MODELING OF THREE PHASE INVERTER FOR PHOTOVOLTAIC APPLICATION

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ABSTRACT

A three-phase inverter for photovoltaic application is developed and simulated using MATLAB/Simulink software. By assuming the PV module is ideal at all weather condition, a basic dc source is used as input for the DC-DC closed loop step up converter. A pulse generator takes the role of an MPPT. The switching frequency is in the range of 500 MHz to 1 GHz at various duty cycles. This output is then used to switch IGBT inverter at 120° conduction mode. PWM Generator is used to generate pulses for carrier-based two-level pulse width modulator (PWM) in bridge converter. This block generates pulses for carrier-based pulse width modulation (PWM) converters using two-level topology. The block can be used to fire the forced-commutated devices three-phase bridges. The modulation index is set at 0.6-0.95, while the frequency is set in rad/sec. The sampling time is in the range of microseconds. The performance of the system is then further analyzed and proven by calculating the load current, inductance, impedance, load power, phase voltage and line voltage.

ABSTRAK

Sebuah penyonsang tiga-fasa untuk kegunaan tenaga solar telah dibangunkan dan disimulasi menggunakan perisian MATLAB/Simulink. Dengan mengandaikan modul tenaga solar yang digunakan adalah unggul, maka sebuah bekalan kuasa arus terus yang paling asas digunakan sebagai sumber kuasa masukan untuk membentuk sebuah litar gelung tertutup arus terus-arus terus. Sebuah penjana isyarat juga digunakan untuk menggantikan peranan penjejak titik kuasa maksimum. Frekuensi pensuian adalah diantara 500 MHz to 1 GHz pada pelbagai kitar kerja. Keluaran peringkat ini seterusnya digunakan untuk pensuisan sebuah penyonsang *IGBT* yang berkonduksi pada 120°. Penjana modulasi lebar denyut pula digunakan untuk menjana denyut pembawa dua-tahap pada pengubah tetimbang. Blok ini menjana denyut terhadap modulasi lebar denyut berasaskan denyut pembawa. Blok ini juga boleh digunakan untuk memicu peranti tetimbang tiga-fasa. Indeks modulasi boleh ditetapkan pada 0.6-0.95, manakala frekuensinya ditetapkan dalam rad/saat. Masa persampelan adalah dalam jurang mikrosaat. Kemampuan system ini seterusnya dinilai dan dianalisa dengan menghitung arus beban, aruhan, galangan, kuasa beban, voltan fasa dan voltan talian.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternate Current
BIPV	Building integrated photovoltaic
Dc	Direct current
EE	Energy Efficiency
ESR	Equivalent series resistance
GHG	Greenhouse gas
GTO	Gate turn off
IGBT	Insulated Gate Bipolar Transistor
kWh	Kilowatt hour
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPPT	Maximum power point tracking
MW	Mega watt
PTM	Pusat tenaga Malaysia
PV	Photovoltaic
PWM	Pulse width modulation
RE	Renewable energy
SVPWM	Space vector pulse width modulation
TNB	Tenaga Nasional Berhad
VSC	Voltage source converter
W	Watt

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Energy technology plays a very important role in economic and social development. The conventional power grid system are huge interconnected meshes. One of the disadvantage of such network is their reliance on large centralized power generation units that are connected to high voltage transmission supplying to medium voltage and low voltage distribution systems.

Traditional power grid supports centralized electrical power generation where the electricity is generated at locations close to source of energy such hydro dams and transported to consumers who are located further away, as shown in Figure 1. During transmission, a significant portion of electrical power is lost. Therefore it is desired to have power generation close to consumption[1].

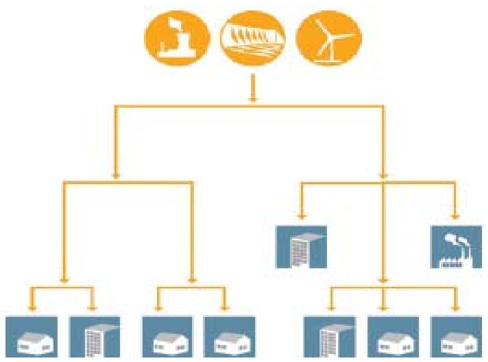

Figure 1 : Conventional Power System

Existing transmission and distribution systems use old technology that do not integrate with digital communication and control technology. In order to meet this growing need, developed societies try to create intelligent means of technologies to distribute electricity more effectively, economically and securely.

1.2 Project Background

Energy is an integral part of the development of Malaysia. Presently, the demand for electricity energy is met by natural gas, coal, petroleum and hydro. The current maximum electricity demand in Malaysia is about 12,000 MW and is projected to grow by about 6% to 8% per annum in the coming years. A total of 9,000 MW of new generation capacity was to be installed and commissioned between the years 2003 to 2010.

From that planned capacity 5,600 MW will be coal fired power plants and the remaining 3,400 MW will be natural gas fired power plants. By the year 2010, the fuel mix in Peninsular Malaysia is expected to be 50% from oil and gas, 40% from coal, and the rest will be from hydro and biomass.

These new coal and gas fired power generators is expected to emit additional 42 million tons $CO2$ annually (34 million tons from coal and 8 million tons $CO2$ from gas). This will lead to a tremendous increase in greenhouse gas (GHG) emissions, thus contributing to the global environmental problems.

To mitigate the negative environmental impact from the electricity supply industry, Malaysia is increasing its efforts to promote renewable energy (RE) and energy efficiency (EE).

Solar energy is the world’s most abundant permanent source of energy that is also an important and environmentally compatible source of renewable energy. The on-going national issues such as the forecast increase of electricity demand, the continuous growth of building industry, and the potential of solar energy, clearly points towards the application of building integrated photovoltaic (BIPV) technology in Malaysia. The BIPV technology will create a sustainable impact to the buildings industry and will be able to substitute part of the conventional fossil fired electricity generators.

Building integrated photovoltaic applications are proven reliable and in some cases are already cost-effective applications as demonstrated in several developed countries. Since the first installation of grid-connected PV systems in 1998, a total of

450kWp of grid-connected PV installed capacity has been recorded in Peninsular Malaysia.

