CHAPTER 1

INTRODUCTION

1.1 GENERAL

Solar Photovoltaic (PV) is a key technology option to realize the shift to a decarbonised energy supply and is projected to emerge as an attractive alternative electricity source in the future. Globally, the solar PV grid connected capacity has increased from 9.4 GW in 2007 to 15.7 GW in 2008 and was 67.4 GW at the end of 2012. Nowadays it is necessary to reduce the costs and increase the efficiency to make solar energy to be more useful. As a result, many research works address the development of solar power system in recent years with improved performances. Power electronics is a green technology, converting electrical energy from one form to another, achieving high conversion efficiency of the solar PV-powered system. The efficiency of solar PV powered-system depends mainly on the efficiency of the Maximum Power Point Tracking (MPPT) circuits.

The aim of this chapter is to present the motivation behind the work done in this research work. The configurations and characteristics of solar PV module and basic DC-DC converter-based MPPT circuits are discussed. The literature survey of previous research is performed and the recent knowledge of DC-DC converter-based MPP tracking circuits are discussed. This chapter provides the main objectives of the research as well as the thesis organization and research contribution.
1.2 PHOTOVOLTAIC ENERGY SYSTEM

The output of solar PV cell is a Direct Current (DC), where the current is determined by the area of the cell and amount of exposed solar irradiation. The voltage of the individual silicon cell is in the order of 0.5V. Thereby, the cell has to be connected in a series to constitute modules with reasonable voltage level. The maximum power is delivered at the operating point, where the magnitudes of PV system and load resistance are equal. This is usually performed by an interfacing DC-DC power converter employing certain MPPT technique and algorithm. The operating point is held at MPP by regulating either the current or voltage of the MPPT converter.

PV systems are usually used in three main fields: 1. Satellite applications, where the solar arrays provide power to satellites, 2. Off-grid applications, where solar arrays are used to power remote loads that are not connected to the electric grid, and 3. On-grid, or grid connected applications, in which solar arrays are used to supply energy to local loads as well as to the electric grid.

The basic element of the solar PV power conditioning system is the DC-DC converter. If the purpose is to charge a battery or regulate a DC- bus as in space and telecom applications, the system can be implemented by using only the DC-DC converter as depicted in Figure 1.1.

![Figure 1.1 Basic element of power conditioning system](image-url)
1.3 REVIEW OF LITERATURE

Solar PV power is an untapped source of energy, thus there still remains a lot of work to be done to make solar PV system as an efficient and reliable as possible. One approach to understanding and improving solar PV system efficiency is digital modeling and simulation. After successfully modeling and simulating solar PV module, it is possible to develop methods to improve system performance. Walker (2001) developed an accurate model for solar PV module using shockley diode equation. The simple model has a photo-current source, a single diode junction and a series resistance, and includes temperature dependences. The model was used to investigate the variation of maximum power point with temperature and irradiation levels. A comparison of buck versus boost maximum power point tracker topologies was made, and compared with a direct connection to a constant voltage (battery) load. The method of parameter extraction and model evaluation in MATLAB was demonstrated for a typical 60W solar panel.

MATLAB-based modeling and simulation scheme, suitable for studying the I-V and P-V characteristics of a PV array under a non-uniform insolation due to partial shading, was discussed by Patel and Agarwal (2008). The simulated solar PV model conveniently interfaces with the power DC-DC converters.

Gow and Manning (1999) developed a general model for solar PV module which can be implemented on simulation platform such as PSPICE or SABER. The model accepts irradiance and temperature as variable parameters and outputs the I-V characteristics for the particular PV cell.

Kawamura et al (2003) investigated the relation between the output lowering due to shaded PV cells and the change of I-V characteristics, using computer simulation. It was proven from the simulation that I-V
characteristics were changed by the condition of the shadow, which covered
the module. The change of I-V characteristics of a PV module with shaded
PV cells was discussed.

Quaschning and Hanitsch et al (1996) developed a model to
describe the relationship between current and voltage of a solar cell in
generation region as well as the breakdowns at positive and negative voltages.
They described a set of suitable numerical algorithms to compute the currents
for a given voltage at the solar cell and vice versa.

