Solar-Powered Multiple-Input Zeta Converter for 48V Applications

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Abstract
To reduce environment pollutants and a current level on high power systems, 48V power applications have been studied on uninterruptible power supply, green telecommunication power system, and micro hybrid electric vehicles with renewable energy sources or alternative energy sources. In the electric vehicle field, large numbers of automobile companies are obligated to supply more electrified vehicles. As these more electrified vehicles use high power, a 48V system has been researched to decrease a current level of the vehicle power system. This paper proposes a solar-powered multiple-input zeta dc-dc converter with high reliability and flexibility for 48V applications. The proposed multiple-input zeta converter system was verified by computer-based simulation results.

Keywords: 48V Applications, Multiple-Input Zeta Converter, Photovoltaic Module, Ripple Correlation Control

1. Introduction
To reduce increasing power consumption and CO₂ emissions, renewable and alternative energy sources such as photovoltaic systems, wind power plants, energy storage systems, and fuel cells are applied in various areas (e.g., island standalone distribution power grid, green base station, solar powered EV charging station, and uninterruptible power supplies). To reduce environment pollutants, many automobile companies in the world should supply a certain amount of more electrified vehicles by regulations and laws. If an automobile company violates these regulations to reduce environment pollutants, such a vehicle company will be subject to substantial fines. Therefore, most companies have developed various more electrified vehicles such as Hybrid Electric Vehicle (HEV), Plug-In Hybrid Electric Vehicle (PHEV) and Plug-In Electric Vehicle (EV). In particular, many automobile companies have developed a 48V mild hybrid system because this vehicle system can obtain high fuel economy with an inexpensive production cost. In addition, the advantages of this 48V vehicle power system can provide more energy and power with less current levels compared with conventional 12V vehicle system. In addition, 48V systems are conventionally used in telecommunication power systems.

This paper proposes a Multiple-Input (MI) dc-dc zeta converter with renewable energy sources to implement a 48V power system that can be used in a range of fields such as telecommunication power systems and vehicular power systems. The proposed solar-powered MI zeta converter can provide high flexibility and reliability with multiple-input sources and a proper switch control method. Moreover, the MI zeta dc-dc converter can convert different voltage levels of input power sources to the required output voltage using the buck-boost operation. Another advantage of MI dc-dc converters is that they can reduce the physical size and cost by using a common output cell, which is a part of the power stage to regulate the input sources, as shown in Figure 1. The common output cell consists of an energy storage inductor, freewheeling diode, and output capacitor and it shares several common elements with respect to the input sources. This study investigated the MI zeta dc-dc converter with two energy sources such as Photovoltaic (PV) modules and 12 V batteries, for 48 V applications.
The remainder of this paper is structured as follows: Section 2 describes the basic operation principle and analysis of the MI zeta converter. Section 3 describes the overall control scheme and control strategy for the maximum power point. Section 4 presents’ simulation results and section 5 concludes the paper with a summary of findings.

Figure 1. Common output cell of multiple-input converters.

Figure 2. Pair of a diode and a MOSFET.

Figure 3. GTO.

2. Multiple-Input Zeta Converter

2.1 Forward Conducting Bidirectional Blocking Switch

Electrical switches can be sorted in two ways: The first classification method is to sort electrical switches according to the number of poles and throwing, such as Single-Pole/Single-Throw (SPST), Single-Pole/Double-Throw (SPDT) and Double-Pole/Double-Throw (DPDT). The other classification method is to classify the electrical switches by the current flow direction and blocking ability, such as Forward-Conducting/Reverse-Blocking (FCRB), Forward-Conducting/Forward-Blocking (FCFB), Forward-Conducting/Bidirectional-Blocking (FCBB), Bidirectional-Carrying/Forward-Blocking (BCFB) and Bidirectional-Carrying/Bidirectional-Blocking (BCBB) switch.

