PIC CONTROL DC TO DC CONVERTER WITH VARIABLE INPUT VOLTAGE AND CONSTANT OUTPUT VOLTAGE FOR PHOTOVOLTAIC INTEGRATION

by

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LIST OF SYMBOLS

t_{On}	Switch on duration
t_{Off}	Switch off duration
T	Switching time period
k	Duty cycle
V_{in}	DC input voltage
V_{out}	DC output voltage
SW	Electronic switch
D	Diode
C	Capacitor
L	Inductor
R	Resistor
V_{SW}	MOSFET drain-to-source voltage
I_{SW}	MOSFET drain current
V_D	Diode voltage
I_D	Diode current
V_L	Inductor voltage
I_L	Inductor current
V_{br}	Diode breakdown voltage
t_{rr}	Diode reverse recovery time
I_{RR}	Diode maximum reverse current
t_a	Time between zero crossing and the I_{RR}
t_b	Time between the diode I_{RR} and 25% of I_{RR}
V_{ref}	Reference value in PIC16F877

Q_{RR}	Storage charged from forward biased conduction to reverse blocking conduction
V_{GS}	Gate-to-source voltage
V_T	Threshold voltage
V_{st}	Sawtooth voltage
$v_{control}$	Control voltage
P_O	Rated output power
P_T	Switch power rating
I_{Lmax}	Maximum inductor current
I_{Lmin}	Minimum inductor current
P_{in}	Input power
P_{out}	Output power
I_{LB}	Average inductor current at boundary condition
I_{outB}	Average output current at boundary condition
I_{in}	Input current
I_{out}	Output current
I_{LBmax}	Maximum average inductor current at boundary condition
$I_{outBmax}$	Maximum average output current at boundary condition
ΔV_{out}	Output voltage ripple
$R_{DS(on)}$	Drain to source on-resistance
V_{FB}	Output voltage feedback value
R1	Voltage divider resistor 1
R2	Voltage divider resistor 2
V_{act}	Actual voltage detect by PIC16F877
I_{act}	Actual current into PIC16F877
$P_{divider}$	Losses in voltage divider

LIST OF ABBREVIATION

AC	Alternating current
ADC	Analogue to digital converter
BJT	Bipolar Junction transistor
CCM	Continuous conduction mode
CMOS	Complementary metal oxide semiconductor
DC	Direct current
DCM	Discontinuous conduction mode
EEPROM	Electrically erasable programmable read only memory
ESR	Equivalent series resistance
GTO	Gate-turn-off thyristor
IC	Integrated circuit
IGBT	Insulated gate bipolar transistor
MCT	MOS-controlled thyristor
MOSFET	Metal oxide silicon field effect transistor
PCB	Printed circuit board
PV	Photovoltaic
PWM	Pulse width modulation
RAM	Random access memory
ZCS	Zero current switching
ZVT	Zero voltage switching

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LIST OF PUBLICATIONS AND SEMINARS

1. Syafrudin Masri and Pui-Weng Chan (2010) Development of a Microcontroller-Based Boost Converter for Photovoltaic System. European Journal of Scientific Research, 41(1), p. 39-47.

2. S. Masri and P. W. Chan (2010) Design and Development of a DC-DC Boost Converter with Constant Output Voltage. The 3rd International Conference on Intelligent and Advanced Systems (ICIAS2010), 15-17 June 2010, Kuala Lumpur.

3. Syafrudin Masri and Pui-Weng Chan (2010) Design of a DC-DC converter with input voltage variable and output voltage constant for photovoltaic application system. The 3rd AUN/SEED Net Regional Conference on New & Renewable Energy (RCNRE 3/2010), 13-14 October 2010, Pulau Pinang.

PENUKAR AT KE AT KAWALAN PIC DENGAN VOLTAN MASUKAN BOLEHUBAH DAN VOLTAN KELUARAN TETAP UNTUK APLIKASI PHOTOVOLTAIK

ABSTRAK

Kebelakangan ini, perhatian terhadap tenaga boleh diperbaharui seperti tenaga solar meningkat secara mendadak disebabkan oleh kesedaran terhadap krisis tenaga. Banyak aplikasi sistem tenaga solar telah direkabentuk. Salah satu aplikasi yang penting adalah menghantar tenaga yang dihasilkan oleh papan solar ke grid tempatan. Suatu voltan tetap perlu diperolehi dari papan solar dalam rekabentuk aplikasi system ini kerana papan solar menghasilkan voltan yang berubah-ubah mengikut perubahan penyinaran dan suhu. Oleh yang demikian, suatu penukar anjak naik AT-AT direkabentuk untuk menganjak naik voltan papan solar yang berubah-ubah ke suatu voltan tinggi yang tetap. Suatu penukar mikrokawalan anjak naik AT-AT diajukan dalam rekabentuk ini. Alat mikrokawalan PIC16F877 digunakan dan melakukan teknik voltan umpan balik di mana ia memantau dan mengukur voltan keluaran penukar anjak naik AT-AT dan membandingkan nilai yang diperolehi dengan voltan rujukan secara berterusan. Perbezaan nilai tersebut digunakan untuk menghasilkan isyarat modulasi lebar nadi yang digunakan untuk mengawal suis dalam penukar anjak naik AT-AT. Keputusan simulasi memaparkan prestasi cadangan rekabentuk. Eksperimen dijalankan di mana penukar tersebut beroperasi dalam mod konduksi berterusan dengan voltan keluaran tetap 24 V, tenaga keluaran 100 W, frekuensi 20 kHz dan dibekalkan oleh voltan papan solar. Keputusan eksperimen memaparkan cadangan rekabentuk berupaya menghasilkan voltan tetap 24 V dengan kecekapan melebihi 72.9% semasa beban 100 W.

PIC CONTROL DC TO DC CONVERTER WITH VARIABLE INPUT VOLTAGE AND CONSTANT OUTPUT VOLTAGE FOR PHOTOVOLTAIC INTEGRATION

ABSTRACT

In recent years, attention towards renewable energy such as solar power had increased dramatically due to the awareness of energy crisis. A lot of solar power application systems had been designed. One of the most important solar power applications is to deliver the power produced by solar panel to local utility grid. A constant voltage should be obtained from solar panel in the design of this application system as solar panel is producing a fluctuating voltage level which depends on irradiation and temperature level. Therefore, a DC-DC boost converter is designed to step up the fluctuating solar panel voltage to a higher constant voltage. A microcontroller based DC-DC boost converter is proposed in this design. A PIC16F877 microcontroller is used and performs a voltage-feedback technique where it continuously tracks and measures the DC-DC boost converter output voltage and compares the measured value to a reference voltage. The differential compared value is used to produce a pulse-width-modulation signal. The signal is used to control a switch in the DC-DC boost converter. Simulation results describe the performance of the proposed design. Experimental work was carried out with the converter operating in continuous conduction mode with constant 24 V output voltage, 100 W output power, 20 kHz switching frequency and supplied from solar panel voltage. The experimental results show that the proposed design is able to produce a constant 24 V with efficiency more than 72.9% at 100 W load conditions.

