A Review of Single Switch 3-Port Converters

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***Abstract*— This review paper examines single switch three port converters (SSC) for off grid solar/battery/load applications. By combining the traditional cascaded buck, boost or buck/boost DC/DC converters and combining the switches, the single switch topology can be realized. The selection of which of these converters to cascade depends upon the specifications required for the circuit. Pulse Width Modulation (PWM) and Pulse Frequency Modulation (PFM) is used to regulate the single switch to perform the required circuit operations. The advantage of the single switch design is fewer components, lower cost, improved reliability and efficiency.**

***Keywords*—battery, boost, buck, DC/DC converter, solar**

I. Introduction

The global demand for energy is ever increasing and the majority of this is met through fossil fuels. This is not a finite resource and it also adds to pollution and global warming. Solar power which is the result of solar panels converting sunlight into energy is one source which has been exploited for many years. With increasing efficiency of this conversion, solar power is able to significantly contribute to decreasing the reliance on fossil fuels.

The drawback with this type of energy is its intermittence even during daylight hours, and it has no output during the night time. The energy produced by the panels could be less, more or exactly what is required to power a connected load. A battery is used as a storage device between the panels and load to store energy which is in excess to what is required, it is also able to deliver power to the load to supplement the solar power if the solar cannot meet the load demand.

DC-DC converters used in solar/battery/load renewable energy systems are integral for the conversion of solar energy into energy to power a load or to store in a battery. The voltages required for the panels, battery and load may not be equal and require changing to different DC voltage levels for the system to operate. In a conventional system one DC/DC converter is used between the solar panels and batteries and another DC/DC converter is used between the batteries and load. These two converters contain multiple switches, diodes, inductors and capacitors.

To replace the two DC/DC converters a single 3 Port DC/DC converter can be used to control this energy flow. The solar panels and output load are connected to the controller via unidirectional ports and the batteries are connected via a bi-directional port. This allows the batteries to charge from the solar panels and discharge to the load when required. The solar panels are also able to feed the load directly.

The approach to develop single stage converters by cascading boost, buck or buck/boost has been investigated by many researchers [1-8].

The SSC converters have at least one switch and several diodes, inductors and capacitors. The three-port converter has fewer components and a smaller footprint than using two separate converters. This results in decreased cost and increased efficiency.

These converters can be isolated, partially isolated or non-isolated. The isolated have a transformer to electrically separate the inputs from the loads. This involves the use of a transformer which reduces the efficiency and increases the size of the controller.

For the non-isolated type many different topologies have been presented in the literature [9, 10], they differ greatly in the number of components used.

The single switch 3 port converter is developed by combing two of the basic types of converters, buck, boost or buck-boost in cascade.

Converters with more than one switch generally use PWM with a fixed frequency to control the duty cycle of each switch independently to control power flow through the circuit.

In an SSC there is only one switch to control the MPPT for the solar panel, load voltage regulation and charging/discharging of the battery.

The control scheme involves introducing Pulse Frequency Modulation (PFM) control of the switch as well as Pulse Width Modulation (PWM). Then both the frequency, f, and duration, D, of the switch can control the functions of the SSC.

The PWM acts on the output side of the converter and keeps the inductor in Continuous Conduction Mode (CCM) using a conventional feedback loop comparing the output voltage with the reference voltage to control the duty cycle, D. The load voltage regulation of the circuit is controlled by this duty cycle. The input side of the converter operates with the inductor in Discontinuous Conduction Mode (DCM) using PFM. The voltage of the solar panel is controlled by adjusting the switching frequency according to the MPPT method chosen to maximize power from the panel. Gate pulses to the switch (MOSFET) are generated by merging the PFM and PWM control.

By combining these two methods and applying them to the single switch, both sides of the converter are able to be controlled independently. The operations of MPPT, output voltage regulation and charging/discharging of the battery can still be achieved by the one switch in the SSC. This is shown in the next three topologies, each with different input/output branches but the same approach to control.