A single input dc-dc converter generally uses an FCFB or BCFB switch, such as IGBT or MOSFET because they do not require bidirectional blocking ability. On the other hand, most MI converters require bidirectional blocking ability to prevent current flow between the input cells. Reverse current flow between inputs cells occur when the voltage difference is in multiple input sources. This problem may cause critical damage to the input sources. Therefore, MI converters should use an FCBB switch, such as a Gate Turn-Off thyristor (GTO) or a series connected diode and MOSFET, as shown in Figs.2 and 3, respectively. As a result, multiple input energy sources, such as PV module, wind generator, fuel cell, or battery can deliver power to electric loads by FCBB switches.

2.2 Switching Strategy

Each input switch uses a Forward Conducting and Bidirectional Blocking (FCBB) electrical switch. The FCBB switch of the input cells requires proper switching control signals because many MI converter topologies generally do not allow the current flow from two or more input cells simultaneously. A time-sharing control method is a suitable strategy for controlling these MI converter switches. Figure 4 shows the switch gate signals for an MI zeta converter (i.e., q_1, q_2, ..., and q_j, which is the jth gate signal of each switch). When all the FCBB switches of the MI zeta converter are assumed to be synchronized, they are turned on at the same time and have the same switching frequency. On the other hand, since FCBB switches have a different duty ratio, the falling edges of each gate signal may occur at different times. The FCBB switches are controlled by the duty ratio of gate signals. In fact, input switches can only operate with effective gate signals (i.e., q_{1eff}, q_{2eff}, ..., q_{eff}), due to the FCBB performance characteristics. Therefore, FCBB switches are turned on by the effective duty ratio (i.e., D_{j_{eff}}) that is the only effective energy transferring period of each duty ratio. In other words, the jth duty ratio, D_{j_{eff}}, can be expressed as

\[
D_{j_{\text{eff}}} = \begin{cases} 
0, & D_j < \sum_{k=1}^{j-1} D_{k_{\text{eff}}} \\
D_j - \sum_{k=1}^{j-1} D_{k_{\text{eff}}}, & D_j < \sum_{k=1}^{j} D_{k_{\text{eff}}} \\
D_j - \sum_{k=1}^{j} D_{k_{\text{eff}}}, & D_j \geq \sum_{k=1}^{j} D_{k_{\text{eff}}} 
\end{cases}
\]
where $V_1 > V_2 > \ldots > V_j$, $D_1 < D_2 < \ldots < D_j$, and $j$ denotes the number of input sources.

Because of the FCBB and time sharing switching method, all switches except for the first switch $S_1$ can be turned on with a zero current switching. The zero current turn-on switching helps improve the total system efficiency of the MI zeta converter.

### 2.3 Steady-State Analysis in Continuous Conduction Mode

The proposed MI zeta converter as shown in Figure 5 was analyzed for only the Continuous Conduction Mode (CCM). In addition, this study only considered two input zeta converter shown in Figure 6 for the easiness of a circuit analysis although the analysis can be extended with a generalized multiple-input dc-dc zeta converter. In addition, this paper assumed that all elements were ideal and the output capacitor was sufficiently large to regulate the output voltage to a constant value. In CCM operation, the average inductor current for $i^{th}$ inductor (i.e., $I_i$) is always greater than zero and the operation mode of this MI zeta converter can be divided into three modes. Figure 7 shows the operating waveforms of each key parameter of the two input zeta converter for three modes in a single switching period.

**Mode 1**: Figure 8 shows the mode 1 of the considered two-input MI zeta converter. This mode is the $D_{in} T_s$
time period in which switches, S₁ and S₂, were turned on simultaneously. In this mode, the free-wheeling diode is turned off. Because of the FCBB switch, only the first input current (i.e., $i_{IN1}$) from the first input voltage source (i.e., $V_{IN1}$) flows through both inductors (i.e., $L_1$ and $L_2$) although switch $S_2$ is also turned on. The current $i_{IN1}$ charges the inductors (i.e., $L_1$ and $L_2$) although the middle capacitor (i.e., $C_1$) discharges the energy stored in mode 3. Therefore, the inductor currents produced by the first voltage source (i.e., $i_{L11}$ and $i_{L12}$) increase linearly as shown in Figure 7. An inductor current, $i_{Lij}$, denotes the current through the $i$th inductor powered by the $j$th voltage sources.

