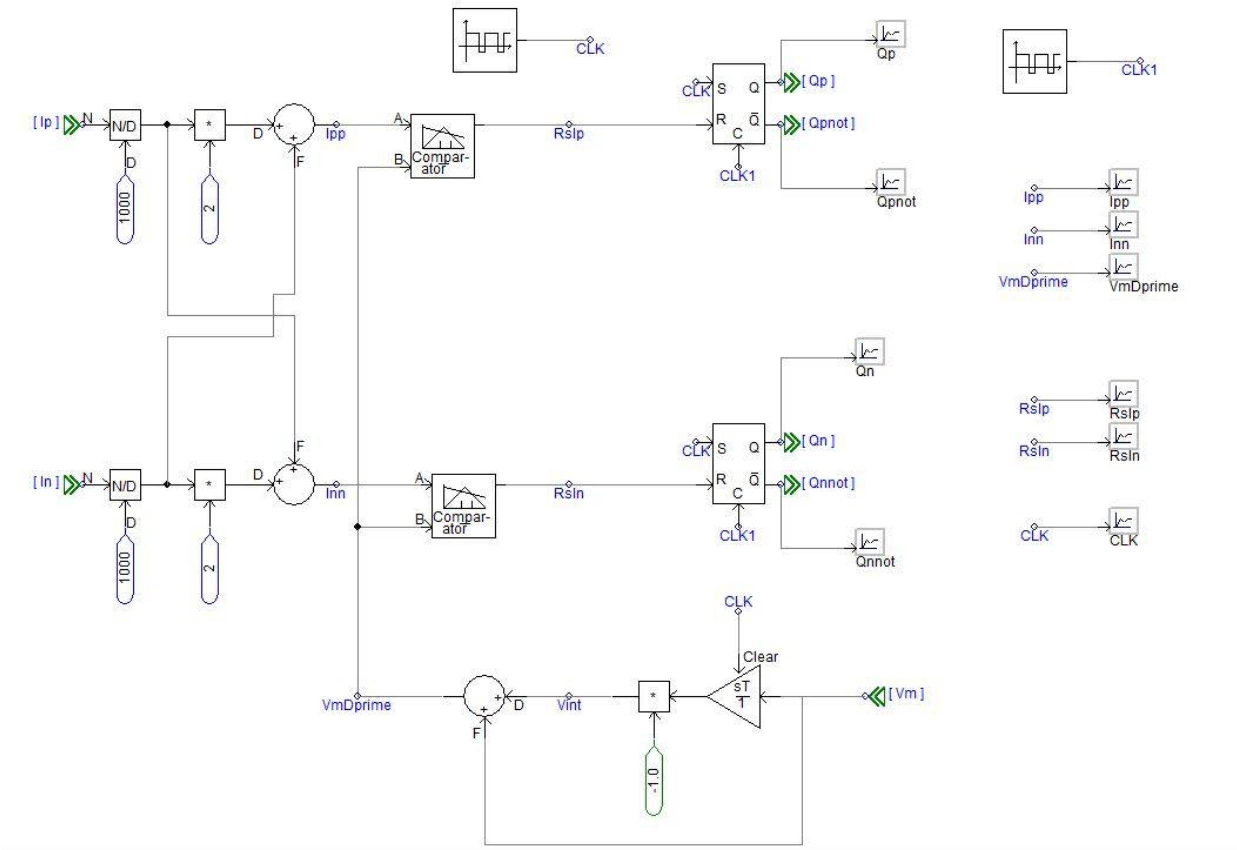

Figure 4-26: One-Cycle Control Core

A second clock is needed however, for the flip-flop to update the state of Q and Q' based off the inputs S and R, which is shown in Figure 4-26 as CLK1. This second clock signal, CLK1, must be faster than the first clock signal, CLK, in order to recognize the R state change from the current values exceeding the V_m value. The unavoidable state of S and R both being equal to "1", is never attained, so long as the current values and V_m do not intersect at the peaks of V_m.

The switching signals from OCC-core block are then sent to the switching logic block in Figure 4-24. The logic block consists of an encoder and various logic gates to implement the truth table in Table 4-1. The encoder takes the region selection signals and converts them from three-bit codes into a single signal for each region. These signals will be high when the cycle is in that particular region and low when

it is not. These single-bit region signals are then passed through various logic gates to send the switching signals from the OCC-core to the corresponding switches.

The last block in the model is the reference signal generator as seen inFigure 4-27. This composes of PLL's that track the phase of each of the voltages and offsets them by 90˚. These are then passed through sin blocks that produce sinusoidal waveforms to represent the reference voltages.