Villalva et al (2009) proposed a method of modeling and simulation
of photovoltaic arrays. The main objective was to find the parameters of the
nonlinear I-V equation by adjusting the curve at three points: open circuit,
maximum power, and short circuit. Given these three points, which are
provided by all commercial array datasheets, the method finds the best I–V
equation for the single-diode photovoltaic model, including the effect of the
series and parallel resistances, and warranties that the maximum power of the
model matches with the maximum power of the real array. With the
parameters of the adjusted I-V equation, one can build a PV circuit model
with any circuit simulator by using basic math blocks.

The maximum power point is an operating point of solar PV at
which it can deliver maximum power to the load. To predict the maximum
power point, many tracking algorithms are available. Esram and chapman
(2007) discussed several techniques for maximum power point tracking of PV
arrays. They showed that at least nineteen distinct methods have been
introduced in the literature, with many variations on implementation. Their
work has served as a convenient reference for future work in PV power
generation. Different MPPT techniques discussed earlier will suit different
applications. For example, in space satellites and orbital stations that involve
a large amount of money, the costs and complexity of the MPP tracker are not
as important as its performance and reliability. The tracker should be able to continuously track the true MPP in minimum amount of time and should not require periodic tuning. In this case, hill climbing/PAO, IncCond, and RCC are appropriate.

MPPT techniques applied to single-stage, grid-connected PV systems are compared by Jain and Agarwal (2007). MPP techniques are compared on the basis of the time taken to reach (track) the MPP, operating point oscillations in the vicinity of MPP and the dependence of the algorithms, if any, on array configuration and parameters. Comparison was also made on the basis of the energy extracted from the PV source during the transient tracking phase.

Liu et al (2008) employed variable step size incremental conductance maximum power point tracking technique in photovoltaic systems to make full utilization of PV array output power which automatically adjusts the step size to track the PV array maximum power point. The MPPT speed and accuracy are improved.

Different from the traditional MPPT approaches, the T-S fuzzy controller directly drives the system to the maximum power point without searching the maximum power point and measuring insolation. Chiu (2010) presented maximum power point tracking control for stand-alone solar power generation systems via the Takagi-Sugeno (T-S) fuzzy-model-based approach.

Kottas et al (2006) presented maximum power point tracking using fuzzy set theory to improve energy conversion efficiency. The maximum power operation of any PV array under different conditions such as changing insolation and temperature was discussed with fuzzy cognitive network.
To have faster dynamics and improved stability when compared to the traditional PAO, Piegari and Rizzo (2010) and Yang and Zhao (2011) proposed Adaptive Perturb and Observer (APA0) method. The APAO MPPT algorithm was set up and validated by means of numerical simulations and experimental tests, confirming the effectiveness of the method. The authors also discussed the main aspects of the MPPT techniques to be taken into the consideration.

A new MPPT system, consisting of a Buck-type DC-DC converter, which is controlled by a microcontroller-based unit, was proposed by Koutroulis et al (2001) and Tung et al (2006). The main difference between the method used in the proposed MPPT system and other techniques used in the past is that the PV array output power is used to directly control the DC-DC converter, thus reducing the complexity of the system. The resulting system has high-efficiency, lower-cost and can easily be modified to handle more energy sources.

Jiang et al (2005) developed a novel three-point weight comparison method that avoids the oscillation problem of the perturbation and observation algorithm which is often employed to track the maximum power point. Furthermore, a low cost control unit is developed, based on a single chip to adjust the output voltage of the solar cell array.

The experimental way to measure the I–V characteristic curve of photovoltaic generators based on DC-DC converters was proposed by Durán et al (2009). The obtained results show that the classical buck and boost converters are not capable of reproducing the whole I–V curve of PV generators. The Single-Ended Primary Inductance Converter (SEPIC) and Cuk converter are good choices for this application.
Walker (2004) proposed an alternative topology of non-isolated per-panel DC-DC converters connected in a series to create high voltage string, connected to a simplified DC–AC inverter buck, boost, buck-boost, and Cuk converters. MATLAB simulations are used to compare the efficiency of each topology as well as evaluating the benefits of increasing cost and complexity. The buck and boost converters are shown to be the most efficient topologies for a given cost, with the buck best suited for long strings and the boost for short strings. While flexible in voltage ranges, buck-boost, and Cuk converters are always efficient or disadvantageous in terms of cost.