The inductor voltages (i.e., $V_{L1}$ and $V_{L2}$) are obtained by the Kirchhoff Voltage Law (KVL) as follows:

$$V_{L1} = V_{IN1}D_{eff} - V_{OUT},$$
$$V_{L2} = V_{IN1} + V_{C1} - V_{OUT}. \tag{2}$$

Where $V_{L1}$ and $V_{L2}$ are respectively the inductor voltages across $L_1$ and $L_2$, $V_{C1}$ is the voltage across the middle capacitor, and $V_{OUT}$ is the output voltage of the MI zeta converter.

**Mode 2:** Figure 9 shows the operational principle of the two input zeta converter in mode 2. This mode is the $D_{2eff}T_s$ time period in which switch $S_1$ is turned on and switch $S_2$ is turned on continuously. The free-wheeling diode is still turned off in this mode. In this mode, only the second input current (i.e., $i_{IN2}$) from the second input voltage source (i.e., $V_{IN2}$) flows through the inductors (i.e., $L_1$ and $L_2$). Therefore, the inductor currents powered by the second voltage source (i.e., $i_{L12}$ and $i_{L22}$) increase and the middle capacitor (i.e., $C_1$) discharges the energy continuously. The inductor voltages (i.e., $V_{L1}$ and $V_{L2}$) can be calculated by KVL as follows:

$$V_{L1} = V_{IN2}D_{eff},$$
$$V_{L2} = V_{IN2} + V_{C1} - V_{OUT}. \tag{3}$$

**Figure 10. Mode 3 of the two-input MI zeta converter.**

**Mode 3:** Figure 10 shows the mode 3 of the two input zeta converter. The length of the time period in this mode is $(1 - D_{1eff} - D_{2eff})T_s$. In this mode, both input active switches (i.e., $S_1$ and $S_2$) are turned off. The free-wheeling diode is turned on at the same time. In this mode, energy stored in the $L_2$ inductor transfers to the load. Therefore, the inductor currents (i.e., $i_{L1}$ and $i_{L2}$) are decreased. The middle capacitor (i.e., $C_1$) is charged from the inductor $L_1$ in this mode.

$$V_{L1} = V_{C1}D',$$
$$V_{L2} = V_{OUT}D', \tag{4}$$

Where $D' = D_{1eff} - D_{2eff}$.

As a result, the output voltage of the two input zeta converter can be obtained by a volt-second valance condition as follows:

$$V_{OUT} = \frac{V_{IN1}D_{1eff} + V_{IN2}D_{2eff}}{1 - D_{1eff} - D_{2eff}}. \tag{5}$$

A peak-to-peak inductor current ripple (i.e., $\Delta i_{Lij}$) is a peak-to-peak ripple of the current through the $i$th inductor produced by the $j$th voltage source. For instance, $\Delta i_{L11}$ means a peak-to-peak current ripple of the first inductor (i.e., $L_1$) caused by the first voltage source. $\Delta i_{L22}$ denotes a peak-to-peak current ripple of the second inductor (i.e., $L_2$) powered by the second voltage source. The peak-
to-peak inductor current ripples of the first and second inductors can be calculated by

\[ \Delta i_{L1} = \frac{D_{1,\text{eff}} V_{I1} + D_{2,\text{eff}} V_{I2}}{L_1} T, \]

\[ \Delta i_{L2} = \frac{(V_{I1} + V_{C1} - V_{OUT}) D_{1,\text{eff}} + (V_{I2} - V_{C1} - V_{OUT}) D_{2,\text{eff}}}{L_2} T. \]

where the total peak-to-peak inductor current ripples (i.e., \( \Delta i_{L1} \) and \( \Delta i_{L2} \)) are the sum of the inductor current ripple caused by each voltage source. That is, such total peak-to-peak inductor current ripples can be represented as follows:

\[ \Delta i_{L1} = \Delta i_{L11} + \Delta i_{L12} \]

\[ \Delta i_{L2} = \Delta i_{L21} + \Delta i_{L22}. \]

