UNIVERSITI PUTRA MALAYSIA

DC-TO-AC INVERTER DESIGN FOR PHOTOVOLTAIC SYSTEM

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By

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To my younger brother Mahmud, who takes the responsibility of the family while I am studying to get the Master of Science Degree

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LIST OF SYMBOLS AND ABBREVIATONS

ARC	Anti-reflection Coating
BJT	Bipolar Junction Transistor
BOS	Balance of System
C	Capacitor
CJP	Cold-Junction Processing
D	Drain
f	Frequency
FF	Fill-Form
G	Gate
I	Insolation
I	Current
IGBT	Isolated Gate Bipolar Transistor
L	Inductor
M	Modulation index
MGD	MOSFET Gate Drive
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NSDB	Non-Sun-Drain-Period
PCB	Printed Circuit Board
PV	Photovoltaic
PWM	Pulse Width Modulation
R	Resistor
S_N	Switch number N, where N = 1,2,3, or 4
SOA	Safe Operating Area
SOG-Si	Solar Grade Silicon
T	Temperature
TTL	Transistor-Transistor Logic
W_P	Peak Watt
θ	Thermal resistance
τ	Time constant
δ	Pulse width
η	Efficiency

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in partial fulfilment of the requirements for the degree of Master of Science

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MOHAMED MOHAMED EDARDAR

March 1999

Chairman: Norman Mariun, Ph.D.

Faculty: Engineering

With the recurrent oil crises and the new environmental boundary conditions for energy production and use, the Photovoltaic, PV, system development can be a very promising strategic solution, which realises together with the Photovoltaic energy cost effectiveness goal, an actual clean, renewable, and alternative energy option. However, the continuos decline in Photovoltaic module prices in the international market gives more attention to design the supplementary equipment with low cost and high reliability, such as DC-to-AC inverter

For that reason, this project has the objective of designing and implementing a prototype DC-to-AC inverter which used to power small houses or huts in the rural areas. The input of this inverter is four batteries of twelve volt, which would be charged by a photovoltaic solar array. The design of the solar array and its controller is not within the aim of this project. However, a theoretical study is given for the photovoltaic system in the first chapters for a purpose of illustration.

The DC-to-AC inverter is designed as a single phase bridge switched mode circuit, using power MOSFET switches and electronic components that are common and with low cost. For the sake of simplicity, a single pulse width modulation is applied which gives a reasonable efficiency with rejection of the third harmonic and its multiple. The detailed analysis of the design and experimental construction of the inverter are discussed in this report.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
Sebagai memenuhi keperluan untuk ijazah Master Sains

MEREKA BENTUK PENUKAR UNTUK APLIKASI SISTEM PHOTOVOLTAIK

Oleh

MOHAMED MOHAMED EDARDAR

Mac 1999

Pengerusi : **Norman Mariun, Ph.D.**

Fakulti: **Kejuruteraan**

Berdasarkan permasalahan minyak kini dan terbatasnya pengeluaran tenaga dan kesannya kepada alam sekitar, maka penggunaan fotovoltaik (PV), dibangunkan untuk memberikan suatu penyelesaian yang strategik. Kita sedia maklum bahawa tenaga fotovoltaik memberi altenatif kepada tenaga yang sedia ada sekarang. Ditambah pula dengan penurunan harga pada modul fotovoltaik di pasaran antarabangsa, telah memberikan tumpuan untuk mencipta peralatan tambahan, pada kos yang rendah, sebagai contoh, penukar DC kepada AC.

Tujuan projek ini adalah untuk mencipta dan melaksanakan prototaip penukar DC kepada AC yang boleh diguna untuk memberi bekalan kuasa kepada rumah kecil di luar bandar. Input untuk penukar ini menggunakan 4 bateri (12 volt), yang boleh dicas semula oleh susunan fotovoltaik suria. Pembentukan susunan sel suria dan kawalannya, bukanlah matlamat kepada projek ini. Walaubagimanapun kajian secara teori mengenai sistem fotovoltaik diberikan pada bab pertama bertujuan memberikan gambaran menyeluruh.

