Multiple Input Single Output Converter with MPPT for Renewable Energy Applications

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Abstract—Multiple Input Single Output (MISO) converters typically employ techniques that yield equal current sharing from each energy source. However, for renewable energy applications this may not be desirable since each source may be rated at different power ratings and/or may experience different operating conditions. A proposed two-stage converter system is presented to incorporate the MPPT control in the MISO system. The initial stage implements the MPPT, drawing as much power from the corresponding source. The second stage regulates the output voltage of the MPPT. To evaluate the performance and efficiency of the proposed system, simulation with two solar panels as the sources was performed using Simulink with various test cases to fully explore the viability of the system. Simulation results were also used to compare with those obtained from a system without the MPPT. Results show that the proposed system with the MPPT stage is able to improve input regulation and increase the total amount of power acquired from the sources compared to the system without the MPPT. Further testing with hardware setup confirms the simulation results and demonstrates that even with large differences in input powers, the most total amount of power is achieved and utilized.

Keywords—MISO converter, MPPT, renewable energy

I. INTRODUCTION

Currently in many rural countries, there is a lack of electric power grid to provide power to their population, especially those living in rural or geographically hard to reach areas. This is evident from Figure 1 which shows rural electrification rate in developing countries [1]. One major reason for this is due to the very low benefit cost ratio in rural areas [2]. The power company will have to invest costly capital if they were to build the infrastructure to transmit and distribute power from a centralized power plant to reach homes in rural areas. To avoid the expensive power grid to electrify these areas, alternative methods in generating the electrical power will be needed.

Multiple ways exist to provide rural electrification. Some examples are gas-powered or diesel-powered generators, other alternatives are local renewable energy sources, such as solar, wind, and hydro power generators. When the power source is small or low, the electricity is used locally and directly to a house. A good example of this is solar house where the solar panels are placed on the roof and the electricity generated is being used directly by the house.

Another method in improving access to electricity in rural areas is through a DC house. The DC house takes advantage of multiple small scale or low power renewable energy sources as well as human or animal power generators that are combined to provide power to a DC bus used to deliver electricity to the house. A DC house is a residential DC electricity system that was developed at Cal Poly State University since 2010. Figure 2 illustrates the block diagram of the DC house system [3]-[7].

Fig. 1. Electrification ratio of rural areas in developing countries [1].

Fig. 2. Simplified DC House project block diagram

As depicted in Figure 2, one important element in the DC House system is the Multiple Input Single Output (MISO) DC-DC converter. This converter enables the house to simultaneously receive electricity from multiple energy sources. Since the start of the project in 2010, there have been multiple versions of the MISO converter [8][9] with the latest
one capable of achieving equal load current sharing among the energy sources while providing higher than 90% efficiency [10]. Despite these achievements, the current MISO converter could undergo further improvements to make it more reliable, flexible, and versatile.

Going back to the MISO converter for use with multiple renewable energy sources, the first iteration of MISO revolved around combining multiple ideal sources together. The first revision designed for the DC House project demonstrated a proof of concept to combine sources using a full bridge isolated converter [10]. With this topology, energy from multiple sources are summed together through a transformer. While initial simulations had promising results, the hardware test resulted in poor efficiency. Another drawback with this design is that it is not modular and thus lacks expandability. The transformer had a fixed number of inputs and so if more inputs were to be added, the transformer would saturate. Even if the transformer were large enough to handle more than the given number of outputs, such a transformer would make it very inefficient circuit.

Another iteration of MISO for the DC House project was proposed in 2017 [11]. This design revolved around using multiple 4-switch buck-boost converters and tying each output in parallel to sum together sources to produce a single 48V output voltage. Tying the outputs of parallel DC-DC converters is much easier said than done, as ensuring no current backflows into converters is the primary problem. Current will backflow into one converter if voltage of any other converter in parallel with it is greater than the voltage of itself. The proposed MISO in [11] solves this problem by adding an additional peak current controller that allows for converters to be operated in parallel and equally share the load current. Overall, the proposed topology with the load current control loop allows for unlimited number of parallel modules without any effect on the efficiency of the converter, making it a very effective MISO. The major drawbacks of this circuit are the complexity, cost, and thermal regulation. This converter topology with the added current control loop adds more components which makes it difficult to implement as an inexpensive solution. Secondly, this design forces equal current sharing. In a true setting, this feature may not be desirable since different renewable sources may provide different amounts of power at any given time which makes equal current sharing impractical, unless energy storage is utilized for each source.