The peak-to-peak inductor current ripple can be calculated by each inductor voltage (i.e., \( V_{L1} \)) as follows:

\[ V_{L1} = L_1 \frac{di_{L1}}{dt}, \]

\[ V_{L2} = L_2 \frac{di_{L2}}{dt}. \]

Using equation (5), (6) and (8), the peak-to-peak inductor current ripples are given by

\[ \Delta i_{L1} = \frac{D_{1,\text{eff}} V_{I1} + D_{2,\text{eff}} V_{I2}}{L_1} T, \]

\[ \Delta i_{L2} = \frac{(V_{I1} + V_{C1} - V_{OUT}) D_{1,\text{eff}} + (V_{I2} - V_{C1} - V_{OUT}) D_{2,\text{eff}}}{L_2} T. \]

The average inductor current through the \( i^{th} \) inductor (i.e., \( I_{Li} \)) can be obtained by the Kirchhoff Current Law (KCL) as follows:

\[ I_{L1} = I_{IN1} + I_{IN2} - I_{C1} \]

\[ I_{L2} = I_{OUT}. \]

The maximum inductor current of each inductor (i.e., \( i_{Limax} \)) can be obtained by

\[ i_{Limax} = I_{Li} + \frac{\Delta i_{Li}}{2}. \]

### 3. Overall Control Scheme

#### 3.1 Proposed 48 V Power System

Figure 11 shows the proposed 48 V power system with an MI zeta converter, PV modules, and battery. Although the output voltage of a conventional MI buck-boost converter is negative, this MI zeta converter has a positive voltage output. In other words, the MI zeta converter can provide a positive voltage without a transformer for the required positive voltage applications. The considered output voltage and power of the proposed power system are positive 48 V and 462 W, respectively. The rated power values of a PV module (i.e., \( P_{IN1} \)) and a battery (i.e., \( P_{IN2} \)) are 82 W and 380 W, respectively. In fact, the PV output power is not always constant. The output power of the PV module varies by the solar irradiation and the PV surface temperature. For example, if a PV module is shaded by clouds, the PV output power decreases so that the PV module cannot provide the Maximum Output Power (MPP). Therefore, a PV module is usually used an MPP tracker. In this study, the PV module is feed forward controlled by Ripple Correlation Control (RCC) to track the MPP\(^5\). In case the PV power is insufficient; a 12V battery provides the insufficient power to the system. To regulate the output voltage of the system, the Proportional Integral (PI) controller is used for the second input source (i.e., battery). Therefore, the considered MI zeta converter is powered by PV and battery and the overall system out-
put voltage is regulated by the PI controller as shown in Figure 11. As the common output cell shares some passive elements, the MI zeta converter can reduce its size and production cost.

### 3.2 Ripple Correlation Control

The output voltage and current of a PV module are changed with its surface temperature, solar irradiation, or other environmental conditions. Therefore, a PV module requires the MPP tracker to be operated at the MPP. A ripple correlation control MPP algorithm which uses the output voltage, current, and power ripple information of the PV module is considered in this study. The PV output power ripple values are known as the product of the current and voltage ripple. This section summarizes this RCC method\(^3\),\(^5\) for the target power system in this study.