Nevertheless, the grid-connected PV application has not tapped the potential of BIPV in the residential and commercial sectors. The estimated technical potential of BIPV in Malaysia based on available building surfaces is about 11,000 MWp.

Some of the projects are pilot project by TNB (Tenaga Nasional Berhad) whereby 6 pilot plants was installed during 1998 – 2001 in various places in Malaysia such as in Uniten, Port Dickson and Subang Jaya [3]. Pusat Tenaga Malaysia (PTM) is another building integrated with photovoltaics, using polycrystalline (47.28kWh) and amorphous (6.08kWh) [3]. This is inevitable evidence that shows solar energy is one of the practical renewable energy sources for Malaysia.

In this context, lots of research needs to be done in order to achieve a reliable and efficient energy. Looking at the grid connected system, whereby the system mainly consists of photovoltaic (PV) modules, inverter, battery, and switching point for the utility [4]. Different types of photovoltaic cell will yield different energy output, meanwhile the controlling technique of inverter is very crucial in championing the PV system. Inverter design should consider the size and capacity of the plant, on the other hand choosing the right controlling technique is needed as well in order to achieve an efficient renewable energy system.

There are many types of inverter used in converting the direct current (d.c) produced by the PV to alternating current (a.c). The conversion is a must in order to suit the AC grid system that have been implemented and practiced for so long. Some of the types that can be used are multilevel inverters such as flyback capacitor, neutral 3 point clamped multilevel inverter, diode clamped inverter and many more. Each topology has its own plus point and drawbacks depending on the usage of it.

Applying certain controlling techniques to the inverters' such as Pulse Width Modulation (PWM), Space Vector Pulse Width Modulation (SVPWM), Step Modulation etc, the efficiency of the conversion can be obtain up to an optimum level. Hence this is another part for research in the PV Grid-Connected system.

1.3 Project objectives

In the integration of renewable energy, the function of inverters is to convert power from DC to AC at the system frequency of operation. Here a DC/AC inverter converts direct current (DC) power generated by a Photovoltaic DC power source to sinusoidal alternating current.

Therefore the main objective of the project is:

i. To design a three phase inverter model using MATLAB/Simulink
ii. To analise the output voltage of the developed system
iii. Develop a modeling complete with its output.

1.4 Project scope

2. Modeling and simulation using MATLAB/Simulink
3. Develop a DC-DC converter and a three phase inverter
4. Use PWM method for the switching operation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The PV system normally uses solar panels, which is in arrays. There are many types of PV system, starting from a cell up to arrays. This is shown in Figure 2.1.

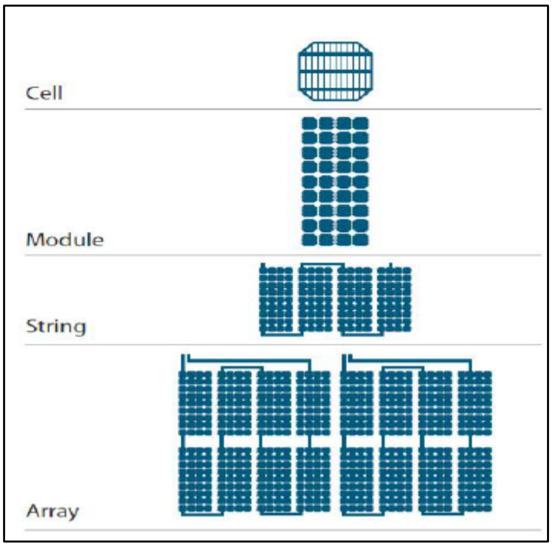

Figure 2.1 : The PV from cell to module

Photovoltaics is a technology that generates direct current (DC) electrical power measured in Watts (W) or kiloWatts (kW) from semiconductors when they are illuminated by photons. As long as light is shining on the solar cell, it generates electrical power. When the light stops, then the electricity also stops[12].

Solar cells never need recharging like a battery. Some have been in continuous outdoor operation on Earth or in space for over 30 years. Table 2.1 lists some of the advantages and disadvantages of photovoltaics. It includes both technical and nontechnical issues.

Table 2.1 : Advantages and disadvantages of photovoltaics [13]

Advantages of photovoltaics	**Disadvantages of photovoltaics**
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is a relatively low-density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	
Low operating costs (no fuel)	High installation costs
No moving parts (no wear)	
Ambient temperature operation (no high temperature corrosion or safety issues)	
High reliability in modules (>20 years)	Poorer reliability of auxiliary (balance of system) elements including storage
Modular (small or large increments)	
Quick installation	
Can be integrated into new or existing building structures	
Can be installed at nearly any point-of-use	Lack of widespread commercially available system integration and installation so far
Daily output peak may match local demand	Lack of economical efficient energy storage
High public acceptance	
Excellent safety record	

2.2 General Characteristics of PV Inverters

Since the production cost of PV electricity is several times more expensive than conventional electric energy, conversion efficiency becomes predominant to the economics of the total PV system. As a consequence extremely high efficiency not only in the nominal power range but also under a part-load condition is a requirement for PV inverters in grid-connected as well as in stand-alone systems.

2.3 Inverters for Grid-connected Systems

This configuration consists mainly of the following components: the PV generator, the inverter and the electric meter as shown in Figure 2.2 [6].

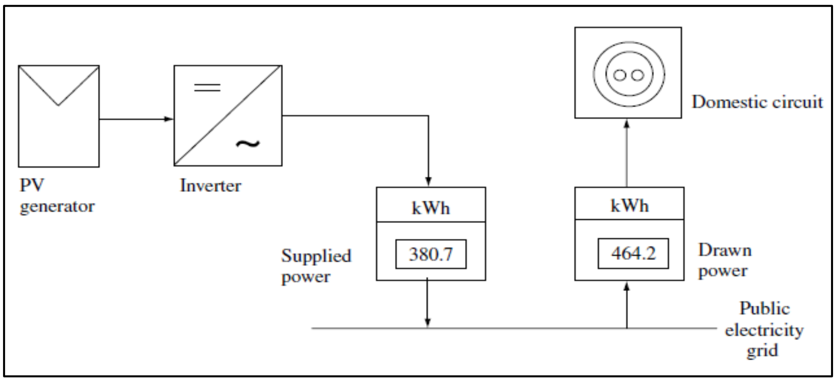

Figure 2.2 : Block diagram of a grid-connected photovoltaic generator.