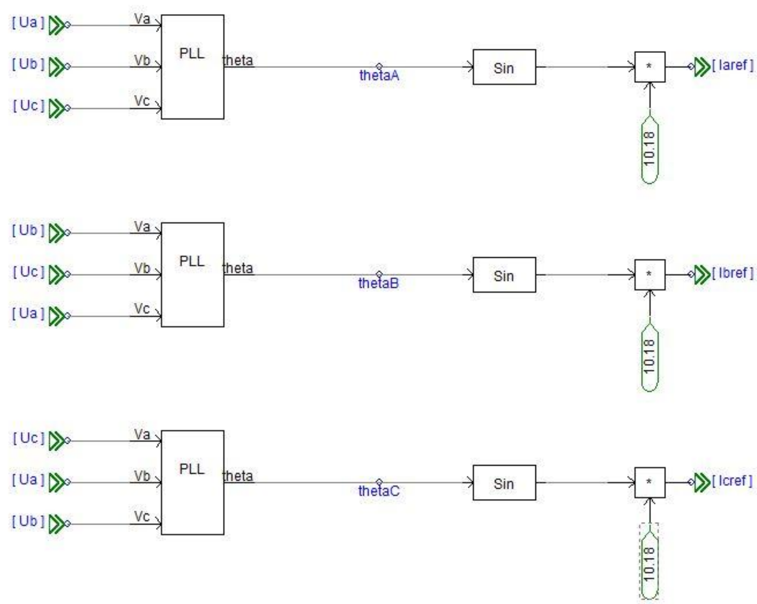

Figure 4-27: Reference Signal Generator

5 Simulation Results

The results from the model are shown in the figures below.