CHAPTER 1

INTRODUCTION

1.0 Background

In recent years, a lot of societies, meetings and conferences had been held in conjunction of greenhouse effect and global warming. One of the major gasses that contribute to the greenhouse effect is carbon dioxide (Kiehl & Trenberth, 1997). Carbon dioxide emissions are mostly produced by the combustion of fossils fuels, by-product of chemical manufactures, and natural emissions. As a lot of the power generations in the world are using fossils fuel, solutions have to be figured out to reduce the emission of carbon dioxide or to replace the power generations which uses fossils fuel with other alternatives. One of the alternatives is by replacing the power generation using fossil fuels with power generation that uses renewable energy such as solar energy, wind energy, and ocean energy. Among these renewable energies, solar energy has the potential to be pervasively developed, as the sunlight is distributed throughout the Earth. Power generation using solar energy has the advantages of environmental friendly, reliable, low maintenance, no noise and wear due to the absence of moving parts and operates silently (Koutroulis et al., 2001; Santos et al., 2006; Veerachary et al., 2003).

Solar energy is generated by photovoltaic (PV) effect using solar cell where it converts sun irradiation into direct current (DC) source (Martins & Demonti, 2002; Skvarenina 2002)**.** A lot of PV application systems had been designed and developed ranging from few hundred watts to megawatts due to its advantages. PV power plants in Germany and Spain are producing power more than 100 GW.h/year (Lenardic, 2001). Besides such a huge power generation, a variety of end user products using PV application system is also developed and available in the market. Consumer products that developed from PV application systems such as battery charger, remote area power supply, and solar vehicles are getting more attention from the people for its benefits and environmental friendly (Soler-Bientz et al., 2006).

Based on the power produced by PV effect, PV application system is mainly divided into two categories which are grid connected system and standalone system (Imhoff et al., 2007). A grid connected system is a system which the power produced by PV panels is send to local utility grid whereas a standalone system is an off grid system which the power produced is stored and not deliver to the utility grid. A standalone system is developed when the local utility generated power is unavailable, undesirable or too costly to hook up to. Standalone systems make use of energy storage system such as battery bank whereas most of the grid connected system has no energy storage system (Imhoff et al., 2007; Kroposki & DeBlasio, 2000). Battery banks are excluded from a grid connected system due to its drawbacks. Battery bank has the disadvantages of limited life cycles, high costs, bulky size, possible environmental pollution and safety consideration (Lo et al., 2009). As suggested by Enslin et al. (1997), battery storage is the second major contributor of capital cost of installing PV system. Therefore, the exclusion of batteries in PV systems is economically advantageous (Martins & Demonti, 2002).

In a grid connected PV system, an alternating current (AC) source is used to connect and deliver power to the utility grid. Since PV panels produce a DC power source which are unable to connect with grid, Martins and Demonti (2002), Kjaer et al.

(2005), Kang et al. (2005) and Raiwan and Nayar (2007) had presented that grid connected PV systems need a dual power processing stage that consists of a DC-DC converter and an inverter. The DC-DC converter is responsible for voltage amplification whereas inverter is used to convert a DC power into AC power, grid interconnection and as active power generator or reactive power compensator (Albuquerque et al., 2010; Yang et al., 2010). The dual power processing stage can be configured with few DC-DC converters, each supplied by a string of PV panels and connected to a single inverter to become a multi-string topology (Bellini et al., 2008; Kim et al., 2009).

1.1 Problem Statements

Although PV panels produce DC voltage, but the voltage is unregulated and changes depends on solar irradiation and temperature level (Hohm & Ropp, 2003; Hua & Lin, 2003; Lee et al., 2008). Therefore, the purpose of a DC-DC converter in grid connected system is not only for voltage amplification as suggested by Kjaer et al. (2005) but it also had to provide a constant DC voltage for inverter in order to produce a constant AC voltage. A constant DC voltage is needed because an inverter is unable to produce a constant AC voltage if the input of the inverter is fluctuating since constant AC voltage is an important parameter in grid connected system for grid synchronizing and power delivering.

In order for the DC-DC converter to produce a constant DC voltage, a suitable control strategy is needed. There are various types of control method available and one of the methods is by using a small computer called microcontroller. Microcontroller based DC-DC converter is designed in this project because it permits easy system modification, simple and less components count compare to control strategy using analogue circuitry. By modifying the microcontroller source code, the microcontroller may perform various functions without changing all of the related components.

1.2 Scope of Work

All applications emphasize on good performance with high efficiency. Nevertheless, a good microcontroller based DC-DC converter needs to be efficient, reliable and robust. For a good performance of microcontroller based DC-DC converter for PV application system, studies and works have to be done in the areas including DC-DC converter topologies and its analysis, control circuits using microcontroller and hardware fabrication. Therefore, the scope of the project including:

i. Design of a DC-DC boost converter.

ii. Constant DC output voltage of 24 V.

iii. Design of a control method using PIC16F877 microcontroller.

1.3 Research Objectives

The aim of this research is mainly to design and develop a microcontroller based DC-DC converter for grid connected PV application system. The main objectives of this research can be summarized as follow:

i. To design and develop a DC-DC converter with constant 24 V DC output voltage from a fluctuating DC input voltage of PV panel with suitable parts and components.

ii. To develop and implement a control strategy for DC-DC converter using microcontroller.

iii. To design and develop a DC-DC converter suitable for grid connected PV system that contains no battery.

1.4 Design Methodology

The research was carried out in two stages via analysis and experimental. The analysis starts with literature studies which are related to this thesis topic. A complete studies and investigations were carried on the solar panel's performance and characteristic, DC-DC converter topologies, and PV application systems. Based on the literature studies, a DC-DC boost converter topology is chosen to fulfill the specification of the PV application system and a microcontroller from Microchip is chosen to do the control system. Based on the analysis, a DC-DC boost converter was designed together with the control system. The control system will be a closed loop system since the objectives of the converter is to produce a constant DC output voltage. The designed DC-DC boost converter was simulated using computer software like SIMCAD, MULTISIM and Matlab Simulink.

After the designing and simulating stage, the DC-DC boost converter was assembled with suitable parts and components and the control system was loaded into a microcontroller. The parts and components were assembled on a printed circuit board (PCB) which was fabricated using ORCAD software. The prototype DC-DC boost converter was run with few tests and experiments. Suitable measurement equipments such as oscilloscope, multimeter and thermometer were used to record the experimental results. Recorded results were analyzed and evaluated to verify with the design. As the evaluation process had completed and shown that the prototype is performed as designed, the final product is fabricated. Figure 1.1 shows the flowchart on how the research is organized.