II. CONVERTER DESCRIPTION

A. Topolgy 1

An approach to develop a family of Single Switch 3-port converters is presented in [1]. They have redesigned the buck, boost and buck/boost so they can either be used as the input or output branch as the battery and switch are now common to both branches. After integration the two converters work independently using PWM and PFM. CCM with PWM controls the load voltage regulation using duty cycle, D, of the switch and DCM with PFM controls the input with MPPT via the frequency, f, of the switch.

The 9 topologies available from the input and output cells are given along with the operational waveforms. A buck-buck example was investigated although the operational modes for all 9 converters are given. From their standard design process any of the 9 topologies could be integrated and analyzed. The buck input and output branches are shown in Figure 1.

A design process is introduced, it takes the input specifications, which determines if the branches will be buck, boost or buck/boost. Then as branch 2 operates in CCM and Vo is controlled by PWM the duty cycle, D, can be determined as can the value for L2. Branch 1 is chosen, it operates in DCM and inductor value L1 is calculated and controlled by the frequency. As the duty cycle remains fairly constant only the frequency, f, is controlling L1 to keep it in DCM.

For the buck-buck example shown in Figure 2, experimental results show L1 operating in DCM and L2 in CCM and the battery charging and discharging currents.

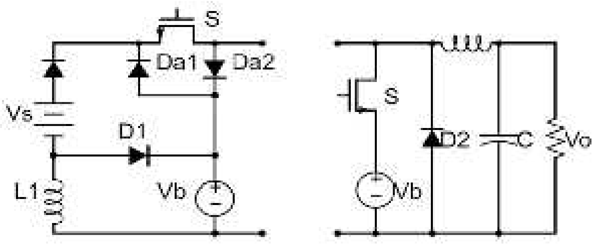

Figure 1: Buck branches, input and output

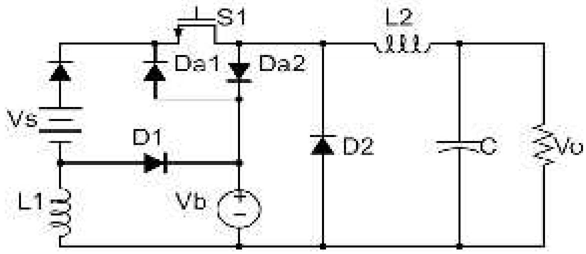

Figure 2: Buck-Buck SSC

For the buck-buck example energy can be transferred directly to the output when the switch is on. If this energy is surplus to that required by the output then the battery is charged through the switch and Da2. If the input energy is less than required by the load, then the battery will supply the extra amount required through Da1 and the switch.

B. Topology 2

Another single switch topology from [2-4] is a boost cascaded with a buck converter.

A conventional boost converter cascaded with a buck converter is presented in Figure 3. The single switch converter is shown in Figure 4.

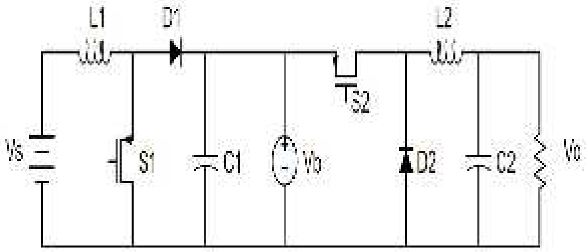

Figure 3: Conventional Boost Buck Converter

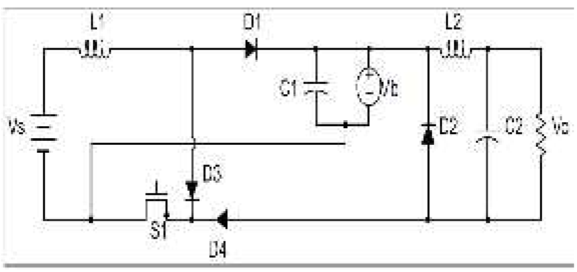

Figure 4: Boost-Buck SSC

The conversion from the 2 switches usually required for two stage conversion, in this case boost cascaded with a buck, can be done as in this case both converters share the same switch. Inductors L1 and L2 remain as does diodes D1 and D2 but 2 new Diodes D3 and D4 are added to control the power flow through the circuit when the switch is either on or off.