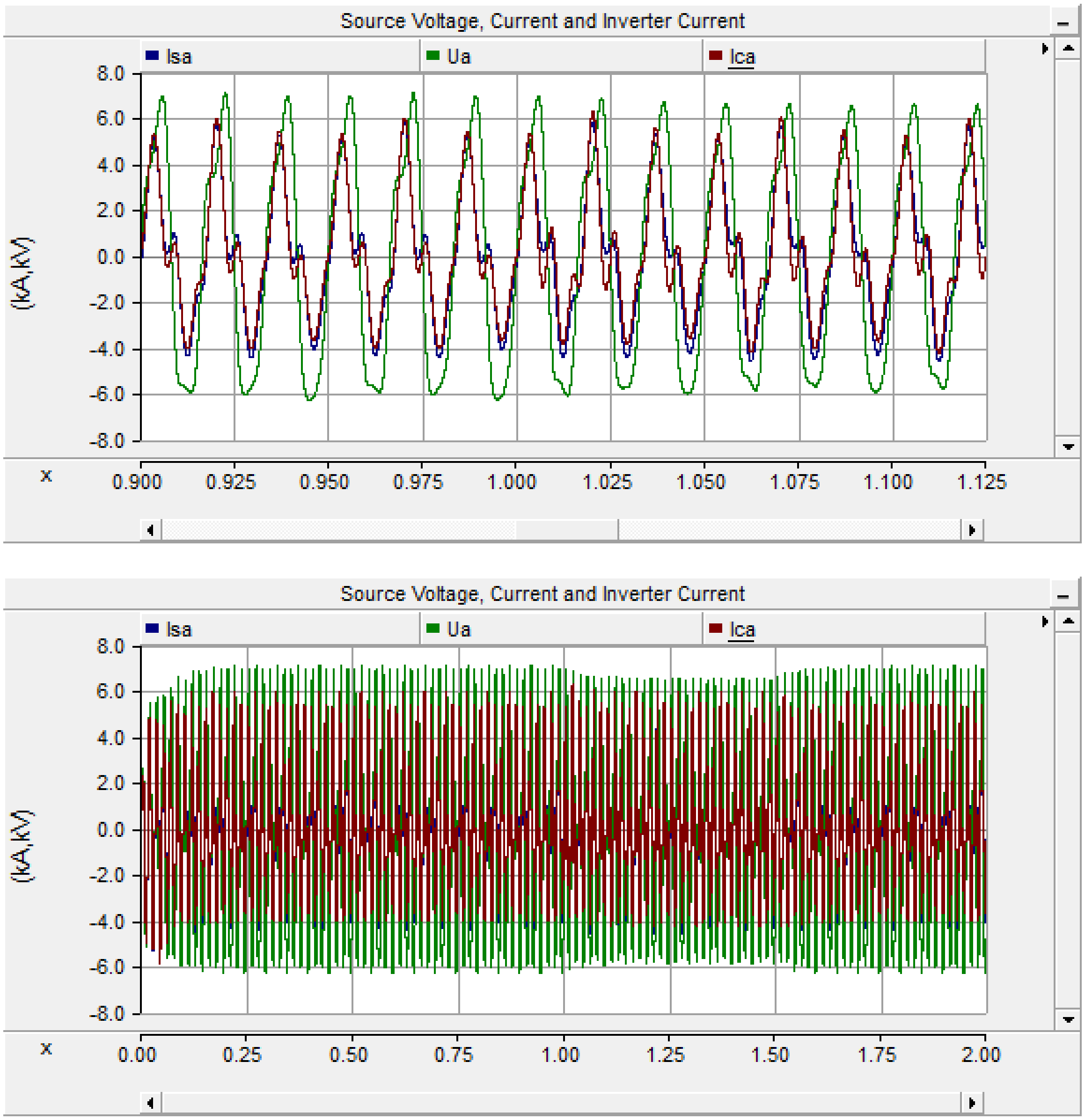

Figure 5-1: Source Voltage and OCC-VAR Current a)Zoomed In b) Total Runtime

Figure 5-1, shows the source voltage and source current and compensation currents for the system. The voltage is lower than the nominal voltage of 12.47kV. The inverter currents are also similarly shaped to the source currents, but both are distorted and not sinusoidal. The fault, which

happens at 1.0 seconds and lasts for 0.5 seconds, simulates the voltage sag, which can be seen in the total runtime.