Penukar DC kepada AC direkabentuk sebagai litar jejambat mod suis, menggunakan suis MOSFET dan komponen elektronik yang biasa dan murah. Supaya mudah, modulasi lebar denyut tunggal digunakan yang boleh memberikan nilai kecekapan munasabah serta menghapus harmonik ketiga dan seterusnya analisa mengenai rekabentuk dan pembinaan ujikaji dibincangkan secara lanjut di dalam laporan ini.

CHAPTER I

INTRODUCTION

Prologue

This thesis contains two parts. The first part is a study of a photovoltaic (PV) system and related topics such as the solar radiation and the solar cell. The photovoltaic effect is the direct conversion of light energy into electricity by solar cells. Electricity is a high quality form of energy, which is suitable for almost every type of energy-consuming activity. It uses range from such highly technical tasks as powering computer or electron beam welders to domestic tasks such as water heating or powering the kitchen toaster. An example of how to design a small photovoltaic system for a home application is given with a description of the subsystems and the cost analysis.

The second part of the project, the main part, is to design and construct a DC-to-AC inverter, which is one of the main components of the photovoltaic system for AC applications. More attention has been given to this part, since the author has done a complete design and the construction of the inverter. The inverter is the circuit which convert the DC, or the direct current, of the solar cells to AC, or the alternating current which is suitable for home applications such as lamps, fans, refrigerators, radios and so on.

Importance of the Project

There are several reasons that attract the researchers to photovoltaic systems and subsystems design. These reasons have been gathered and presented by the author in this thesis in Chapter II. It is more important in developing countries where the majority of the population lives in dispersed communities in rural areas. The provision of an electricity supply to these areas are difficult and costly; extension of the mains grid over difficult terrain is generally not economic for small power loads and the use of diesel generator sets relies on availability of fuel supplies and maintenance skills. The only limitation of using the photovoltaics as a source of energy is the cost. As a result emphasis is put in most scientific research and development institutions to reduce the cost to the minimum. The goal of reducing the cost of the photovoltaic system to be equivalent to the other sources of the energy will put it in the first options to be chosen because of its other advantages presented in Chapter II.

Research works are being carried out to reduce the cost in the field of solar cells as well as the other parts of the system such as batteries, inverters, system controllers and so on. In this project a DC-to-AC inverter has been designed and constructed for a photovoltaic application. This inverter has the same working principles as the other power-electronic devices and circuits. But three important factors should be given more emphasis in the designing an inverter for photovoltaic application as follows:

1- Simplicity: Most of photovoltaic applications are applied in communication systems or the rural areas with a low population where the connecting to the utility grid is difficult. In these areas it is also difficult to find people who have high skills of maintenance. Consequently, a system with a high reliability is important in these applications To improve the total reliability of the subsystems, the inverter circuits should be simple to reduce the probability of circuit failure A simple circuit gives a chance for a person with a moderate skill to maintain the circuit when fault occurs.

2- High efficiency: The solar cell efficiency in the markets now is in the range of 10% to 15%. As a result most of the solar energy converted to electrical energy is required to be used at the load, and to minimise the losses in the other parts of the system.

3- Low cost: This is the most important factor to be achieved while keeping the other factors within an acceptable range. Reducing the cost of the inverter will share in reducing the total cost of the system.

Objectives of the Project

In this project the author has the aim to master the knowledge in two fields, which usually is faced by the electrical and electronic engineers in their jobs. The first is in designing the system, which gives the author the ability to design and implement electrical system in different applications, once he exposed to one of these systems. The design of electrical system will give the electrical engineer the chance to deal with other factors which is not an electric in its nature such as the geographical and weather effects, the system location and the people. The photovoltaic system has been chosen for such a study because of its importance, which the author presented in his thesis.

The second, is the circuit design. This will give the author more chance to deal with requirements of designing and constructing the electronic and power circuits Testing the circuit also allow the author to know more about the problems of circuit design and comparison is made between the theoretical values and the measured ones. The DC-to-AC inverter gives more chance to deal with low currents and voltage of the control circuit that mainly contains an electronic digital and analogue devices. On the other hand the power circuit deals with higher currents and voltages, which requires more safety precautions for the circuits and the operators.

