Bi-Directional Multi-Mode Grid tied Converter for Solar Energy Conversion Systems

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***Abstract* — The rapid growing interests in renewable energy, such as solar energy, outweigh the benefit of distributed grids in current grid networks. Innovative topologies for renewable energy conversion systems that integrate with electric grids and energy storage systems are being proposed, each with limited modes of operation for the various needs in smart grid applications. In this paper, we propose a modified version of a multi-source converter, which uses a small number of elements to accomplish each task of multi-mode operation in a smart-grid. The proposed approach is verified by simulations in MATLAB. We found that by introducing an additional switch in the converter's output allows the reverse flow of current, enabling current to charge a battery from the grid while maintaining the integrity of the former modes of operation.**

***Index Terms*—Battery Storage, Bi-directional Converters, Micro-grid, Multi-Mode Converters, Renewable Energy, Smart-grid**

I. Introduction

Traditional fossil fuel power plants are built away from cities due to the air pollution they produce. Despite their steady performance, the amount of energy lost in transmission lines can be significant. This energy loss can be reduced by distributing power plants inside the city. On the other hand, with increasing the load demands, these distributed generation systems can help diminish the need for new fossil power plants. Renewable energy sources, such as solar arrays, are known for their clean source of energy, and their power plants are rapidly being built on the vicinity of cities and within the cities themselves. This paradigm shift is becoming apparent in the U.S., as renewable energy electricity generation is projected to increase from 462 billion kilowatt-hours in 2010 to 469 billion kilowatt-hours in 2015[1]. Many countries are promoting their plans to multiply their solar energy generation plants by facilitating the procurement of solar plants and offering incentives. To date, the U.S. has nine of the thirteen biggest photovoltaic solar projects in the world [2].

As renewable energies become more readily available in the residential sector, DC devices in residences can be supplied energy from the DC bus of a microgrid. There are advantages in utilizing a DC bus source as opposed to the synthesized AC source for these devices. Even though current AC/DC converters offer huge amounts of power savings thanks to the advances in power electronic conversion systems, it is still more reliable and efficient to utilize the DC bus due to the reduced amount of components in comparison to AC-DC converters.

Solar energy is a well known and favorable type of renewable energy source, which generates DC power. However, solar, wind, and other types of renewable energies are inherently intermittent in nature, meaning they cannot supply the load demand continuously. To provide a more rigid flow of electricity, solar energy is integrated with utility grid with energy storage systems and other available renewable energy sources such as wind energy. Hybrid energy systems are capable of providing better power quality and reliability and can improve the system performance. As an example, wind and solar energy are somewhat complementary on a daily or seasonal basis [3-4]. Having an energy storage system may stabilize the energy generated from renewable sources, specifically during sporadic climate changes that can affect the output of renewable energy sources dramatically, and thus increasing the reliability of the DC bus. In this paper, we propose an amendment to an existing topology, which may serve to regulate DC voltage into an inverter or a DC bus and charge/discharge a battery storage system. The hybrid system in this paper is combination of photovoltaic, energy storage system and the utility grid. Bi-directionality of converter provides a good power exchange among sources, load and DC-voltage bus. This concept is illustrated in Fig.1.

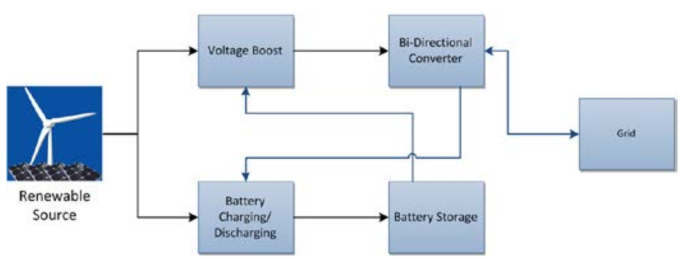
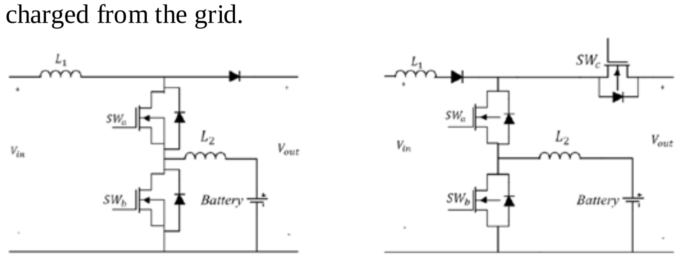


Fig. 1. The smart-grid functionality allows the battery to be charged from the grid.