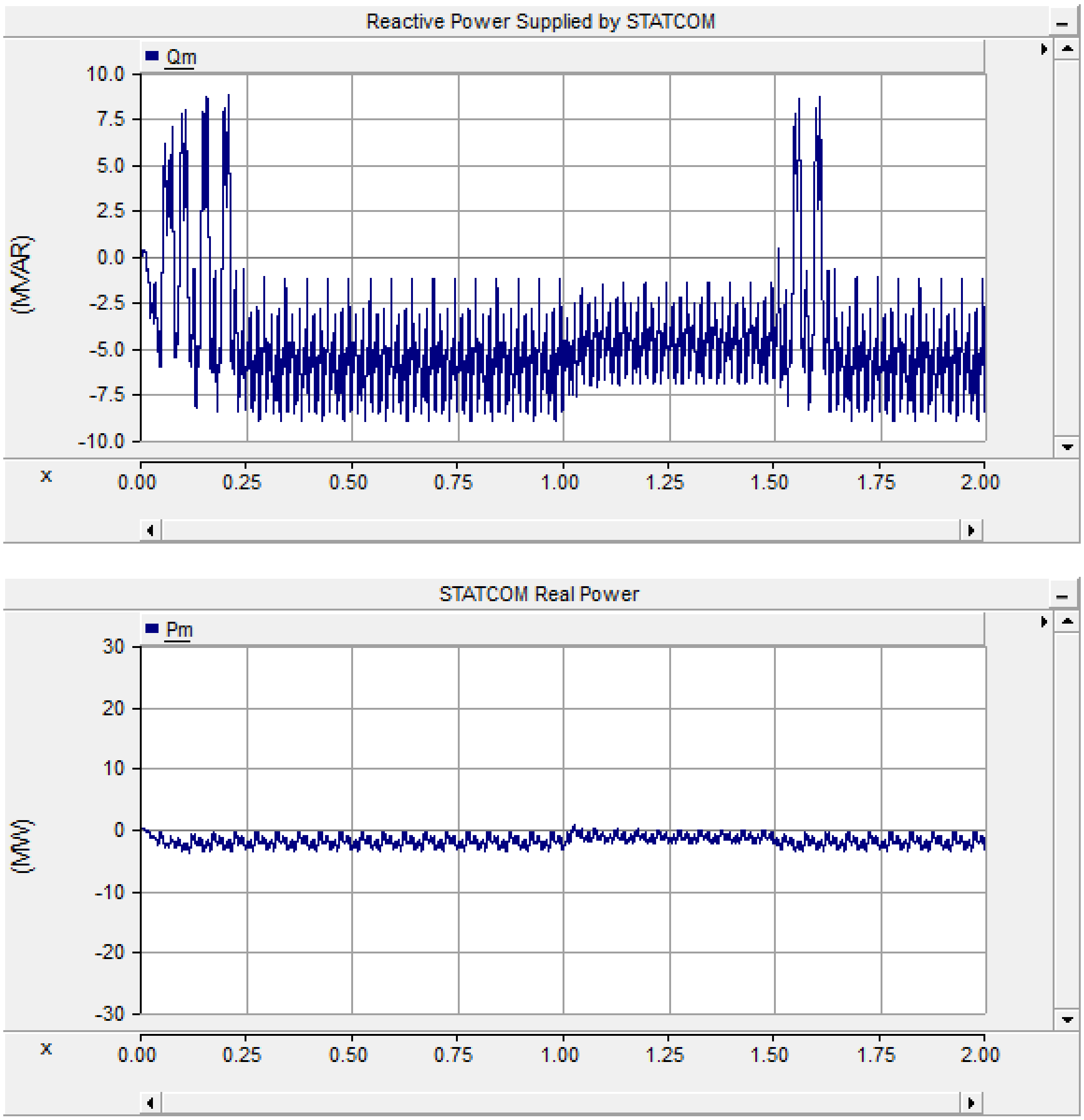

Figure 5-2: Reactive and Active Power of OCC-VAR

Figure 5-2 shows the reactive and active power of the device. The active power is kept at a minimal level close to zero, which is desired of a STATCOM device. The reactive power is negative however, as it should be positive to show that it is supplying reactive power to the grid.

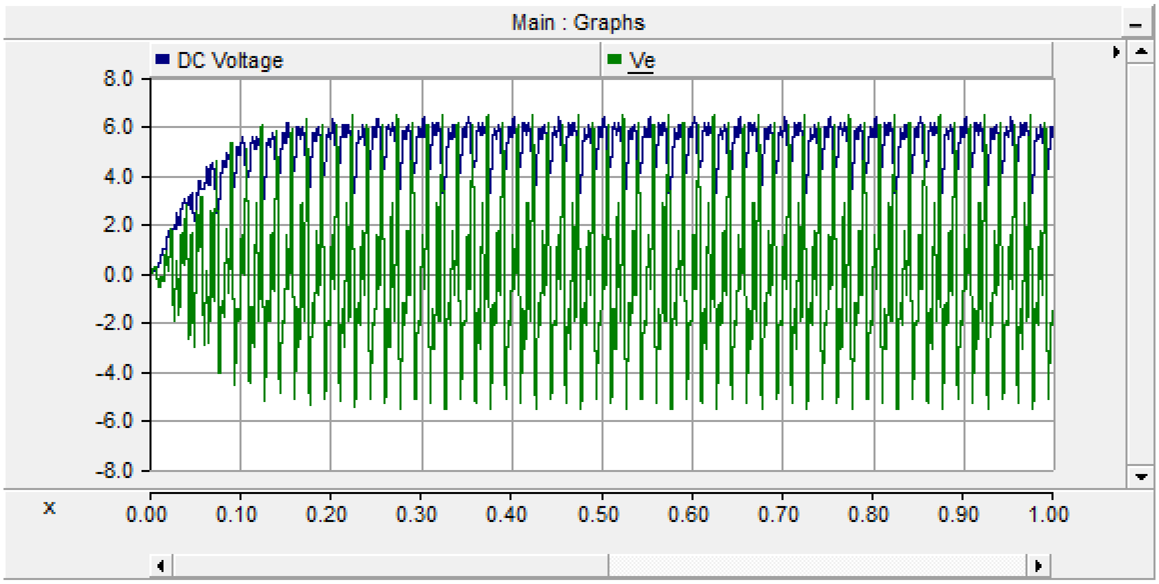

Figure 5-3: Inverter AC Voltage and DC Voltage

Figure 5-3 shows the AC side voltage of the inverter as well as the DC voltage. The DC voltage should be higher than the AC side inverter voltage in order to produce reactive power. The DC voltage should ideally also be kept constant, in order to prevent the device from producing or absorbing reactive power. Based on the results from Figure 5-2, the DC voltage is kept constant enough to keep the active power low.