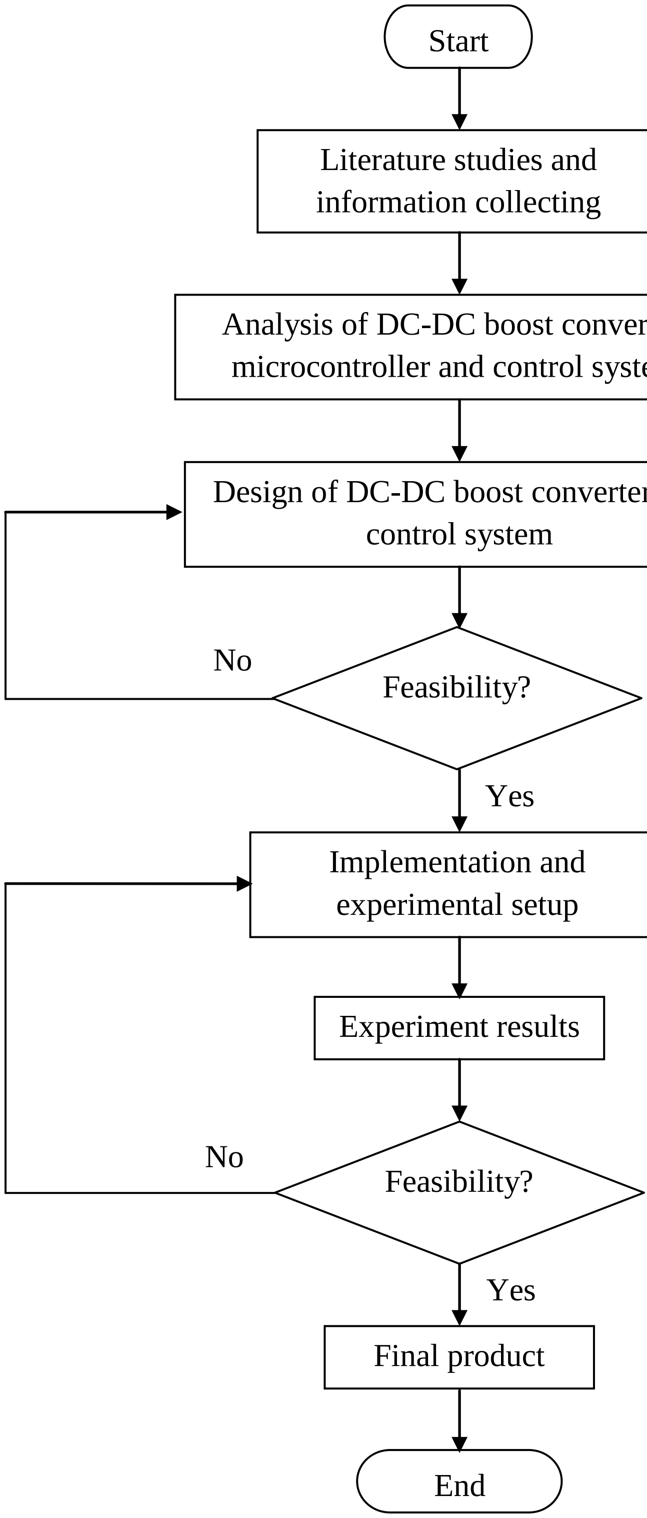

Figure 1.1: Flowchart of research work

1.5 Thesis Outline

This thesis consists of five chapters namely: Introduction, Literature Review, Design and Development of DC-DC Converter, Results and Discussion, and Conclusions.

Chapter 1 introduces the background of the research, problem statements, scope of work, aim and objectives of the research, design methodology and the overall thesis outline.

Chapter 2 starts with literature surveys on DC-DC converters including types of converters, their operations and waveforms. Characteristics for power switching devices and its switching schemes are presented. Control principles such as voltage-mode control and current-mode control are discussed. The properties and basic operation of microcontroller are also discussed in this chapter. This chapter end with the selection of DC-DC converter for grid connected PV system.

Chapter 3 covers the approaches and methods in designing the selected DC-DC converter. The designing process is divided into three main parts which are the power circuit, control circuit and interface circuit. In power circuit, it includes the calculation and selection of components while in control circuit, it describes the design to generate control signal for power switch. Next, it presented the interface circuit connection between power and control circuit.

Chapter 4 shows the simulation results using computer softwares. Experiments were carried out on the hardware to verify the design and the results are illustrated in tables, graphs, waveforms and figures. Analysis and discussion of the simulation and experimental results are presented in this chapter.

Chapter 5 concludes the overall research findings. Suggestions and future works are shown in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Generally, a grid connected PV system requires a power converter to convert DC voltage produced by solar panel to AC voltage that is suitable for supplying AC utility grid voltage. Kjaer et al. (2005) shows a few types of power converter that are able to perform the converting process either by single power processing stage or dual power processing stage. A single power processing stage consists of an inverter that converts a DC voltage to AC voltage, synchronizing AC voltage with utility grid, voltage amplification and grid current control (Kjaer et al., 2005). On the other hand, a typical dual power processing stage of grid connected PV systems consists of a DC-DC converter and an inverter. The control mechanism of a dual power processing stage is easier compare to single stage, since it had two different control systems. Besides, a dual stage grid connected PV system is more reliability and robust. It will be easier to troubleshoot if failure occurred in the system. Martins and Demonti (2002) and Kang et al. (2005) show a dual power processing stage for grid connected PV systems which Martins and Demonti (2002) used a flyback converter whereas Kang et al. (2005) used a buck-boost converter as the DC-DC converter. They used DC-DC converter either to increase the solar panel voltage or modulating the converter output current to be a rectified sine wave which is then direct coupled with a full-bridge inverter. The full-bridge inverter will produce an AC voltage and synchronized it with the utility grid voltage.

There are a variety of DC-DC converters available. Each of it has pros and cons in a grid connected PV system. For example, the flyback converter as proposed by Martins and Demonti (2002) needs a transformer which increases the size, weight and cost. The buck-boost converter suggested by Kang et al. (2005) is also having drawbacks such as it produces an inverting output voltage polarity and limited duty cycle making it difficult to increase the solar panel voltage. Since each DC-DC converter may bring drawbacks, selection of the suitable converter for grid connected PV system should be made carefully by fully understanding their operations and performances.

2.1 Solar Cell Characteristic

Solar cell is the fundamental and the only power generating element in PV application systems. Solar cells are connected and assembled together to form a solar panel or PV panel. Since PV panel produces limited amount of power, PV panels are connected in series and parallel to form a PV array in order to achieve high power generation. Although the total amount of power generated by solar cell, PV panel and PV array is different, but the characteristic is the same. The symbol and equivalent circuit of a solar cell is shown in Figure 2.1.