PV inverters can be categorised in various ways according to the topology, the operation principle, the type of the connection to the grid and by application. Based on the connection to the grid inverters can be:

a. Single-phase inverters refer to inverter structures applied in small scale roof-top systems (of until 5 kWp).

b. Three-phase inverters refer to larger systems, which is mostly the case for on-grid PV systems and are connected of course to a three-phase supply system. The basic three-phase inverter consists of three single line inverters, which are connected to each load terminal. So, it is not actually a true three-phase inverter and this is because a three-wire topology will require relatively high DC voltage values (around 600 V for a 400 V three-phase grid) and is limited to 1000 V due to safety reasons in installation procedures. Also the monitoring and control for islanding requirement becomes more difficult in relation to three single phase connections [7].

The inverter as an electronic oscillator is required to generate a pure sine wave synchronized to the grid as stated before.

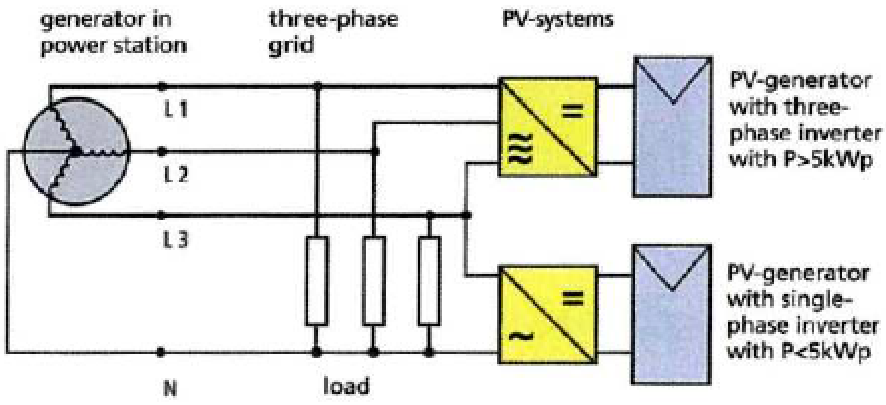

Figure 2.3: Principle of connecting PV systems to the grid with a single-phase and three-phase inverter [8]

According to the size and the application, inverters can be central, string, multistring and module kind [9], [10]. Central inverters are connected with more than one or all the parallel strings of PV modules and can be of some kW until one MW of power range.

String inverters are connected to each string of the PV array seperately and their range of power is a few KW (0.4 - 2 kW). Multi-string inverters are a rather new concept according to which, several strings of different configation (different PV modules) and orientation can be connected together. For this reason, necessary DC-DC converters are used to provide the same output signal to the input of the multi-string inverter. Multi-string inverters increase the efficiency of the system since every string can track its own MPP. Their range varies from 1.5 kW to 6 kW.

Module-type inverters are connected to each module seperately transforming it in a PV AC module. Their use is still limited and their range is from 50 to 400 W.

Taking into consideration that the PV modules produce DC power at a low voltage, the system's output requires some adjustment to be fed as AC power at the votage of the grid as cited before. The inverters used for this adjustment and apply diferent operation principle are [8], [11]:

2.4 Line-commutated.

Such invertrs use switching devices (thyristor bridge or IGBT) that control the switch-on time only. The switch-off time is done by reducing the circuit current to zero by using the voltage of the grid. The name line-commutated represents exactly this grid controlled dependance, meaning the inverter uses the voltage of the grid to decide the turn on and turn off time of these thyristors. One disadvantage is that they produce a square wave current output, which introduces undesirable harmonic components, which can be reduced by the use of filters. This principle is used today less especially in single phase inverters.

2.5 Self-commutated.

Such inverters are more complicated and use switching devices (IGBT and MOSFET) that can control the switch-on and switch-off time and adjust the output signal to the one of the grid. The self-commutated inverters are the predominant technology in PV power sources because of their ability to control the voltage and current output signal (AC side), regulate the power factor and reduce the harmonic current distortion. Especially, since the role of PV inverter has become more vital, this operation principle is offering the capabilty to cover the multiple services and increase the resistance to the grid disturbances. Depending on the type of pulse they control, either voltage or current, self-commutated are divided to voltage source and current source inverters.

2.6 Voltage source inverters (VSI).

VSI realize the DC side as a constant voltage source and the output current is changing with the load. For this reason is normally connected to the grid with an inductance so as not to supply with current infinitely when there is not voltage or phase match between inverter and grid.

2.7 Current source inverters (CSI).

Respectively, CSI the DC source appears as a constant current input and the voltage is changing with the load. The protection filter is normally a capacitance in parallel with the DC source.

Self-commutated inverters produce very good sine wave outputs with the use PWM technic and low pass filters [8].

Another basic criterion for categorizing PV inverters is whether or not use galvanic isolation (transformer) to connect to the grid. There are many advantages and disadvantages in each type to be considered, with Electromagnetic Interference (EMI) being one of the most important issue. Inverters with low-frequency transformers (50 Hz) or high frequency transformers (10 kHz to 50 kHz) have the DC circuit seperated from the AC circuit, offering recuction of EMI. However, the big size especially when using low frequency transformers, the lower efficiency of the inverter due to transformer losses and the extra cost turn the attention to transformless topologies and their improvement to work in higher power ranges than today [8].

Transformless topologies still need more innovative and complicated solutions to become competitive especially in terms of electrical safety. Furthermore, in cases when the the DC output of the PV system is not as the one of the grid or higher, a step-up DC-DC converter is needed. Thus, part of the losses that were avoided from not using a transformer are compensated by the use of the converter. Nevertheless, almost all the typical applied inverter structures today need a boosting and require a DC-DC converter [12]. In general, there are numerous different topologies of inverters that could apply in grid connected systems.

