COMPARISON BETWEEN PWM AND SVPWM THREE-PHASE INVERTERS IN INDUSTRIAL APPLICATIONS

by

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ABSTRACT

Two different three-phase inverters are introduced and compared showing the differences and similarities between them in terms of output power, implementation, challenges and efficiency. Both inverters use the same feedback controller and both have the same input voltage and the same load levels.

The first inverter is a three-phase sinusoidal pulse width modulation (PWM) inverter that generates gate-control signals using a sinusoidal wave source. It is shown that pulse width modulation utilizes a simpler approach to convert DC power into AC.

The second inverter is a three-phase space vector pulse width modulation (SVPWM) inverter. SVPWM inverters utilize a space vector (reference vector) to create the desired sinusoidal waves. SVPWM proved to have less total harmonic distortion (THD% = 1.15%) and faster response time (114ms) with an output error of 0.13V. this compares with a sinusoidal PWM (THD% = 3.73%, response time = 136ms and output error = 0.23V). SVPWM proves to have better overall performance.

MATLAB's Simulink is used to build and test the performances of each inverter and then compare the inverters with a pre-existing three-phase grid.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Since its discovery, electricity has proved to be the most reliable and efficient way for operating devices [1]. Heat, wind and other forms of energy can be used to generate electricity, which is transmitted over long distances and transformed back into any form of power needed.

This thesis starts with the design process of a standard full-bridge single-phase inverter. Single-phase inverters are the basic building block for three-phase or multiphase inverters [2]. Industrial applications of inverters vary from adjustable speed AC drives to converting renewable energy to AC form [2]. Later in chapter 2 the single-phase full-bridge inverter design is expanded into a three-phase inverter. Using two approaches to control the three-phase inverter, sinusoidal pulse width modulation PWM and space vector as a reference in SVPWM.

Single-phase inverters produce low power for smaller applications. For medium to high power applications three-phase inverters are needed [2]. Three-phase inverters have to generate three-phase output with controllable magnitude, phase and frequency. A standard three-phase inverter is shown in figure 3.1.

All inverters are constructed using power switches, switching causes the output to have discrete values (figure 2.2). To obtain a smooth output current the load should have inductance at the harmonic frequencies [2].

Chapter 2, titled “Inverter Design”, presents an overview of single-phase full-bridge inverter. The design process and implementation are covered. It also describes the control methods used with single-phase inverters.

Chapter 3, in this chapter the single-phase inverter is expanded into three-phase inverter. It describes method of generating PWM for three-phase PWM inverters. First method uses a sinusoidal waveform to generate the control signals. The second method uses a space vector as a reference to generate the control signals.

Chapters 4, the different approaches (PWM and SVPWM) are designed using Simulink. It starts with PWM signal generated using a sinusoidal wave and then using a space vector. Space vector model includes αβ transformation, sector selection, fundamental times and switching time generation.

Chapter 5, using the same parameters and loads for both inverters, both are tested and then compared with a grid reference. The output voltage and current are measured and displayed. Total harmonic distortion is also measured for both inverters

Chapter 6 shows the IEEE 1547 standards governing inverters to be used as grid-tie inverters (inverters connected to the grid).

Appendix A, describes the design and implementation of Buck, Boost and Buck-Boost converters and their importance in today’s systems.

2. INVERTER DESIGN

2.1. INTRODUCTION

While traditional generators provide AC power directly, most of the renewable resources provide DC power. Inverters have the task of converting that DC to AC using a switching mechanism that gives AC voltage as an output.

The switching is accomplished using power electronic switches controlled by a signal source. PWM is used to generate signals (pulses) varying in width. The wider the pulse the higher the output voltage is.

To generate an alternating current the output voltage need to have positive and negative cycles. This is achieved by using at least two switches (upper and lower legs) the upper switch is responsible of the positive cycle and the lower switch is responsible of the negative cycle [2].

PWM will have varying range of output control signals depending on the inverter functionality. In the simplest inverter with two switches two signals are needed while in three-phase inverters six or twelve signals might be needed depending on the design. Since the input and output voltages are not fixed at any given moment, the inverter should have a feed-back sent to the controller, which in turn will modify the switching signal fed to the switches to correct the output errors.

2.2. INVERTER DESIGN

Figure 2.1 show the design of a full-bridge inverter. It consists of four switches, two for the positive cycle and the other two for the negative cycle. Only one switch from the top and one from the bottom can be on simultaneously, this will protect the source from voltage feedback [2].

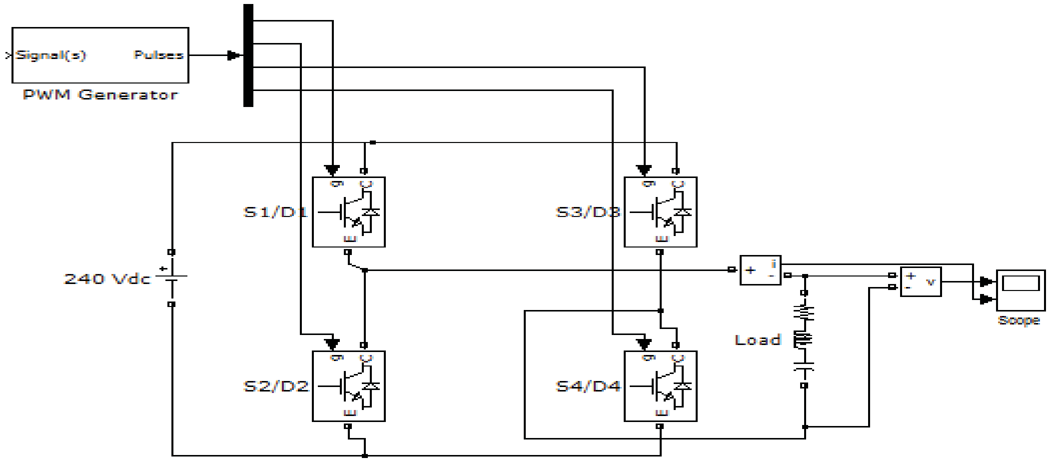


Figure 2.1. Single-phase, Full-bridge inverter

Since S_1 and S_3 or S_2 and S_4 cannot be on at the same time (the current will flow back to the source), there will be four different states of operation (1, 2, 3 and 4) and they are shown in table 2.1.

The cycle is repeated periodically to achieve the desired output frequency. Normally 60Hz in the United States.

Table 2.1. Switch states in a single-phase full bridge inverter

State #	State	Active Components	V_{aN}	V_{bN}	V_o
1	S_1, S_4 on. S_2, S_3 off	S_1, S_4, D_1, D_4	$V_{in}/2$	$-V_{in}/2$	V_{in}
2	S_2, S_3 on. S_1, S_4 off	S_2, S_3, D_2, D_3	$-V_{in}/2$	$V_{in}/2$	$-V_{in}$
3	S_1, S_3 on. S_2, S_4 off	S_1, S_3, D_1, D_3	$V_{in}/2$	$-V_{in}/2$	0
4	S_2, S_4 on. S_1, S_3 off	S_2, S_4, D_2, D_4	$-V_{in}/2$	$V_{in}/2$	0

The output voltage of the full bridge inverter is a square waveform with a fundamental component centered at the fundamental frequency [2]:

$$v_o = v_i m_i \tag{2.1}$$

where v_o is the output voltage, v_i is the input voltage and m_i is the modulation index.

Harmonics are the distortion in the output waveform which occurs at integer multiples of the fundamental (desired) frequency. For the full-bridge inverter used the harmonics generated are the odd harmonics and the even ones are self-eliminated [2].

The system shown in figure 2.1 is connected to $24V_{dc}$ source and 1500VA load. Figure 2.2 shows the output voltage of the inverter at $170V_{p-p}$ and the output current is shown in figure 2.3.

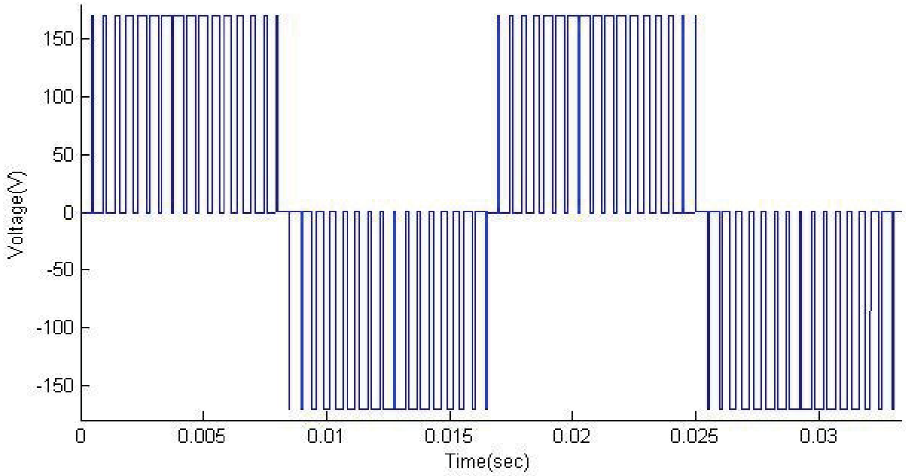


Figure 2.2. Full-bridge inverter output voltage

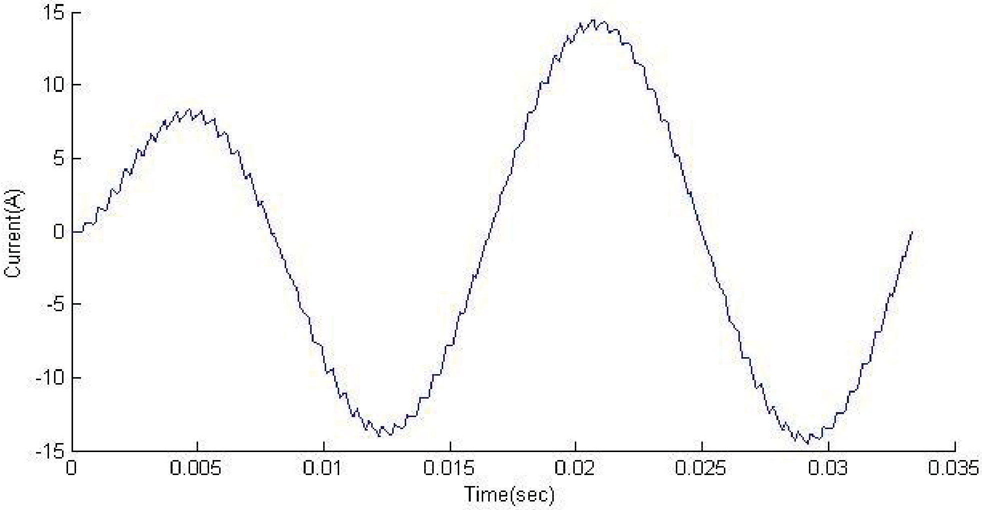


Figure 2.3. Full-bridge inverter output current

2.3. CONTROL OF VOLTAGE SUPPLIED TO THE INVERTER

Several methods were proposed to achieve control over the inverter's input most of which are obsolete [3]:

- Induction regulators.

- Saturable reactors.
- Magnetic amplifiers.
- Phase-controlled rectifiers.
- Transistor controlled rectifiers.
- Semiconductor switching-type DC voltage controls.

Semiconductor switching-type DC voltage controls is what is also known as DC/DC converter which has been discussed later in Appendix A.

2.3.1. Control of Voltage within the Inverter

The most efficient and widely used method to control voltage within the inverter is Pulse Width Modulation. Other methods that are not used anymore are: Parallel Inverter-Commutation Angle Control and Parallel or Series Inverter Frequency Control.

PWM is easy to implement since the only variable is the pulse width. By increasing the time the switch is on, the output voltage will increase and vice versa. Since the input voltage and the loads connected to the inverter are always changing, PWM inverter should keep the output voltage within the desired range.

2.3.2. Control of the Voltage Supplied To the Load

To control the voltage delivered to the load by an inverter, one of these methods could be used [3]:

- Saturable reactors.
- Magnetic amplifiers.

- Induction regulators.
- AC phase controlled rectifiers.

All of these methods have no effect on the inverter itself. The control over the output voltage is done between the inverter and the load. Adding an external component between the load and the inverter will introduce will increase the cost and reduces the efficiency of the design.

3. THREE-PHASE INVERTER DESIGN

3.1. INTRODUCTION

When transmitting power over long distances or from the generation station the power has to be in three-phase form. The idea of three-phase power system networks was introduced by Nikolai Tesla in 1887 for mainly two reasons [4]:

- It is cheaper to transmit power in three-phase than single or two-phase, speaking in conduction lines needed for the same amount of power.
- Large machines and heavy loads require more power than a single-phase can deliver.

Since a whole cycle of an AC signal takes 360° to complete. Three-phase will require the cycle to be divided into three equally spaced signals. 120° is the phase shift needed between each two signals. The generator, the transmission lines and the loads should all understand and work within this constraint.