The switch must now control both the buck and boost converter as they share a single switch, so a unique control signal is presented.

The PWM signal for the switch is conventional with PI closed loop feedback which changes the duty cycle, D, to regulate the output voltage. PFM is also used, varying the frequency, f, of the switch to obtain MPPT from the solar panels, using a conventional ramp generator.

In [3, 4] this topology is further explored with a resettable integrator to replace the conventional ramp generator for the PFM signal but still achieves MPPT.

Reference [3] shows the three operating modes for the converter plus the design equations for the inductors and capacitors. Simulations and experimental results for show the approach is effective in controlling the MPPT and voltage regulation in the circuit. Inductor L1 is operating in DCM and L2 operates in CCM.

Reference [4] goes further and presents 5 operational modes for the battery including charging, discharging and idle states. The maximum voltage and current stress ratings of the components is compared to that of a converter with the conventional design. A cost comparison between the proposed and conventional converter show a reduced cost for the single switch design and a reduction in switching losses.

C. Topology 3

A buck converter cascaded with a buck/boost converter has been presented in [5-8]. The conventional buck and buck/boost converter is shown in Figure 5. Figure 6 shows the two conventional converters combined into a single switch SSC.

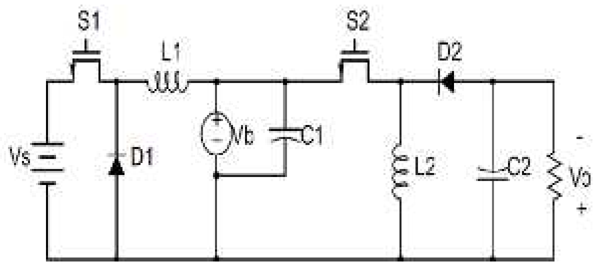

Figure 5: Conventional Buck into Buck/Boost Converter

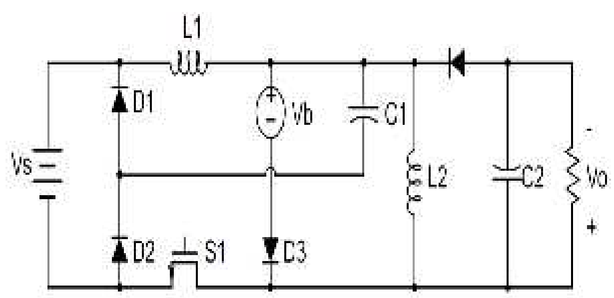

Figure 6: Buck-Buck/Boost SSC

All these papers have the same circuit topology so operate in the same manner. L1 controls MPPT and battery charging wile L2 delivers energy to the load. Capacitor C1 accepts ripple current from the battery which is used to stabilize the dc link voltage. C2 absorbs ripple current to the load. Switch, S, provides a return path for the solar and battery current while D2 and D3 provide paths to the battery current while the switch is on. The diode D3 provides the energy transferring path from inductor L1 to battery, Vb, whereas the diode D4 provides the linking between the output load and inductor L2.

In the proposed design, the battery serves two functions: maintains a steady dc-link voltage and balances the energy difference between PV generation and load changes. The charging/ discharging of the battery is determined by the PV input power and load output power.

There are four operation modes, each one is characterized by different energy exchanges between the solar panel, battery, energy storage elements, inductors and capacitors, and the connected load.

In [5] the circuit in Figure 6 is used. Design equations for the inductors and capacitors are given along with tables showing the voltage and current stresses on the components for both this topology and the conventional converter and the estimated cost comparison of the two types of converter.

