DESIGN AND DEVELOPMENT OF A MICROCONTROLLER-BASED SINGLE INPUT MULTIPLE OUTPUTS (SIMO) POWER SYSTEM FOR OFF-GRID PHOTOVOLTAIC APPLICATIONS

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DEDICATION

This thesis is dedicated to my father Alhaji Mustapha Imam Sitti, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother Malama Ruqayya Umar Chikaji, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Cross-regulation problem and power dissipation due to multiple switching are mostly encountered among single-input multiple outputs (SIMO) converters. In present research, a SIMO flyback converter is designed and developed to evaluate the effect of switching frequency and overcome cross-regulation error. The developed converter system has four output levels of $24\ \mathrm{V}, 12\ \mathrm{V}, 9\ \mathrm{V}$ and $5\ \mathrm{V}$ and contains minimum number of components with low cost (USD20) and power dissipation (<2%). Ferrite-core transformer is used to generate four output voltage levels. All the four windings are wound around a common core and the developed system provides high efficiency and reduce dissipations. As voltage is applied at the primary coil, a magnetic field is generated around the core due to mutual inductance. The magnetic field strength induced into the core depends on the number of turns, current and voltage in the winding. The percentage error at the outputs of the SIMO converter is more on terminals with less number of windings; the higher the voltage the less the error. The average switching frequency f_{sw} against k (a control parameter for switching frequency) is notably higher with lower k. However, for small k, (i.e. at high switching frequency), the voltage regulation is tighter and more accurate. Therefore, $0.1 < k < 0.2$ has been set and the regulation error are limited to $< 1\%$. The switching and control techniques operate at an average switching frequency of 199 kHz with small frequency fluctuations and output voltage ripples around 10 mV (i.e $< 0.1\%$ of V_0) under nominal conditions of $V_i = 12\ \mathrm{V}$. Efficiencies of 97%, 97.3%, 98.2% and 98.4% have been obtained across the four terminals for 24 V, 12 V, 9 V and 5 V respectively.

ABSTRAK

Masalah pengawalaturan-silang dan pelesapan kuasa disebabkan oleh pensuisan berganda kebanyakannya ditemui di penukar input-tunggal output-berganda (SIMO). Dalam kajian ini, penukar terbang balik SIMO direka dan dibangunkan untuk menilai kesan frekuensi pensuisan dan mengatasi ralat pengawalaturan-silang. Sistem penukar yang dibangunkan mempunyai empat aras keluaran iaitu 24 V, 12 V, 9 V dan 5 V dan mengandungi komponen yang berkos rendah (USD 20) dan pelesapan kuasa (<2%). Transformer teras ferit digunakan untuk menjana empat voltan keluaran. Kesemua empat belitan dilititkan di sekeliling teras yang sama dan sistem yang dibangunkan memberi kecekapan tinggi dan mengurangkan pelesapan. Oleh sebab voltan dikenakan di gegelung utama, medan magnet dijana di sekitar teras kerana aruhan saling. Kekuatan medan magnet yang diaruh ke teras bergantung pada bilangan lilitan, arus dan voltan dalam lilitan. Peratusan ralat pada keluaran penukar SIMO lebih banyak pada terminal dengan kurang bilangan lilitan; semakin tinggi voltan semakin kurang ralat. Purata frekuensi pensuisan f_{sw} kepada k (parameter kawalan untuk frekuensi pensuisan) adalah lebih tinggi pada k yang lebih rendah. Walau bagaimanapun, pada k yang lebih rendah (frekuensi pensuisan tinggi), pengawalaturan voltan lebih rapat dan lebih tepat. Oleh itu, $0.1 < k < 0.2$ telah diatur dan ralat pengawalaturan dihadkan kepada $< 1\%$. Teknik pensuisan dan kawalan beroperasi pada frekuensi pensuisan sekitar 199 kHz dengan turun naik frekuensi yang kecil dan voltan riak keluaran sekitar 10 mV ($< 0.1\%$ daripada V_0) di bawah keadaan nominal $V_i = 12$ V. Kecekapan 97%, 97.3%, 98.2% dan 98.4% diperolehi merentas empat terminal 24 V, 12 V, 9 V dan 5 V.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
CMC	-	Current Mode Control
CPU	-	Central Processing Unit
CRT	-	Cathode-Ray Tube
CSI	-	Current Source Inverter
DC		Direct Current
EMF	-	Electromotive Force
GPIO	-	General Purpose Input and Output
GTES	-	Grid-Tied Energy Storage
HDMI	-	High Definition Multimedia Interface
IC	-	Integrated Circuit
IDE	-	Integrated Development Environment
IoT	-	Internet of Things
I-V	-	Current-Voltage
LAN	-	Local Area Network
LED	-	Light Emitting Diode
MOSFET	-	Metal-Oxide Semiconductor Field Effect Transistor
MPP	-	Maximum Power Point
MPPT	-	Maximum Power Point Tracker
NOOBS	-	New Out of Box Software
PC	-	Personal Computer
PCC	-	Point of Common Coupling
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
RE	-	Renewable Energy
RMS	-	Root-Mean Square
SD	-	Secure Digital
SEPIC	-	Single-Ended Primary Inductor Converter
SIC	-	Serial Interface Camera