(a) (b)

Fig. 2. (a) Original method. (b) Proposed method which places the original diode besides the L_1 inductor and places a four quadrant operating MOSFET in its place.

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II. Conventional Structure of the Multi-Mode Single Leg Converter.

In paper [5], a novel method is proposed that utilized only two switches (single leg), one diode, and two inductors to implement different converter modes in the bi-direction operation of DC/DC converters. This was an improvement to the conventional boost and bi-directional DC/DC converters by removing a switching element from the converter, while still offering the same functionalities and modes. In [5], the battery is charged in only one mode of operation. Generated voltage can boost up/down and charge/discharge the battery at the same time a DC voltage is being supplied to the output of the circuit.

However, the methods on [5] allowed the battery to be charged from the renewable source only, and not from the grid. In this paper, the switch is re-introduced and the configuration was changed for the benefit of an additional mode. In this additional mode, the battery can be charged from the grid when the renewable source is absent or not sufficient to supply power to the battery. Despite the re-configuration of the single leg converter, the four former proposed modes of operation worked.

The placement of the switch to the proposed converter does not introduce any new switching losses during the original four modes, for the primary purpose of the switch is to act as a gate that allows current from the output into the battery, and as a diode for voltage boost operations (See fig. 2). In these four modes, the properties of the MOSFET allow the switch to behave like a diode when no pulse is felt at the gate.

The converter in [5] was limited in interactions between the renewable energy source and the battery, load, or both. By taking advantage of the bi-directionality capability of inverters, the excess grid power can be rectified by the inverter and stored in the battery. This proposed configuration allows more interaction among the renewable energy source and grid, including the battery. This useful feature is capable of storing excess power from grid and renewable energy power in the battery when the load demand drops, and may serve as smart grid function that helps regulate the utility grid.

This paper is structured as follows. In the first section, the four modes in [5] are re-tested with new configuration, and briefly describe each mode of operation. That same section will introduce and cover the new mode and derives its corresponding equations. The second section will cover the controller design and explain how to find the desired duty cycles for the MOSFET switches. In the final section, we will present our simulation results from MATLAB's Simulink followed by a conclusion, which presents the limitations of this configuration and future endeavors.

III. Proposed Method for the Interaction Between Renewable Energy Source, Battery, and Grid

The schematic for proposed configuration is shown on fig. 2. As seen on this figure, the diode is replaced with a bi-directional MOSFET and placed in series with L_1, which will become essential to block the current from flowing into the PV source in the proposed mode of operation. The four original modes are the Main Boost Mode, the Boost-Buck Mode, the Boost-Boost Mode, the Battery Boost Mode, and the Reverse Buck Mode. In the Main Boost mode, the single leg converter increases the voltage that is supplied to the inverter. In the Boost-Buck mode, energy is stored in the battery while voltage is supplied to the inverter or DC bus simultaneously. During high load demands, the Boost-Boost mode can supply the inverter with energy from the PV source and the battery simultaneously. And during cloud cover, energy can be supplied to the inverter from the battery in Battery-Boost mode.

In cases in which grid peak shaving is desired, the battery can be charged from the grid. The grid alone can supply the current to the battery through a buck operation in the Reverse Buck Mode. Times in which is critical to charge the battery from the grid include peak shaving during inclement weather or nights, when PV source cannot provide sufficient current to charge the battery, when the load demand drops, or to store energy during times when grid energy costs are low.