Enslin et al (1997) proposed a low-power low-cost highly efficient maximum power point tracker to be integrated into a photovoltaic panel. This integrated MPPT uses a simple controller in order to be cost effective. Furthermore, the converter has to be very efficient, in order to transfer more energy to the load than a directly coupled system. This is achieved by using a simple soft-switched topology. The higher conversion efficiency at lower cost will result in making the MPPT an affordable solution for small PV energy systems.

Lim and Hamill (2000) presented MPPT for solar arrays using DC-DC converter. The MPPT system comprises a solar array, a buck DC-DC converter feeding a battery, and a controller.

Tse et al (2002, 2004) and Chung (2003) developed a novel technique for efficiently extracting maximum power from photovoltaic panels. A SEPIC or Cuk converter operating in discontinuous inductor–current or capacitor–voltage mode is used to match with the output resistance of the panel. By injecting the switching frequency with a small-signal sinusoidal variation and comparing the maximum variation and the average value at the input voltage, the MPP can be located. This method is simple and elegant without requiring any digital computation and approximation of the
panel characteristics. The nominal duty cycle of the main switch in the converter is adjusted to a value, so that the input resistance of the converter is equal to the equivalent output resistance of the solar panel at the MPP.

$V^2$-based MPPT scheme using a SEPIC converter topology was discussed by Veerachary (2005). For a given solar insolation, the tracking algorithm changes the duty ratio of the converter such that the solar PV voltage equals the voltage corresponding to the maximum power point. This is done by the tracking algorithm, which mainly computes the power proportional to square of terminal voltage and changes the duty ratio of the converter so that this power is maximum.

Chiang and Shieh (2009) developed a modeling and controller design of the PV charger system implemented with the SEPIC converter. The control objective is to balance the power flow from the PV module to the battery and the load such that the PV power is utilized effectively and the battery is charged with three charging stages.

Incremental conductance MPPT with Cuk converter used to extract maximum power from the solar PV was discussed by Safari and Mekhilef (2011). The proposed system is different from the existing MPPT systems by eliminating the PI control loop and investigating the effect of simplifying the control circuit.

Snyman and Enslin (2012) evaluated maximum power point tracking converters using some basic power components. The parallel power conversion technique is used to enhance the energy conversion efficiency in the PV system.

Bennett et al (1993) compared different converter topologies with solar PV model which was developed by removing the series and/or parallel
resistors. The models were expected to yield similar results due to the large parallel resistance and small series resistance to see if the dynamic behavior of the PV system depended on the converter used.

Algazar et al (2012) proposed a new technique for MPPT for stand alone PV system. A fuzzy logic controller was applied to a DC-DC converter to extract maximum power increase the efficiency of energy production from solar PV.

Cuk (1983) invented a new converter called Cuk converter which offers higher efficiency, low or zero output ripple, and greatly reduced Electro Magnetic Inference (EMI), but at the same time achieves the general conversion function. It is capable of either increasing or decreasing the output voltage depending upon the duty ratio of the switching transistor.

The Cuk converter topology uses capacitive energy transfer between the input and output stages rather than the inductive energy transfer of other converters, resulting in nonpulsating input and output currents. Also three discontinuous operating modes of Pulse Width Modulation (PWM) converters are considered. Maksimovi and Cuk (1991) proposed a general DC and a general small-signal AC model for PWM DC-DC converters. Middlebrook (1998) discussed the state-space averaging method to analyze the DC-DC converter.

