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# Development of a New Controller for Solar Home System: PWM Charge Controller & DC to DC Converter (12V to 120V)

Mohammad Shariful Islam, Hasmaini Mohamad* and S.Z. Mohammad Noor

*Abstract*— **Solar Home System (SHS) is a stand-alone power solution in isolated places where there is no connectivity to the national power grid. Currently, an off-grid SHS has a solar panel, a lead-acid battery, a Pulse Width Modulation (PWM) solar charge controller, and 12V DC power operated electrical home appliances; in some cases, a DC to DC converter or a DC to AC inverter has been connected. So far, various SHS packages have been introduced, each with a set of product features and prices. Since the majority of SHS are small in size, producing energy is inadequate to satisfy the customer's demand. This study introduces a new feature that incorporates both analog PWM solar charging techniques and a DC to DC (12V to 120V) converter to satisfy the needs of existing off-grid SHS users. The design of solar charging includes improved charging techniques i.e surge voltage and lightning protection. The result produced is a noise-free switching gate drive signal and high-performance fixed-frequency current mode controllers. The new controller's design also reduces the number of devices in the SHS; thus reduces the controller's total production cost.**

*Keywords:* **Pulse Width Modulation, fixed frequency current mode, noise free gate drive signal, charging efficiency, self-power consumpation, reduce the number devices.**

## I. INTRODUCTION

SOLAR energy alone has seen significant growth in recent years. Photovoltaic (PV) innovation is the most promising, advantageous, and promising of all green technologies for converting solar energy into electrical energy, with or without battery backup. Primarily in third-world countries, it appears that there is a lack of electrical energy, which has influenced rural areas. However, the World Bank and the International Development Agency have launched an off-grid solar home system in that area to facilitate the community in carrying out their daily tasks such as cooking, working, and studying [2]. People in rural areas have significantly changed their lifestyles in order to incorporate a stand-alone solar home system (SHS).

The manufacturer initially introduced the solar home system in a variety of products and services with varying sizes of solar modules including 30Wp, 40Wp, 50Wp, 65Wp, 80Wp, 100Wp, and 120Wp [14]. SHS components include a solar panel, a lead-acid battery, a charge controlling device, and a suitable load predicated on the needs of the customer. The features of the charge controlling devices and various DC powered loads have indeed been developed. The three generations of the SHS have been segmented according to the upgrading of the solar home system of components. Whenever the solar home system solution was first launched, it included some components such as a solar panel, lead-acid battery, solar charger, 12V powered DC lamp, black and white television, radio, and so on. The load was connected at a limited distance, where all components connected to flow high current through the cables. Initially, when the solar charge controller was used as a voltage regulator device, the charging efficiency was not maintained. In [13] solar charging systems and 12V DC powered loads were upgraded, and a new feature enhancement system was launched by Infrastructure Development Company Limited (IDCOL); that features are PWM solar charging mechanism, mobile phone and LED lantern charging port.

In [1], charge controller functions were designed on the principle with PWM controlled DC to DC converter for charging the battery. The PIC microcontroller was used to implement PWM charging techniques, but certain crucial considerations were not established such as self consumption, electromagnetic interference (EMI) surge voltage and lightning safety. In [7] & [15], charging controls are used mostly based on the Single-ended primary-inductor converter (SEPIC) PWM technique. The SEPIC-based converter is often used in battery-powered operating devices. A PWM-based charge controller can be used to maximize output power depending on the temperature of both panel and irradiance conditions. In [8] and [25], the solar charge controller was designed to monitor the charging level of the maximum power point. This power of

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solar panel was transferred to the battery for effective performance comparison which includes Perturb and Observes (P&O) method. It is not a suitable controller for the small size of applications and it is suitable for large scale solar systems. In [11] and [30], the basic system includes discrete time control as well as PI-compensator were used to track the maximum power points (MPPs) of the solar panel. The framework has been held tight to the Maximum Power Point Tracker (MPPT), consequently achieving the maximum allowable transfer of power from the solar array. Nevertheless, this design was suitable for more than 1kW solar system. If those are key design parameter, it must be considered in the design or probably lightning protection, self consumption and etc is just additional factors that can be considered to improve the system performance.

In [2], the system has difficulty to accurately configure and optimize the solar charging mechanism. It is ideal for a large-scale solar home device under shielded grid-connected areas; where the input voltage was 48V DC and used the Li-Ion battery. In [22], the PV input voltage was fed to both the dc-dc converter as well as to the single-phase inverter. In [13], this design was performed through a DC-DC converter or Buck converter that employs a programmable micro-controller to convert energy using a DC-AC inverter into a widely accessible form. Remote users could use a 12V DC solar home system, however there are some limitations at the customer's end. The self-consumption of solar charger is enormous. The primary way for most solar homes and businesses to save energy is to reduce self-consumption as it is connected to the system for 24 hours. In [35], [36], [37], and [38], Switch Mode Power Supplies (SMPS) were created to rapidly change voltage and current because of DC-DC power converters. This enables surrounding devices and input power lines to be interrupted by EMI noises. Consequently, EMI noises become a major issue.