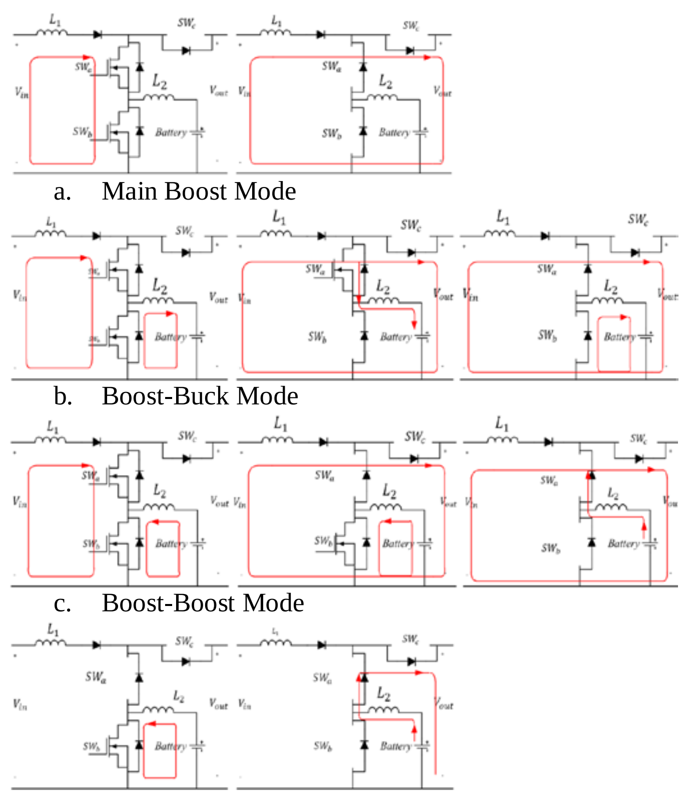
A. *Main Boost Mode*

In this mode, SW_a and SW_b have the same duty ratio. Together, both switches form a boost converter that boosts the PV input voltage. During this mode, SW_c behaves as a diode by sending zero to its gate. The basic input to output principle of boost converters applies to this mode, where:

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

In which,

$$D = \frac{T_{on}}{T_s} \tag{2}$$



a. Main Boost Mode

b. Boost-Buck Mode

c. Boost-Boost Mode

d. Battery Boost Mode

Fig. 3. The original four modes of operation still operate under the same principle as before.

B. Boost Buck Mode

For this mode, the duty ratio of SW_a is longer than SW_b. This way, the PV voltage is boosted during the time both SW_a and SW_b are “ON”. During the time SW_a remains “ON” and SW_b turns “OFF”, the PV supplies energy to the load and charges the battery. In this mode, SW_c behaves as a diode. To determine the output of the boost converter for this mode, the equations become:

$$V_{out} = \frac{V_{in}}{1 - D_{boost}} \tag{3}$$

In which,

$$D_{boost} = \frac{T_{on-boost}}{T_{s-boost}} \tag{4}$$

To charge the battery, the equations become:

$$V_{batt} = D_{buck} V_{in} \tag{5}$$

Where,

$$D_{buck} = \frac{T_{on-buck}}{T_{s-boost}} \tag{6}$$

C. Boost-Boost Mode

Here, we have the opposite case from the Boost-Buck mode, in which the duty ratio of SW_b is longer than SW_a’s. This allows the battery to discharge energy to the inverter when the PV energy generation is not sufficient. During this mode, SW_c behaves as a diode. This mode boosts the input voltage while discharging the battery to supply the load. The equations for this mode are:

$$V_{out} = \frac{V_{in}}{1 - D_{boost1}} \tag{7}$$

In which,

$$D_{boost1} = \frac{T_{on-boost1}}{T_s} \tag{8}$$

And

$$V_{out} = \frac{V_{batt}}{1 - D_{boost2}} \tag{9}$$

In which,

$$D_{boost2} = \frac{T_{on-boost2}}{T_s} \tag{10}$$

D. Battery Boost Mode

The Battery Boost mode is useful in the case of input fault such as cloud cover, or damaged modules, etc. Since our modification to the converter, the state for SW_a is no longer relevant while SW_c acts as a diode. In this mode, the battery supplies the inverter with energy via the mathematical equations (11) and (12).

$$V_{out} = \frac{V_{batt}}{1 - D} \tag{11}$$

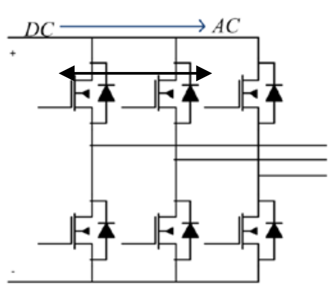


Fig. 4. A three phase full bridge inverter can act as a diode bridge rectifier in reverse when no signals are sent to the gates.