In the actual implementation of renewable energy sources for the DC House system or for any other system, it will be most beneficial if each source operates at their respective maximum power point (MPPT) to allow the most energy to be used or stored by the users. As described earlier, the latest MISO design for the DC House project uses the equal current sharing scheme and does not incorporate the MPPT controller. The proposed system presented in this paper addresses this issue by exploring another version of MISO that utilizes the MPPT controller.

II. DESIGN REQUIREMENTS

Figure 3 illustrates the simplified block diagram of the proposed Multiple Input Single Output (MISO) system with Maximum Power Point Tracker (MPPT) controller. The nominal input voltage chosen for the DC-DC Converter block is 24V. Renewable energy sources such as photovoltaics (PV) provide the input voltage in in the actual system and therefore will vary depending on the operating condition of the source. The DC-DC converter is designed to output nominal average output voltage of 12V at any current that is most efficient for the PV. This allows the use of step-down or Buck converter for the DC-DC converters. With the PV sources, the first buck converter implements the MPPT controller, ensuring maximum energy from the PV regardless of any condition. The second converter transforms the voltage outputted from the first converter to the required 12V output for the DC Bus and to combine output currents from the parallel converters.

The proposed converter will be designed to be a modular buck converter where each converter is capable of supplying varying amount of current for each converter up to their rated value. The input voltage specification of the first converter with MPPT will be between 17V and 40V which will be the output voltage range of the PV source. By utilizing the MPPT, the first converter enables maximum output power to be drawn from the PV. This consequently produces output voltage that will vary; hence, the need for the second buck converter. The output voltage of the second converter will sit at 12V. Table 1 provides the summary of design requirements for the proposed system.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Output Power</td>
<td>60W</td>
<td>The lower range of the converter is meant as a proof of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>concept for use with off the shelf PV</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>17-40V</td>
<td>This range of input voltages allows for the compatibility</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with 24V solar panels depending on load</td>
</tr>
<tr>
<td>DC Bus Voltage</td>
<td>12V</td>
<td>A 12V bus is common and practical for most DC applications</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 95%</td>
<td>The system must minimize power loss to get the most out of the sources</td>
</tr>
</tbody>
</table>

III. SYSTEM DESIGN

Figure 4 shows the block diagram of the total system. The proposed converter has two step-down stages; therefore, there are two buck converter designs to consider. The design of the first stage involves choosing the MPPT buck converter controller. Currently, there are no MPPT buck converters that do not revolve around charging a battery; hence, the first buck converter is controlled through a microprocessor. The decision making for the microprocessor was primarily ease of use. The simplest microprocessor to use with plenty of documentation is the Arduino, with the main drawback being that the processor by itself may not be enough to drive the MPPT stage.

The primary additional component needed for the first converter is the gate driver. The final chosen gate driver was the LTC7004. This gate driver operates up to 60V, enough to
account for any input spikes from the input of the solar panel and can allow for a full pass through. The output of the gate driver will match the timings of the input within 10nS, giving plenty of headroom for operation at 300kHz. The power used by the gate driver IC is miniscule as the total current needed to operate is around 225μA, with minimal external components to use; thus, simplifying its implementation.

Fig. 4. Low level block diagram of a single converter.

The Arduino cannot provide the input to the gate driver alone and requires additional components which were chosen based on practicality, ease of implementation and availability. The Arduino cannot provide any sort of square wave greater than 10kHz; and thus, an oscillator is chosen. Selecting a switching frequency greater than 10kHz allows for physically smaller component selection and a higher efficiency. The frequency driver chosen for the input of the MPPT gate driver is the LTC6992-1 with frequency set by a resistor and voltage-controlled duty cycle. The LTC6992-1 is chosen as it is relatively simple to implement, with just a resistor and a capacitor needed to set the output frequency, and a DC voltage to control the duty cycle.