SID	-	Serial Interface Display
SIMO	-	Single Input Multiple Outputs
SSD	-	Solid-State Drives
USB	-	Universal Synchronous Board
VSI	-	Voltage Source Inverter
VMC	-	Voltage Mode Control
Wi-Fi	-	Wireless Fidelity

LIST OF SYMBOLS

P_{PV}	-	PV panel's nominal powe
U_c	-	Mean voltage across the capacitor
u	-	Voltage ripple amplitude
ω	-	Generated sinewave's rotational frequency
I_L	-	Current generated in the light
T	-	Temperature
P_{PV}	-	PV panel's nominal power
U_c	-	Mean voltage across the capacitor
u	-	Voltage ripple amplitude
ω	-	Generated sinewave's rotational frequency
I_L	-	Current generated in the light
I_o	-	Dark saturation current
T	-	Temperature
n	-	Ideality factor
V_D	-	Voltage (V) across the diode
q	-	electron charge
I_{SC}	-	Short circuit current (A)
I_S	-	Reverse saturation current (A)
k	-	Boltzmann's constant
V_o	-	Output voltage
i_o	-	Output current
L	-	Inductance

K_t	-	Topology constant
f	-	Frequency
f_{sw}	-	Switching frequency
R_T	-	Timing resistor
C_T	-	Timing capacitor
Ac	-	Transformer's core area
i_c	-	Capacitor current
i_{LP}	-	Transformer's primary current
T_{OFF}	-	Switching OFF time
T_{ON}	-	Switching ON time
V_L	-	Inductor voltage
E	-	Induced EMF
Φm	-	Transformer's core magnetic flux
B_m	-	Maximum magnetic flux density
J	-	Current density
t_{ch}	-	Battery charging time
t_d	-	Battery discharging time
I_{max}	-	Maximum current
V_{NL}	-	No load voltage
V_{FL}	-	Full load voltage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A complete photovoltaic (PV) system consists of three basic units; PV panel, converter/inverter unit and the storage unit. The PV unit constitutes of PV cells which are connected together and generate Direct Current (DC) [1]. The converter/inverter unit changes the low level DC voltage supplied by the PV panel into high level DC or AC [2]. To improve the PV system's design flexibility and energy production abilities, DC − DC converters are connected at the centre between the PV panels and the inverter which provides voltage amplification [3]. DC − DC converter is generally being applied for the sole purpose of changing the unregulated DC into a regulated and controlled DC output at desired voltage levels [4]. The storage unit comprises of the battery that provides short-term to medium-term power saving by applying match between power density and energy density to meet the PV system's storage demand [5].