Constant voltage MPPT is used. A switching frequency of 100kHz balances the conduction loss, switching loss and the limit of hardware. All values for components are presented and experimental results are presented for driving a 7-14W water pump.

Reference [6] also uses the circuit show in Figure 6 and also use PFM for MPPT control by impedance matching and the output load voltage is regulated using normal duty cycle feedback control.

Calculations for the inductors and results for varying irradiance and temperatures of the solar panel to indicate MPPT performance using incremental inductance are presented. No design equations for the capacitors are given. Conventional PWM is used to control the CCM in L2. The system comes out of MPPT and into constant charging to protect the battery from overcharging.

In [7] Perturb and Observe MPPT is used for frequency control of L1 and PI controllers for load voltage regulation. Only the equation for L1 is given, no other component calculations.

In [8] this paper presents the same circuit but introduces a new MPPT Tracking algorithm based on P&O to improve tracking speed based on the relation between optimum voltage and atmospheric temperature.
The temperature variation considered in this study is between 5°C and 55°C. It shows that as the temperature decreases optimum voltage is increasing and vice-versa. It shows the

temperature and optimum voltage in a PV system is inversely proportional.

P&O with large step forward ($\Delta V = 2v$) and small step reverse ($\Delta V = 0.5v$) plus the assumption that the optimum voltage from the PV system is nearly constant at different insolation levels and inversely proportional to temperature variation for a given insolation.

To control the PV output voltage a reference voltage is compared to the current voltage and a PI controller is used with a variable frequency generator signal to track the temperature variation.

III. DISCUSSION

The SSC is developed by combing two of the basic types of converters, buck, boost or buck-boost in cascade. The choice of topology depends upon the circuit requirements and voltage levels of the solar panels, battery and load. Even with the use of only one switch the two stages of the converter can be operated independently.

Regardless of the topology all the circuits use PFM and PWM to control the single switch. It can regulate the output voltage by controlling the duty cycle, D, and control the output of the solar panel using MPPT methods with the frequency, f. But due to the high voltage stress problem, it can only be used for low to medium power applications, this was shown in Table II in [5] and Table 1 from [4].

Only [4] and [5] claim any results for increased efficiency. [4] project that they have achieved a 4% efficiency increase by their proposed design as well as reduced size, cost and power loss. [5] Shows their design has an efficiency of 85-90% over the input power range compared to 70-75% for a conventional converter.

All topologies, due to their nature, will have increased reliability due to fewer components plus smaller size and cheaper cost.

All papers except [4] assume that the components used are ideal and have no power or switching losses and the battery is able to charge or discharge at any time.

Suggestions for future work on SSC by the authors,

1) Limitation of the charging circuit
2) Other modulation and control methods
3) Application in other renewable power systems
4) Auxiliary and protection circuits for low irradiation situation and battery control
5) Rearrangement of the regulation schemes
6) Output regulation and CCCM/CVCM of the battery
7) The two inductors integrated into one magnetic core
8) Extend operation range by letting branch two into DCM

IV. CONCLUSION

A review of single switch 3 port converters, SSC, for solar/battery/load systems was investigated in this paper. Three topologies were examined although with the design processes included many more topologies could be developed. In all circuits a single switch operates with additional diodes as compared to the two switch converters but less components overall. To control the circuits two variables need to be controlled with the one switch. All papers use Pule Width modulation and Pulse Frequency modulation with feedback for both signals for the circuit to act synchronously. MPPT for the solar panels and load voltage regulation was achieved.

From the suggestions for future work, the most important, to make the circuits viable as standalone SSC, is the regulation of the battery in terms of charging and discharging. Either new control methods or adding an additional switch must be investigated. The circuits in their current form give results of improved reliability and cost due to fewer components, and some show improved efficiency, but they are not ready to be implemented without further considerations for the battery.

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