2.8 Switch Mode Inverter

Switch-mode dc-to-ac inverter is used in ac power supplies and ac motor drives with the objective to produce a sinusoidal ac output whose magnitude and frequency can both be controlled. In single-phase or three-phase ac systems there are two common inverter topologies used. First is the half-bridge or a single leg inverter, which is the simplest topology, as shown in Figure 2.4.

It is used to produce a two-level squarewave output waveform using two semiconductor switches S_1 and S_2. A centertapped voltage source supply is needed; it may be possible to use a simple supply with two well-matched capacitors in series to provide the center tap. Another topology is known as the full-bridge inverter. It is used to synthesize a two-level or three-level square-wave output waveform but with double the amplitude compared to half-bridge. There are two inverter legs in a full-bridge topology as shown in Figure 2.5, namely leg *a* and leg *b*.

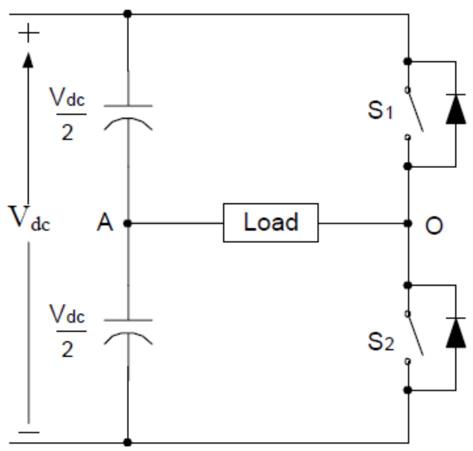

Figure 2.4: Half-bridge configuration.

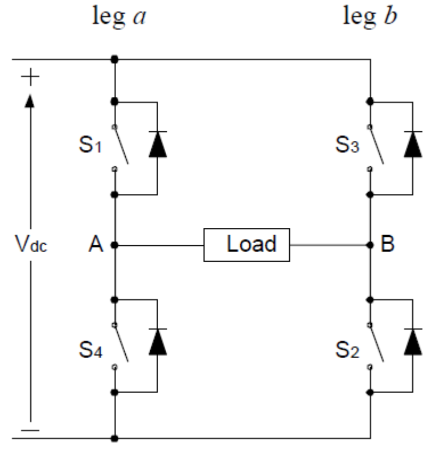

Figure 2.5 : Full-bridge configuration.

For each inverter leg, the top and bottom switches have to be complementary to avoid shoot-through fault, i.e. if the top switch is closed (on), the bottom must be open (off), and vice-versa. Both switches, S_1 and S_2 for half-bridge inverter are never turned on at the same time. Similarly for full-bridge inverter, both S_1 and S_4 should not be closed at the same time, nor should S_2 and S_3. To ensure the switches not closed at the same time, each gating signal should pass through a protection mechanisme known as a "dead time" circuit before it is fed to the switches gate [9,10].

A two-level output waveform of half bridge and three-level output waveform of full bridge single-phase voltage source inverter are shown in Figure 2.6 and 2.7, respectively.

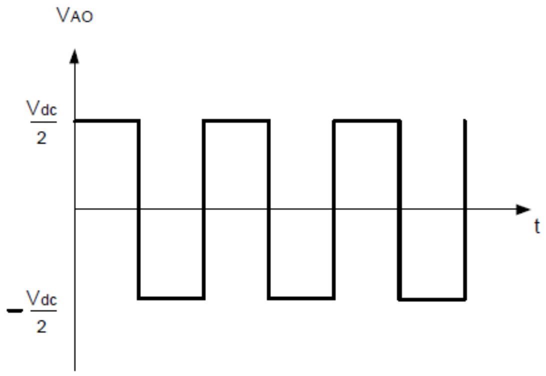

Figure 2.6 : Two-level output waveform of half-bridge configuration.

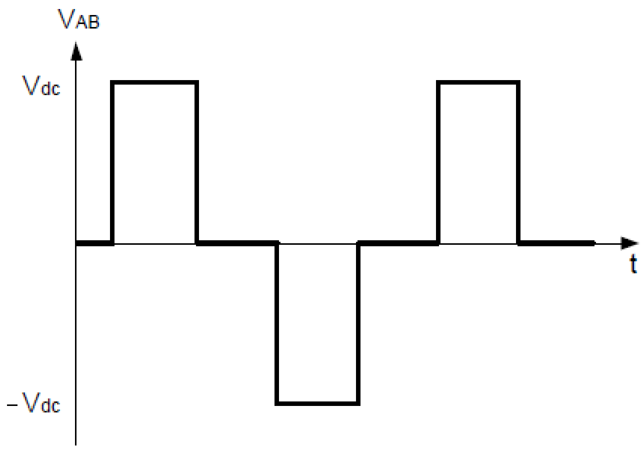

Figure 2.7 : Three-level output waveform of full-bridge configuration.

2.9 Converters

Converters serve as an interface between the source and load (14) as shown in Figure 2.8. It convert one type or level of a voltage or current waveform to another and classified by the relationship between input signal and output signal as shown in Table 2.5.

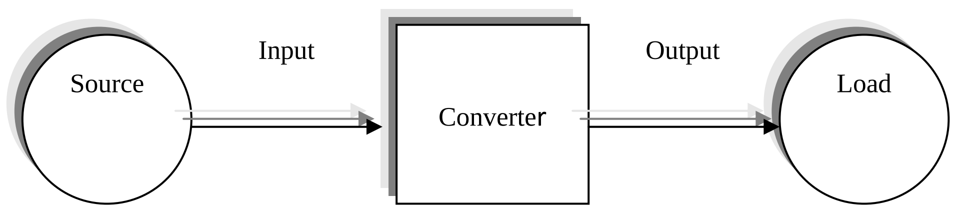

Figure 2.8: Basic converter system.