In [3], control criteria, energy storage management, and the DC-AC inverter or DC-DC converter are all necessary aspects of an off-grid solar home system. A controller device oversees the charging and discharging of the energy storage mechanism. A DC-AC function is to convert energy into a form which can be used instantly. This device is important, because of preponderance of equipment operate using AC power.

Currently, power electronics engineering has smartly introduced the most reliable power solution. An incandescent light bulb would shine equally brightly when powered by 120V DC or 120V RMS AC. DC high voltage PWM IC would run from 80V to 450V DC voltage. So, laptop, fan, LED TV and standard AC products can run on high voltage DC (120V), and the power conversion loss will minimize. Other hand, DC to DC conversion (12V to 120V) is a procedure for minimizing power loss to transmit power at the desired load end. Due to high voltage DC means that the total energy is passed in smoothly as per load required which cause voltage values will be high and the current values will be low so that the power will be transmitted with the full load requirement to minimize power loss. Minimizing power loss is a key factor in the SHS. Also, due to limited wires, there has a barrier to connecting the load.

However, the power conversion unit and the charge controller are separate devices, while the two devices have separate self-consumption, although the power conversion loss is more than 30%. In special cases, it is difficult to convert the power from 12V DC to 220V AC with minimum power loss. Therefore, conversion unit and PWM solar charger is compacted as a design of new controller for existing off-grid solar system.

Therefore, it is important to consider minimizing self power consumption, surge protection, minimizing product's cost in the controller design. The contribution of this research project are as follows:

1) To develop a new analog PWM converter that used a fixed frequency current controlling algorithm to reduce EMI noise in an off-grid solar system.

2) To design a compact single-stage boost DC to DC flyback converter integrated with the designed analog PWM charge controller for the existing off-grid solar system. It will reduce the number of devices to maintain the noise-free switching gate signal.

3)To reduce the designed controller's self-power consumption. As it has been connected for 24 hours, it is critical to reduce the system-connected controller's self-power consumption.

In this study, PWM solar charging circuit and DC-DC (12V - 120V) converter are designed using Altium, LT-spice, PI Expert and Proteus. Two functional circuits are combined in a single circuit using same reference parameters considering decrement of self-power consumption. In the proposed research work, compact design of the main circuit integrated with the controller are created with certain element and criteria for reliability of the system.

## II. RESEARCH FRAMEWORK

It is important to consider the optimization parameters of solar charging circuits. There have been issues in developing some design topologies for PWM solar charger and DC-DC converter.

PWM is a technique for tracking an analog signal and producing a digital output. By comparing the ramp or carrier signal with the error between the desired output voltage signal and the true output voltage signal, the PWM constant frequency signal can be obtained.

Three major topological components dominate the output of the fly-back converter: the primary switch, the secondary rectifier, and the transformer. The transformer has a significant impact on converter efficiency as a single feature. Buck-boost and flyback converters are effectively lossless resistors when operating under interrupted conditions. The open loop of these converters controls the waveform.

The Fixed Frequency Current Mode algorithm has evolved into a dynamic self-supply mechanism that significantly simplifies the configuration of the auxiliary supply and voltage common collector (Vcc) capacitor by enabling internal startups, transients, latch standby, and other features. Dynamic self-

supply is important for keeping the controller alive when no switching pulses are accessible, including when the controller is blown out, or to keep the controller from stopping during a transient load when Vcc can drop. It also contains a timer-based fault detection mechanism for overload detection and dynamic compensation to ensure maximum power despite of input voltage. Fig.1. show the block diagram of the research framework for this study-