Thesis Layout

The thesis is organised into five chapters. Chapter I gives an introduction to the author's work and his objective of designing and constructing the DC-to-AC inverter for a photovoltaic application.

Chapter II contains a literature review of both the photovoltaic systems and the DC-to-AC inverter. A general description of a photovoltaic system and related subjects such as the solar radiation and solar cells' operation and construction is given. This knowledge is basic for a system designer. More emphasis is given in this chapter for the study of DC-to-AC inverters, since the author has designed and built the inverter in the laboratory. Inverter theory, inverter types and topologies, the power semiconductor devices, and the required protection circuits are described and analysed.

In Chapter III, a design for a photovoltaic system and methods used in system sizing are given. This is followed by the main design, the inverter. The voltage and current values of the circuit are calculated. Then the components required to construct the circuit are chosen.

Chapter IV contains the results of the tested circuit at different points and with different loads. Oscilloscope waveforms of the circuit output are presented. A discussion of the results is also included in this chapter.

In Chapter V, a general conclusion about the research work has been presented and recommendations for future work and the areas of possible improvements has been discussed.

CHAPTER II

LITERATURE REVIEW

Photovoltaic Historical Background

Photovoltaics have been technologically driven since the discovery of the silicon cell. In the first few years following the invention of the solar cell, it was limited to the space application because of its high cost, hundreds of US dollars, which is relatively small in relation to the total project cost. Following 1973 oil crisis, interest in photovoltaics as a terrestrial source of power increased. Many countries insisted photovoltaic research, development and demonstration programs.

In 1974, the goal was to reduce the cost by a factor of a hundred, to improve the working lifetime by a factor of ten times and the efficiency by a factor of two. Since then, modules cost has decreased from USD70/peak watt (W_P) to about USD2/W_P for amorphous silicon modules and about USD4/W_P for wafer silicon modules. Lifetime increased from months to years, more than twenty years. Efficiency goal of 10% was easily met by using silicon wafers of 13-14%. Amorphous silicon modules have yet to exceed 10% (Hill, 1989).

Why Photovoltaics?

PV modules provide an independent, reliable electrical power source at the point of use making it particularly suited to remote or inaccessible locations. PV systems are technically and economically viable. Their principal advantages are:

1- PV systems have no fuel requirements:

In remote areas diesel or kerosene are erratic and often very expensive. The recurrent costs of operating and maintaining PV systems are small.

2- PV systems are modular:

A solar array is composed of individual PV modules so each system can be sized to meet particular demand.

3- PV system can be used to improve quality of life:

For example, the provision of lighting in a rural school allows evening education or community activities. Refrigeration at a health centre improves effectiveness of immunization programmes.

4- PV systems are highly reliable:

The reliability of PV modules is significantly higher than of diesel generators and wind generators.

5- PV systems are easy to maintain:

Operating and the routine maintenace requirements are simple.

6- PV modules have a long life:

There is a little degradation in performance over 15 years.

7- PV systems provide national economic benefits:

Reliance on imported fuels such as a coal and oil is reduced.

8- PV systems are environmentally harmless:

There is no harmful pollution through the use of a PV system.

9- PV systems are economically viable:

On a life cycle cost basis and taking into consideration the higher reliability of PV, many small applications can be more economically powered by PV than with diesel systems or other small power supplies (Derrick et al., 1991).

Photovoltaics Applications

The photovoltaics industry is growing rapidly throughout the world. The previous markets in professional systems for telecommunications, cathodic protection etc. are still growing, whilst the applications in developing countries have passed beyond the demonstration stage into an acceptance of photovoltaic systems as a reliable engineering solution to specific problems. In recent years, the most rapidly growing market segment has been in consumer products, but this is likely to be overtaken by the grid-photovoltaics, in research, in production, and in applications has developed such momentum that its future is assured as a major technology.

Photovoltaics have been used in space since the first years of solar cell applications, but they found the widest range of applications in terrestrial applications. At present there are three market categories for photovoltaic systems as the following (Partain, 1995):

1- Consumer market: there are many applications under this category. Examples of them are: small electronic devices, garden light, battery charger, security lighting, ventilation systems, and water pumping.