In which the duty ratio of SW_b is,

$$D = \frac{T_{on}}{T_s} \tag{12}$$

E. Reverse Buck Mode

The Reverse Buck Mode (RBM) benefits from the SW_c switch and makes use of the bi-directionality of the interconnected inverter. This is accomplished by either sending no pulses to the MOSFETs of the universal bridge, in essence converting the universal bridge into a full bridge rectifier (see Fig.4.), or by controlling the individual MOSFET switching cycles to achieve a desired DC voltage. Subsequently, this system converts the AC grid voltage into DC for battery charging. In this mode, we made SW_{c1} “OFF”, SW_{c2} “ON”, and SW_b “OFF”. In this way, the battery is charged from the rectified grid voltage by varying the duty of SW_a. When the SW_a is “ON”, V_{rect} is transferred to the battery and the inductor current I_{L1} increases. This is mathematically expressed as:

$$\Delta I_{L2} = \frac{V_{rect} - V_{batt}}{L_2} DT_s \tag{13}$$

Where, ΔI_{L2} is the inductor ripple current. When SW_a is “OFF”, then inductor current in L_2 decreases in the rest of the period T_S. This is expressed as

$$\Delta I_{L2} = \frac{V_{batt}}{L_2}(1 - D)T_s \tag{14}$$

By equating (13) and (14), we derived the RBM input to output relation.

$$\mathrm{V_{batt}} = DV_{rect} \tag{15}$$

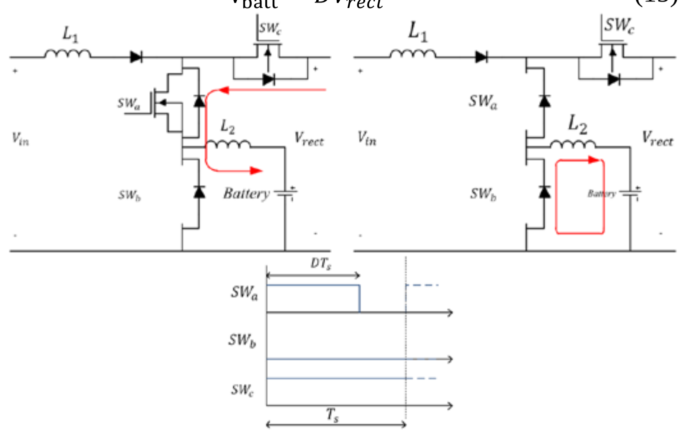


Fig. 5. Reverse Buck Mode charges the battery when SWa is “ON” and when no renewable power source is available.

IV. Control Scheme

A control scheme was designed for proposed Reverse Buck Mode. This scheme consisted of a Lag compensator (Proportional-plus-integral controller) which increases the low-frequency loop gain, such that the output is better regulated at DC and at frequencies below the crossover frequency. The controller transfer function is defined as:

$$G_c(s) = G_0(1 + \frac{w_L}{s})$$

where ω_L is inverted zero. PI controller integrates the error signal at low frequencies, such that the disturbance-to-output transfer function approaches zero.

We chose ω_L as one tenth the crossover frequency to avoid significant changes in the phase margin, otherwise our phase margin is corrupted and would require us to add a Lead compensator to our controller. G_0 is selected in such manner to achieve the desired crossover frequency, and has a unity loop gain at desired cross over frequency.

The Bode plot for the system is shown in fig. 6. As can be seen it has small degree phase margin which is not desired. By changing the crossover frequency, the system can achieve better stability in this mode. With this controller, the output can reach an approximately zero error in steady state and output loop disturbances are attenuated.

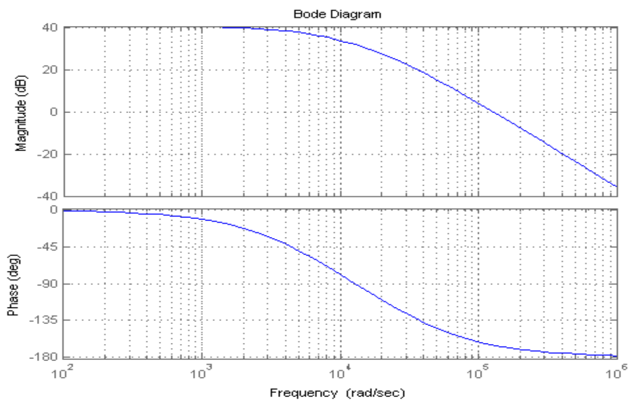


Fig. 6. converter control-to-output transfer function

As seen on fig. 7. , after setting the reference voltage on 54 volt, the steady-state error becomes zero after almost 0.14 seconds, and it reaches the desired output voltage.