Three-phase inverters are a special type of inverters that convert a DC input voltage into a three-phase output voltage. The DC input has to be large enough to provide the power necessary to generate three-phase AC voltage.

Figure 3.1 shows a simple three-phase inverter designed using six switches, two for each phase, the inverter have two legs an upper and lower to provide the positive and negative cycles of the AC voltage cycle.

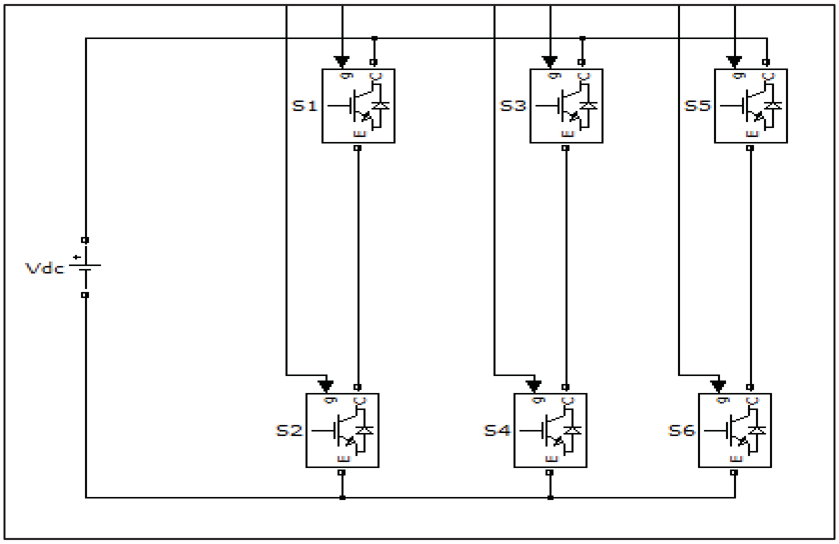


Figure 3.1. Three-phase inverter

As in the full-bridge inverter, S_1 and S_2 or S_3 and S_4 or S_5 and S_6 cannot be simultaneously open or the current will flow back to the source causing a short circuit.

Table 3.1. Switching states of a three-phase inverter

State #	State	v_{ab}	v_{bc}	v_{ca}
1	S_1,S_4 and S_6 are on S_2,S_3 and S_5 are off	v_i	*0*	$- v_i$
2	S_1,S_3 and S_4 are on S_2,S_5 and S_6 are off	*0*	v_i	$- v_i$
3	S_2,S_3 and S_4 are on S_1,S_5 and S_6 are off	$- v_i$	v_i	*0*
4	S_1,S_4 and S_5 are on S_2,S_3 and S_6 are off	$- v_i$	*0*	v_i
5	S_2,S_5 and S_6 are on S_1,S_3 and S_4 are off	*0*	$- v_i$	v_i
6	S_1,S_4 and S_5 are on S_2,S_3 and S_6 are off	v_i	$- v_i$	*0*
7	S_1,S_3 and S_5 are on S_2,S_4 and S_6 are off	*0*	*0*	*0*
8	S_2,S_4 and S_6 are on S_1,S_3 and S_5 are off	*0*	*0*	*0*

There are eight valid states in a three-phase inverter six of those (1 – 6) will produce an output voltage while two (7 and 8) will produce zero voltage on all lines [2]. The states are listed in table 3.1.

3.2. THREE-PHASE PWM INVERTER

A three-phase inverter (shown in figure 3.1) will include: six IGBT/Diode switches (S_1,S_2,S_3,S_4,S_5 and S_6) . The diode will prevent the current from flowing back to the source when the switch is on. Pulse Width Modulating algorithm generating 6-pulses is needed to provide the switches with the driving signals.

Since the output is a square wave constructed from infinite number of sinusoidal harmonics, a pure sine wave is obtained by using filters. Normally the filtering is done with inductors or through the load itself [5].

A three-phase inverter unlike a single-phase inverter must be able to provide a 120° out of phase voltages. To achieve that the modulating frequency (m_f) must be in multiples of three to create 120° phase shift [2].

3.3. THREE-PHASE SVPWM INVERTER

Space vector pulse width modulation became a standard for the switching power inverters and a lot of research has been done on this topic. Many implementation methods were tested and even dedicated hardware circuits were developed to support SVPWM inverters [6].

SVPWM is an advanced method that requires higher computation power. The objective of SVPWM is to generate output voltages equal to a given reference voltage. Space Vector PWM

3.3.1. The αβ Plane

A three dimensional plane can be transformed into a two dimensional plane by using a transformation matrix. In the case of SVPWM the three dimensional plane is the three-phase voltage and the two dimensional plane is the αβ plane. The αβ plane contains a voltage vector with a magnitude and angle [6].

For a three-phase voltage to be represented in a two dimensional plane it needs a voltage reference with a magnitude an angle such as V_{ref} and θ.

In three-phase balanced system the voltages V_a, V_b and V_c can be represented as [7]:

$$V_a = Vsin(\omega t) \tag{3.1}$$

$$V_b = Vsin\left(\omega t + \frac{2\pi}{3}\right) \tag{3.2}$$

$$V_c = Vsin\left(\omega t + \frac{4\pi}{3}\right) \tag{3.3}$$

$$V_a + V_b + V_c = 0 \tag{3.4}$$

where V_a, V_b, V_c are the three-phase voltages and ω is the angular frequency.

The transformation process (also known as Clarke transformation) is done using the following equations (in the negative abc sequence):

$$V_{ref} = V_\alpha + jV_\beta = \frac{2}{3}[V_a + aV_b + a^2V_c] \tag{3.5}$$

Where:

$$a = e^{\frac{2j\pi}{3}}, \qquad a^2 = e^{\frac{4j\pi}{3}} \tag{3.6}$$

Equation (3.5) can be rewritten as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.7}$$

Similarly:

$$V_\alpha = V_a - \frac{1}{2}V_b - \frac{1}{2}V_c \tag{3.8}$$

$$V_\beta = \frac{\sqrt{3}}{2}V_b - \frac{\sqrt{3}}{2}V_c \tag{3.9}$$

The magnitude of the reference voltage is given by:

$$|V_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \tag{3.10}$$

And the angle θ is:

$$\theta = \tan^{-1}\frac{V_\beta}{V_\alpha} \tag{3.11}$$

Since the inverter used have an upper and lower legs and each have three eight switching states are needed: 000, 001, 010, 011, 100, 101, 110, 111 [8]. Six of these states will generate an output signal (similer to a three-phase sinusoidal PWM inverter) 000 and 111 being non-active switching states with all gates being open or closed. The six states 001, 010, 011, 100, 101, 110 are shown in figure 3.2 between each two states there is a sector with the total of six sectors [6][7].

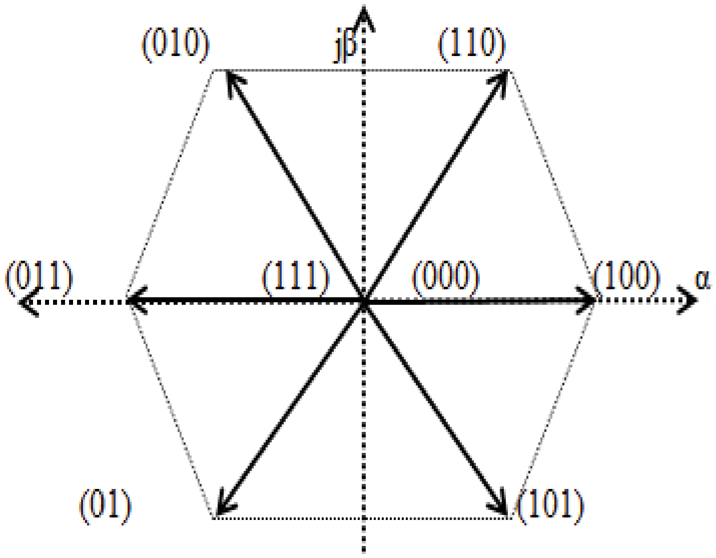


Figure 3.2. Voltage sectors in the αβ Plane

3.3.2. Sector Selection

Finding the sector in where the reference vector resides is simple. The vector can only fall in one of six sectors 1 – 6 with each two sectors being 60º apart. Comparing the angle θ with the limits of each sector enables the sector selector to determine the current sector and the corresponding states associated with it.

The limits of each sector and the corresponding sector number are listed in table 3.2.

Table 3.2. Using θ for sector selection

V_{ref} angle	Sector Number
$0 \leq \theta < \frac{\pi}{3}$	1
$\frac{\pi}{3} \leq \theta < \frac{2\pi}{3}$	2
$\frac{2\pi}{3} \leq \theta < \pi$	3
$-\pi \leq \theta \leq -\frac{2\pi}{3}$	4
$-\frac{2\pi}{3} \leq \theta < -\frac{\pi}{3}$	5
$-\frac{\pi}{3} \leq \theta \leq 0$	6

3.3.3. Duty Cycle Calculations

The duty cycle in each sector must be determined and since each sector consists of three vectors (shown in figure 3.3) . Equations (3.10) and (3.11) are used to find the location of the reference vector's magnitude and angle.

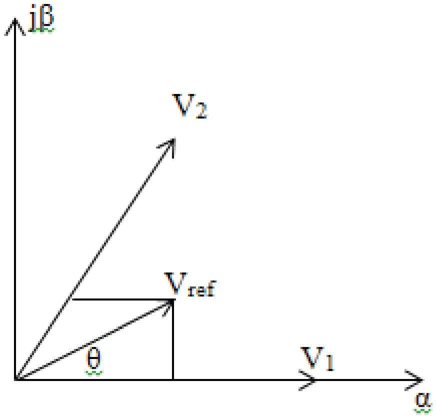


Figure 3.3. V_{ref} in the first sector

For simplicity sector one was used to find the duty cycle values corresponding to T_1, T_2 and T_0 [6] [7].

$$V_{ref} \times T_{cycle} = V_1 T_1 + V_2 T_2 + V_0 T_0 \tag{3.12}$$

where T_{cycle} is the time needed to complete a whole cycle

$$T_{cycle} = T_1 + T_2 + T_0 \tag{3.13}$$

for the first sector:

$$\left|V_{ref}\right| \sin(\theta) = \frac{T_2}{T_{cycle}} \times |V_2| \sin\left(\frac{\pi}{3}\right) \tag{3.14}$$

or:

$$T_2 = T_{cycle} \times M \times \frac{\sin(\theta)}{\sin\left(\frac{\pi}{3}\right)} \tag{3.15}$$

where M is the modulation index and is equal to:

$$M = \frac{\left|V_{ref}\right|}{|V_2|} \tag{3.16}$$

similarly for T_1:

$$T_1 = T_{cycle} \times M \times \frac{\sin\left(\frac{\pi}{3} - \theta\right)}{\sin\left(\frac{\pi}{3}\right)} \tag{3.17}$$

and for T$_0$:

$$T_0 = T_{cycle} - T_1 - T_2 \tag{3.18}$$

The general expression for the other sectors duty times. For T$_1$:

$$T_1 = T_{cycle}\frac{\sqrt{3}}{V_{DC}}V_{ref}\left[\sin\left(\frac{n}{3}\pi\right)\cos(\theta) - \cos\left(\frac{n}{3}\pi\right)\sin(\theta)\right] \tag{3.19}$$

and for T$_2$:

$$T_2 = T_{cycle}\frac{\sqrt{3}}{V_{DC}}V_{ref}\left[-\sin\left(\frac{n-1}{3}\pi\right)\cos(\theta) + \cos\left(\frac{n-1}{3}\pi\right)\sin(\theta)\right] \tag{3.20}$$

where n = 1, 2, 3, 4, 5, and 6. And V$_{DC}$ is the DC input voltage.

Table 3.3. Duration times for the six active sectors

Sector	Duration Times		
	T$_1$	T$_2$	T$_0$
1	$T_{cycle} \times M \times \sin\left(\frac{\pi}{3} - \theta\right)$	$T_{cycle} \times M \times \sin(\theta)$	$T_{cycle} - T_1 - T_2$
2	$T_{cycle} \times M \times \sin\left(\frac{2\pi}{3} - \theta\right)$	$T_{cycle} \times M \times \sin\left(\theta - \frac{\pi}{3}\right)$	$T_{cycle} - T_1 - T_2$
3	$T_{cycle} \times M \times \sin(\pi - \theta)$	$T_{cycle} \times M \times \sin\left(\theta - \frac{2\pi}{3}\right)$	$T_{cycle} - T_1 - T_2$
4	$T_{cycle} \times M \times \sin\left(\frac{4\pi}{3} - \theta\right)$	$T_{cycle} \times M \times \sin(\theta - \pi)$	$T_{cycle} - T_1 - T_2$
5	$T_{cycle} \times M \times \sin\left(\frac{5\pi}{3} - \theta\right)$	$T_{cycle} \times M \times \sin\left(\theta - \frac{4\pi}{3}\right)$	$T_{cycle} - T_1 - T_2$
6	$T_{cycle} \times M \times \sin(2\pi - \theta)$	$T_{cycle} \times M \times \sin\left(\theta - \frac{5\pi}{3}\right)$	$T_{cycle} - T_1 - T_2$

Equations (3.19) and (3.20) can be used with any of the active sectors. For the inactive sectors (7 and 8) T$_0$ is used which does not depend on the location of the reference voltage (shown in table 3.3).