In order to control the duty cycle of the output, an input voltage between 0-1 volt is necessary. At 0V, the output is ground, and at 1V, the output is at 100% duty cycle. The Arduino cannot provide a controllable voltage between 0 and 1V and requires a separate source. Therefore, a digital to analog converter (DAC) fully controls the gate driver. The digital to analog converter communicates with the Arduino in order to provide a DC voltage which in turn drives the LTC6992-1. The MCP4921 DAC was chosen based on its ease of use, 12-bit resolution, and 5V compatibility with the rest of the board. The MCP4921 has a Serial Peripheral Interface (SPI) instead of an Inter-Integrated Circuit (I2C) communication protocol, which allows for ease of use. I2C requires pull up resistors and operates slower compared to SPI, which does not require any form of pull up resistor. This reduces the number of components needed to drive the MCP4921, making it easier to use. Secondly, the DAC has a 12-bit resolution, meaning if VREF is held to 1V through a resistor divider, the minimum step the DAC has between 0 and 1V is as follows:

\[ V_{\text{Step}} = \frac{V_{\text{ref}}}{2^{12}} = \frac{1V}{2^{12}} = 0.245mV \]  

(1)

In order to implement the MPPT, the Arduino needs to read in feedback from the input of the converter. This is done by implementing a current sensor as well as a voltage sensor in order to calculate the power delivered to the converter. The current sensor revolves around using a low ohmage sensing resistor as well as an amplifier. The amplifier chosen is the LT6106 due to its simple implementation with only two resistors needed to set the gain. An RC filter is added to the output of the current sense amplifier in order to ensure that there is an accurate current reading. Since the output resistor used is 10kΩ, an output filter can be made by implementing a low pass RC filter, where a capacitor is placed in parallel with the output resistor. Equation below describes the RC transfer function:

\[ \tau = \frac{1}{2\pi RC} = \frac{1}{2\pi(10k)(1n)} = 16kHz \]  

(2)

The next step in the design is choosing the controller for the second stage of the converter. Since this stage functions as voltage regulation, a standard buck converter is satisfactory. The LT3864 is chosen as it has a 100% duty cycle pass through, which can be used if the input voltage is close to the output voltage. The first component that needs to be sized is the inductor. Sizing the inductor value involves the operating frequency, expected input/output voltages as well as the maximum output current of the converter.

\[ L = \frac{(V_{\text{in}} - V_{\text{out}})V_{\text{out}}}{\Delta I f} \]  

(3)

The next components that are sized in both buck converters are the input and output capacitors. These are designed to combat ripple voltage expected on both input and output. Following the Buck topology, the output capacitor value depends on the inductor value, whereas the input capacitor does not. Equations below were used to solve for both the input and output capacitor values, respectively.

\[ C_{\text{out}} = \frac{(1-D)\%dV_{\text{out}}f^2}{\Delta V_{\text{in}}^2} \]  

(4)

\[ C_{\text{in}} = \frac{D(1-D)I_{\text{out}}}{\Delta V_{\text{in}}^{0.5}} \]  

(5)

The final components to size are the switches (MOSFETs) and diodes of the converter. For these components, the two main ratings are their peak voltage and average current rating. For the Buck converter, the maximum voltage across the high side MOSFET and the diode is equal to the input supply voltage. However, possible ringing can occur across the MOSFET due to parasitic inductance and capacitance on traces connecting to the switch. Therefore, the voltage rating of both components should also be at least 1.5x higher than the supply voltage across them switch. The difference between the MOSFET and the diode is their current, whose average values are calculated as follows:

\[ I_{SW} = I_{\text{out}}D \]  

(6)

\[ I_{\text{diode}} = I_{\text{out}}(1 - D) \]  

(7)

Fig. 5. Board layout of the first stage.
Once all components are selected, board design follows. The design of only the first stage of the system is realized as the second stage utilizes a commercially available demo board. The demo board is chosen as it is already rated to run at 12V output with an input voltage between 12V and 55V. The rated current for the components on the demo board are 5A, which meets the rated output current of the proposed system. The board design for the first stage was done using Kicad. The board is designed to be approximately 2.65” by 3.2” inches, with wide traces for the power and ground. The red traces are top copper and the bottom traces are green. The signal ground is placed farther away from both the power and signal grounds in order to ensure that there is minimal noise disrupting the control stage to allow for most accurate readings. The board layout of stage is shown in Figure 5.

IV. SIMULATION RESULTS

There are two simulations that were done for this converter. Simulations for this concept were challenging to prove as Simulink, the software used to simulate the MPPT algorithm, did not have any models or reliable way to simulate the components that would be used in the final converter. Secondly, within LTSpice, there is no practical way to accurately simulate neither MPPT algorithms nor solar panels.

The initial simulation that was done in Simulink was to provide proof of concept for how well the MPPT algorithm would perform with an additional voltage regulation stage as well as a fixed resistive load. Figure 6 shows the model that is used to represent both stages in parallel.

Fig. 6. Simulink Model of the Parallel Converters.