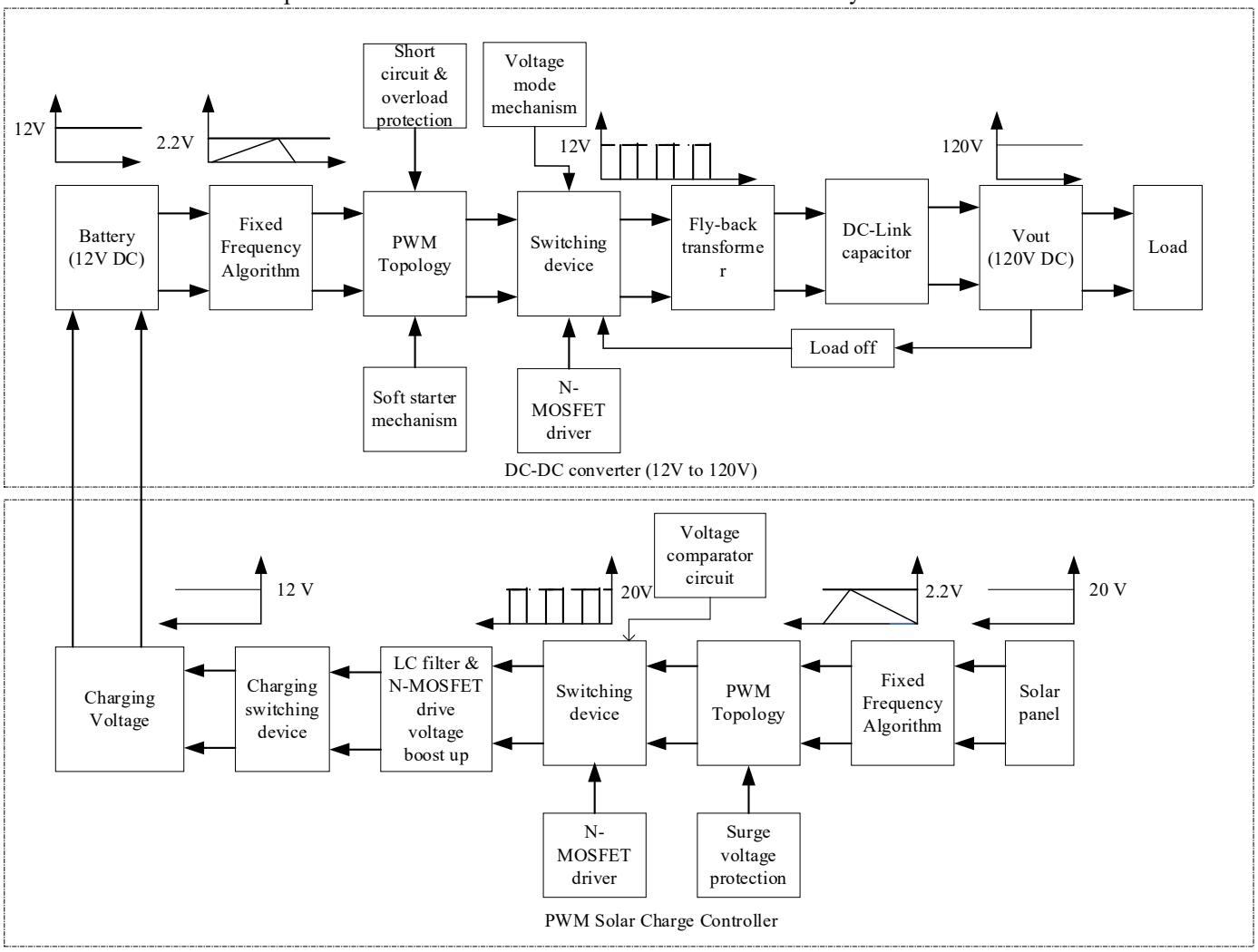


Fig.1. Overall block diagram of research framework.

## III. DEVELOPMENT OF A NEW CONTROLLER

The new controller for solar charging circuit based on fixed frequency current mode controller is simulated using LT-Spice software. Detail design of each controller's component is explained in this section.

### *A. Designing the fly-back transformer*

A specific method for selecting the inductance value is defined, and the inductance value and turn of ration are calculated based on the transfer power and switching frequency. The two inductance values are set up parallel in the primary side with respect to the secondary inductance due to flow the high current at primary end. The energy that accumulates in the magnetic field is transmitted to the output capacitor as well as the load during the fly-back operation.

### *B. Designing the gate drive circuit*

In semiconductor devices, gate drive circuits can be used to improve the performance. The N-MOSFET gate drive circuit limits or stops the amplitude and rate of rise of the switching voltage, reducing power consumption. The simplest drive circuit consists of a resistor and a capacitor connected by a thyristor or transistor. NPN and PNP transistors can be used to create the circuit, which is the path for discharging the gate capacitance of an N-channel MOSFET. Fig.2. show the block diagram of gate driver circuit –

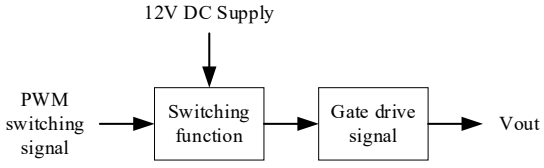


Fig.2. Block diagram of gate driver

### C. *Soft start*

PWM signal initiates at zero duty cycle but has no internal soft-start control. Thus soft start mechanism as shown Fig.3 is designed using the combination of PNP transistor, resistor, and capacitor.

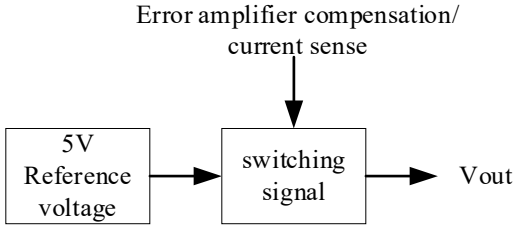


Fig.3. Block diagram of soft start mechanism

### D. *Voltage mode*

The transformer's primary winding current is converted to voltage based on the transformer's secondary winding turn ratio. Fig.4 shows the voltage mode mechanism adopted in this study. A saw-tooth waveform acts as an input signal to be used at the current sense terminal through an oscillating timing capacitor & resistor, and then that signal is compared to the error voltage. The error amplifier is compared to the artificial ramp voltage using a PWM comparator.