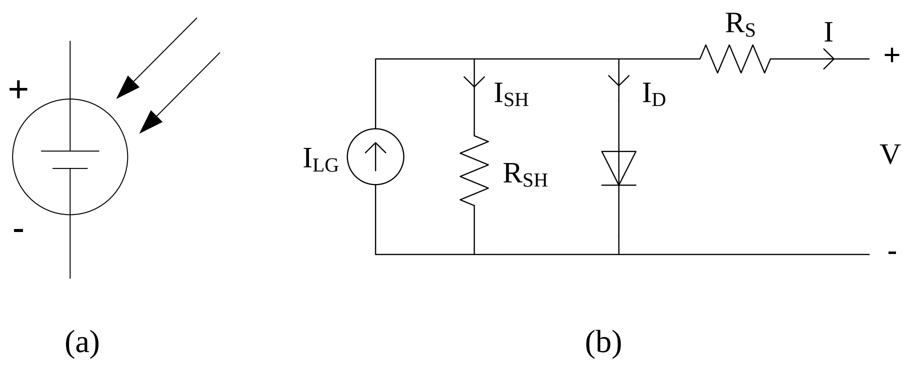

Figure 2.1: Solar cell (a) symbol, (b) equivalent circuit

An ideal solar cell is modelled by a current source in parallel with a diode. But in practice no solar cell is ideal, therefore a shunt and series resistance component are added to the model. From the solar cell model, the cell output current is given by

$$I = I_{LG} - I_D - I_{SH} \tag{2.1}$$

and the characteristic equation yields

$$I = I_{LG} - I_{os} \left\{ \exp\left[\frac{q}{AkT_C} \left(V + IR_S \right) \right] - 1 \right\} - \frac{V + IR_S}{R_{SH}} \tag{2.2}$$

where

I and V = cell output current and voltage

I_{LG} = light-generated current

I_{os} = cell reverse saturation current

q = electronic charge

A = diode ideality factor

k = Boltzmann's constant

T_C = cell temperature in ^{0}C

R_S = series resistance

R_{SH} = shunt resistance

The typical output characteristic of a solar cell is shown in Figure 2.2. From the figure, solar cell produces maximum power at the knee of current-voltage curve. The maximum power point for a single cell is different for different irradiation and temperature level. Figure 2.3 shows the variation of a solar cell output characteristic as function of irradiation and temperature level. It is seen that the temperature changes affect mainly the solar cell output voltage whereas the irradiation changes affect mainly the solar cell current (Koutroulis et al., 2001).

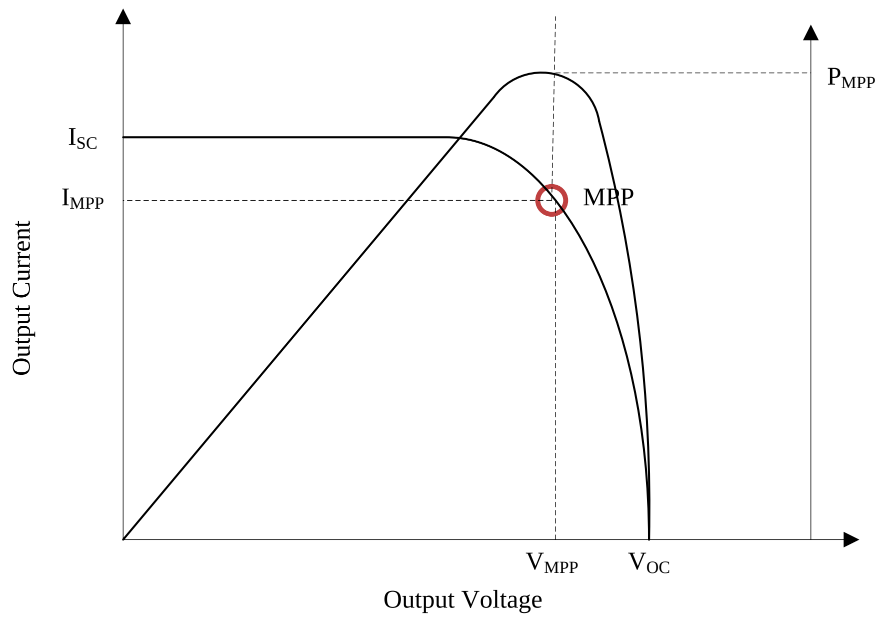

Figure 2.2: Typical solar cell current-voltage and power-voltage characteristic

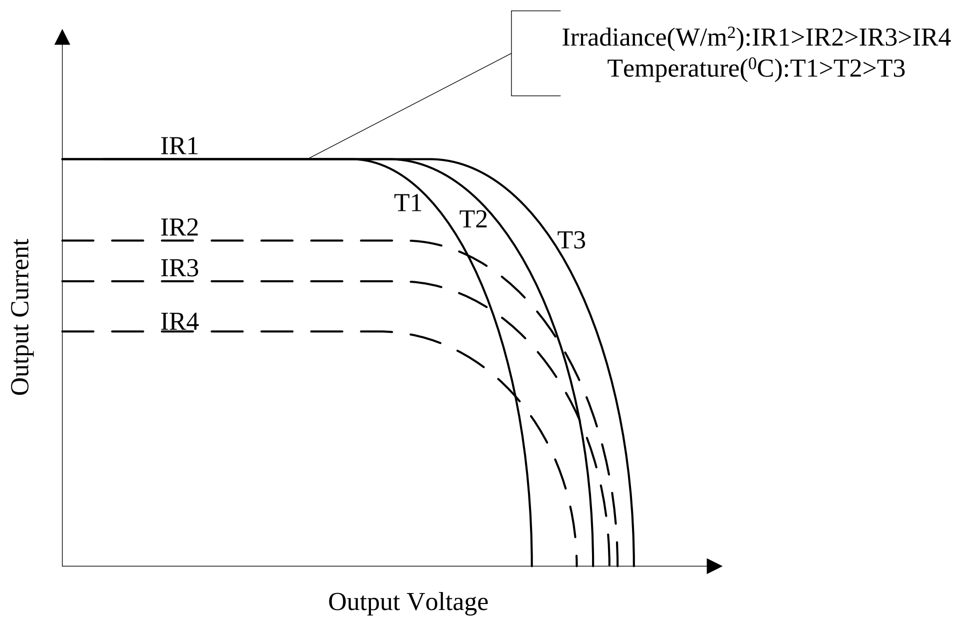

Figure 2.3: Typical solar cell output characteristic based on insulation and temperature changes

2.2 DC-DC Converters

Besides PV panel, power converter is another important device in PV application system. As mentioned, DC-DC converter is a power converter that converts DC voltage from one level to another voltage level either higher or lower. There are only two basic topologies of DC-DC converter which are step-down (buck) converter and step-up (boost) converter. By adding modification to these basic converters, a few more DC-DC converters are derived such as buck-boost converter, Cúk converter, half-bridge converter, full-bridge converter, forward converter and flyback converter. As the technology in power electronics is improving, a lot of new designs and topologies are coming out of these basic converters as shown by Wu et al. (1998). Figure 2.4 shows the classification of DC-DC converter topologies.