3.3.4. Switching Time

The duty cycle times for each sector are used to create the switching (control) signals applied to the gates [8]. Table 3.4 lists all the switching states available.

Table 3.4. Switching states with their corresponding sectors

Sector	Upper leg signals		Lower leg signals	
1	S_1	$T_1 + T_2 + \frac{T_0}{2}$	S_2	$\frac{T_0}{2}$
	S_3	$T_2 + \frac{T_0}{2}$	S_4	$T_1 + \frac{T_0}{2}$
	S_5	$\frac{T_0}{2}$	S_6	$T_1 + T_2 + \frac{T_0}{2}$
2	S_1	$T_2 + \frac{T_0}{2}$	S_2	$T_1 + \frac{T_0}{2}$
	S_3	$T_1 + T_2 + \frac{T_0}{2}$	S_4	$\frac{T_0}{2}$
	S_5	$\frac{T_0}{2}$	S_6	$T_1 + T_2 + \frac{T_0}{2}$
3	S_1	$\frac{T_0}{2}$	S_2	$T_1 + T_2 + \frac{T_0}{2}$
	S_3	$T_1 + T_2 + \frac{T_0}{2}$	S_4	$\frac{T_0}{2}$
	S_5	$T_2 + \frac{T_0}{2}$	S_6	$T_1 + \frac{T_0}{2}$
4	S_1	$\frac{T_0}{2}$	S_2	$T_1 + T_2 + \frac{T_0}{2}$
	S_3	$T_2 + \frac{T_0}{2}$	S_4	$T_1 + \frac{T_0}{2}$
	S_5	$T_1 + T_2 + \frac{T_0}{2}$	S_6	$\frac{T_0}{2}$
5	S_1	$T_2 + \frac{T_0}{2}$	S_2	$T_1 + \frac{T_0}{2}$
	S_3	$\frac{T_0}{2}$	S_4	$T_1 + T_2 + \frac{T_0}{2}$
	S_5	$T_1 + T_2 + \frac{T_0}{2}$	S_6	$\frac{T_0}{2}$
6	S_1	$T_1 + T_2 + \frac{T_0}{2}$	S_2	$\frac{T_0}{2}$
	S_3	$\frac{T_0}{2}$	S_4	$T_1 + T_2 + \frac{T_0}{2}$
	S_5	$T_2 + \frac{T_0}{2}$	S_6	$T_1 + \frac{T_0}{2}$

4. INVERTER MODELING

4.1. INTRODUCTION

Using software programs to model a system for testing purposes is cheaper than physically building the system. Simulink is considered one of the leading programs to be used with power systems and it has many useful features needed to study power system.

The switching part of the inverter is shown with all of its components. The generation of the pulses to drive the six switches in PWM is done using sinusoidal signals and a single carrier signal. Building a space vector PWM inverter needs several parts to: create the αβ plane, find V_{ref} and the angle θ, decide which sector is currently being used, and find the duty cycle and fundamental times.

4.2. PWM THREE-PHASE INVERTER MODELING

Using Simulink a three-phase PWM inverter can be designed using six IGBT/Diode gates and a PWM generator with feedback input.

PWM signal generator uses the combination of two signals (shown in figure 4.1): a sinusoidal signal and a triangular carrier signal. The two signals are compared, when the sinusoidal signal is greater in value than the carrier signal the output is one otherwise it will be zero. This output signal is then used to control the switches of the inverter.

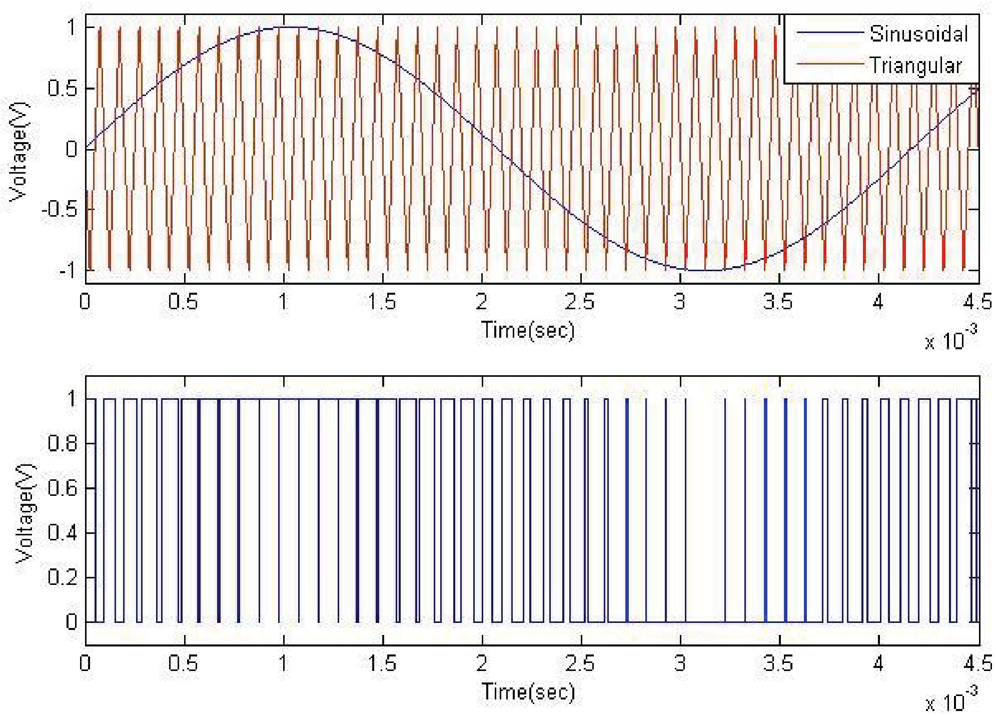


Figure 4.1. PWM signal generation

Figure 4.2 shows the inverter with the PWM and the feedback signal.

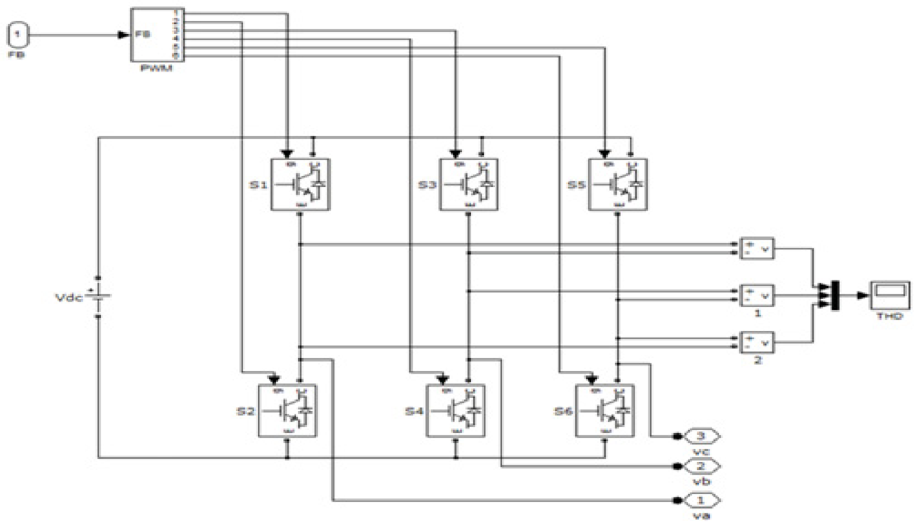


Figure 4.2. Three-phase PWM inverter model

Figure 4.3 shows the inside of the PWM where there is three sine wave sources and a triangular signal with the comparison and data conversion parts needed.

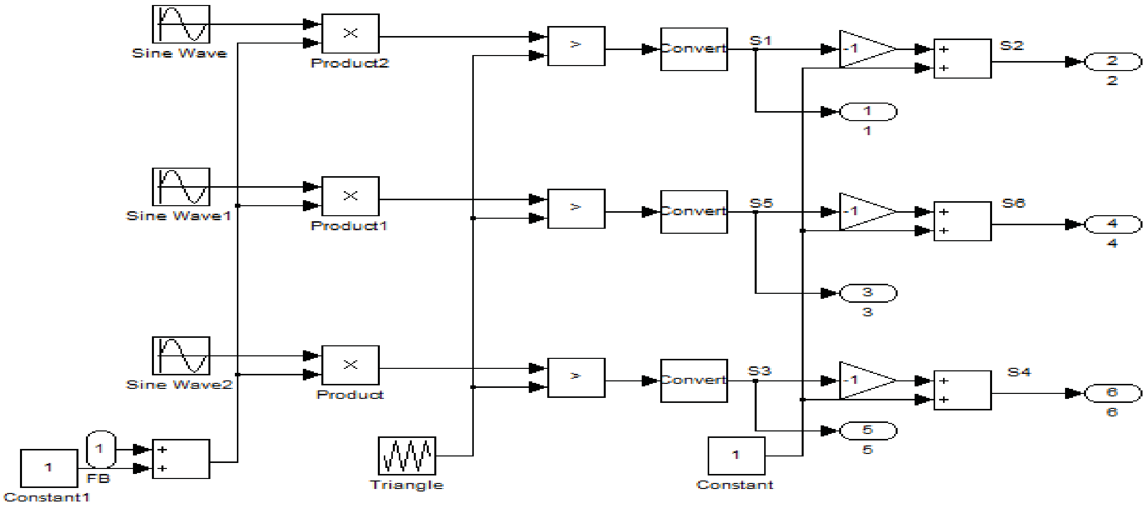


Figure 4.3. Three-phase PWM generation

4.3. SVPWM THREE-PHASE INVERTER MODELING

There are several parts needed in the design of a three-phase space vector pulse width modulation inverter. Each part is described separately in the next sections.

4.3.1. αβ transformation

The Simulink part responsible for generating and calcuating the values of V_α, V_β, V_{ref} and θ is shown in figure 4.4. Next step would be evaluating the fundamental time duration for each sector T_1, T_2 and T_0 (since at any given moment V_{ref} will be between two active states and one zero state).

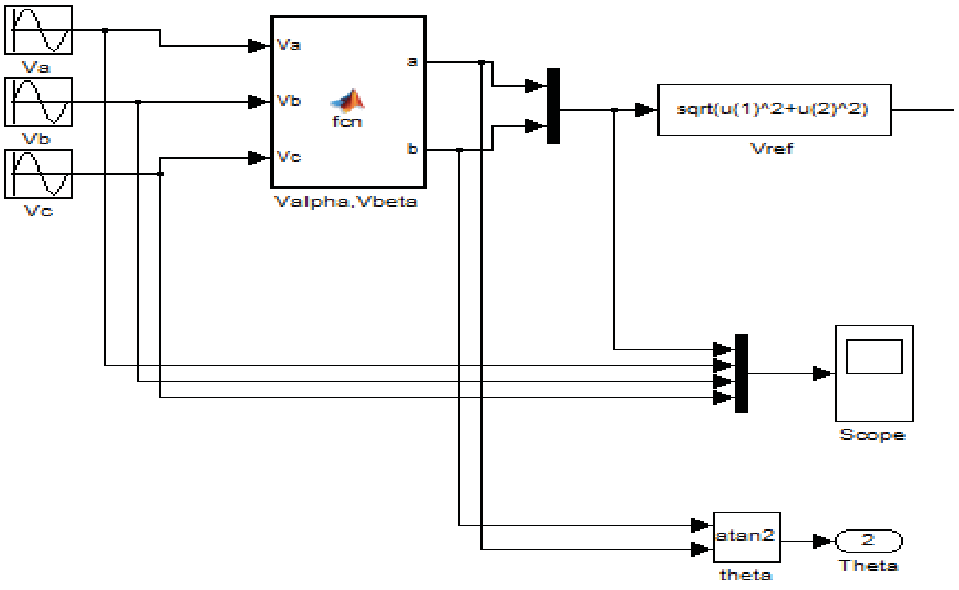


Figure 4.4. Simulink model used to generate V_α, V_β, V_{ref} and θ

The MATLAB function used to generate α and β is:

```
function [a,b] = fcn(Va,Vb,Vc)
sq23 = sqrt(2/3);
a = sq23*(Va-(Vb/2) - (Vc/2));
b = sq23*((sqrt(3)*Vb/2) - (sqrt(3)*Vc/2));
```

4.3.2. Sector selection

Sector selection is achieved by a comparing the angle θ with the limits of each sector to determine which sector the reference voltage is in. Using a mix of rational operators $(<, \leq, >, \geq)$ and logic AND for comparison.

```
(0<u[1] && u[1]<=pi/3)*(1)+(pi/3<u[1] &&
u[1]<=2*pi/3)*(2)+(2*pi/3<u[1] && u[1]<=pi)*(3)+(-
pi<=u[1] && u[1]<=-2*pi/3)*(4)+(-2*pi/3<u[1] && u[1]<=-
pi/3)*(5)+(-pi/3<u[1] && u[1]<=0)*(6)
```

4.3.3. Fundamental Time calculation

To find the fundamental times (T_0, T_1, and T2). The sampling time, sector number, the angle and modulation index where used in addition to some math functions as shown in figure 4.5.