Lin (1997, 2007, and 2010) presented an isolated Zero-Voltage Switching (ZVS) Cuk converter with double-ended rectifier to reduce switching losses on power semiconductors, decrease voltage stresses on rectifier diodes, and achieve power delivery to the output load in both the positive and negative half cycles of the secondary winding voltage. An auxiliary switch and a clamp capacitor are connected in parallel with the primary side of the transformer to absorb all the energy stored in the
transformer leakage inductance. The resonant inductance and the clamp capacitance are resonant to achieve ZVS of the auxiliary switch. The resonant inductance and output capacitance of the main switch are resonant to achieve ZVS turn-on of the main switch.

Wu et al (2008) proposed a boost converter with coupled inductors and a buck-boost type of active clamp. In the converter, the active-clamp circuit is used to eliminate the voltage spike that is induced by the trapped energy in the leakage inductor of the coupled inductors. The active switch in the converter can still sustain a proper duty ratio even under high step-up applications, reducing voltage and current stresses significantly. Moreover, since both main and auxiliary switches can be turned on with Zero-Voltage Switching, switching loss can be reduced, and conversion efficiency therefore can be improved significantly.

Costa and Duarte (2004) developed a Cuk converter featuring clamping action, pulse width modulation, and soft-switching commutation. The soft switching commutation was proposed to overcome the limitations of the conventional Cuk converter.

Duarte et al (1997) presented a technique to generate a complete family of two-switch pulse width-modulated with active clamping DC-DC converters, featuring soft commutation of the semiconductors at zero-voltage.

Lin and Huang (1997) proposed Zero-Current Switching (ZCS) Cuk converter in order to achieve power factor of unity, less harmonic control contents, zero switch loss, simpler control stage, higher power density and unidirectional power flow. Optional principles, design analysis, small-signal models and conditions achieving zero switching loss for the proposed converter are described.
The regulation of the output voltage of photovoltaic arrays was analyzed by Villalva and Ruppert (2008) and Villalva et al. (2010). DC-DC buck converter is used as an interface between the PV array and the load. The input voltage of the converter is controlled in order to regulate the operating point of the array. Besides reducing losses and stress because of the bandwidth-limited regulation of the converter duty cycle, controlling the converter input voltage reduces the settling time and avoids oscillation and overshoot, making easier the functioning of maximum power point tracking methods.

Xiao et al (2007) discussed the use of youla parameterization to design a stable control system for regulating the photovoltaic voltage. In photovoltaic power systems, both photovoltaic modules and switching-mode converters present non-linear and time-variant characteristics, which result in a difficult control problem.


Bernardo et al (1998) analyzed non-linear phenomena in closed-loop Pulse Width Modulated DC-DC converters. The authors introduced a non-linear switching map which is related to synchronous switching. The author proposed a possible explanation of the sudden jump to chaos exhibited by DC-DC converters.

The periodic and chaotic behaviors of DC-DC converters under certain parametric condition were analyzed by Li et al. (2009-B). Li et al. (2009-A) proposed Chaotic Pulse Width Modulation (CPWM) to distribute the harmonics of the DC–DC converters continuously and evenly over a wide
frequency range, thereby reducing the EMI. The output waves and spectral properties are simulated and analyzed.

Zhou et al (2012) studied chaos in three typical topology power electronic converters with a close loop controller. They discussed the existing methods to control chaos and analyzed the features.

The design of analogue chaotic carrier, which can be used in PWM DC-DC converters to reduce EMI, was proposed by Li et al. (2007, 2010). The designed chaotic carrier is simpler and much cheaper than a corresponding digital implementation. Morgul (1995) developed a chaotic oscillator circuits to generate the chaotic signals by coupling chua diode with Wein bridge oscillator in parallel. The designed chaotic carrier is simpler and much cheaper than a corresponding digital implementation. According to the simulation and experimental results obtained, the analogue chaotic carrier can greatly suppress EMI of DC-DC converters while the other characteristics of the boost converter are well maintained.

Ma et al (2012) discussed sampled-data model and applied it to analyze the dynamics of Cuk converter. The results show that the four eigen values of the converter can be two pairs of complex conjugates, and that one pair may move out of the unit circle as some parameters are varied. This causes occurrence of slow-scale oscillation as a result of the Neimark–Sacker bifurcation in the input stage of the converter. A washout filter is used to control the bifurcation so as to stabilize the converter, and the effects of parameters of the filter on the stability of the converter are analyzed.