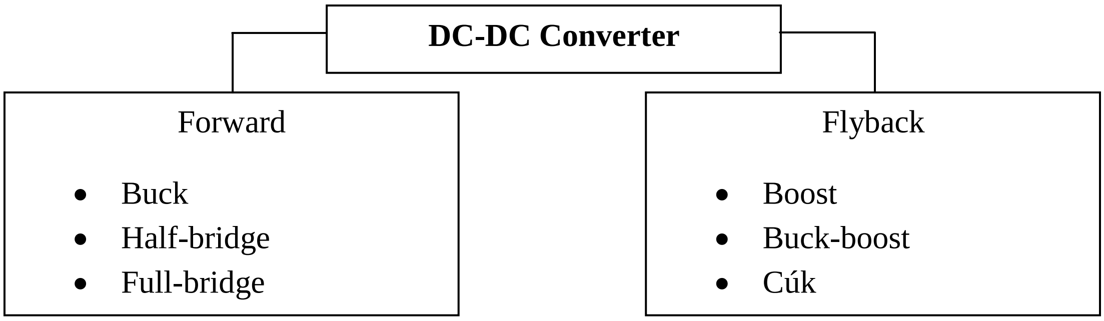

Figure 2.4: Classification of DC-DC Converters

The main functions of a DC-DC converter are:

i. To convert an unregulated input DC voltage to a regulated output DC voltage.
ii. To regulate the output DC voltage against load and line variations.
iii. To provide isolation between the input source and load.
iv. To produce multiple output DC voltages using isolated converter.

2.2.1 Buck Converter Topology

A buck converter is a power converter that produces an output voltage which is lower than its input voltage (Mohan et al., 2003; Rashid, 2007; Skvarenina, 2002). Figure 2.5 shows the basic circuit of a buck converter whereas Figure 2.6 shows its typical waveforms.

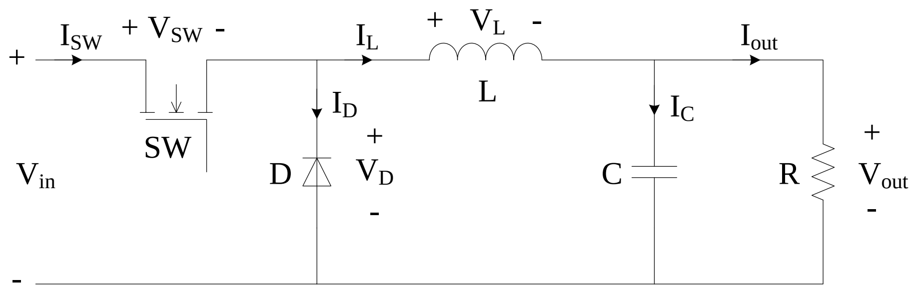

Figure 2.5: Buck converter

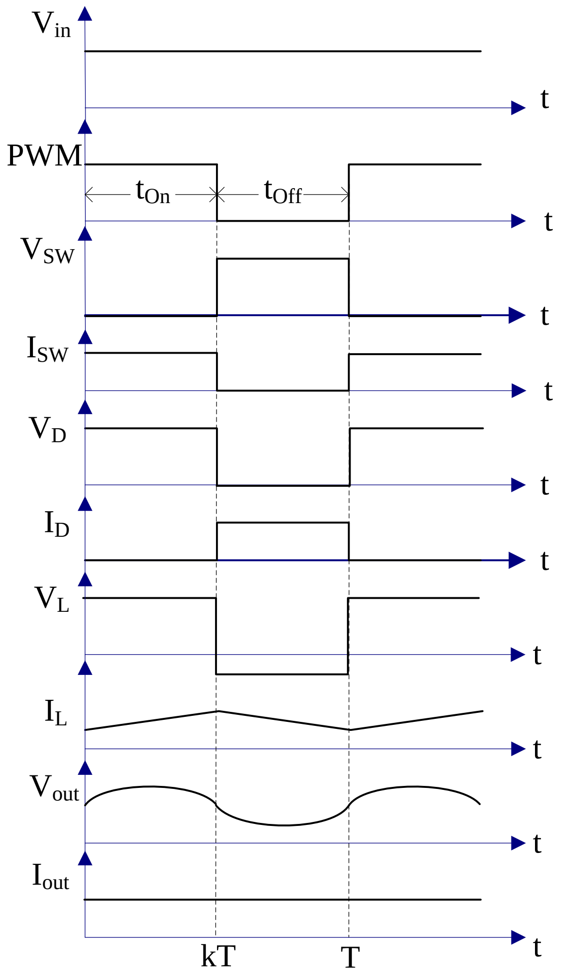

Figure 2.6: Typical waveforms for Buck converter

A buck converter consists of an electronic switch SW, diode D, filter inductor L, filter capacitor C and load resistance R. The formula between input voltage V_{in} and output voltage V_{out} can be obtain by switching SW on and off. When SW is switch on for time duration t_{On}, D is reversed biased and input current flows to the output through inductor. When SW is turn off for time duration t_{Off}, D is forward biased and output is supplied by the energy store in the inductor during the on state. By analysing the circuit during on and off state using Kirchhoff Law, the buck converter yields a relation of

$$V_{out} = kV_{in} \tag{2.3}$$

where k is the duty cycle and defined as the ratio of the SW on time duration to the switching time period T and is expressed as

$$k = \frac{t_{On}}{T} \tag{2.4}$$

Koutroulis et al. (2001) proposed a standalone PV application system using buck converter to charge a battery as shown in Figure 2.7. The buck converter steps down PV panels' voltage of 89.6 V to battery voltage using Intel's CMOS microcontroller as the control system. There is a drawback using buck converter in the system because it requires a higher PV panels' voltage than the battery voltage. It means that the system needs a certain quantity of solar panels. The system will not operate if the PV panels' voltage is lower than the battery voltage. In this case, a boost converter is needed to perform the task.

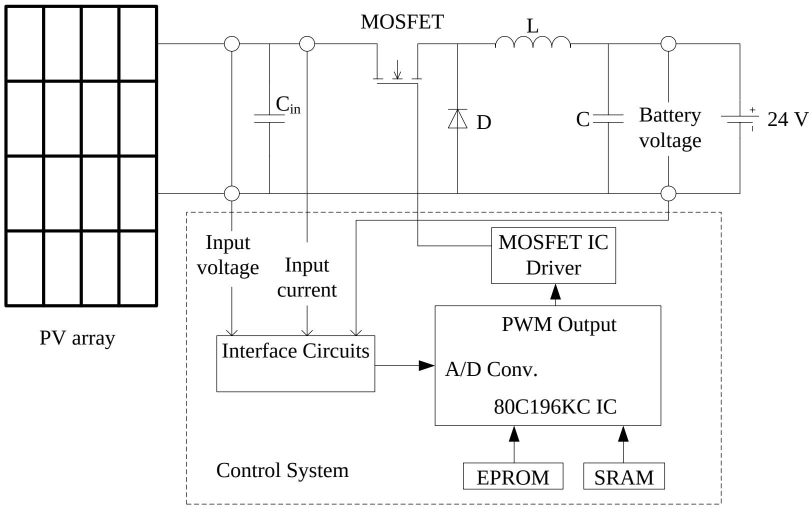

Figure 2.7: Koutroulis et al. (2001) proposed system

2.2.2 Boost Converter Topology

As the name implies, a boost converter is a power converter which produces an output voltage greater than the input voltage (Mohan et al., 2003; Rashid, 2007; Skvarenina, 2002). A boost converter consists of the same components as buck converter but the arrangement of the components is different. Figure 2.8 shows the arrangement of components for a boost converter whereas Figure 2.9 shows the typical waveforms. During t_{On}, the inductor current rises linearly and energy is stored. When SW is turned off, input current continues to flow to the load through the inductor together with the discharging energy stored in inductor. Thus, it is boosting the input voltage and result in higher output voltage. The amplified of output voltage depends on how much the inductor is being charge. Or by other word, it is depending on how long is the SW on time duration or the duty cycle. The relationship of its input voltage and output voltage can be expressed by