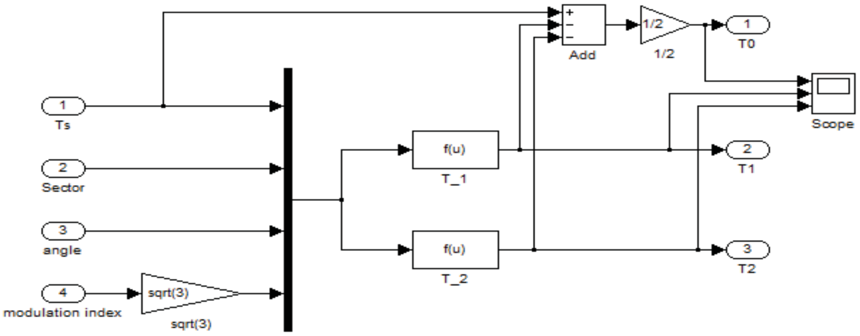


Figure 4.5. Calculating fundamental cycle times T_0, T_1, T_2

T_1 is found using the following MATLAB function:

```
u(1)*u(4)*(sin(u(2)*pi/3)*cos(u(3))-
cos(u(2)*pi/3)*sin(u(3)))
```

Similarly T2 could be found using the following MATLAB function:

```
u(1)*u(4)*(sin(u(2)*pi/3)*cos(u(3))-

cos(u(2)*pi/3)*sin(u(3)))
```

4.3.4. Switching Times

Three switching signals are needed at any given moment and the other three can be the exact inverse of the original three. In the inverter however the upper leg and lower leg operate opposite to each other.

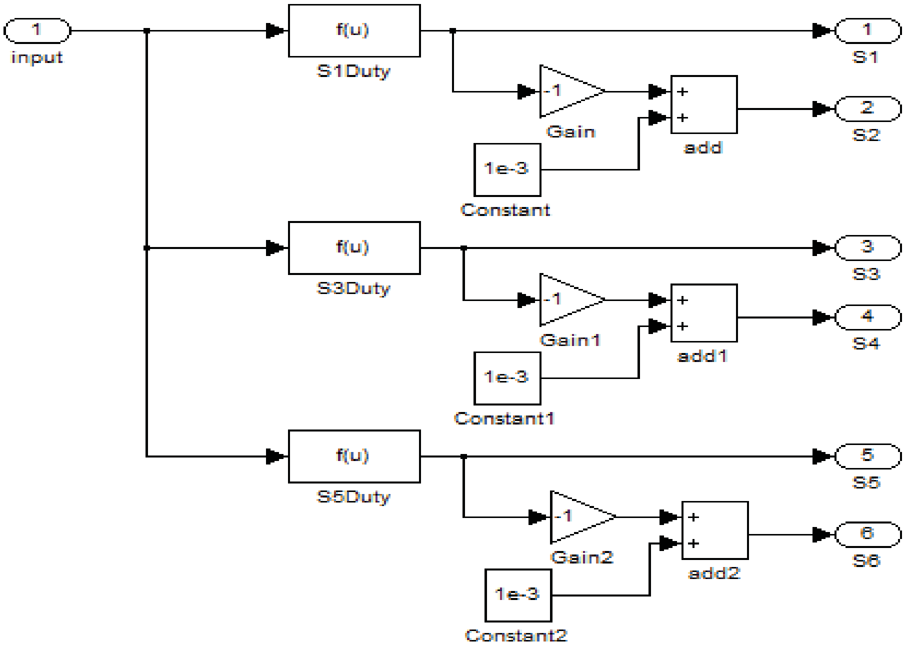


Figure 4.6. Sinusoidal signals generation

Figure 4.6 is the Simulink model used to generate the switching times.

Given that inputs are T_0, T_1, T_2 and sector number in the same exact order, S_1 the MATLAB function used is:

```
(u[4]==1)*(u[1]+u[2]+u[3])+(u[4]==6)*(u[1]+u[2]+u[3])+(u[
4]==2)*(u[1]+u[2])+(u[4]==3)*(u[1])+(u[4]==4)*(u[1])+(u[4
]==5)*(u[1]+u[3])
```

S_3 function is:

```
(u[4]==1)*(u[1]+u[2]+u[3])+(u[4]==6)*(u[1]+u[2]+u[3])+(u[
4]==2)*(u[1]+u[2])+(u[4]==3)*(u[1])+(u[4]==4)*(u[1])+(u[4
]==5)*(u[1]+u[3])
```

And S_5 is:

```
(u[4]==6)*(u[1]+u[2])+(u[4]==1)*(u[1])+(u[4]==2)*(u[1])+(
u[4]==3)*(u[1]+u[3])+(u[4]==4)*(u[1]+u[2]+u[3])+(u[4]==5)
*(u[1]+u[2]+u[3])
```

These signals are useless since they are not PWM signals, to generate PWM signals a carrier signal must be used. A saw-tooth signal is a perfect carrier signal and the control signals are obtained by comparing the switching signals and the carrier signal. When the value of the switching signal is greater than the value of the carrier signal the output is set to 1 otherwise it is set to 0.

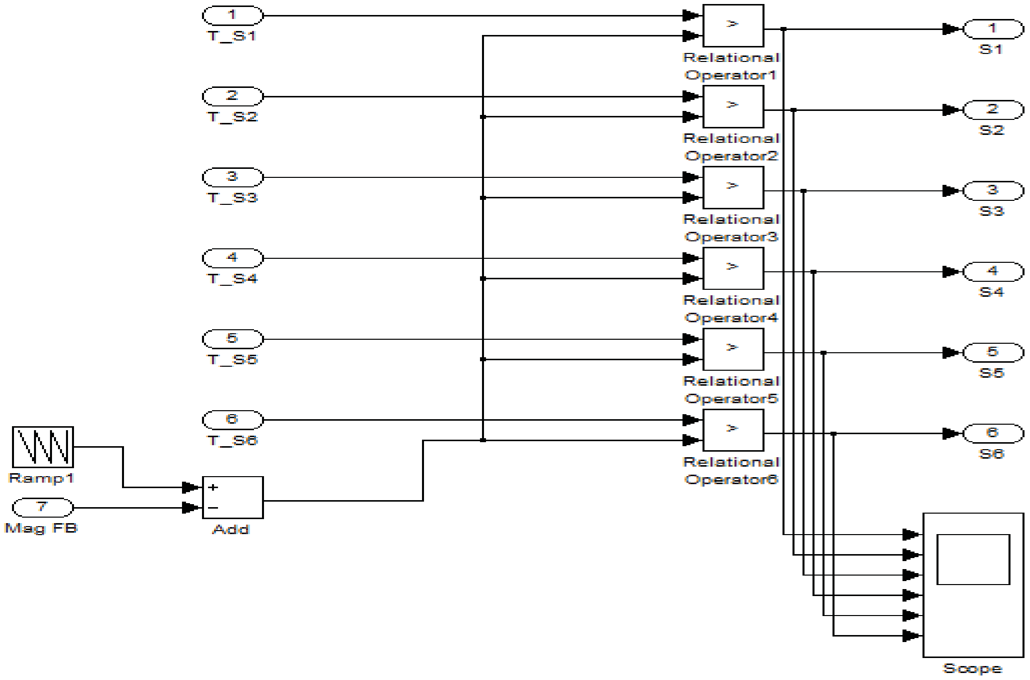


Figure 4.7. Switching signals generation

The generation of the switching signals is done using the model shown in figure 4.7.

4.3.5. The actual inverter

The only difference between a SVPWM inverter and a sinusoidal PWM inverter is the generation of the switching signals. Hence the inverter part is exactly the same in both configurations.

5. IMPLEMENTATION

5.1. INTRODUCTION

The two inverters shown in figures 5.1 and 5.4 are connected to equal loads and both have same parameters:

- 12KW+j9Kvar Y-connected floating load is connected to both inverters.
- 1000 V_{DC} supplied to both inverters.
- 480V_{RMS} grid source for comparison purposes.
- Voltage control fed to the sinusoidal signal in the PWM by alternating the limits of the output of the sine wave.
- Voltage control fed to the saw-tooth signal in the SVPWM by alternating the limits of the saw-tooth signal, when increased the output of the inverter drops.

5.2. THREE-PHASE PWM INVERTER RESULTS

Figure 5.1 shows the three-phase PWM inverter which consists of:

1. Three-phase PWM inverter.
2. Grid Simulation block.
3. Voltage control block.
4. I, V measurement block.

5. Balanced three-phase load.

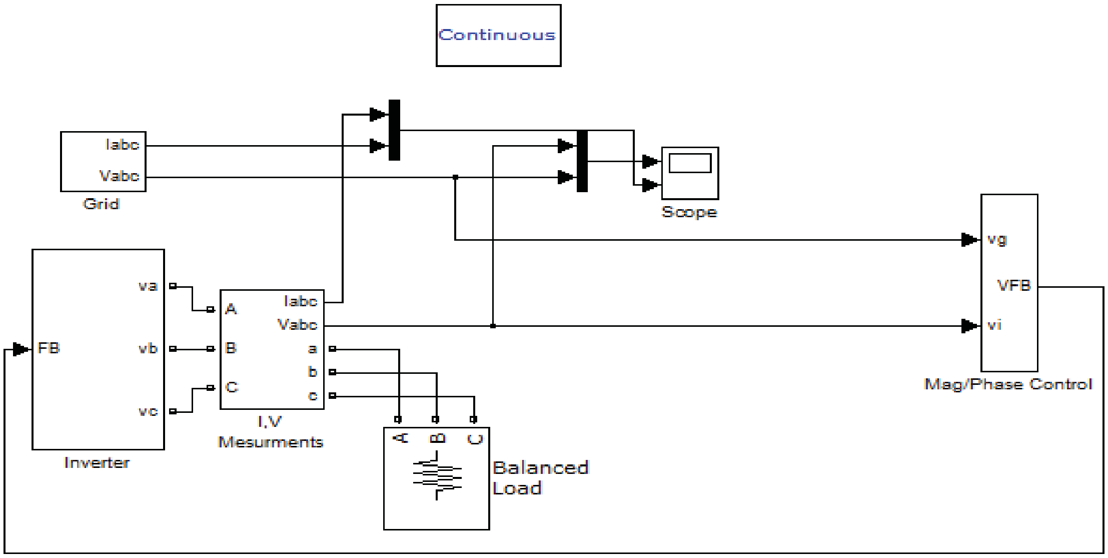


Figure 5.1. Three-phase PWM inverter

The output voltage V_{ab} of the three-phase PWM inverter is shown in figure 5.2

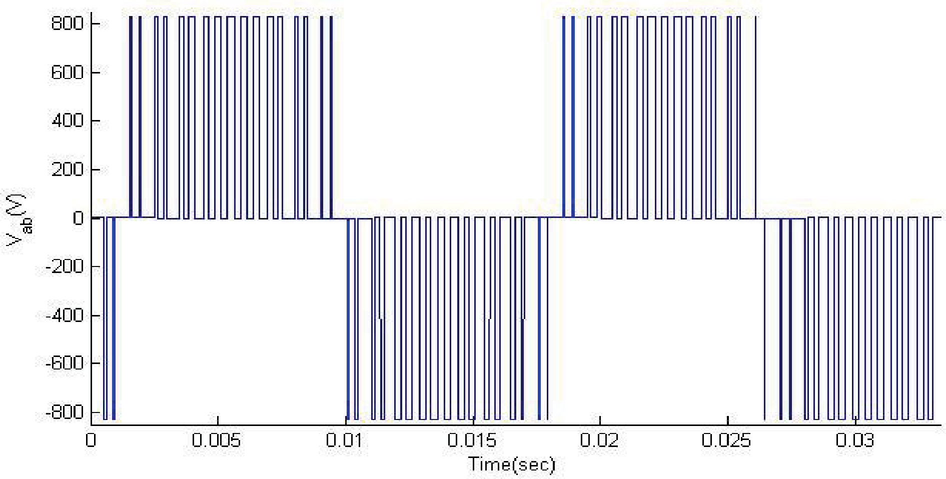


Figure 5.2. Three-phase PWM output voltage

The output RMS voltage of the inverter is 479.77 V (compared to the grid at 480 V)

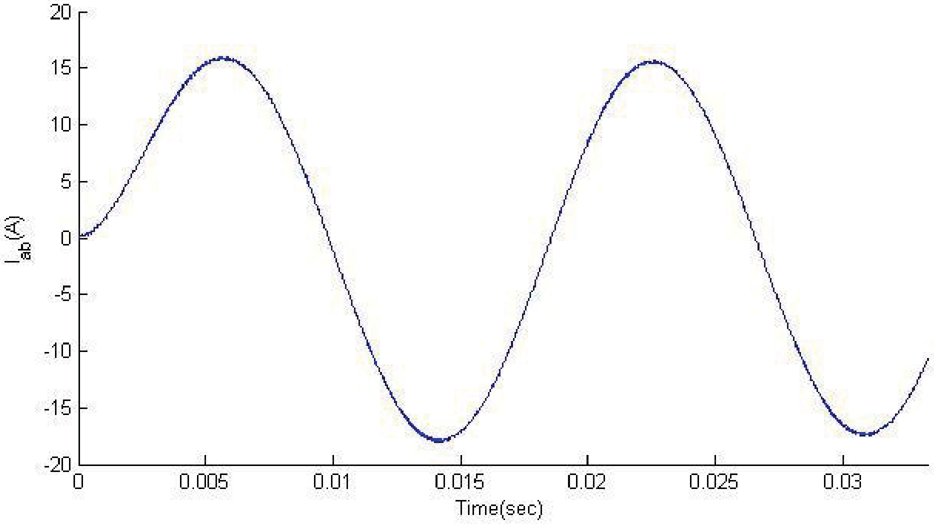


Figure 5.3. Three-phase PWM output current

Figure 5.3 shows the output current of the three-phase PWM inverter.