The simulation works well as a proof of concept although it does not represent the actual components nor component values that will be used in the final converter. However, the takeaways from the simulation are as follows. At similar irradiances, the two converters will current share evenly, especially when both converters have enough power from the solar panels. When there is not enough power between both inputs to provide power to the load, both output voltages drop. When there is a difference in irradiance, yet enough power, there will be a difference in the current sharing. The top converter has an irradiance of 1.2kW and the bottom converter has an irradiance of 1kW.

Secondly, the MPPT stage is important as the power from the solar panel is processed through the MPPT stage before the voltage regulation stage. When connecting the second stage directly to the PV, it is noticed that the second stage does not regulate the output voltage as well as if the MPPT stage is in between the PV and second stage. At the same irradiance on the input of both converters, there is no output voltage. The irradiance on the input needed to be increased for the same load as when there is an MPPT stage. Another concern is that both stages reduces the overall efficiency of the system, however, the overall efficiency that is reduced is better found through the second simulation; however, it can still be gleaned that the first stage is necessary.

Thirdly, when the load draws close to the maximum power of both inputs, the MPPT acts as a passthrough. This drives home the point that regardless of being a pass-through stage, the first stage can still provide regulation for the second stage.

The second simulation is done in LTSpice to ensure that the converter will work through both the first and second stage at various operating points. The first stage is tested without the DAC, which is replaced with an ideal voltage source instead. Overall, simulations with just the first stage are as expected, with the gate driver following the LTC6992-1 closely, as seen in Figure 7. With non-ideal components, the efficiency of the buck converter is above 93% at full load.

Fig. 7. Schematic of the first stage.

The second stage is simulated separately from the first stage. It is based off the LT3846 evaluation board, as seen in Figure 8. Components in LTSpice are changed based on values of the DC2434A evaluation board. The second stage is tested with a broad set of operating conditions such as the lowest input voltage at 12V and full load at 5A which would still regulate the output voltage.

Fig. 8. Schematic of the second stage.

The second stage lowest input voltage that maintains a regulated output voltage at full load can be as low as 12V with a simulated efficiency of 99%. This is simply because the converter is operating as a pass through, and any loss occurs from the inductor and sense resistor in series with the output. When the converter is operating nominally at 24V, the efficiency decreases to 95% efficiency under full load.

Once the second stage is verified, it is then combined with the first stage to demonstrate the functionality and operation
of the whole system. Again, operation of the converter is tested at nominal operating conditions, with an input of 24V and load at 5A as well as boundary operating conditions such as minimum and maximum input voltages. Under normal operating conditions, the efficiency of the entire system operates at approximately 93% efficiency including the power used by the various IC’s. When the second stage operates at a lower duty cycle, the efficiency begins to drop. Table 2 examines various operating conditions such as input voltage to the LTC6992-1, voltage at the output of the first and second stages and efficiency.

**TABLE II. SIMULATION RESULTS OF THE PROPOSED SYSTEM AT VARIOUS OPERATING CONDITIONS**

<table>
<thead>
<tr>
<th>Modulation(V)</th>
<th>1st Output(V)</th>
<th>2nd Output(V)</th>
<th>Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>12.8</td>
<td>11.97</td>
<td>92.3077</td>
</tr>
<tr>
<td>0.6</td>
<td>21.77</td>
<td>11.97</td>
<td>93.2792</td>
</tr>
<tr>
<td>0.8</td>
<td>30.825</td>
<td>11.97</td>
<td>91.4216</td>
</tr>
<tr>
<td>1</td>
<td>Vin</td>
<td>11.97</td>
<td>94.6372</td>
</tr>
</tbody>
</table>

Once the verification of a single converter is completed, converters are tested in parallel. To simulate different operating conditions of solar panels, the input voltage to the total converter will be different as well as the modulation voltage between each converter. However, current sharing is not expected in this. An example of both converters at full load in parallel is shown in Figure 9. Both converters are operating under nominal conditions, with different duty cycles on the first stage. Voltage of both outputs regulate to 12V with current not being shared evenly, as shown in Figure 10. The currents of both converters are 4.513A and 4.723A, respectively.

Next, boundary conditions are explored, where one converter is operating at close to pass through while the other is not, and by varying duty cycles. Once steady state is reached, it is observed that the converter with the higher duty cycle, will carry more current regardless of the voltage on the input of the converter. The parallel operation of the converters is proven to work provided enough power; however, since there is not a practical nor quick way to simulate a PV within LTspice with known open circuit voltages and short circuit current, hardware testing is needed to verify both Simulink and LTspice models.