$$V_{out} = \frac{1}{1-k} V_{in} \tag{2.5}$$

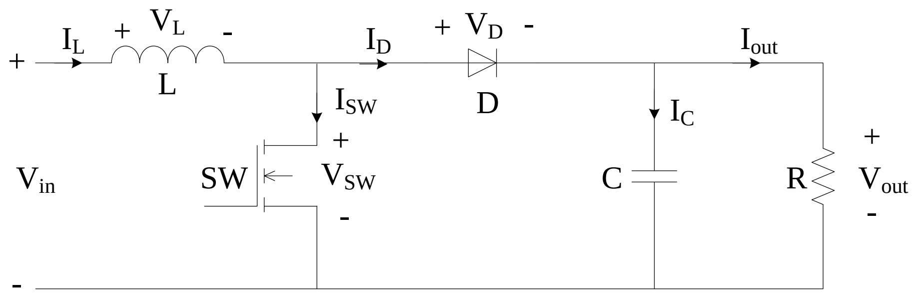

Figure 2.8: Boost converter

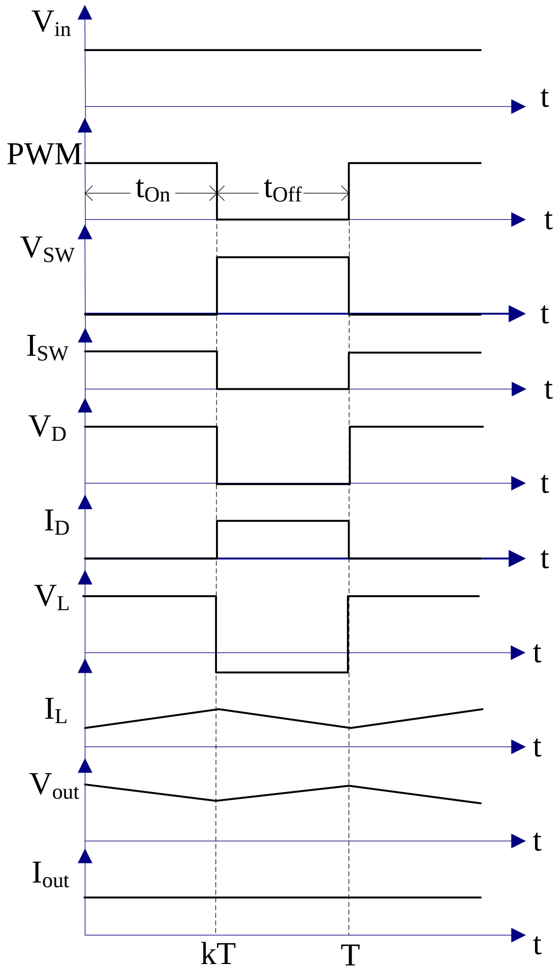

Figure 2.9: Typical waveforms for Boost converter

As proposed by Antunes et al. (2006), a boost converter is used in PV application system which it steps up PV panel voltage from the range of 91 V to 105 V to output voltage at 106 V. The authors introduced a passive non-dissipative turn-on turn-off snubber to achieve a higher efficiency boost converter.

2.2.3 Buck-boost Converter Topology

Buck converter and boost converter are the basic topologies of DC-DC converters. By cascading buck converter with boost converter, a new DC-DC converter is derived and called buck-boost converter. Since buck-boost converter is the combination of buck and boost converter, thus it can perform both functions. Thus the output voltage of a buck-boost converter can be either higher or lower than its input voltage. Besides, the output voltage polarity of a buck-boost converter is opposite to its input voltage. This converter is also known as an inverting regulator (Rashid, 2007). The components of a buck-boost converter are similar as buck and boost converter but the placement of components is different. Figure 2.10 shows the circuit of a buck-boost converter whereas Figure 2.11 shows the typical waveforms. The operation of buck-boost converter starts when SW is turned on and D is reverse biased. During this time, energy builds up in the inductor. When the switch is turned off, the energy stored in inductor will now transferred to output and the inductor current will fall until SW is turn on again. No energy is supplied by the input during this interval (Mohan et al., 2003). The output-input voltage conversion ratio can be expressed as

$$V_{out} = \frac{k}{1-k} V_{in} \tag{2.6}$$

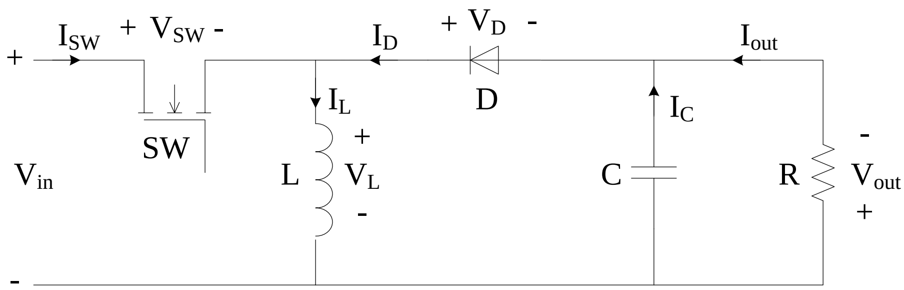

Figure 2.10: Buck-boost converter

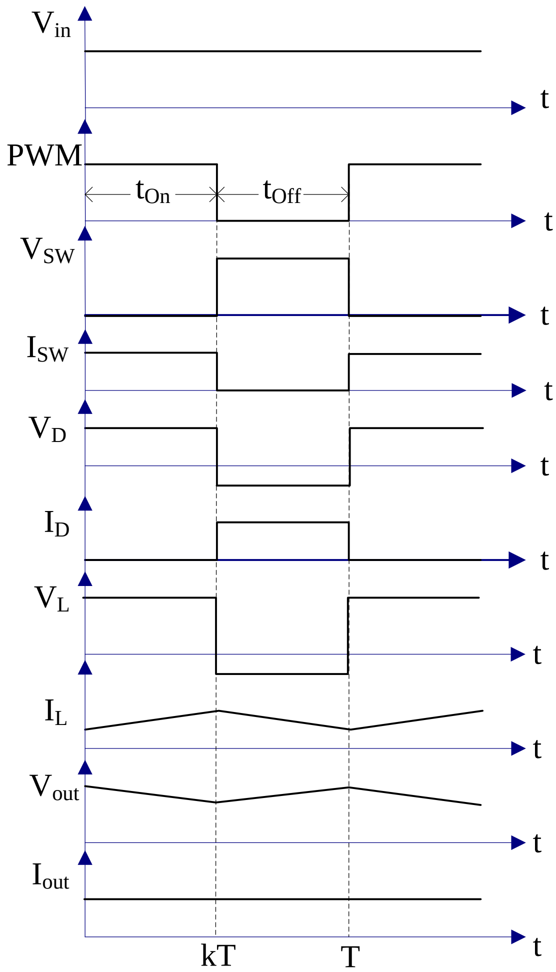

Figure 2.11: Typical waveforms for Buck-boost converter

A grid connected PV system consists of buck-boost converter and a full-bridge converter is proposed by Kang et al. (2005) as shown by Figure 2.12. The proposed buck-boost converter operates in Discontinuous Conduction Mode (DCM) which makes the output current a sinusoidal wave. A higher input current peak is increased when the converter operates in DCM and it required higher current rating of switching devices. Thus, it is not suitable for high power applications. Besides, it is not providing a constant voltage for the full-bridge inverter.