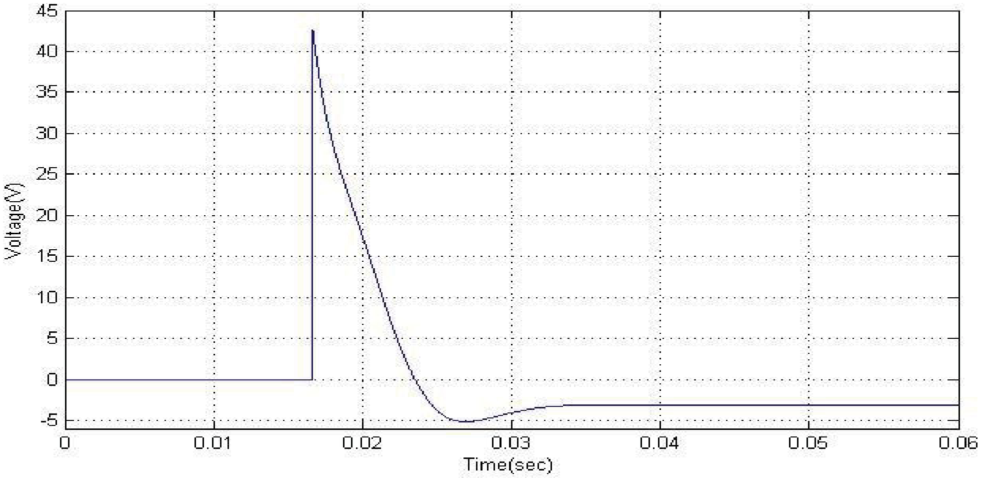


Figure 5.4. Sequence analyzer output for PWM inverter

Using a discrete three-phase sequence analyzer with negative sequence the difference between the grid and the inverter is found and shown in figure 5.4. The same output is also used to generate a feedback signal to the inverter. The feedback signal is fed to the sinusoidal signal inside the PWM generator shown in figure 4.3. THD of phase-a is 3.73%

5.3. THREE-PHASE SVPWM INVERTER RESULTS

Figure 5.5 show the Simulink model for three-phase SVPWM inverter. The components are:

1. $\alpha\beta$ transformation and V_{ref}, θ.
2. Sector selection.
3. Switching time calculations
4. Three-phase PWM Inverter.
5. Grid Simulation block.
6. Voltage control block.
7. I, V measurement block.
8. Balanced three-phase load.

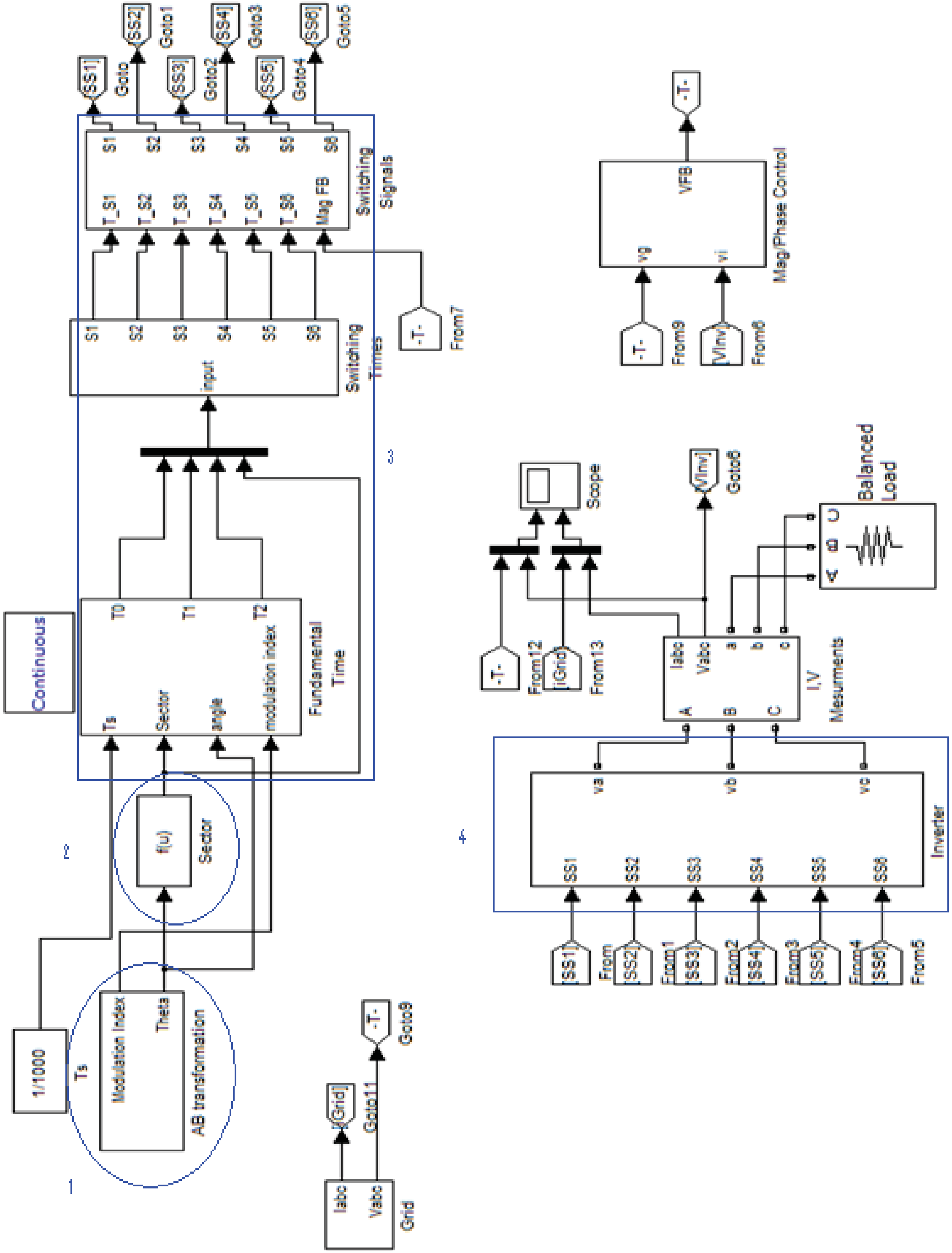


Figure 5.5. Three-phase SVPWM inverter

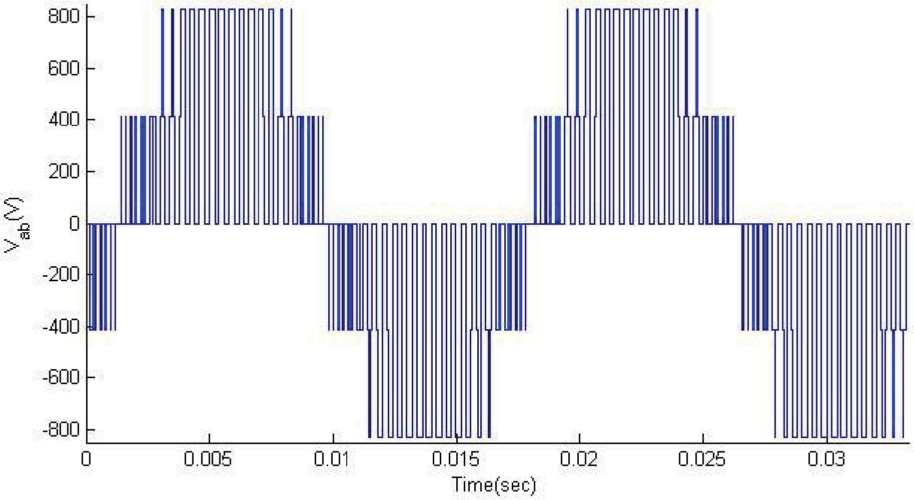


Figure 5.6. Three-phase SVPWM inverter output voltage

The output voltage of the three-phase SVPWM inverter is shown in figure 5.6. The RMS value of the output is 479.87V (compared to 480V in the grid).

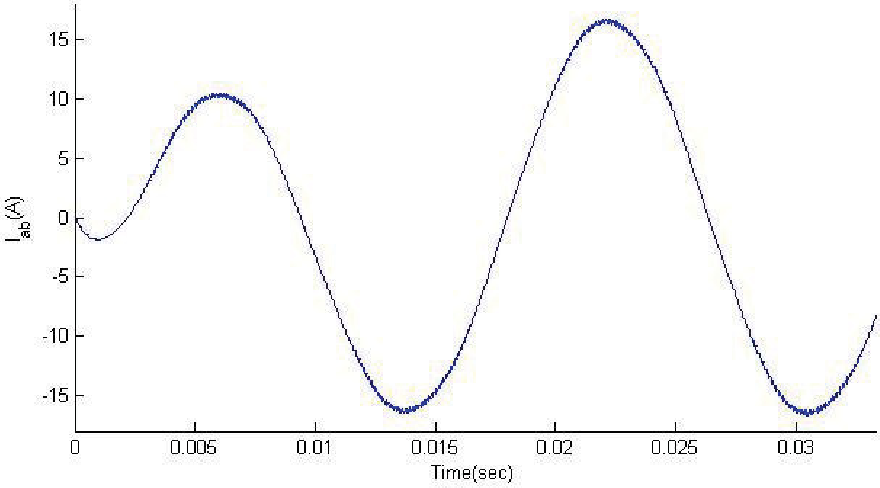


Figure 5.7. Three-phase SVPWM inverter output current

Figure 5.7 show the output current of the three-phase SVPWM inverter.

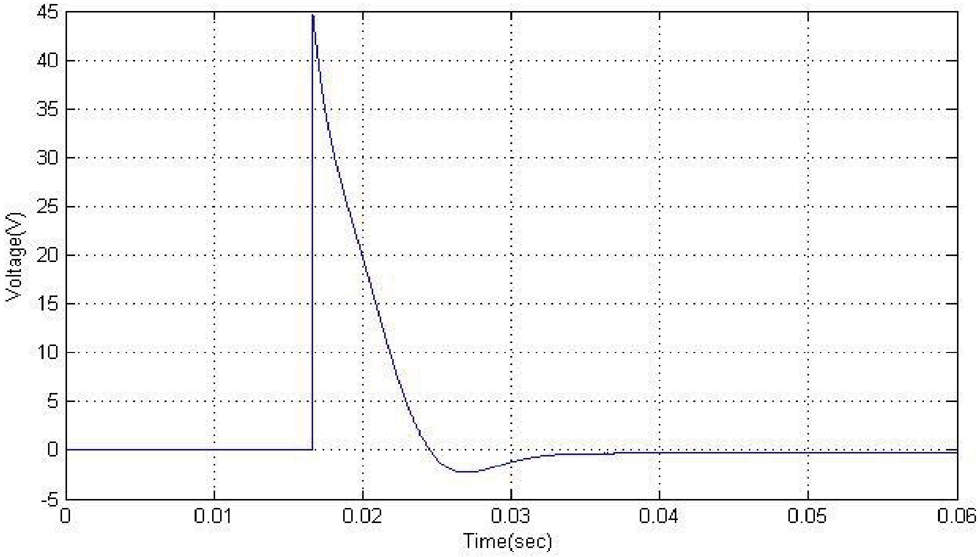


Figure 5.8. Sequence analyzer output for SVPWM inverter

As in the three-phase PWM a discrete three-phase sequence analyzer with negative sequence is used to find the difference between the grid and the inverter (shown in figure 5.8). The voltage difference is then used to generate feedback signal fed to the saw-tooth signal in figure 4.7. THD of phase-a is 1.15%.

Table 5.1 shows the differences between the two inverters in terms of total harmonic distortion, output voltage error, time before final value is reached and output power.