Converter circuits capable to operate in different mode, depending on electronic circuit used, high frequency switching semiconductor and applied control system. Thus, converters are capable to operate in multiple stages in a process with different type of converter involve as shown in Figure 2.9.

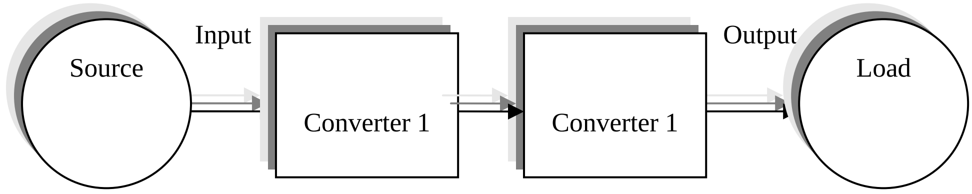

Figure 2.9: Two converters are used in a multistep process.

Table 2.5: Classifications of converters.

Type of converter	**Functions**
ac input/dc output	The ac/dc converter that produces a dc output from an ac input. It classified as a rectifier.
dc input/ac output	The dc/ac converter produces an ac output from a dc input. It classified as an inverter.
dc input/dc output	The dc/dc converter produces a dc output from a dc a dc input. It classified as a regulator.
ac input/ac output	The ac/ac converter produces an ac output from an ac input. Used to change the level and/or frequency of an ac signal.

2.10 DC-DC converter

2.10.1 General overview of DC-DC converter

DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desire voltage output. It classified as a regulator as it useful when a load requires a specified dc voltage or current but the source is at a different or unregulated dc value. General DC-DC converter block diagram shown in figure 2.10.

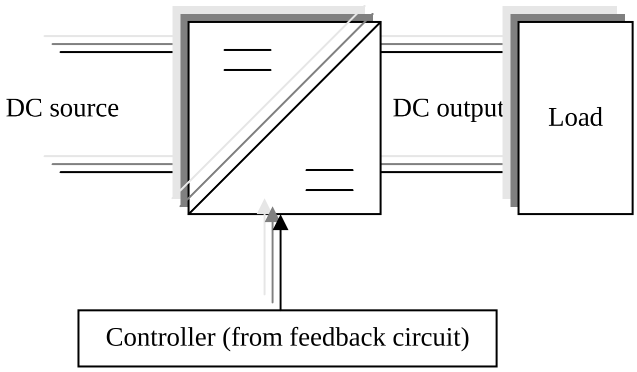

Figure 2.10: General DC-DC converter block diagram.

DC-DC converters include buck converters, boost converters, buck-boost converters, Cuk converters and full-bridge converters (15). The DC-DC converter is considered as the heart of the power supply, thus it will affect the overall performance of the power supply system (16).

Switched DC-DC converters offer a method to increase or decrease an output voltage depend on application or system. DC-DC converters may be operated in two modes, according to the current in its main magnetic component, inductor. The current fluctuates but never goes down to zero is called Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) occur when the current fluctuates during the cycle, going down to zero at or before the end of each cycle.

Energy is periodically stored into and released from a magnetic field in an inductor. Usually, this is applied to control the output voltage so that the output voltage remains constant even though input voltages keep changing. There are two general categories of DC-DC converters that is non-isolated DC-DC converter (Buck, Boost, Buck-Boost) and isolated DC-DC converter (Flyback, Forward, Push-Pull, Full-Bridge, Half-Bridge).

Non-isolated DC-DC converter were used when the input to these converters is often an unregulated DC voltage, which is obtained by rectifying the line voltage, and therefore it will fluctuate due to changes in the line voltage magnitude. Switched-mode

DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desired voltage level (17).

Isolated DC-DC converter, full-bridge converter and half-bridge converter are derived from the step-down converter. Flyback converters are derived from the buck-boost converters. Forward converters and push-pull converters are derived from the step-down converters with isolation.

2.10.2 DC-DC converter switching

There are two switching condition that need to be applied, that is when ON and OFF as shown in Figure 2.11.

When ON,

Output voltage is the same as the input voltage and the voltage across the switch is 0V.

When OFF,

Output voltage = 0V and current through the switch = 0A. In ideal condition, power loss = 0W since output power equal to input power.

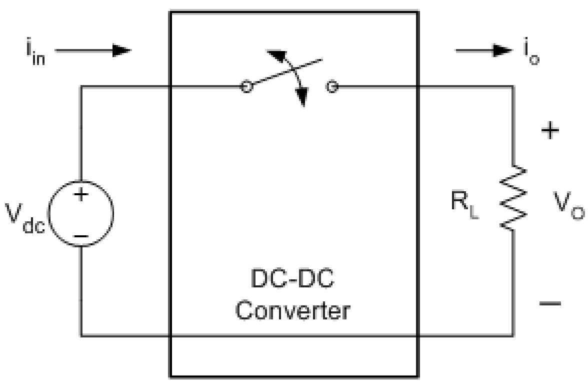

Figure 2.11: Switching of DC-DC converter.

ON and OFF resulting in pulse as shown in Figure 2.12 where switching period, T , is a one full cycle (360°) of a waveform ranging from t_{ON} to t_{OFF} pulse.