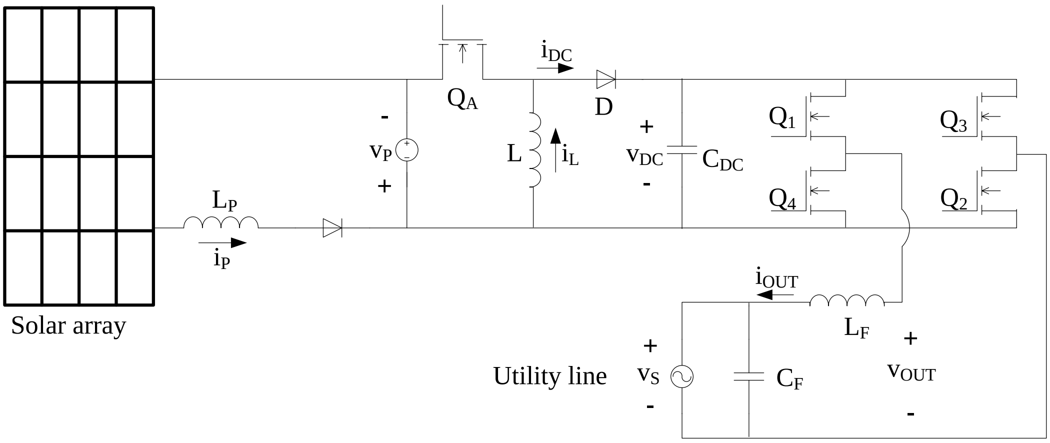

Figure 2.12: Kang et al. (2005) proposed system

2.2.4 Cúk Converter Topology

The Cúk converter is named after its inventor Dr. Slobodan Cúk. A non-isolated Cúk converter is similar to buck-boost converter which it provides a regulated output voltage either higher or lower than its input voltage and the output voltage polarity is opposite with respect to the input voltage (Mohan et al., 2003; Rashid, 2007; Skvarenina, 2002). Unlike previous converters that use inductor as the main energy storage component, Cúk converter uses capacitor as its main energy storage element (Mohan et al., 2003). Figure 2.13 shows the circuit of a non-isolated Cúk converter. It has an additional inductor and capacitor compare to buck-boost converter whereas Figure 2.14 shows its typical waveforms. When SW is turned off, capacitor C1 is being charged by the input source through L1 and at the same time, inductor L2 feeding stored energy to the output stage. On the other hand, when SW is turned on, D is reverse biased. The stored energy in C1 is now transferring to the load and L2 through SW and input source feeding energy into L1 and continues with next cycle. By performing analysis on the operation of Cúk converter during switch on and off, it yields the output–input voltage relationship by

$$V_{out} = \frac{k}{1-k} V_{in} \tag{2.7}$$

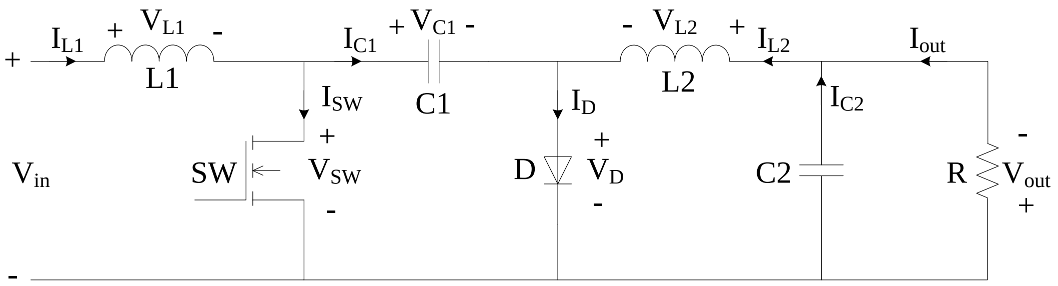

Figure 2.13: Cúk converter

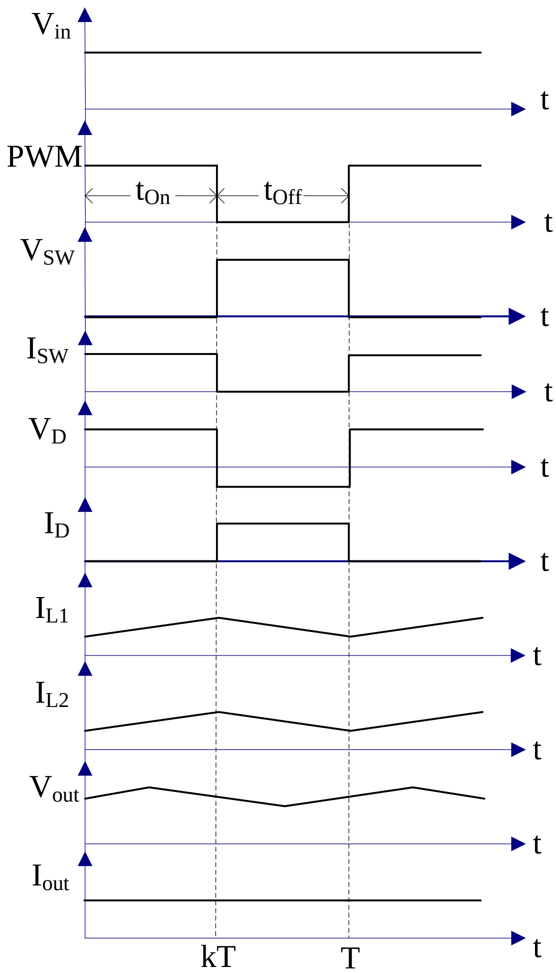

Figure 2.14: Typical waveforms for Cúk converter

A PV system using Cúk converter was proposed by Raiwan and Nayar (2007). In their system, the output voltage of the converter is kept constant by connecting a battery to the output stage. Therefore, any changes in the duty cycle are not supposed to regulate the output voltage. Besides, a common disadvantage of Cúk converter compare to other DC-DC converters is having a higher number of reactive components and high current stress on the SW, D and C1 (Rashid, 2007).

From the analysis, all the DC-DC converters are capable of unidirectional power flow which the power is send from input stage to output stage via different type of connections. They use inductor and capacitor as the storage elements and filter elements to smooth out the current harmonics. Table 2.1 shows the summarize comparison of each DC-DC converter topologies.