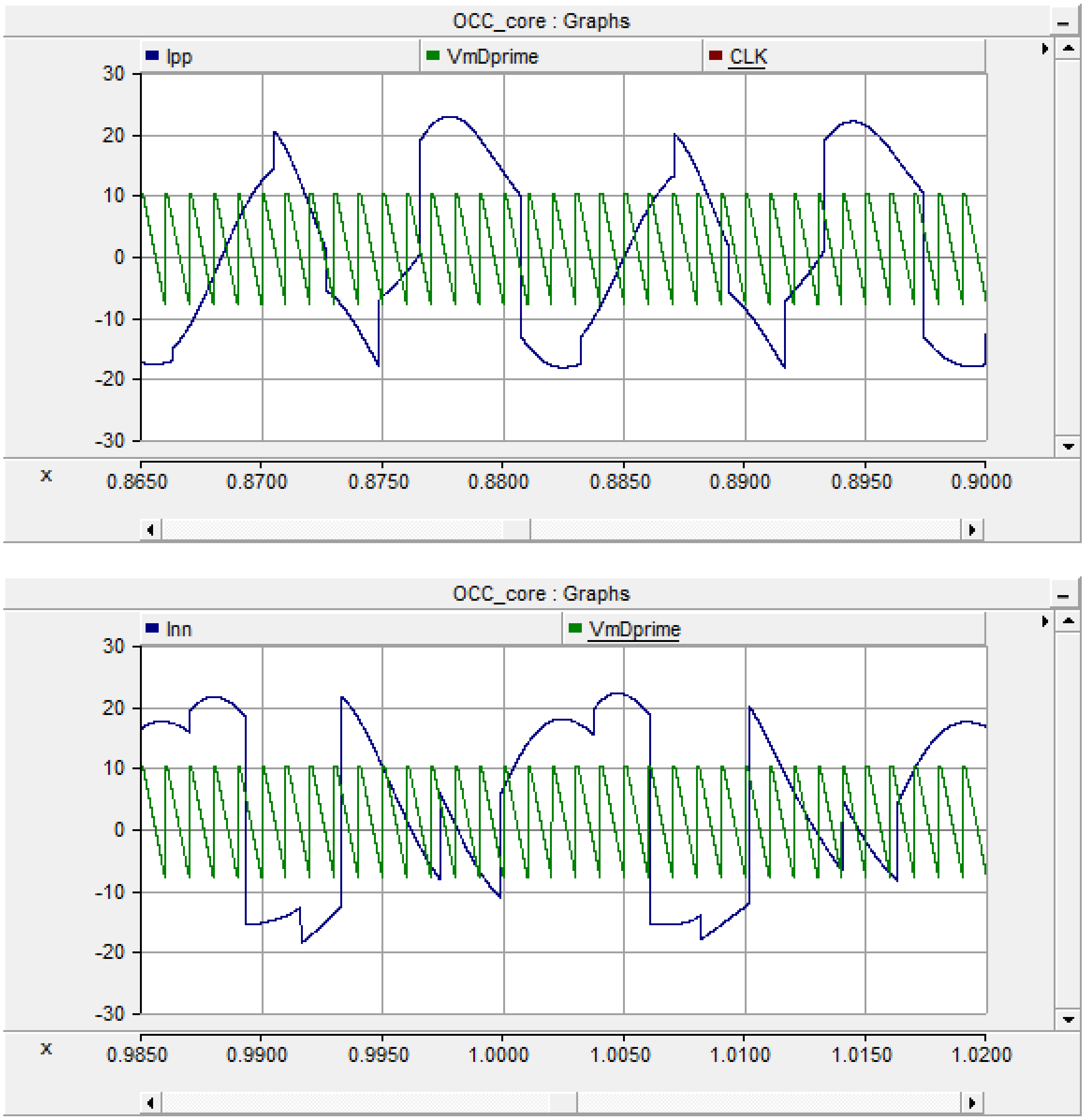

Figure 5-4: OCC-Core Comparator Inputs

Figure 5-4 shows the comparator inputs that represent the two sides of the control equation, Eq. 3-44. The results should be similar to Figure 4-20, however the inputs that represent the right hand side of Eq. 3-44 are not producing the triangular wave that is seen for an inductor current. The input is also greatly exceeding the integrated value, V_m.

6 Conclusion

The results show that the OCC-VAR is not working according to the project goals. However, according to [23] and [24], there are stability issues associated with OCC. This is seen in Figure 5-4, where one of the inputs to the comparator is greatly exceeding the other and going beyond a range that makes them comparable. Because OCC is only a recently developed technology, there are also various parts of the control scheme that are vaguely described due to the limited resources and papers on OCC, especially OCC-VAR.

According to [23], another OCC controlled device is implemented with simpler features, such as not having to use Phase Locked Loops (PLLs) in order to generate the reference current. The proposed topology in this paper also claims to solve the stability problem in [24]. However, the use of extra filters in this control topology and the lack of multiple sources make it more challenging to create a model.

Overall, this project requires more research in implementing OCC. Stability issues along with harmonics issues are the main problems in preventing the proposed model from functioning, as seen in the results. Different control configurations should be researched and analyzed to produce a better functioning model.

7 Bibliography

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