2- Industrial market: they are also called professional systems; Examples of this category are: telecommunication links, remote sensing, cathodic protection, navigation lights, military equipment, irrigation pumping, and refrigeration services

3- Social benefits market: usually the governments support the applications of this category. Examples of this category are: lighting and power supplies for remote areas, battery charging stations, pumping for drinking water, lighting in rural clinics, blood storage refrigerators, remote weather measuring, emergency telephones, and road lighting.

Solar Radiation

The solar efficiency of a photovoltaic system depends critically on the spectral distribution of the radiation coming to us from the sun. The study of the solar insolation is complex and involved one that is a field all by itself. Here a brief survey of information is presented about solar insolation and the way in which this information can be interpreted (Faherenbruch and Bube, 1983).

Solar insolation: the radiation when integrated over one-hour periods. The symbol I is commonly used.

Irradiance: the radiation flux on a unit area of a spherical surface.

Air-mass: the bath length through the atmosphere is conveniently described in terms of equivalent air-mass Am_{mr} .

Solar constant: the rate at which energy is received on a unit surface perpendicular to the sun direction in free space at the earth's mean distance from the sun.

One-sun: is used to define 1000 watt/m^2 .

Bright sunshine: hours when sunshine is bright enough to cast a shadow.

The sun has a diameter of 865,000 miles, and radiates energy at rate of some $3.8x10^{20}$ Mwatts. The energy output from the sun is considered being constant (Neville, 1995). The distance between sun and earth varies from 92 to 95 million miles. This variation implies that the light energy reaching the earth in June (when the earth is at its maximum distance from the sun) is approximately 94% of the light energy reaching the earth in December. The energy density available to a collector positioned just outside the earth's sphere, which is known by a solar constant, is measured variously as lying between 1.353 and 1.418 Kwatt/m^2 .

Once the sunlight has reached the earth's atmosphere a number of additional effects play a part. These effects result from the weather, and photon absorption by water vapour, ozone, and other atmospheric constituents. They have the general overall effect of reducing energy density in sunlight at the earth's surface. Atmospheric effects are at minimum on a dry, cloudless day with the sun that directs overhead. Under these conditions (known collectively an air-mass one, AM_1) the power flux in sunlight at earth's surface is 1.07 Kwatt/m^2 at a potential energy of approximately 12 hours a day of sunlight. Air-mass zero AM0 condition corresponds to a solar flux density of 1.353 kwatt/m^2 and a potential of 24 hours of sunlight each day.

Two other factors influencing the availability of a solar energy are geometric in nature. The first, the earth rotates on its axis with a period of approximately 24 hours. Hence, sunlight is available for only an average of 12 hours a day. Second, the earth's axis of rotation is tilted approximately 23.5° to the normal of its plane of revolution about the sun. Together, these two effects act to produce a shift in number of hours of daylight and a geometrical situation in which the sun is almost never directly overhead (Neville, 1995).

Solar Spectrum

The sun is a complex radiator whose spectrum can be approximated by a 6050 ^{o}K black body. In outer space 98% of total energy radiated by the sun lies between (0.25 and 3.0) $x10^{-6}$ m wavelength.

A significant fraction of solar spectrum irradiance lies at wavelengths greater than $1.15x10^{-6}$ m. this region of the solar spectrum is often termed the far infrared, as opposed to the near infrared, which lies between 0.7 and 1.15 $x10^{-6}$ m. This far infrared has been demonstrated is not available to solar cells as energy source. This is a major limitation on the efficiency of energy produced by photovoltaic devices.

Effects of Earth's Atmosphere

Both intensity and spectral distribution of radiation arriving at the earth's surface depend on the composition of the atmosphere, as well as the path length of the radiation through the atmosphere. The most important parameters of the atmosphere are: 1) water content, 2) the turbidly coefficient, B, expressing the effect of haze and related scattering, 3) the cloudiness of the sky, and 4) the effect of the ground reflection (Faherenbruch and Bube, 1983).