Table 2.1: Summarize of DC-DC converter topologies

Type	Function	Equation
Buck	Step down voltage	$V_{out} = kV_{in}$
Boost	Step up voltage	$V_{out} = \frac{1}{1-k} V_{in}$
Buck-boost	Step up or step down voltage with negative polarity respect to common input voltage	$V_{out} = \frac{k}{1-k} V_{in}$
Cúk	Step up or step down voltage with negative polarity respect to common input voltage	$V_{out} = \frac{k}{1-k} V_{in}$

2.3 Power Semiconductor Component

As mentioned previously, a DC-DC converter consists of four main components; an inductor L, electronic switch SW, diode D and filter capacitor C. All the components either active or reactive components in DC-DC converter contribute losses. Proper understanding of the behaviour and operation of these components can result in an efficient DC-DC converter.

2.3.1 Diode

Diode is a two terminals electronic component namely anode and cathode that allow current to flow in unidirectional path. It blocks current in the opposite direction. Figure 2.15 shows the symbol and I-V characteristic of a diode.

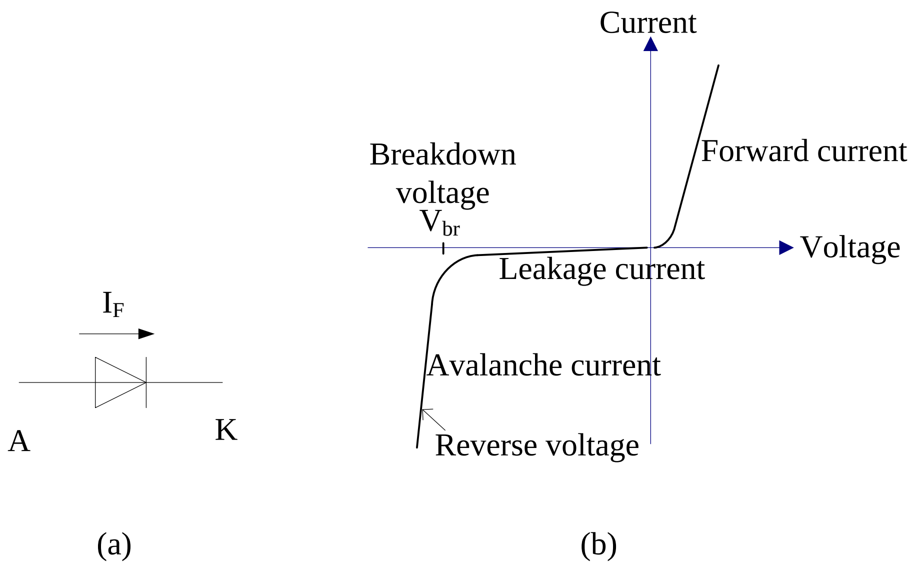

Figure 2.15: (a) Symbol, (b) Characteristic of diode

When the anode terminal voltage is higher than the cathode terminal, the diode is said to be in forward biased mode and forward current I_f flows through the device. During this time, the diode has a relatively small voltage drop across it and the magnitude of this voltage drop depends on types of diodes. On the other hand, when cathode terminal has higher potential than anode, the diode is reverse biased. A small leakage current flows from cathode to anode as shown by Figure 2.15(b). Diode reverse blocking region is controlled by the breakdown voltage. Once the reversed voltage is higher than the breakdown voltage, the diode will short circuit and damaged (Mohan et al., 2003; Rashid, 2004; Skvarenina, 2002).

During turn on, diode can be considered as an ideal switch because it turns on rapidly compared to transients in power circuit. During turn off, diode current reverses and takes time to fall to zero. The time taken is called reverse recovery time, t_{rr} as shown in Figure 2.16 and it is measured from initial zero crossing of the diode current to 25% of maximum reverse current I_{RR}. There are two types of recovery which are soft and abrupt recovery (Rashid, 2004).

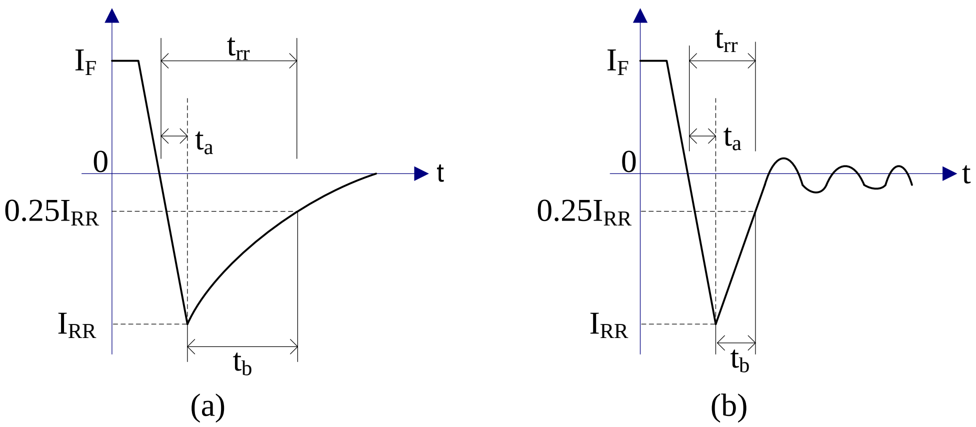

Figure 2.16: (a) Soft recovery, (b) Abrupt recovery

Total reverse recovery time is given by

$$t_{rr} = t_a + t_b \tag{2.8}$$

where;

t_a is the time between zero crossing and the maximum reverse current

t_b is the time between the maximum reverse current I_{RR} and 25% of I_{RR}.

The storage charged from forward biased conduction to reverse blocking conduction, Q_{RR} is given by

$$Q_{RR} \cong \frac{I_{RR}\, t_a}{2} + \frac{I_{RR} t_b}{2} \tag{2.9}$$

Substituting and rearranging term yields,

$$I_{RR} \cong \frac{2Q_{RR}}{t_{rr}} \tag{2.10}$$

The peak reverse recovery current, I_{RR} may also expressed in reverse *di/dt* as

$$I_{RR} \cong t_a \frac{di}{dt} \tag{2.11}$$

Equating equation (2.8) and (2.9) gives,

$$t_{rr} t_a = \frac{2Q_{RR}}{di/dt} \tag{2.12}$$

If t_b is negligible as compared to t_a, equation becomes

$$t_{rr} = \sqrt{\frac{2Q_{RR}}{di/dt}} \tag{2.13}$$

and

$$I_{rr} = \sqrt{2Q_{RR} \frac{di}{dt}} \tag{2.14}$$

Softness factor, SF of a diode is given by

$$SF = \frac{t_b}{t_a} \tag{2.15}$$

2.3.2 Electronic Switch

Electronic switch is an important device in DC-DC converter where it performing on and off operation. There are various kinds of electronic switches such as thyristor, gate-turn-off (GTO) thyristor, bipolar junction transistor (BJT), metal oxide silicone field effect transistor (MOSFET), insulated gate bipolar transistor (IGBT), MOS-controlled thyristor (MCT), etc. Each electronic switch has its own merits and demerits. Thus, the selection of electronic switches is depending on their