The chaotic behavior in current mode controlled SEPIC converter operating in continuous conduction mode by varying the reference current $I_{ref}$ was analyzed by Kavitha and Uma (2010). It was observed that the system changes from a stable buck-like operation to an unstable boost-like operation
by varying $I_{\text{ref}}$. Bifurcation diagram was plotted for control signal and capacitor voltage with $I_{\text{ref}}$ as bifurcation parameter. Resonant parametric perturbation control technique was applied to suppress chaos. Effects of phase shift and frequency mismatch were also analyzed.

Poddar et al (1998) demonstrated that DC–DC buck and boost converters with current or voltage feedback exhibit chaos for significantly large ranges of parameter values. The authors presented two methods for controlling chaos which are particularly suitable for switching circuits. The results of numerical investigation and experimental implementation were presented with reference to the duty cycle controlled buck converter.

Kavitha and Uma (2011) analyzed the bifurcations in current-controlled Luo topology, operating in continuous conduction mode using continuous-time model. The stability of the system was analyzed by studying the locus of the complex eigen values, and the characteristic multipliers locate the onset of Hopf bifurcation. The 1-periodic orbit lost its stability via Hopf bifurcation, and the resulting attractor is a quasi-periodic orbit.

Li et al (2007) suggested the prony method for chaotic spectral estimation of DC-DC converters. As compared with the FFT method, the prony method has shown its merits, such as improving the frequency resolution and accuracy in locating the harmonics. The prony method can distinguish the DC component and AC component of a signal.

The traditional EMI suppression technology was discussed by Li et al. (2009). He analyzed the use of chaos theory and chaos control to reduce EMI as well as to motivate more efforts in theoretical research and engineering practice.
Cafagna and Grassi (2005) illustrated an experimental study of a current-programmed DC-DC boost converter, with the aim of investigating possible pathways through which the converter may enter chaos. In particular, based on experimental measurements, it is shown that variations of input voltage and reference current can generate periodic, sub-harmonic, quasi-periodic and chaotic behaviors.

A chaotic pulse width modulation scheme was proposed by Wang et al (2007) to reduce the conducted electromagnetic interference in motor drives.

Yinghua et al (2012) attempted to reduce the electromagnetic interference of traditional PWM inverter using soft switching PWM inverter. The EMI conductive noise of AC inverter system was measured, analyzed and compared under hard switching and soft switching, respectively.

### 1.4 PROBLEM FORMULATION

The demand for electric energy increases rapidly due to the global population growth and industrialization. The increase in the energy demand requires electric utilities to increase the generation. To overcome the problems associated with generation of electricity from fossil fuels, renewable energy sources can be blended in the energy mix. One of the renewable energy sources is the light received from the sun. A significant advantage of photovoltaic system is the use of the abundant and free energy from the sun. The sun light can be converted to clean electricity through the photovoltaic process.

Despite the increasing use of PV systems, these systems still face a major obstacle due to the high capital cost and low efficiency when compared with other renewable technologies. In addition, the fluctuations in the output power due to non-linearity might lead to undesirable performance. These
obstacles can be overcome by utilizing the recent technology in developing low cost PV cells and efficient power conditioning system. As a result, many research works address the development of power conditioning system in recent years with improved performances.

To maximize the overall power generation of solar PV powered system, the operation point of each PV module is at its own MPP and improves converter conversion efficiency of power conditioning system.

The DC-DC converters used in solar power conditioning system are highly non-linear circuits, a great variety of strange phenomena have been observed, including sub-harmonics, quasi-periodic oscillations, and chaotic behaviors. In particular, it has recently been observed that a large number of power electronic circuits can exhibit deterministic chaos.

Even though most of the approaches proposed until now are very interesting, they mainly present theoretical or simulated results. As a consequence, there is a lack of experimental analysis on the parameter domains for which chaotic behavior may occur in solar PV system. Therefore, this research work aims at bridging this gap by presenting an experimental study of some dynamic phenomena that can occur in voltage mode controlled Cuk converter based solar PV system.