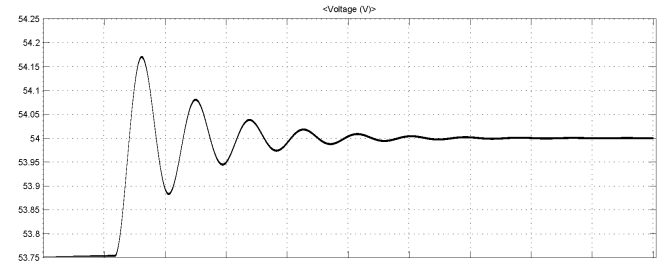


Fig. 7. output voltage transient response with PI controller

V. Simulation Results

The three-switch multimode converter was implemented and simulated in MATLAB's Simulink. Values chosen for the different elements and modes are listed on Table I.

Table I

Simulation Parameters

Nominal Output Voltage	160V	Inductor (L1)	0.8mH
Battery Voltage	50V	Inductor (L2)	0.6mH
Initial Battery SOC%	0.5	Battery Type	NMH

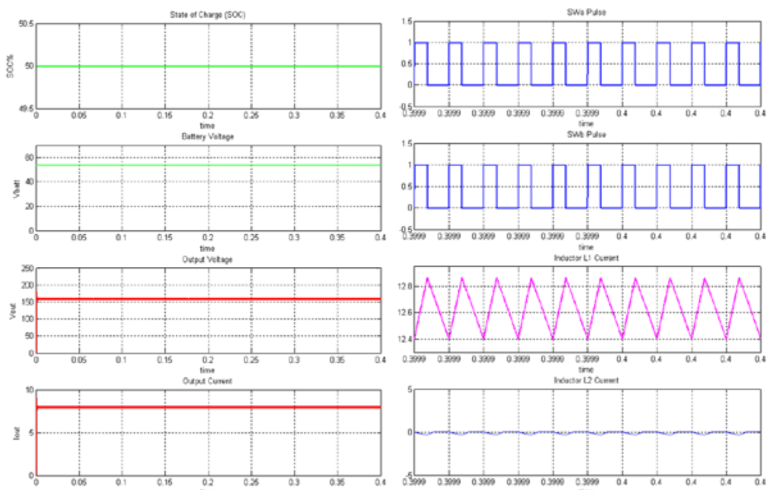


Fig. 8. Main Boost Voltage Results.

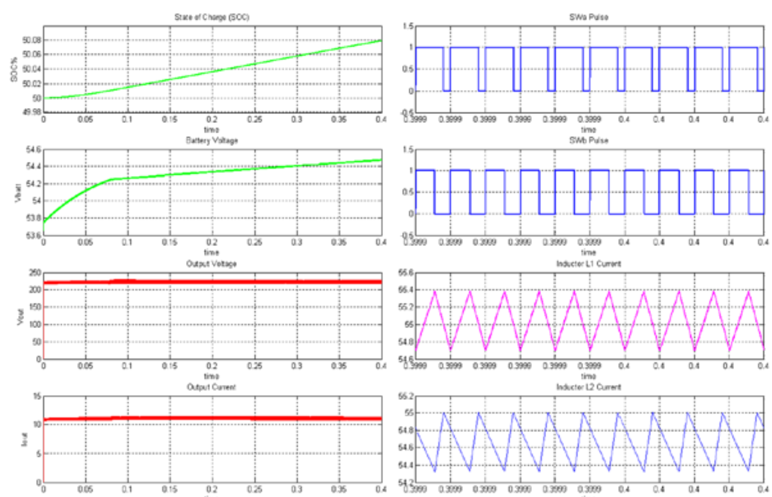


Fig. 9. Boost Buck Mode Results.

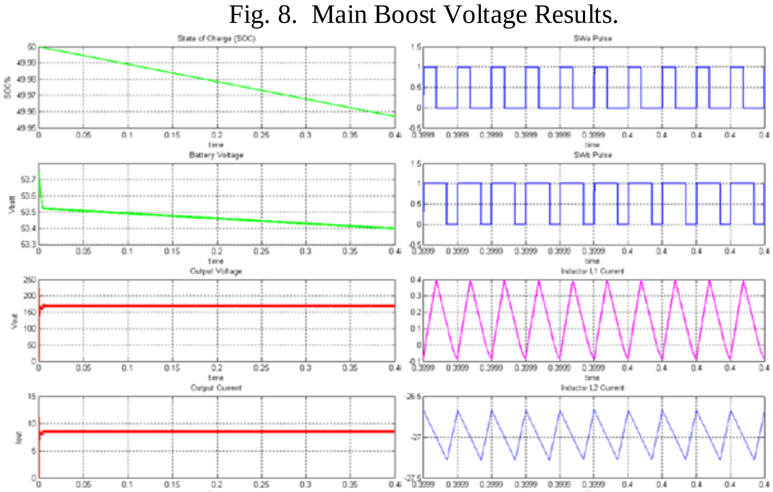


Fig. 10. Boost Boost Mode Results.