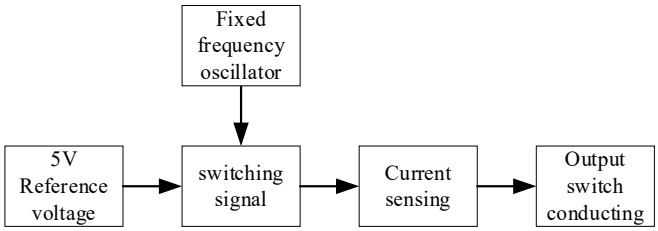


Fig.4. Block diagram of voltage mode mechanism

### E. *Designing the N-MOS gate drive*

The charge on the boot condenser must applied in maintaining the high-side transition for N-MOSFET. Because of drain to source voltage is just lower than gate to source voltage. Fig.5. is used to N-MOSFET gate driver mechanism.

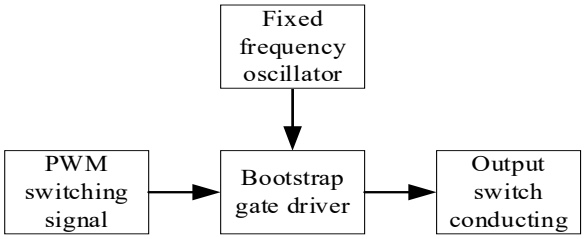


Fig.5. Block diagram of N-MOSFET driver for solar charger

### F. *Techniques for reducing the self-power consumption*

There have been two techniques implemented to minimize self-power consumption: The following are specific elements of the technique-

i.The dedicated off program enables the fixed-frequency current control mode to accomplish exceptionally low no-load input power consumption through "sleeping" the entire system. Based on frequency fold-back, the controller has exceptional efficiency in light load conditions even as consuming very small stationary power. Specific frequency, ramp compensation, and versatile latch feedback enable the controller to generate an excellent output for the desired design.

ii. The controller utilizes an LCD and LED display as system status indicators: this system status should be publicized two to three times each day, for just roughly 30 seconds. However, that power is employed for 24 hours, it is also one type of power consumption. This function is served by the push switch circuit mechanism, which is comprised of an Op-amp and an NPN transistor- as shown in Fig.6.

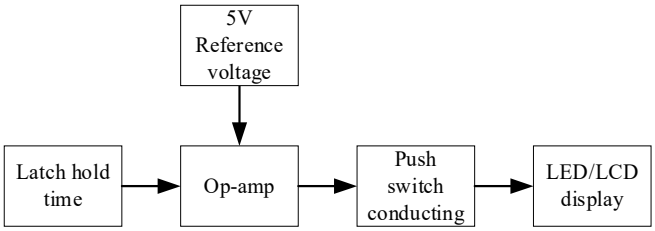


Fig.6. Block diagram of push switch technique

### G. *Designing the voltage comparators*

Fig.7. shows the block diagram of voltage comparator. The two input voltages are compared by a voltage comparator. The Op-amp voltage comparator is used as a simple circuit that demonstrates the threshold stress and hysteresis width.

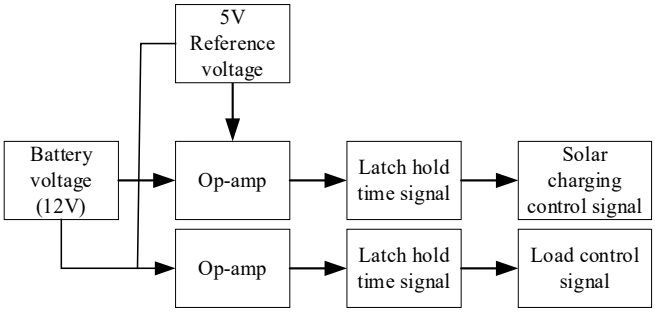


Fig.7. Block diagram of voltage comparator

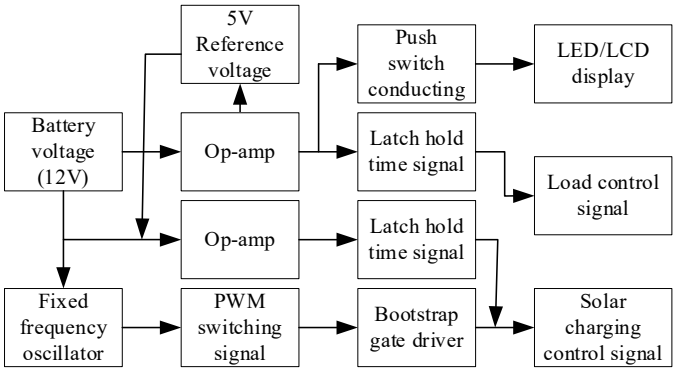


Fig.8. Block diagram of solar charger

The operational amplifier determines the various voltage switching thresholds depending on the battery's voltage conditions. These have two major switching components: one is for solar charging with a battery and the other for a load

connected to a battery. The hysteresis potential difference between both the solar charging disconnect and reconnected points is 0.7V. The hysteresis voltage difference between the load disconnect and reconnect statements seems to be 1V. The PNP transistor and resistor voltage dividing programming are being used to set the hysteresis threshold values.