Table 5.1. Comparison between three-phase PWM inverter and SVPWM inverter

Category	PWM inverter	SVPWM inverter
THD%	3.73%	1.15%
Voltage Error(V_{RMS})	0.23	0.13
Settling Time(ms)	136	114
Active Power(W)	5435	5402

6. IEEE 1547, STANDARD FOR INTERCONNECTING DISTIBUTED RESOURCES WITH POWER SYSTEMS

6.1. INTRODUCTION

IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems was introduced to facilitate electric power systems integration with the already running grid, it provide a set of standards and constrains to protect both the grid and all the devices connected to it. The standard was approved by the IEEE in June 2003 and it was approved by the American National Standard in October 2003 [9].

In 2005 the USA Federal Energy Policy Act stated that “Interconnection services shall be offered based upon the standards developed by the Institute of Electrical and Electronics Engineers: IEEE Standard 1547 for Interconnecting Distributed Resources with Electric Power Systems, as they may be amended from time to time".

6.2. LIMITATIONS OF IEEE 1547

The IEEE 1547 does not cover all possible connections or scenarios, thus it does not apply to:

- “P1547.5 Draft Technical Guidelines for Interconnection of Electric Power Sources Greater than 10MVA to the Power Transmission Grid”, was withdrawn leaving that sector uncovered by the IEEE standards.
- All sources should be operating on 60Hz.
- Generation side protection, control and operations.

6.3. IEEE 1547 REQUIREMENTS

IEEE 1547 lists a thorough and deep explanation for safety and reliability when connecting any electrical generation sources to the grid. The most important of those are [10]:

6.3.1. Voltage Regulation

As the voltage at any given moment is not constant because changing loads and on/off cycles, the generation site is not allowed to actively regulate voltage at the point of connection between the site and the grid. Using equipment such as load tap-changing transformers and capacitor banks helps maintaining the whole system voltage at a reasonable range, +10 percent to -5 percent of the operational system voltage.

Problems arising from cycling generation i.e. renewable energy sources like wind and solar, can affect the regulation of voltage greatly, also there is the problem of the power factor PF, which occurs when reactive power is either generated or consumed. Harmonics generated during a DC/AC conversion and one-phase to three-phase conversion also introduces instability.

6.3.2. Power Monitoring

IEEE 1547 requires distributed generation sources rated at 250 kVA or greater at the point of common coupling with the utility grid to be provided with power monitors responsible of:

- Monitoring connection status weather the system is connected or not.
- Real and Reactive power output at the source.
- Operating voltage at the connection point.

Using the collected data values helps the utility companies addressing safety and operation concerns. Power monitoring is not important when the generated power is small compared to the connected loads or when the generation site is self-protected with reverse power relaying and power inverter controls.

6.3.3. Grounding

Grounding is essential for distributed generation sites to help keep the voltage within ratings during faults and islanding operation. IEEE1547 also requires that the grounding scheme used to comply with the utility company in case of a ground fault. Using sensors can help detect ground faults as they happen and effectively disconnect the distributed generation site to avoid overvoltage scenarios.

6.3.4. Synchronization

Synchronization addresses the importance of keeping the voltage magnitude, frequency, phase angle, and phase rotation to be within acceptable tolerance limits.

6.3.5. Back-Feed

Back-feed happens when the utility grid goes offline meaning that the distributed generation site does not feed the grid when it is down. Disconnecting the distributed generation sites can be done using manual switches to help utility personnel manually disconnect the site from the grid at the point of coupling. Another way is to use remotely controlled switches that can be activated by the utility. Commonly a sensory type switch could be used to automatically detect and disconnect the site at the common coupling point in case of power outage or failure.

As a rule the distributed generation site should allow a five minute period after the fault is fixed to reconnect, this period would allow the system voltage and frequency to stabilize before the system is connected again.

6.3.6. Abnormal Operating Conditions

As mentioned before the distributed generation site should always operate within the limits allowed by the grid, power outage and other abnormal conditions regarding voltage and frequency.

6.3.7. Islanding

Islanding happens when the distributed generation site is operating on a part of the grid that has been disconnected due to a failure; this is a problem that requires the system to be disconnected within two seconds after the islanding is discovered. Two seconds is enough to ensure that the loads will not receive overvoltage or disturbed frequency after the utility is disconnect, it will help loads to adjust to the new state and prevent any damage to the loads and the grid too.

7. CONCLUSION AND FURTHER RESEARCH

Due to the growing of fast processing, research today shows great interest to develop new or to modify PWM control to obtain better performance. The conventional PWM introduced in section 3.2 is considered one of the simplest methods used in inverters and can be implemented using simple analogue IC circuit. Although sinusoidal PWM is simple it has some drawbacks including inefficiency, it gives more total harmonic distortion and does not fully support today's application.

Some of these drawbacks led to the development of more sophisticated PWM techniques such as SVPWM. This technique gives better output voltage compared to a sinusoidal PWM inverter. Furthermore, it minimizes the total harmonic distortion in the output.

As seen in table 5.1 SVPWM proved to have better overall performance. The output power on the other hand is less than the output power obtained from the sinusoidal PWM inverter.

The design of sophisticated PWM algorithms requires more computing power. Field-programmable gate array (FPGA) and other digital ICs have become cheaper and more affordable. Thus, algorithms like SVPWM can be easily designed and implemented.

Further research is required to study the benefits and to enhance the performance of space vector modulation. Different methods of control and harmonic elimination must be also considered.

APPENDIX A

CONVERTER DESIGN

A.1. INTRODUCTION

A converter’s role in renewable energy systems is similar to voltage regulators, it will provide constant output voltage within acceptable range of input voltage whether it is higher or lower than the desired output. Power electronic semiconductor switches are used in converters for their efficiency, high operating frequency and their small size. Feedback loops can adapt faster under higher frequencies, meaning less fluctuations in the output [2].

The functionality of a DC/DC converter can be summarized as follows:

- Change the voltage level of the source to the desired output.
- Provide constant voltage output under different load conditions.
- Provide insolation between the source and the load.
- Satisfy safety standards and regulations.

A.2. STEP DOWN (BUCK) CONVERTER

This type of converters is used to reduce the voltage level between the input and output terminals. It consists of voltage source V_S, an inductor L, a capacitor C, a diode D and a switch S [2].

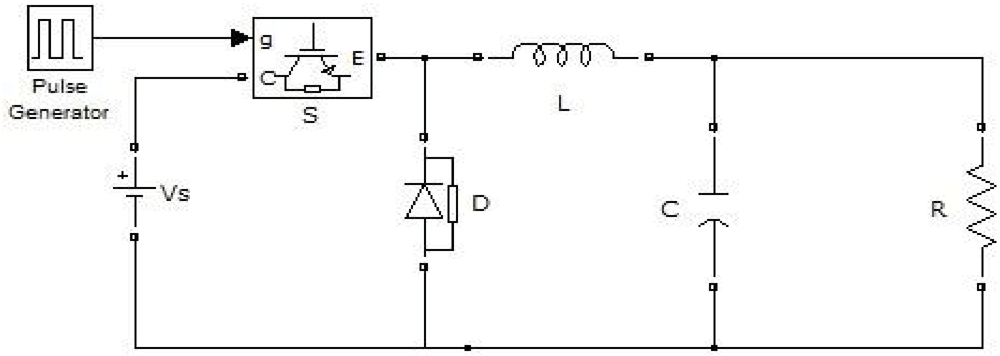


Figure A.1. Buck converter

When the switch is on the diode will not conduct any current and the input voltage will charge the inductor and the capacitor. When the switch is turned off the current is passed to the inductor causing the output voltage to drop.

The equations governing the operation of the converter can be summarized in:

$$(V_S - V_O)DT = -V_O(1-D)T \tag{A.1}$$

where:

V_S: source voltage.

V_O: output voltage.

D: duty ratio.

T: cycle length.

And the relation between the source and output voltage is given by:

$$\frac{V_O}{V_S} = D \tag{A.2}$$

As seen above D is always less than one hence the output voltage is always less than the input voltage.

The values of L and C are derived from the following equations – in Continuous Current Mode CCM the values should be greater than L_b and C_{min}.

$$L_b = \frac{(1-D)R}{2f} \tag{A.3}$$

$$C_{min} = \frac{(1-D)V_O}{8V_r L f^2} \tag{A.4}$$

where V_r is the ripple in the output voltage.

The figures below show the output signals are shown for a buck converter with the following parameters:

- V_S = 10V.
- L = 30μH.
- C = 25 μF.
- R = 10Ω.
- f = 100 kHz.
- D = 0.5.

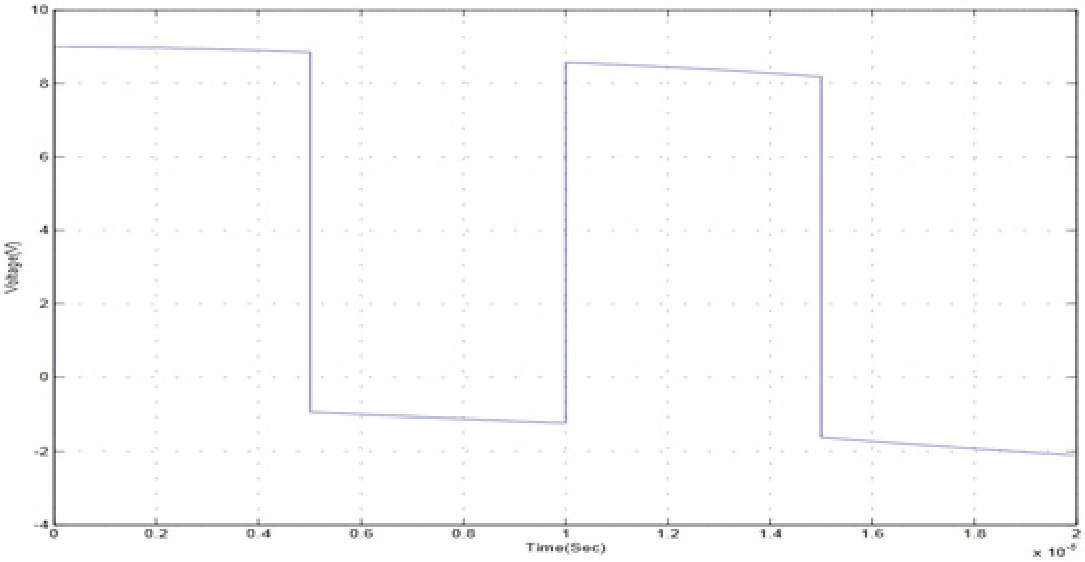


Figure A.2. Inductor voltage

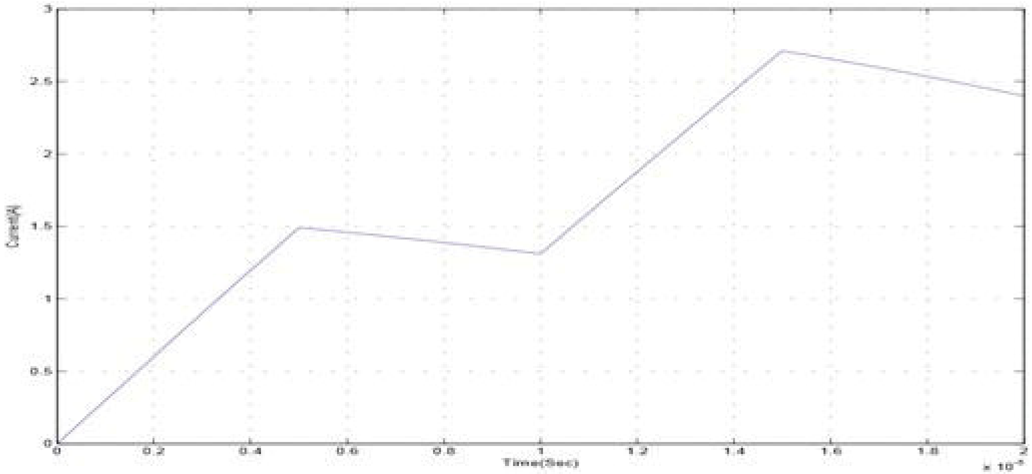


Figure A.3. Inductor current

The output voltage according to equation (A.2) should be 5V but due to the losses in the components it dropped to 4.11V as shown in figure A.4.