**V. HARDWARE RESULTS**

After the design of the boards, the next step is to physically construct both boards and program them. Additionally, since the irradiance of solar panels varies when out in sunlight and does not provide a controlled test setup, two Rigol-DP832 power supplies are programmed to behave as solar panels. An electronic load and multimeters are used to control the load and measure the power on the output. The entire system is shown in Figure 11, consisting of the black microcontroller controlling the purple MPPT board which is in series with the green evaluation board. Tests are performed with and without the maximum power point stage in order to compare the performance of DC-DC converters under the two scenarios.

![Fig. 11. A string of the MPPT System with Output Voltage Regulation Stage.](image)

Table 3 shows that when both converters are operating close to maximum load, one board will always be pulled more to its maximum power point (MPP), and it compensates the rest of the power from the other board. Examining what the perceived input resistance gives an idea of how close to the MPP each converter is operating at. In Tests 1 and 3, one converter is operating more closely to its MPP instead of balancing the power equally. For Test 1, power supply #2 operates at about 2W away from its MPP or at ~97% max input power. In Test 3, power supply #1 can provide up to 55W, operates at 5W away from its MPP, or 91.5% max input power. Thus at maximum load, the MPPT stage draws one converter to its peak input while allowing the second converter in the system to provide the additional power. The MPPT stage in both Test 2 examines the converter’s operation when the power needed from the load is far less than the maximum power point. In this case, where the load isn’t as demanding, both converters share similar amounts of power. Test 4 examines a drastic difference in the operating power, yet still close to the maximum load available. Test 4 has the correct resistances at which the converters should operate; however, the current that each is supplying is incorrect and it does not track with the solar panel. The ideal power that the two converters should have been operating are approximately 44W and 52W, or 19.71V at 2.236A and 26.55V at 1.95A. This limitation is most likely due to the operating conditions of the power supply itself and its inability to emulate the IV characteristics of a real solar panel.

The next test was done without the MMPT board. This is done by tying the DC-DC converters directly to the Rigols. The same test cases from Table 3 are repeated and the results are listed in Table 4.
Firstly, in all the test cases in Table 4, output current from each path is within at least 5% of an even split in total output or load current. Simply tying power supplies together means that the power supplies are forced to draw even amounts of current. Secondly, notice that the input resistances now of all the converters approach the MPP; however, there isn’t one converter in any case that is pulled to the MPP. Test 4 shows that well where the second Rigol operating at 65W is not pulled towards its MPP and operates at 45W instead. Since the buck converter only regulates the output voltage, in Test setup 2 when there is an input power less than 50% of the load power demanded, the buck converter drops out as it cannot regulate itself to the MPP. Thus, it cannot provide the most amount of power while still operating in regulation. Since the buck converter only regulates the output voltage, in Test setup 2 when there is an input power less than 50% of the load power demanded, the buck converter drops out as it cannot regulate the input power to provide the demanded power. Therefore, without the MPPT stage, the two buck converters cannot operate with large differences in current, not large differences in input power. Compared to Table 3, the system draws a more uneven split of current with the most uneven split occurring at 25% from the midpoint current as resulted in Test 4.

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One conclusion that we can draw from these tests is that an overall system without an MPPT stage would be limited by the solar panel with the least amount of irradiance and thus power. Moreover, the efficiency of the total system is not heavily impacted by the trade-off where the system will be able to operate at higher loads. Comparing both setups as shown in Figure 12, we can see that the highest difference in efficiency occurs in Test 3, with a difference of ~3%.

The system presented in this paper provides proof of concept that without the MPPT stage, power would be limited by the smallest available power source. Incorporating the MPPT stage in the system allows for additional power from the source and prevents the power source with lowest amount of power from limiting the system. Results also indicate that the MPPT stage are most beneficial when the power differential between solar panels is the greatest. Furthermore, even with the additional components in the system as a trade-off, the test results show insignificant decrease in the overall efficiency of the system of about 2-3%. This project can be improved with better testing setups, algorithms, and a board redesign.

VI. CONCLUSION

The system presented in this paper provides proof of concept that without the MPPT stage, power would be limited by the smallest available power source. Incorporating the MPPT stage in the system allows for additional power from the source and prevents the power source with lowest amount of power from limiting the system. Results also indicate that the MPPT stage are most beneficial when the power differential between solar panels is the greatest. Furthermore, even with the additional components in the system as a trade-off, the test results show insignificant decrease in the overall efficiency of the system of about 2-3%. This project can be improved with better testing setups, algorithms, and a board redesign.

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