## IV. Results and Discussion

Analog PWM comparator with eight characteristics including current limit control or sinks peak current, feedback voltage loop for stability, slope compensation, oscillation timing for fixed-frequency operation, signal and power returning ground, PWM drive waveform signal for N-MOSFET can be seen in Fig:9, Vcc clamp voltage source, and voltage reference for the timing resistor (RT) and timing capacitor (CT) were used to fix the oscillation timing; where the RT resistor is connected to the reference voltage and the CT capacitor is connected to ground. The fixed frequency oscillation timing (focs) has been delineated by the RT/CT values, using the formula in Equation (1).

$$f_{ocs} = \frac{1.72}{R_{RT} \times C_{CT}} = \frac{1.72}{12K\ X\ 220P} = 651.5\ kHz \quad \ldots\ldots (1)$$

The waveform for the fixed frequency algorithm is seen in the Fig 9 and 10. Timing resistor values should be greater than 5K and timing capacitor values should be between 1nF and 100nF. The total supply current tends to vary with the output current, as well as the quiescent current is 0.5mA. The function has been either continuous conducting method (CCM) or discontinuous conducting method (DCM). It depends on the input voltage and loading condition (DCM) at the ouput terminal. PWM controller output can be shut down to sink current or command zero duty cycle by applying an external voltage to the PWM controller's compensation. For system stability, the feedback voltage ($V_{FB}$) should be less than 1.5V. This voltage is obtained from the error amplifier's inverting input. The current sense ($I_{SENSE}$) terminal is connected between the source of the MOSFET and the sense resistor to add the slope compensation of a voltage ramp, where $R_{SENSE}$, resistor value is less than 0.05, $V_{SENSE}$ voltage is 1 volt, that peak $I_{SENSE}$ defines the following formula –

$$I_{SENSE} = \frac{V_{SENSE}}{R_{SENSE}} = \frac{1}{0.05} = 20A \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

According to Equation (2), short circuit protection current and overload protection current are decided by the value of $R_{SENSE}$ resistor and its across the voltage. The $I_{SENSE}$, signal is a noninverting signal that is compared to that same error gain voltage to make sure the device's reliable operation. The effect of even a high impedance supply rail in comparison to the ground is an issue when it comes to noise-free PWM signal. Because of snubber circuit is used at the PWM driver's output terminal, one PNP transistor and one NPN transistor are used to ensure a noise-free N-MOSFET drive gate PWM signal. MOVs (Metal Oxide Varistor) have been connected in series to the solar panel port to prevent surge voltage triggered by lightning.

The voltage of a sawtooth wave is determined by the value of the timing resistor (RT) and the value of the timing capacitor (CT). The red waveform represents a sawtooth wave, and the green waveform represents the PWM switching signal that follows the sawtooth wave. Because of the high impedance supply rail in regards to ground, this same noise-free gate drive signal is completely reliant on V CC voltage, which is combined with V IN capacitor (C7= 2200F). Fig 8 illustrates the block diagram of the solar charging portion.

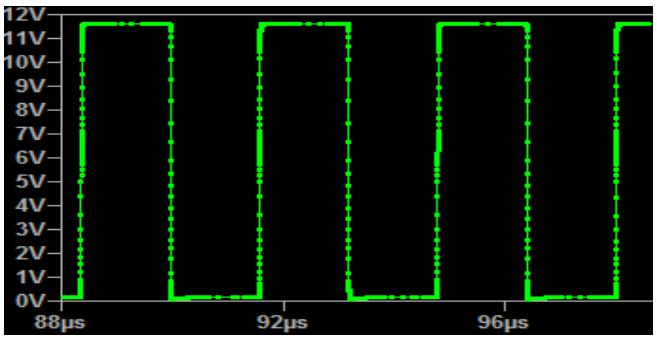


Fig.9 PWM drive signal for N-MOSFET

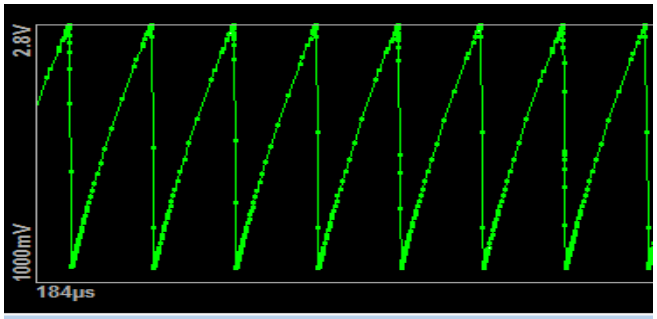


Fig.10. Waveform of voltage ramp.