There are two basic forms of electrical energy transmission used; Direct Current (DC) and Alternating Current (AC) [6]. Each having its specific field of application. Due to its ability to give a constant low or constant high voltage, most digital gadgets and appliances nowadays are designed to work on (DC) power [7]. In common practice, the available power on the grid or off-grid is Alternating Current (AC) and electric infrastructure around the world is based on (AC) voltage with a few exceptions. Therefore, the Direct Current (DC) provided by Solar PV modules needs to be converted to (AC) to make it useful [8]. Inverters circuits are used to change the DC signal (from solar panel or batteries) into AC signal. The DC generated by either the PV cells or batteries is feed to small electronic appliances (loads), especially in off-grid applications. The DC from photovoltaic source must be converted to AC using for grid-connected inverters before it can be sold to electric utilities or be used for commercial applications.

As mentioned earlier, for most of the low power devices (house hold devices) runs on DC current as most of these gadgets invloved built-in circuitry to convert AC to DC current. As such, it is now a vital issue to develop methods and means to transform and regulate either $\mathrm{DC-DC}$, $\mathrm{DC-AC}$ or $\mathrm{AC-DC}$ conversion in an efficient and most profitable manner. Without this ability, the utilization of devices would be restricted to the only available power form. Therefore, this project proposes the use of DC current generated by the PV cell for such devices and gadgets without converting into $\mathrm{DC-AC-DC}$. The conversion stages from $\mathrm{DC-AC}$ or $\mathrm{DC-AC-DC}$ cause loss of significant energy. The application of proposed system is specifically for off-grid installation in remote locations.

The photovoltaic panels output voltage is unstable due to instability of the irradiances [9-11]. In common practice, $\mathrm{DC-DC}$ converters are employed to get constant and regulated output with different voltages [12]. There is a consistent demand for highly efficient $\mathrm{DC-DC}$ converters for various DC applications [11]. Single input multiple output (SIMO) converter enables various outputs, minimizes components number and production cost [13]. Various electronic devices have different voltage requirement, and a single output converter may not satisfy their requirements efficiently [14]. DC fan, television, or laptop may require higher amount of power than mobile phone, and the power required by phones may be too small as compared tolaptops, etc.

The use of various conversion stages from $\mathrm{DC-AC-DC}$ in small off-grid power systems introduces a lot of losses due to conversion processes. The total losses in converters are incurred during operation due to conduction and switching [15]. The power dissipation can be eliminated or significantly reduced by minimizing the number of switches and components in the circuitry [16]. In this work, the switches have been reduced from two, three or four as the case may be as reviewed and presented in [11] to only one, while other converters such as [17-22] are designed with either more than a single switch or multiple components. Existing multiple-output (MO) converters can be divided into two types: isolated and non-isolated converters [23]. For an isolated *n*-output converter, it makes use of a transformer that has *n* secondary windings to distribute energy into the outputs. In many cases, only one output has a closed-loop control and tight regulation [24]. Other outputs are generated through coupling of the secondary windings. Therefore, the outputs of a MO converter are not independently controlled.

Lefedjiev et al [24] proposed a multiplexed approach in which packets are steered by a controller to achieve cross regulation. But the approach support only constant current and constant voltage which may not serve variable load demands effectively. Jin et al [25] adopted two identical back-to-back connected MOSFETs, which ensures a unidirectional current flow across the main inductor. But the limitation is, the two MOSFETS add to the system's power dissipation and the unidirectional current flow makes effective cross-regulation impossible. To reduce the power dissipation, regulate all outputs and provide a closed-loop feedback control, a single-input multiple outputs (SIMO) flyback converter is proposed with a single switch and a closed-loop feedback control using optocoupler connected to all the four outputs. This enables regulation of all the outputs and reduction of dissipations due to multiple switchings. The UC3843' responsible for generating the pulsed-width modulation signal to trigger the IRF3205 switch into operation is immune to noise and controlled by the load demand via a feedback control loop. The best frequency for the switching operation with less dissipation is evaluated to determine the best operating condition.