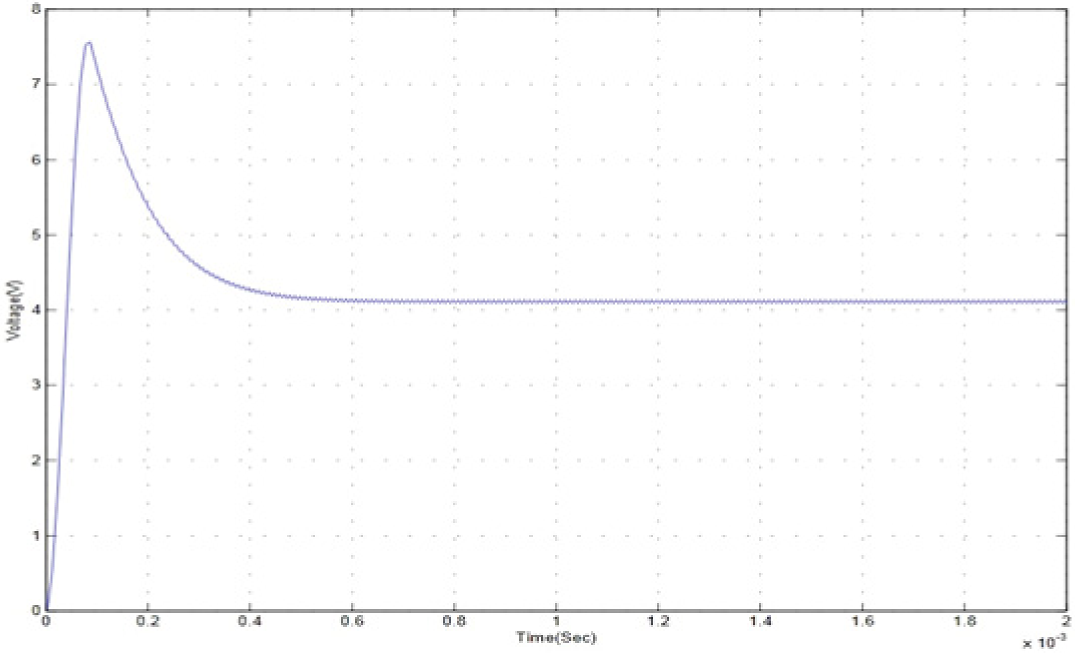


Figure A.4.Buck converter output voltage

A.3. STEP UP (BOOST) CONVERTER

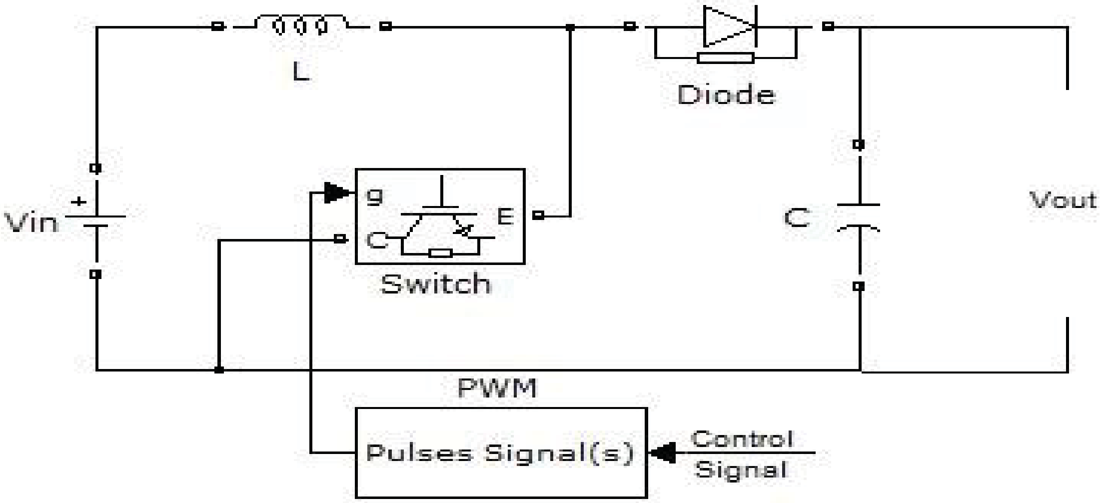


Figure A.5. DC/DC boost converter

Boost converters generates higher output voltages from smaller inputs using the same components with the inductor connected directly to the source:

The equations governing a boost converter are:

$$V_S DT = (V_O - V_S)(1 - D)T \tag{A.5}$$

$$\frac{V_O}{V_S} = \frac{1}{1 - D} \tag{A.6}$$

Since a boost converter will operate in CCM. The values of L and C will depend on the load R, switching frequency f_s and the duty ratio D. thus the minimum value for L will be:

$$L_b = \frac{(1 - D)^2 DR}{2f_s} \tag{A.7}$$

The minimum value for C will depend on the duty ratio D, output voltage V_O, load R and switching frequency f_s:

$$C_{min} = \frac{DV_O}{V_r R f_s} \tag{A.8}$$

The figures below show the output for a boost converter with these parameters:

- D = 0.5.
- f_s = 100 KHz.
- L = 60 µH.
- C = 100 µF.
- R = 10 Ω.
- VS = 10 V.

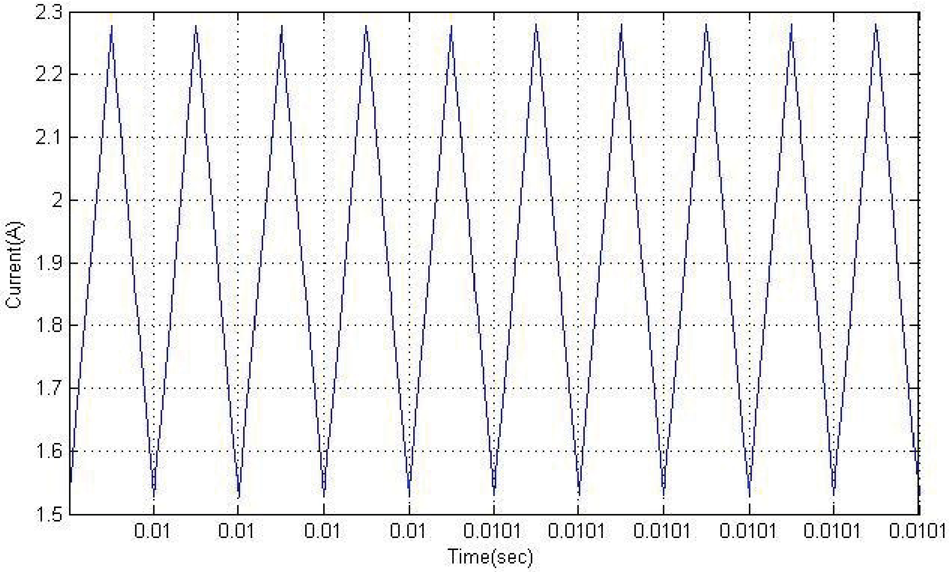


Figure A.6. Inductor current

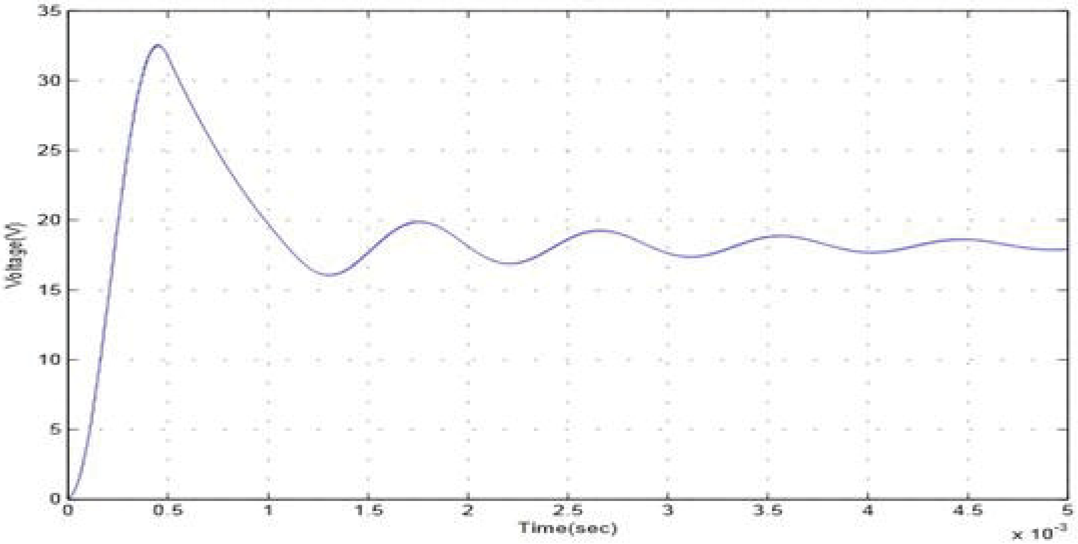


Figure A.7. Output voltage

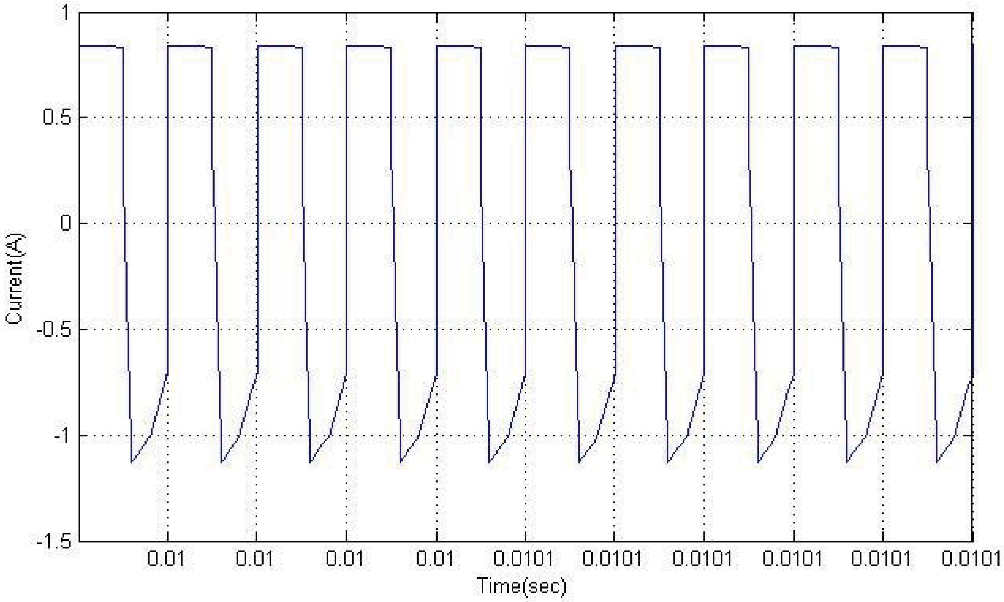


Figure A.8. Capacitor Current

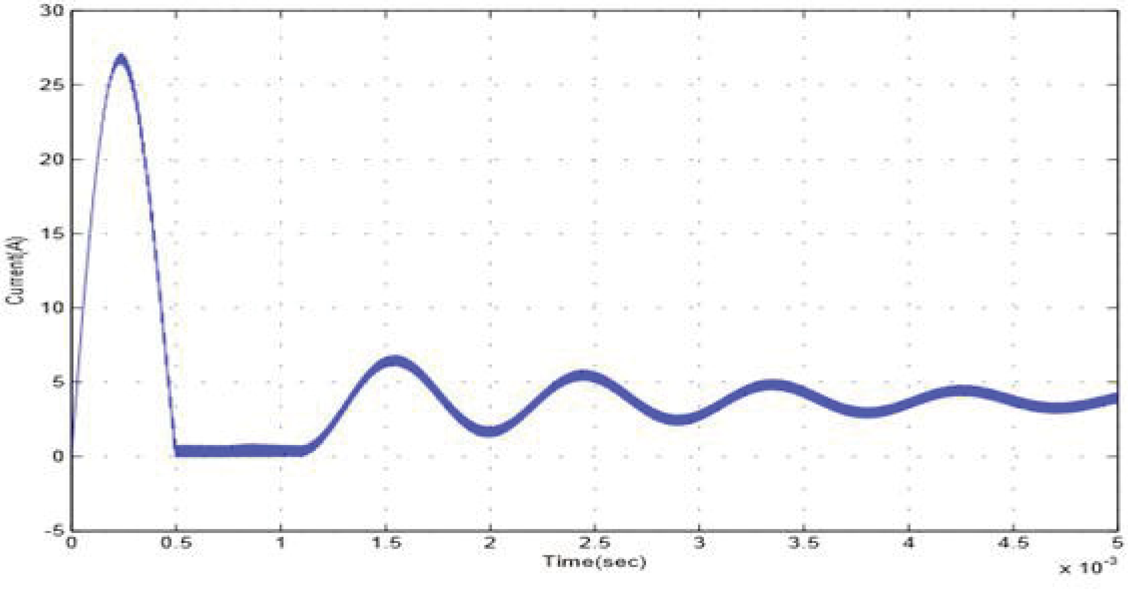


Figure A.9. Source current

A.4. BUCK-BOOST CONVERTER

A buck-boost converter has the ability to increase or decrease the output voltage by changing the duty ratio of its switching signal [2].

Figure A.10 below shows an open-loop converter with all of its components.

The converter consists of a switch S, diode D, inductor L, Capacitor C and a load R. assuming that the duty ratio has a boundary value of D_b when $D > D_b$ the converter acts as a step-up converter. If $D < D_b$ the converter is considered a step-down converter.