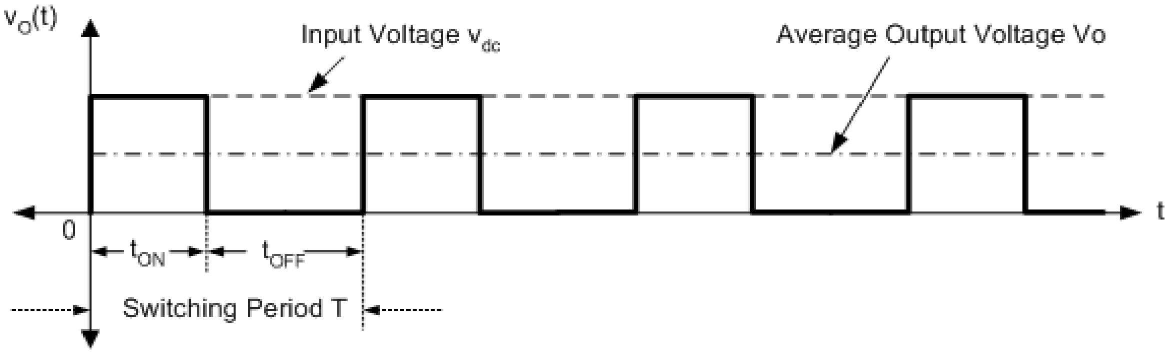

Figure 2.12: Switching pulse

Thus, duty cycle, D, which depends on t_{ON} and range of duty cycle is $0 < D < 1$. If switching frequency, f_s , is given,

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} f_s \tag{2.2}$$

Average DC output voltage,

$$\overline{V}_0 = \frac{1}{T}\int_0^T v_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_i dt = V_i D \tag{2.3}$$

There are two modes of operation in DC-DC converters based on inductor current, i_L,

i) Continuous Conduction Mode (CCM), when $i_L > 0$.

ii) Discontinuous Conduction Mode (DCM) when i_L goes to 0 and stays at 0 for some time.

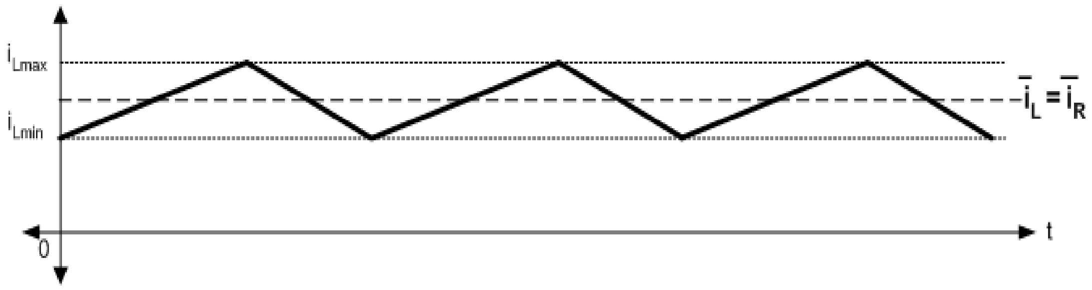

Figure 2.13: Continuous Conduction Mode.

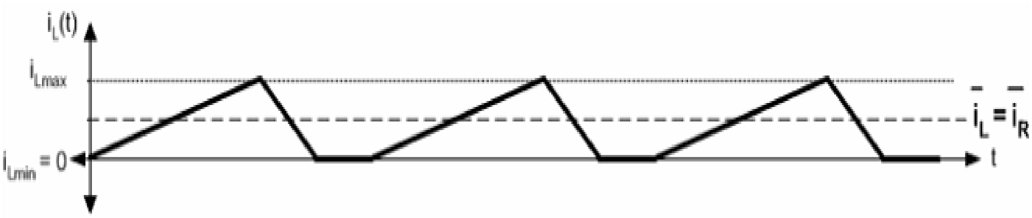

Figure 2.14: Discontinuous Conduction Mode.

In steady state and periodic operation, inductor charges and discharges with V_{avg} DC voltage across inductor in one period = 0. Thus, inductor looks like a short circuit as shown in Figure 2.15.

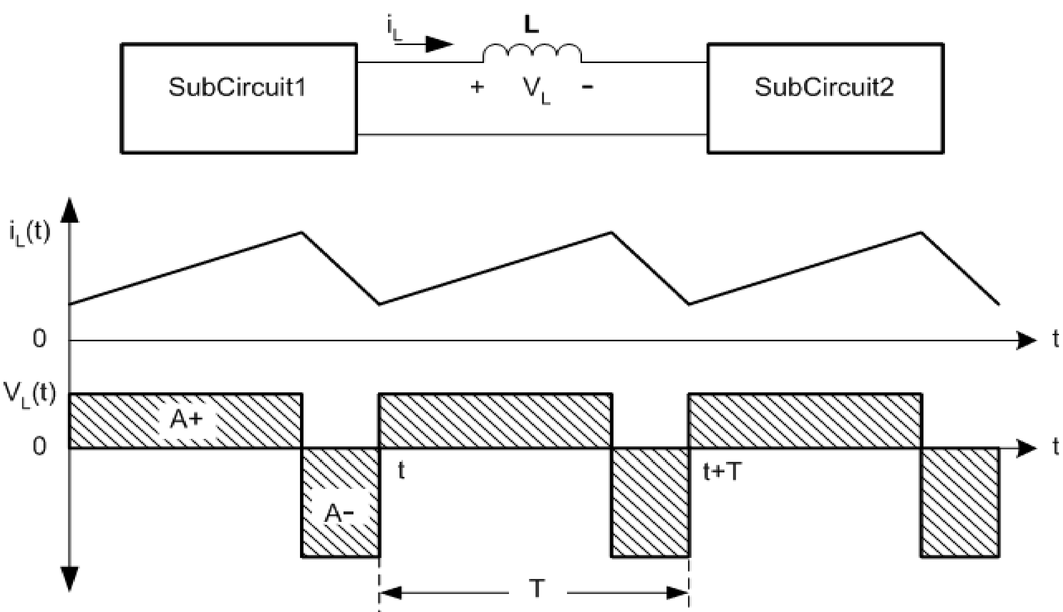

Figure 2.15: Inductor current and voltage during short circuit.

2.11 Boost converter

2.11.1 Boost converter overview

DC-DC converter is called Boost converter when average output voltage is higher than input voltage. Power stage also consists of a switch, diode and inductor. Boost converter as shown in Figure 2.16, converts an unregulated source voltage, V_s , into a higher regulated load voltage, V_o .