Also the DC-DC converter used in solar PV system should be stable and the input voltage be kept within the specified range under disturbances at the source voltage and the change in irradiation.

1.5 OBJECTIVES OF THE THESIS

The efficiency of solar PV system used in space satellite mainly depends on the efficiency of DC-DC power conditioning process. High efficient DC-DC converter has to be designed which is more suitable in solar
PV application. Unfortunately, the performance of solar PV system is affected due to non-linear dynamics in DC-DC converter used in MPPT system, and leads to undesirable operation in solar PV system. Also DC-DC converter used in solar PV system should be stable and the input voltage is kept within the specified range under disturbances at the source voltage and the change in irradiation. With above motivation, the PV powered DC-DC Cuk converter-based MPPT system is considered in this research. The objectives of the research work are stated as follows:

- To model the solar PV module for studying the effect of temperature and irradiation on the performance of the PV module.
- To analyze, simulate and implement the direct control Adaptive Perturb and Observer MPPT algorithm with Cuk converter using micro-controller to track maximum power from solar PV module.
- To implement and compare different control methods in terms of their performance in suppressing ripples, reducing peaky electromagnetic inference and increasing converter conversion efficiency in MPPT circuits of the solar PV powered Cuk converter system with good steady state performance.
- To investigate experimentally and control the non-linear dynamics such as chaos non-linearity in Cuk converter-based solar PV system.
- To design a voltage controller for regulating the output voltage of the solar PV module so that the input voltage of the DC-DC Cuk converter-based solar PV system is chaotic free and regulated for the change in irradiation. The stability of the DC-DC Cuk converter-based solar PV system is analyzed for the supply disturbances.
1.6 OUTLINE OF THE THESIS

This thesis titled “Design and analysis of DC-DC converter for solar PV system” delineates the implementation and steady state analysis of MPPT DC-DC converter circuits with four different control methods in order to improve the converter conversion efficiency and spectral performance of solar PV powered system. The block diagram of analysis of Cuk converter based solar PV system is shown in Figure 1.2. This dissertation is divided into seven chapters.

Figure 1.2 Analysis of Cuk converter-based solar PV system
Chapter 1 deals with the basic concepts, motivation behind the work, literature survey and the objectives of the research.

Chapter 2 discusses the basic concept of solar PV, various types of MPPT algorithm and power electronics DC-DC converters-based MPP circuits. It also explains the existing MPPT DC-DC converter circuits and drawbacks of existing converter circuits, various types of control methods in MPPT circuits.

Chapter 3 presents the simulation and implementation of Adaptive Perturb observer MPPT algorithm with Cuk converter using micro-controller.

Chapter 4 discusses four different control methods, i.e., periodic carrier with PWM, ZVS switching, ZCS switching, chaotic carrier with chaotic PWM which are proposed to improve converter conversion efficiency of MPP tracking circuits and to minimize the converter output voltage ripples. The converter conversion efficiency and Power Spectral Density (PSD) values of the fundamental component of the output voltage are compared.

Chapter 5 discusses the hardware implementation of Cuk converter- based MPPT using Adaptive Perturb and Observer algorithm to track maximum power. The steady state performance analysis of various control methods on Cuk converter based MPPT system is also carried out.

Chapter 6 deals with the input voltage regulation for solar PV powered Cuk converter system. The linear model of solar PV module is used for computer simulation. A voltage controller is designed to regulate the input voltage (solar PV module output voltage) of solar PV powered Cuk converter system for the change in irradiation with hardware validation. Also this chapter deals with the experimental study of dynamic behavior and route to chaos in solar PV-powered Cuk converter system.
In chapter 7, a review of work reported, major conclusions reached and contributions made are dealt with. Recommendations for further research are also stated.

1.7 CONCLUSION

A brief survey of the techniques and methods available in the literature for effective implementation of design and analysis of MPPT DC-DC converter circuits has been discussed. The motivation for the present work has been brought out. The organization of the thesis has also been presented briefly.