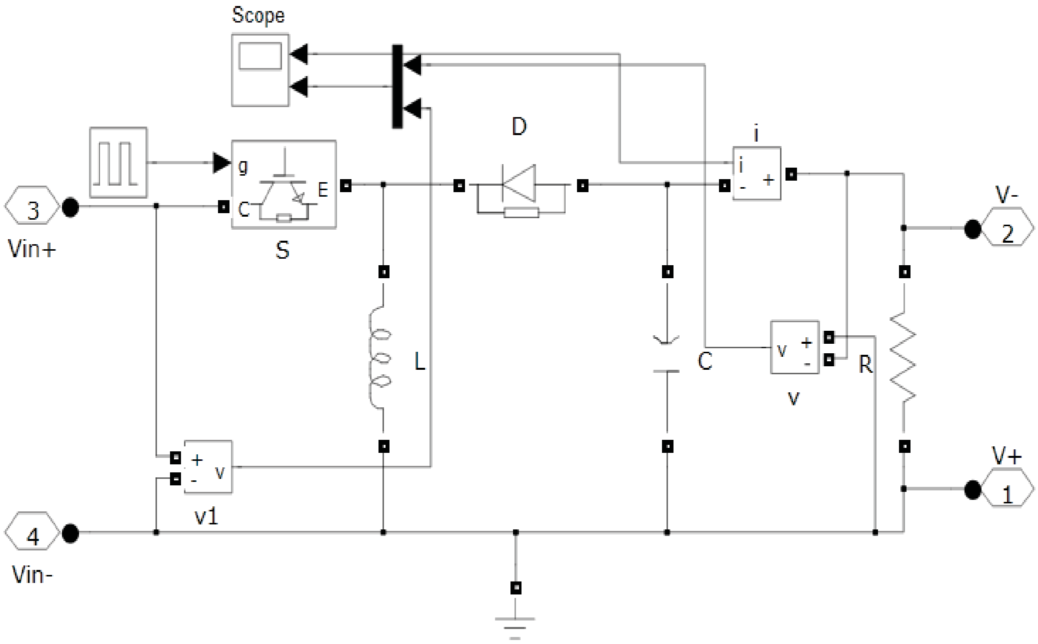


Figure A.10. Buck-Boost Converter.

The relationship between the input voltage and output voltage is given by the following equation:

$$V_S DT = -V_O(1 - D)T \tag{A.9}$$

Then:

$$\frac{V_O}{V_S} = -\frac{D}{1 - D} \tag{A.10}$$

The boundary value should be set for the inductor.

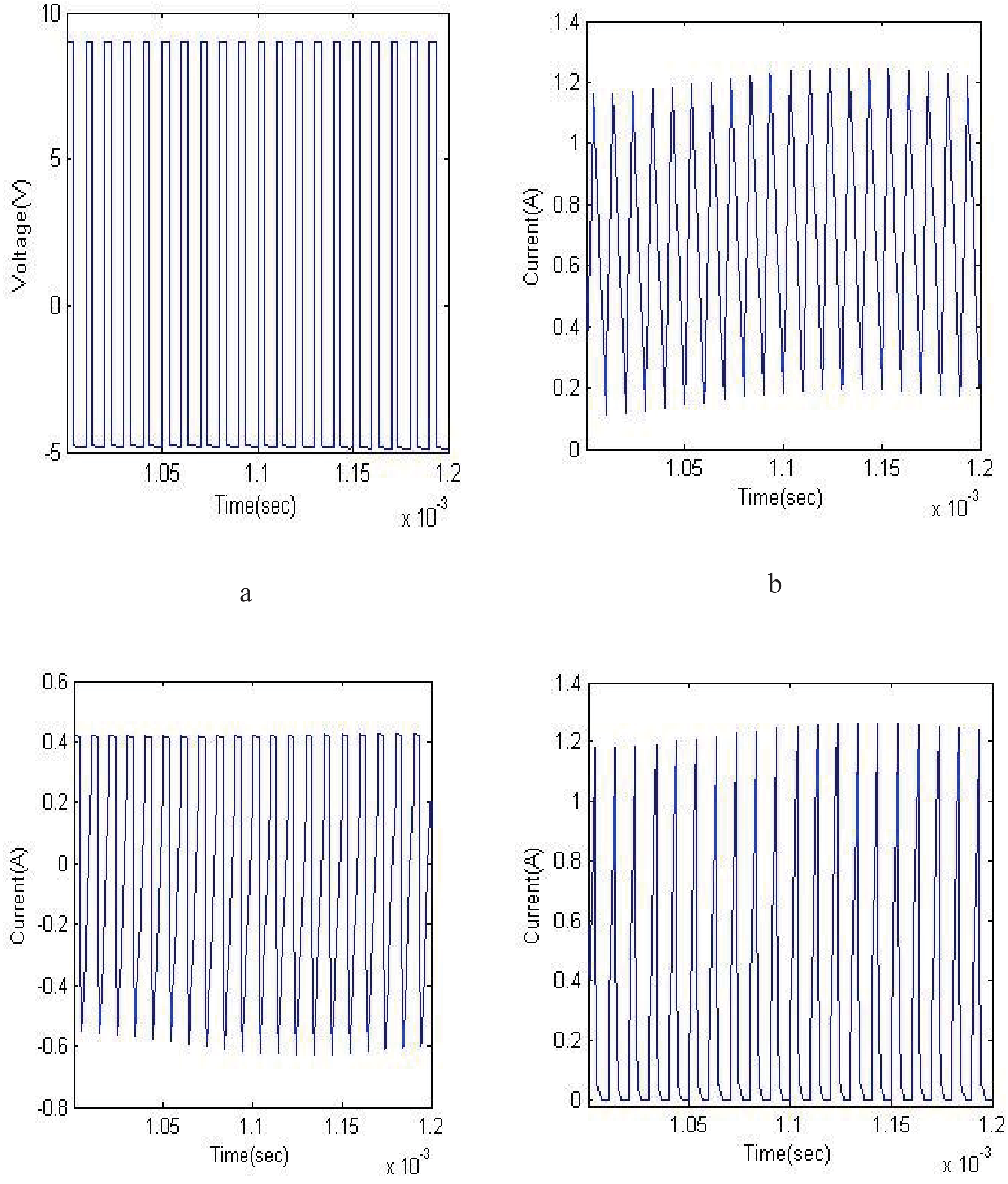
$$L_b = \frac{(1 - D)^2 DR}{2f_s} \tag{A.11}$$

And the capacitor would be the same as of a boost converter

$$C_{min} = \frac{DV_O}{V_r R f_s} \tag{A.12}$$

Finally the output voltage and current wave forms are shown in figure A.12 for the given component values:

- D = 0.35.
- f_s = 100 KHz.
- L = 30 μH.
- C = 25 μF.
- R = 10 Ω.
- V_{in} = 10 V.



a

b

c

d

Figure A.11. a. Inductor voltage, b. Inductor current, c. Capacitor current, d. Source current

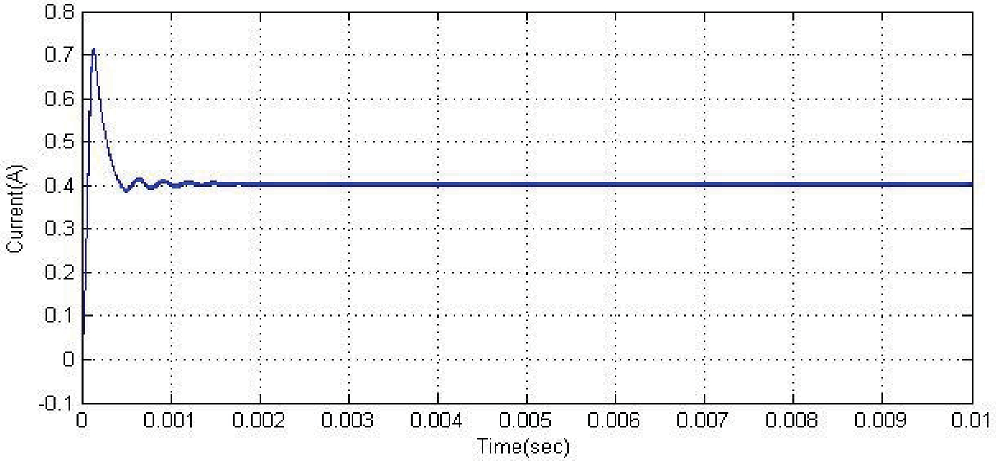


Figure A.12. Output current of buck-boost converter

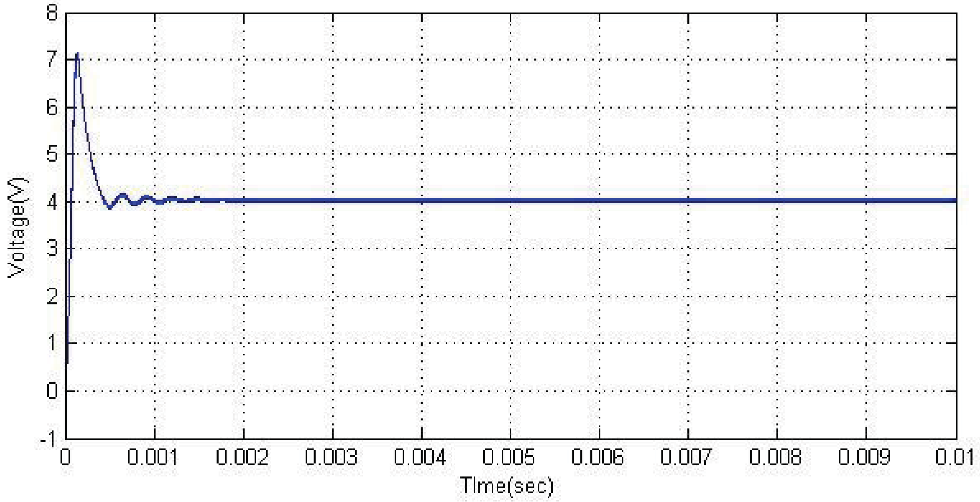


Figure A.13. Output voltage of buck-boost converter

A.5. DC/DC CONVERTER CONTROL METHODS

A converter has to maintain a regulated output voltage using some sort of control method over its components. To achieve that goal two methods are used, voltage controlled or current controlled converters [2][3].

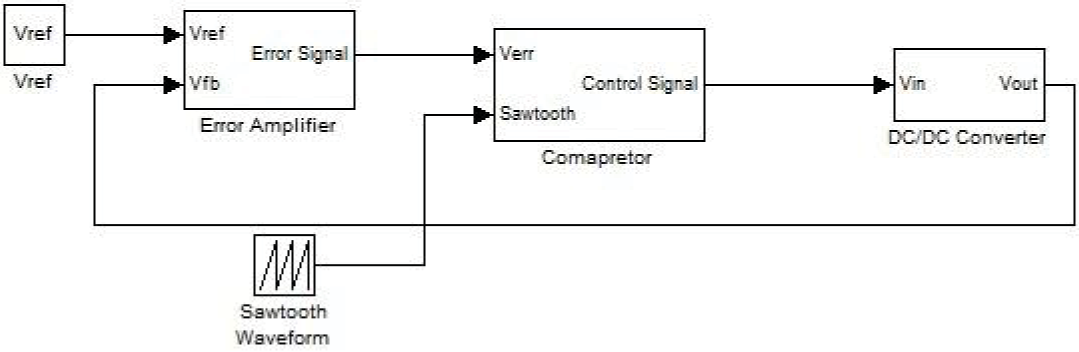


Figure A.14. Voltage controlled converter

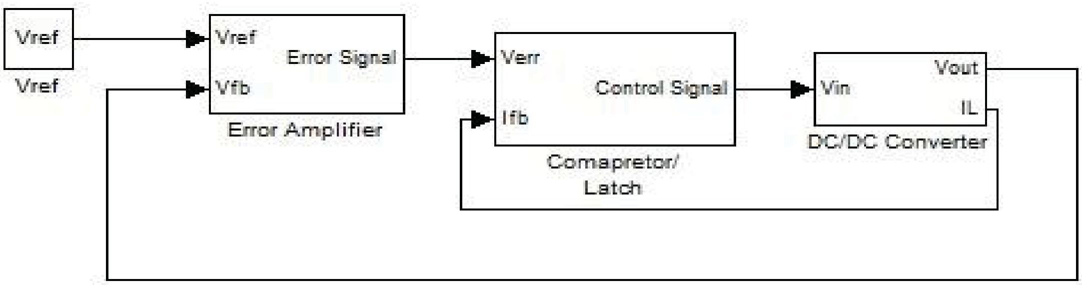


Figure A.15. Current controlled converter

In voltage controlled converters the output voltage is subtracted from a reference voltage V_{ref}, then the signal is amplified and passed to a comparator. The comparator then used to find the difference between the converter's output and the reference voltage. The signal is then combined with a constant saw-tooth signal to operate the switch.

Current controlled converters use the same method above but the inductor current is used as a reference. The inductor current will be similar to the saw-tooth signal used earlier.

8. REFERENCES

[1] Hadi Saadat, “Power System Analysis”, Third Edition, PSA Publishing, 2010.

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