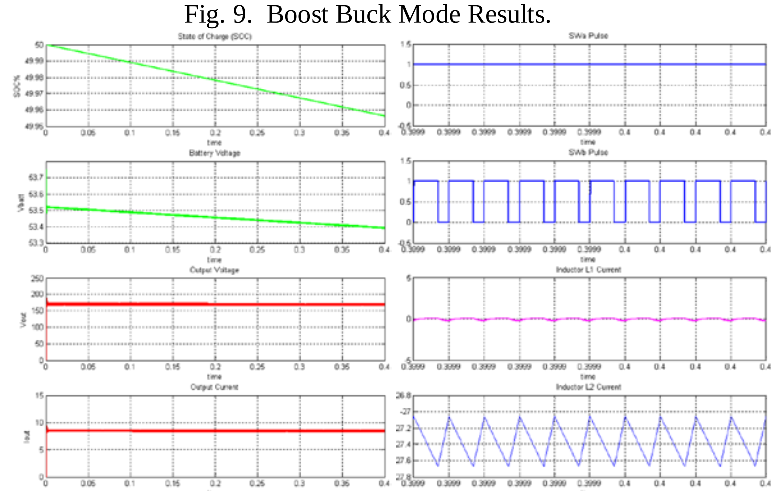


Fig. 11. Battery Boost Mode Results.

The duty ratios were generated by sending control signals to a PWM generator which employed a $10\mu s$ repeating ramp waveform. Also, a similar voltage source to V_{in} was used in our model to simulate an ideal rectification from the grid. The Simulink model was run for 0.4 seconds.

The battery chosen for our simulations was of a Nickel Metal Hydride with a nominal voltage of 50V. Other noteworthy parameters includes number of cells in series, and number of cells in parallel and Internal Resistance. Nonlinear model of the battery shows a good approxiamtion of the real available NMH batteries. This battery has 42 cells in series with nominal voltage of 1.18 volt for each cell. The Maximum capacity for each cell is 7 AH. The total resistance of the battery with Internal Resistance of 0.002 Ohms for each cell is 0.0084 Ohms. Experimental validation of the model shown a maximum error of 5% (when SOC is between 10% and 100%) for chare and dischare dynamics.[Matlab help. menu].

As seen on figs 8-11, the behavior of the former four modes are not altered with the addition of SW_c and the input/output equations are not affected. Fig. 8 demonstrates the Main Boost Mode, which boost the input voltage to $160V$ with negligible current going into the battery (ΔI_{L2}).

Fig. 9 shows the Boost Buck Mode, which boosts the voltage in the beginning of the time period T_s and then charges the battery while maintaining the output voltage at its nominal value. Fig. 10 shows the Boost-Boost mode, which provides power to the grid from the grid and input sources. Fig. 11 shows the Battery Boost Mode. For this mode, the input voltage was set to zero, and the duty ratio of SW_b was regulated to provide $160V$ in the output. The current through inductor L_1 was effectively zero.

The Reverse Buck Mode simulation results are seen on Fig. 12. The regulation of SW_a allowed the battery to be charged from the rectified grid voltage. At an initial battery state of charge (SOC) of 50%, the operating voltage of the battery was around 50V. Therefore, the battery would not charge for any duty cycle less than 0.5. This is due to duty cycle relationship of equation (15), expressed as:

$$\frac{V_{batt}}{V_{rect}} = D \approx \frac{50V}{100V}$$

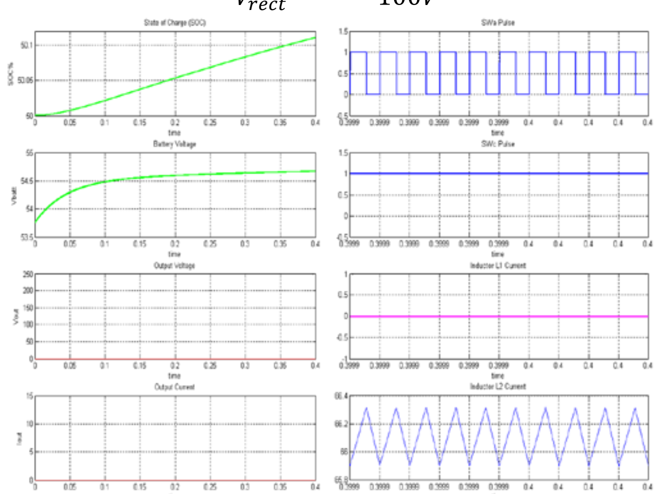


Fig. 12. Reverse Buck Mode Results.

VI. Discussion

It is somewhat possible to charge the battery from two sources by modifying SW_c into a four quadrant operating switch (that is a MOSFET configuration that allows for the positive and negative exchange of voltage and current through it). The four quadrant operating MOSFET is illustrated on fig. 13a. The four quadrant flexibility was used to preclude any current from flowing into each of the respective sources, and solely supply current to the battery. This mode is desired, since it could increase savings by storing the energy when the electric rate is low, and utilizing it when it is high in the following day(s).

In this mode, SW_a remains "ON" for the entire period while SW_{c1} is "OFF", and SW_b becomes "ON" for d_bT_s seconds. In this mode, SW_{c2} may cycle "ON" for d_cT_s seconds during the remaining period $(1-d_b)T_s$ (See Fig. 13b). Consequently, during the d_bT_s the PV charges the L_1 inductor, which is the amount of energy that will be pushed into the battery when SW_b turns "OFF". During this period of time, the grid remains disconnected from the battery. When SW_{c2} turns "ON", the grid supplies energy to the battery for the remaining duration of time. It is during this period of time that both the PV and the grid should charge the battery.

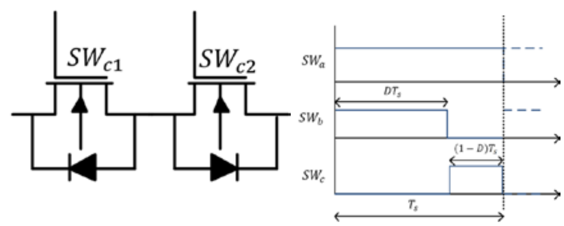


Fig.13. (a) Four Quadrant Bi-Directional Switch. (b)The basic order of switching operation to charge the battery from energy of the PV source and the rectified grid voltage simultaneously.

Formulas for two scenarios under this mode were derived. In the first scenario in which both SW_a and SW_b are "ON", the ripple current of both inductors is calculated as follow:

$$\Delta I_{L2} = \frac{V_{bat} d_b T_s}{L_2} \tag{16}$$

And,

$$\Delta I_{L1} = \frac{V_{in} d_b T_s}{L_1} \tag{17}$$

During the time that SW_{c2} turns "ON" and SW_b is "OFF", the ripple current of both inductors are mathematically described by:

$$\Delta I'_{L2} = \frac{V_{rect} - V_{batt}}{L_2} d_c T_s \tag{18}$$

and,

$$\Delta I'_{L1} = \frac{V_{in} - V_{rect}}{L_1} d_c T_s \tag{19}$$

However, unlike the previous method, (16) and (18) cannot be equated with (17) and (19) to find the input/output relationships. This may be due to the inequality of inductor currents (L_1 and L_2) during the short time gap which SW_b and SW_{c2} are both "OFF". Due to this characteristic, the input/output equations cannot be derived precisely.

VII. Conclusions

This paper proposed an additional switching element to an existing method at the expense of adding a valuable capability. The goal was to add smart grid functionalities to this novel application with the introduction of minimal switching elements that ultimately reduce power electronics costs of renewable energy systems. The proposed configuration introduced more interaction between the grid and the energy storage system and while maintaining low switching losses compared to conventional boost and bi-directional DC/DC converters. While it was only possible to charge the battery from the grid with this configuration, charging the battery from both the PV source and the grid simultaneously present several challenges.

It is of active interest to introduce the ability to charge the battery from both sources simultaneously to enhance the feasibility of this topology as an economical and complete smart grid system. Topologies such as those in [6], or time shared basis flyback converters present viable approaches to this task.

VIII. References

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