To further improve solar power system performance, enhance efficiency and proper utilization of the generated power, good management, monitoring and control of the distribution and consumption is of great importance [26]. Internet of Things (IoT) provide a wide technological advancement and platform for home management and domestic loads automation. A smart controller can be developed based on IoT to monitor, control and manage the appliances connected to photovoltaic power system. The controller can schedule appliances to turn ON or which should use the generated power, thereby minimize wastages and enhance the performance, while serving the needs of various appliances as well [27].

1.2 Problem Statement

One inherent drawback of SIMO flyback converters is cross-regulation problem which has reached 6% and above [24, 28], resulting in recreating power dissipation due to multiple switchings [29]. Hence, there is need to reduce it to a fraction of 1% [24]. The power dissipation is consuming up to 36% of the converter system's efficiency [30]. To minimize power consumption and dissipation in portable devices, efficient DC-DC converters with a wide range of regulated voltages and currents with minimum number of switches is highly desirable [31]. However, low power density of SIMO systems due to dissipations are major obstacles to system efficiency and performance [18, 32-35]. Generally, for a solar power system with multiple outputs for various voltage levels, high switching frequencies are employed [36], which make them unsuitable for off-grid applications. Also, the use of multiple switching devices and iron-core transformers in power systems lead to high switching and conduction losses respectively. The power systems using high switching frequencies are susceptible to higher power dissipation, parasitic inductance and capacitance of the switching devices [37], thereby reduce the efficiency of the entire solar power systems.

In a multi-output converter, the major camplication is the voltage at one output which is affected by the load current of the others, leading to cross regulation error. However, in many cases of the existing SIMO converters such as [18, 20, 38-40] and many others, only one output is controlled by a closed-loop and tight regulation. Belloni et al [20] used independent switches for each of the four outputs, making the system more vulnerable to power dissipation. In all these implementations, inductors and/or transformers are normally the largest off-chip components. Transormer's secondary windings are used to couple the remaining outputs, making other outputs not independently controlled. The need remain consistent for the tightly regulated multiple outputs voltages [41-44]. Thasreef et al [45] used a coupled-inductor to achieve voltage gain and used proportional-integral (PI) control to regulate the firing pulse to produce the control output. But this method can only be used on one output at a time, all the four outputs cannot be regulated by the firing pulse concurrently. In addition, cross-coupling of these magnetic components can affect system performance and induce more conduction losses.

Power dissipation occur during the period when the switch is ON while switching losses occur when the switch in the circuitry swings between ON and OFF states [46]. Switching losses are function of current flowing in the device, switching frequency and the dynamic characteristics of the device. However, during switching process, the power dissipation increases with increase in switching frequency. This is because as the switching frequency increases, each switching duration has a large fraction of switching cycle duration [47]. Chen et al [48] used low frequency to switch the input stage and high frequency to switch the output stage. Using low frequency at the input simplifies the design while higher frequency at the output enables higher dynamic response of the system, but the method requires additional capacitors, increases complexity and doesn't enable better cross-regulation. This is the reason that led to obtaining 73% peak efficiency of the system. Hence, the more the switches and components in the power systems the more the power dissipation and the poorer the cross-regulation.

Voltage regulation of a multiple-output DC-DC converter is typically done with only one control variable, the duty cycle [49]. From the control point of view, duty cycle alone cannot accurately control several independent outputs [49]. Therefore there always exists a DC regulation error in one or several of the outputs. The most commonly used regulation method is to sense one output and leave the other outputs unattended [49]. The sensed output is accurately controlled while the unsensed outputs are cross-regulated. The cross-regulation range depends on the load conditions and the power stage parameters [50]. Therefore, a SIMO flyback converter is proposed as a prototype to be used in regulating and reducing switching frequency to 200 Hz, eliminating power dissipation to less than two percent (<2%) and cross-regulate all outputs simultaneously and concurrently via a closed-loop feedback control using optocoupler sensor connected to UC3843 oscillator IC, which is being controlled by the load demand to trigger the switch. The target is to have efficiency of up to 98% and reduce power dissipation to a negligible fraction.