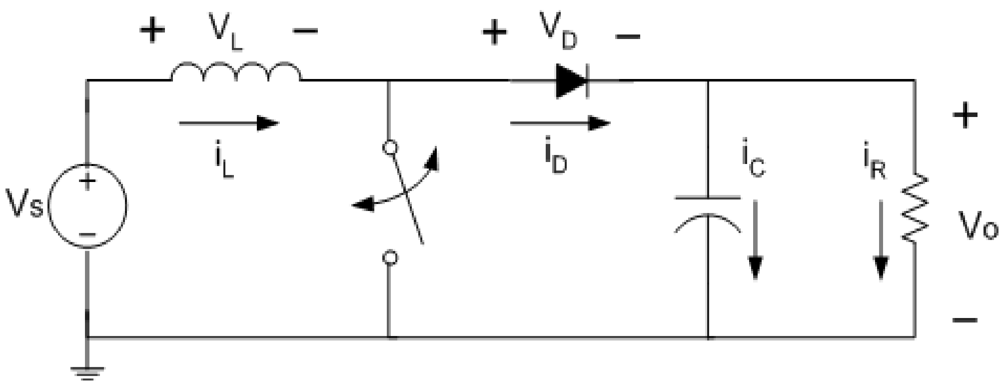

Figure 2.16: Boost converter circuit.

When the switch is closed, as shown in Figure 2.17, the diode is reverse biased and the source voltage charge the inductor. Input is disconnected from the output, therefore no energy flows from input to output. The capacitor discharges into the load.

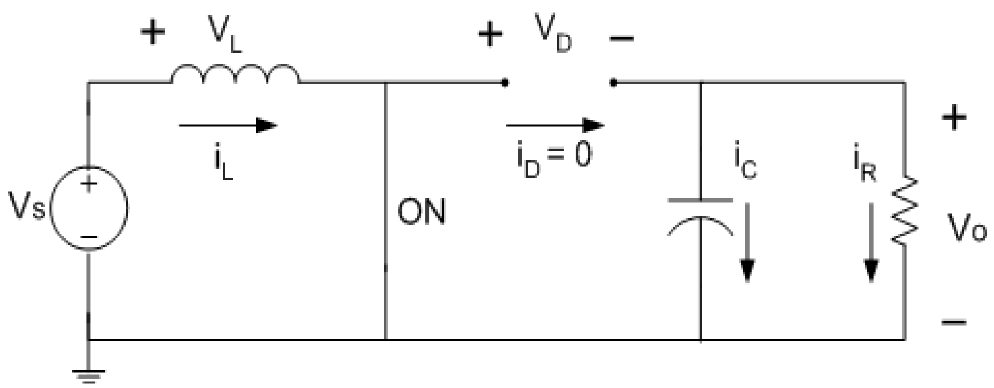

Figure 2.17: Boost converter circuit with switch closed.

When the switch is open, as shown in Figure 2.18, the diode conduct as it become a forward biased. At this point, energy stored in the inductor and source voltage are supplied to the capacitor and the load create higher voltage output than the source voltage.

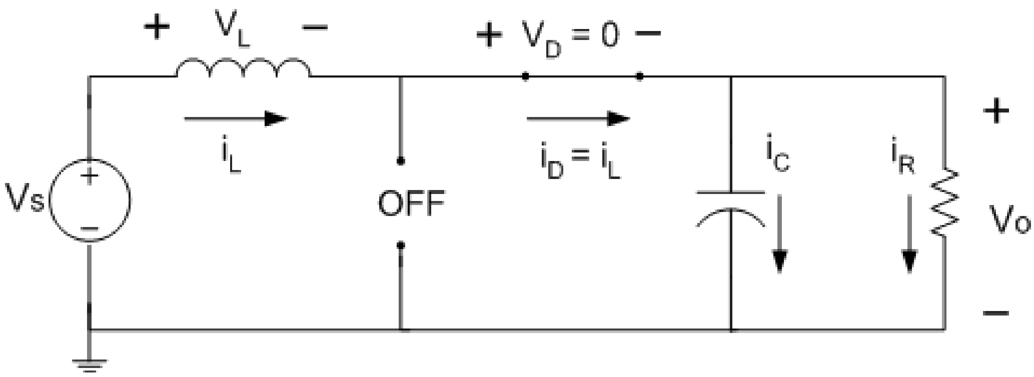

Figure 2.18: Boost converter circuit with switch opened.

Where,

$$V_{L_{OFF}} = V_s - V_o \tag{2.4}$$

When switch is closed,

$$V_L = V_s$$

$$= L\frac{di_L}{dt} \tag{2.5}$$

Thus,

$$\Rightarrow \frac{di_L}{dt} = \frac{V_s}{L} \tag{2.6}$$

Since the derivative of i_L is a positif constant, therefore i_L must increase linearly.

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta dt} = \frac{\Delta i_L}{DT} = \frac{V_s}{L} \tag{2.7}$$

The output voltage, V_L and output current, i_L signal for switch closed condition is shown in Figure 2.19 correspondent to equation (2.6) and (2.7).