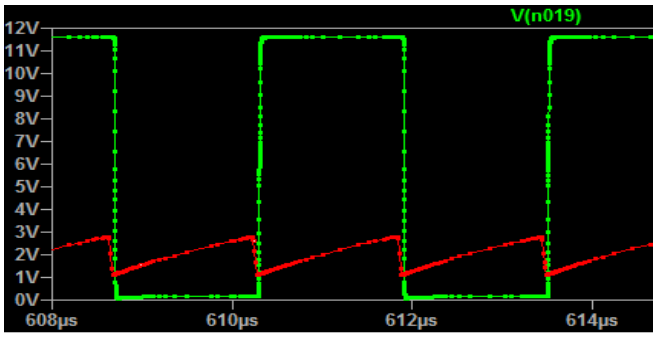


Fig.11. Waveform of voltage ramp and PWM output

Table.1. show the switching alignment according to the various conditions of battery voltage. Proposed PWM charge controller integrated with DC to DC converter: The DC-DC offline converter is designed using fixed frequency current mode algorithm, that is implemented by certain peripheral components. Current limit control or peak current sinking, feedback voltage loop for stability, slope compensation, oscillation timing for fixed-frequency operation, signal & power returning ground, PWM drive signal for N-MOSFET, Vcc Clamp voltage source, and voltage reference for error amplifier all are features of this analog PWM comparator. The fixed frequency value is defined by the timing resistor and

capacitor. A timing resistor (R3=12K) connects Vref and RT/CT, and a timing capacitor integrates RT/CT and GND: Therefore, the frequency of oscillation can be defined by the equation 3 –

$$f_{sw} = \frac{1.72}{R_{RT} X C_{CT}} = \frac{1.72}{12K\ X\ 330P} = 434\ \text{KHz} \quad \ldots\ldots\ldots(3)$$

TABLE I
SWITCHING ALIGNMENT ACCORDING TO THE VARIOUS CONDITIONS OF BATTERY VOLTAGE

| No of case | Battery voltage | Load condition | Switching status | Functional status |
|---|---|---|---|---|
| Case no - 1 | 14.5V | 10A | High Voltage Disconnect (HVD) | • Solar charging is disconnected<br>• Load connected<br>• Battery full charged |
| Case no - 2 | 13.8V | 10A | High Voltage Reconnect (HVR) | • Solar charging is reconnected<br>• Load connected<br>• Battery status is healthy |
| Case no- 3 | 11.5V | 10A | Low Voltage Disconnect (LVD) | • Solar charging is connected<br>• Load disconnected<br>• Battery status is deep discharged |
| Case no- 4 | 12.5V | No-load | Low Voltage Reconnect (LVR) | • Solar charging is connected<br>• Load reconnected<br>• Battery status is fit for discharge |

The output switching frequency ($f_{sw}$) is determined by the frequency of oscillation *($f_{osc}$)*. The timing resistor should be assigned a rating greater than 5K.

It has distinctive advantages, such as the potential to generate the switching pulse in undervoltage lockout mode with a startup current of less than 1mA. Throughout a transistor-based snubber circuit, a PWM switching signal drives the gate of an N-channel MOSFET. The cause of 434 kHz oscillation signals has induced capacitance at the gate of N-Channel MOSFET, having caused the original PWM signal to be destroyed with respect to equation (3). A snubber circuit will ensure the gate signal is noise-free. For overshoot and undershoot voltage protection, a Schottky diode (MUR460) is connected at the gate of an N-MOSFET (IRFP250N). It has a high impedance from the supply rail to ground, and the input and output share the common ground point. $V_{CC}$ power line is the main supply of output current, which can be controlled by a current limiting resistor (R9= 1000K). This circuit's quiescent current is 0.5mA. The total output current depending on the gate charge of external power N-MOSFET ($Q_g$) and switching frequency ($f_{sw}$). Switching frequency ($f_{sw}$) is equal to oscillation frequency ($f_{osc}$). The output drive current can be calculated using the following formula-

$$I_{OUTPUT} = Q_g\ X\ f_{osc} = Q_g\ X\ f_{sw}\ \ [f_{osc} = f_{sw}\ ] \ldots\ldots\ldots\ldots\ (4)$$

MOSFET gate drive resistor (R6= 10Ω) is power resistor, switching loss minimization and EMI performance depends on this resistor. PWM comparator has a noninverting current sense port, that can be compared proportionally between the voltage across $R_{SENSE}$ and the voltage of error amplifier output. Typically, $V_{SENSE}$ voltage is 1V, where it has a RC filter (C10: 100nf and R5: 1KΩ) for balancing the capacitive load. The time constant of the RC filter is less than oscillation timing. The PWM comparator has a compensation port, that can be performed two acts with 1MHz bandwidth, which are the source and current sink. This port can be grounded by an NPN transistor to shut down the system in external force. Pulse width modulation signal starts at zero duty cycle, so it needs to add a soft start mechanism at the compensation point. It is designed using three components, are resistor (R19: 100Ω), capacitor (C13: 10nf), and PNP transistor (Q4). $V_{REF}$ is a 5V voltage source bypass the ground, which provided charging voltage for oscillation timing and act as an independent voltage source.