1.3 Research Objectives

This study is aimed to design and construct a power system unit comprising of single-input multiple-outputs (SIMO) flyback converter for off-grid PV applications. A robust intelligent controller is also designed and incorporated to manage, monitor and control input voltage supply and drop, output loads and scheduling via the use of Raspberry microcontroller and Internet of Things (IoT) The specific objectives are:

i. To optimize the performance of SIMO flyback converter by regulating and reducing the switching frequency.
ii. To implement effective cross-regulation of all the SIMO flyback converter's outputs sumultaneously by using closed-loop feedback control via the use of UC3843 IC and optocoupler to sense the output currents concurrently.
iii. To optimize the performance of the SIMO flyaback converter by reducing power dissipation, power losses and conduction losses.

1.4 Scope of Study

The proposed system is divided into two parts: SIMO DC − DC flyback converter and IoT-based controller.

The SIMO converter uses minimum input voltages of range 3 V − 48 V to give multiple output voltages of 5 V, 9 V, 12 V and 24 V DC. The proposed converter is implemented with a ferrite-core magnetic transformer (acting as a coupled-inductor). 5, 9, 12 and 24 winding turns on the transformer to give different output voltages of 5 V, 9 V, 12 V and 24 V DCrespectively. UC3843 oscillator supplies the astable pulses and is used to sense the current at the output via a feedback topology using optocoupler sensor to cross-regulate all outputs for effective PWM supply by the UC3843 oscillator via a feedback control loop.

The control unit is designed to use a Raspberry Pi W microcontroller based on IoT techniques, which has the ability for wireless communication. The controller is developed with robust ability to connect or disconnect supply to the loads or inverter from the SIMO converter, monitor and control distribution of power to the connected loads and enhance efficiency by blocking leakages. It controls domestic appliances such as light bulbs, television, fan, fridge/freezer, laptop computer, phone charger and washing machine and performs scheduling. The control topology is able to manage the power of the proposed converter/inverter and prevent losses due to distribution and random access.

1.5 Significance and Original Contributions of the Study

Off-grid photovoltaic systems can provide an affordable means of getting access to electricity depending on the availability of the solar energy at the places. Therefore, off-grid PV systems have potentials to compensate the outage of power in remote areas. The significance of off-grid solar systems is to optimize suitable designs to tap and generate the available solar energy at most economically feasible cost and enhanced efficiency to satisfy the energy demands. This study would open doors for academic research and technological advancements and would contribute to development of both knowledge and technology.

The evaluation of the SIMO flyback converter's efficiency and determining its performance by incorporating closed-loop regulation via the use of UC3843 IC to cross-regulate all outputs contributes towards the development of technology and knowledge, especially solar power systems and devices by introducing a new idea of achieving high efficiency power conversion of up tp 98.4% and utilisation through cross-regulation of all outputs of SIMO power systems concurrently. This has been achived through the use of UC3843 oscillator, single IRF3205 switch and multiple windings on a ferrite-core inductor. The study explores the use of advanced techniques with a new approach to monitor and control PV systems and appliances connected to it, thereby enabling utilization of information technology in the field of solar power technology and education.

1.6 Thesis Structure and Organization

The research background, problem statement, objectives, scope, significant of this research are presented in chapter 1. The overviews of photovoltaic power system, their topologies and configurations, power systems development, power system control, power system intelligent control and smart homes are discussed in chapter 2. The processes of designing and details of development of the basic parts SIMO flyback converterand IoT-based controller of this project are explained in chapter 3. The obtained results and discussion are presented in chapters 4 and 5 respectively. The conclusion and future recommendation are given in chapter 6. Appendices and references followed at the end of the thesis.

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