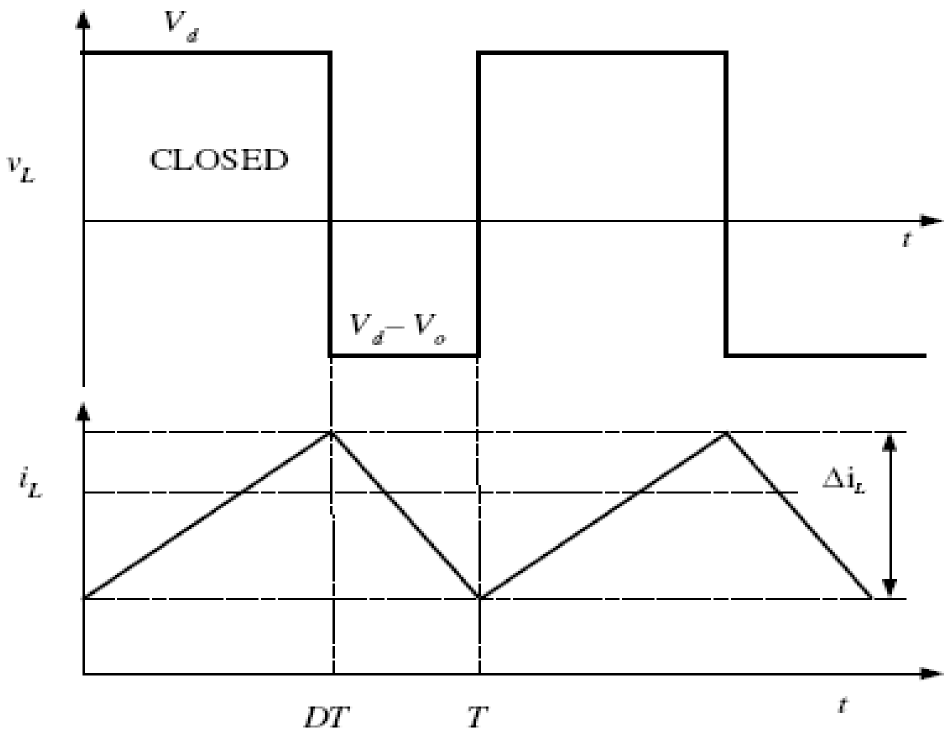

Figure 2.19: Current and voltage when switch is in closed condition.

2.11.2 Switch open analysis

When switch is open,

Inductor voltage,

$$V_L = V_s - V_o$$
$$= L\frac{di_L}{...} \tag{2.8}$$

Thus,

$$\Rightarrow \frac{di_L}{dt} = \frac{V_s - V_o}{L} \tag{2.9}$$

Since the derivative of i_L is a negative constant, therefore i_L must decrease linearly.

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta dt} = \frac{\Delta i_L}{(1-D)T} = \frac{V_s - V_o}{L}$$
$$\left(\Delta i_L\right)_{opened} = \left(\frac{V_s - V_o}{L}\right)\cdot(1-D)T \tag{2.10}$$

The output voltage, V_L and output current, i_L signal for switch closed condition is shown in Figure 2.20 correspondent to equation (2.9) and (2.10).

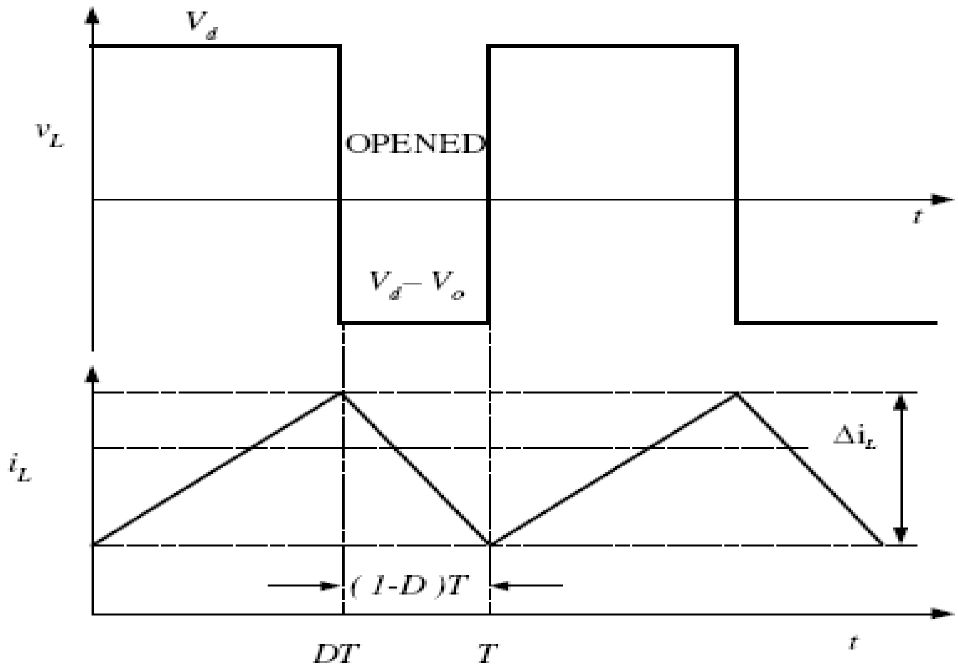

Figure 2.20: V_L and i_L **signal for switch closed condition.**

In steady-state operation,

$$\left(\Delta i_L\right)_{closed} + \left(\Delta i_L\right)_{opened} = 0$$

$$\left(\frac{V_s}{L}\right)\cdot DT + \left(\frac{V_s - V_o}{L}\right)\cdot(1-D)T = 0$$

$$\Rightarrow V_o = \frac{V_s}{1-D} \qquad (2.11)$$

Average output voltage is higher than input voltage when considering one switching period as follow,

$$V_{LON}t_{ON} + V_{LOFF}t_{OFF} = 0$$

$$V_S DT + (V_S - V_O)(1-D)T = 0$$

$$\boxed{V_O = \frac{1}{1-D}\cdot V_S} \qquad (2.12)$$

For inductor current, I_L,

$$V_s I_s = \frac{{V_o}^2}{R} \qquad (2.13)$$

$$V_s I_L = \frac{\left(\frac{V_s}{1-D}\right)^2}{R} = \frac{V_s^2}{(1-D)^2 R} \qquad (2.14)$$

Average inductor current,

$$I_L = \frac{V_s}{(1-D)^2 R} \tag{2.15}$$

Inductor current, for I_{Lmax} and I_{Lmin},

$$\begin{aligned} I_{\max} &= I_L + \frac{\Delta i_L}{2} \\ &= \frac{V_s}{(1-D)^2 R} + \frac{V_s DT}{2L} \end{aligned} \tag{2.16}$$

$$\begin{aligned} I_{\min} &= I_L - \frac{\Delta i_L}{2} \\ &= \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L} \end{aligned} \tag{2.17}$$

For CCM and steady state condition,

$$\begin{aligned} & I_{\min} \geq 0 \\ & \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L} \geq 0 \end{aligned} \tag{2.18}$$

$$\begin{aligned} L_{\min} &= \frac{D(1-D)^2 TR}{2} \\ &= \frac{D(1-D)^2 R}{2f} \end{aligned} \tag{2.19}$$

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