The selected transformer is designed to double winding turn at primary side cause of low voltage high current path, while the secondary winding has single turn cause of high voltage low current path to consider the switching frequency of 434 kHz. Magnetizing inductance depends on the continuous conducting mode of the duty cycle. The primary side of the transformer is connected with a drain of N-MOSFET (IRFP250N) and a single-phase ultrafast power diode (D5: MUR460). It is connected with a parallel RC filter (R10: 220KΩ & C7: 13.8nf) cause of protecting the primary winding at the off condition of the duty cycle. The maximum turn ratio of the transformer depends on the reflected voltage ($V_{REF}$) and output voltage ($V_{OUTPUT}$). Primary to secondary turn ratio is calculated using the following formula:

$$N_{PS} = \frac{V_{REFLECTED}}{V_{OUTPUT}} \ldots\ldots\ldots\ldots\ldots\ (5)$$

Desired voltage rating of N-MOSFET and output voltage rating depend on the primary to secondary turn ratio of the transformer. Fig.12. shows the desired block diagram of DC-DC converter –

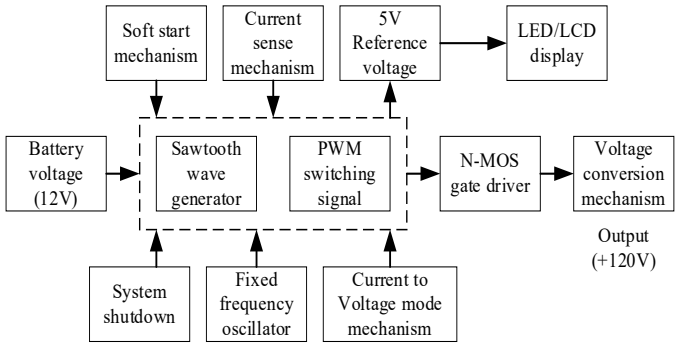


Fig.12. Block diagram of DC-DC converter

The level of conversion voltage is determined by the transformer's secondary turn ratio, N-MOSFET, ultrafast power diode, and output capacitor. The capacity of power conversion is based on the properties of the core, winding wire, and core size. It is a straightforward procedure for converting DC voltage to use the fixed frequency current control mode algorithm to

obtain DC 120V from a DC 12V supply.


Fig.13.Voltage waveform of Input & output (Vn002 – Red color: Output voltage waveform & Vn011 – green color: MOSFET- gate drive voltage waveform)

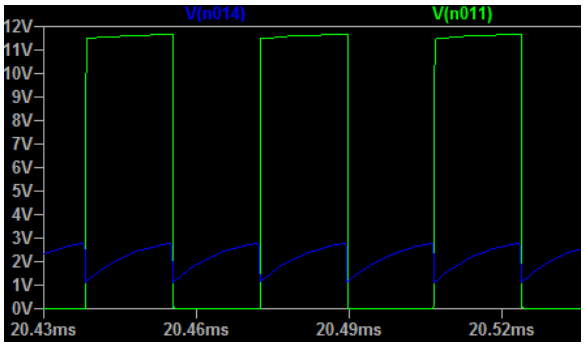


Fig.14. Waveform of MOSFET gate drive & oscillation timing (Vn011 – green color: MOSFET gate drive switching waveform & Vn014 – blue color: oscillation timing waveform).

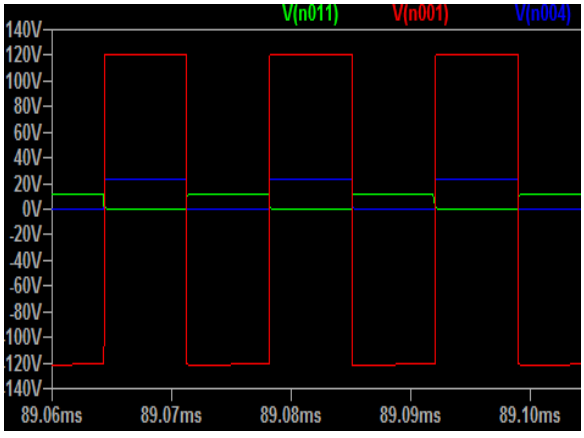


Fig.15. Waveshape of MOSFET gate drive signal and voltage waveshape across transformer winding.

Fig.15. shows the MOSFET gate drive switching waveform (Vn011 – green color), voltage waveform across the primary winding of transformer (Vn004 – blue color) and voltage waveform across the secondary winding of transformer (Vn001 – Red). The primary winding of transformer has induced 12V PWM waveform (Fig.14.) and the secondary winding has induced ±120V. A ultra fast diode has connected between the terminal of secondary winding of transformer and DC link capacitor for rectifying the -120V. As a result, it has obtained expected output voltage +120V DC, that shows in Fig.13.

## V. Conclusion

The research paper represents a design of a new controller for the off-grid solar home system, that incorporates PWM solar charging and a DC-DC converter (12V to 120V). Those research works enhance some features such as surge voltage protection which is applied 65.24KV as spike voltage; short circuit protection which is tested at output load terminal to flow the current is 6mA; overload protection which is tested at output load terminal to obtain output voltage 54V and current 2.1A across the 500Watt load . Reducing self-power consumption is 30.51mW that are introducing a push switch mechanism and a fixed frequency algorithm. The overall testing techniques are performed in accordance with the battery voltage under various load conditions, taking into consideration all parameters.The design has compacted as a new controller including common ground single stage to integrate the PWM Solar charging and DC-DC conversion unit. The suitable charging range is 10Wp up to 400Wp solar panels and the suitable load connected range is 1Watt up to 350Watt to predicate upon this simulated wave-shape analysis. That is introducing the soft start mechanism at zero duty cycle. The fixed frequency current control mode is used as voltage mode with designing a flyback transformer. However, the analog circuits for controlling parts are the goal of this study. There is no need for shielding to protect against EMI noise. Besides that, the unexpected noisy signals that eliminate the main signals in the presence of a high-frequency transformer are ignored by the analog circuits.

## Appendix-A

TABLE II
Measurement of Self-Power Consumption

| Portion | Voltage (V) | Current (µA) | Power (mW) |
|---|---|---|---|
| PWM Solar Charger | 12.27 | 53.96 | 0.662 |
| DC-DC converter controller | 12.27 | 994.59 | 12.2 |
| voltage comparator | 12.27 | 1221 | 14.99 |
| Push switch mechanism | 12.27 | 216.057 | 2.65 |
| Total self-power consumption | | | 30.51 |

## Appendix-B

SURGE VOLTAGE PROTECTION TEST:

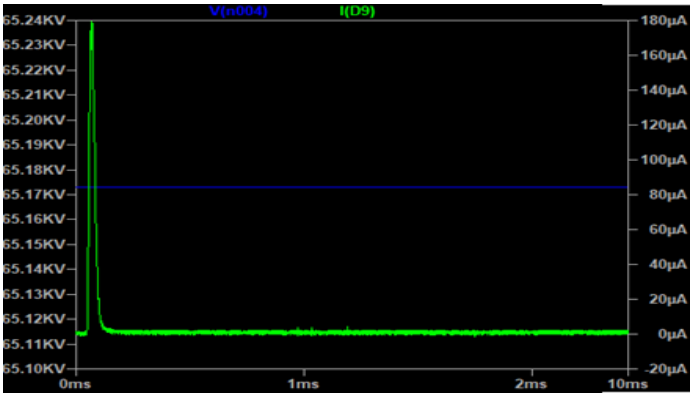


Fig 16: Voltage wave form across the solar panel during lightning voltage

## APPENDIX-C

### OVERLOAD PROTECTION TEST:

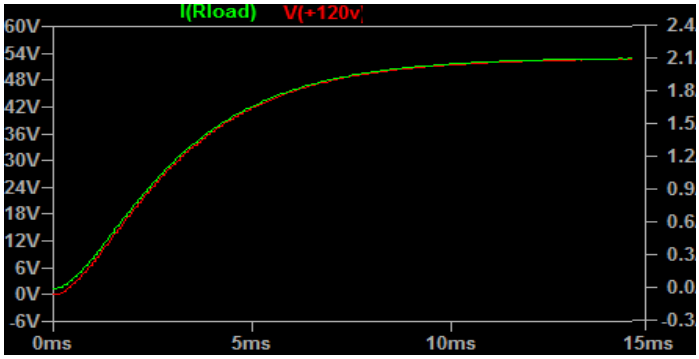


Fig 17: Voltage and current waveform under overload condition.

## APPENDIX-D

### SHORT CIRCUIT PROTECTION TEST:

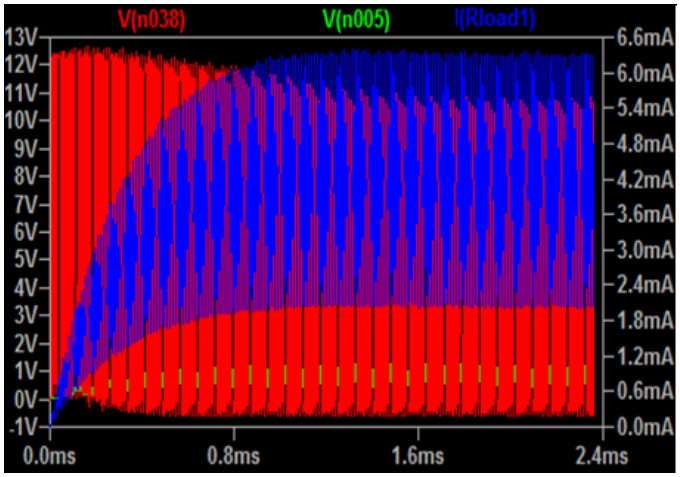


Fig 18: Voltage and current waveform under short circuit condition.

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