Figure 12 shows the \(P-V\) and \(I-V\) characteristic curves of a PV module. In Figure 12, the \(x\)-axis denotes the PV module voltage and the \(y\)-axis represents the PV module power and current. In Figure 12, the factors related to the PV output power (e.g., solar irradiation and PV surface temperature) are assumed to be constant. Figure 12 can be divided into two sections that are the left and right side of the MPP. The operating points which are denoted by “under the MPP” in Fig. 12 should move toward the right to track the MPP. This means an increase in the PV module voltage or current. On the other hand, the operating points which are represented by “above the MPP” in Figure 12 should move toward the left so that the PV module operates at the MPP. This means a decrease in the PV module voltage or current. As a result, if the differential value of the PV module output voltage or current is positive (e.g., \(dv_{IN}/dt\) or \(di_{IN}/dt\) is positive) and if the differential value of PV module output power is also positive (e.g., \(dp/dt\) is positive), a PV module operates under the MPP (e.g., \(v_{IN} or i_{IN}<V_{MPP} or I_{MPP}\)). On the other hand, if the differential value of PV module output voltage or current is positive (e.g., \(dv/dt\) or \(di/dt\) is positive) and if the differential value of PV module output power is negative (e.g., \(dp/dt\) is negative), a PV module operates above the MPP (e.g., \(v_{IN} or i_{IN}>V_{MPP} or I_{MPP}\)). In other words, the product of PV module differential power and voltage (e.g.,\(dp/dt\times dv_{IN}/dt\) or power and current (\(dp/dt\times di_{IN}/dt\)) represents that a PV module operates under the MPP, above the MPP, or at the MPP. In other words, a PV operating point is under the MPP in which \(dp/dt\times dv_{IN}/dt\) is negative, and a PV operates on the MPP when \(dp/dt\times dv_{IN}/dt\) is zero. In the proposed MI zeta converter, this can be represented as follows\(^3\),\(^5\):

\[
D_{eff1}(t) = -k\int (dp_{IN1}/dt) \times (dv_{IN1}/dt) dt , \tag{12}
\]

or

\[
D_{eff1}(t) = k\int (dp_{IN1}/dt) \times (di_{IN1}/dt) dt , \tag{13}
\]

where \(dp_{IN1}/dt\) is the differential value of the PV module output power, \(dv_{IN1}/dt\) is the differential value of the PV module output voltage, \(di_{IN1}/dt\) is the differential value of the PV module output current, \(D_{eff1}\) is the effective duty ratio of the first switch, and \(k\) is a positive proportional constant. When the converter is designed with a high frequency to have a lower physical size and high density, the input capacitor of a PV module may cause a phase shift of the PV module output current\(^5\). Therefore, this paper used (16) instead of (17) for the phase shift.

Figure 13. Photovoltaic simulation model\(^3\),\(^6\).

Figure 14. \(P-V\) and \(I-V\) curves of the simulated PV module.

### 3.4 Photovoltaic Simulation Model

As shown in Figure 13, a simple and reasonably accurate photovoltaic simulation model with current source,
resistors and diodes\textsuperscript{5} was used to simulate the proposed converter and MPP tracking of the PV module. In this PV simulation study, the solar irradiance and the PV surface temperature was assumed to be constant for the simplicity of an analysis. Therefore, the I-V and P-V curves show only one MPP (e.g., 82W) and a local MPP caused by such environmental factors does not exist in this study as shown in Figure 14. However, the PV module of this MI zeta converter can track the MPP with the considered the MPP tracking method even though there exist many local MPPs under practical conditions.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure15}
\caption{Proposed MI zeta converter power stage scheme for 48V applications.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure16}
\caption{PV module output power vs. PV module voltage.}
\end{figure}

4. Computer-based Simulation results

Figure 15 shows the proposed MI zeta converter power stage scheme for 48V applications. The power stage consisted of the PV module of which the maximum voltage and the rated power were 15.6V and 82W respectively. A 12V battery with the rated power of 380W was used as the second input source. The PV module was connected with 1500\mu F input capacitor and the common output cell included 300\mu H energy storage inductors (i.e., L\textsubscript{1} and L\textsubscript{2}), free-wheeling diode, 300\mu F middle capacitor, and 1500\mu F output capacitor. The output load was 5\Omega of which rated power was 462W and the output voltage was +48V. To verify the proposed power stage of the MI zeta converter, this study investigated computer-based simulations. Figure 16 shows the PV module output power and voltage in the transient state. As shown in Figures 16 and 17, the PV module output power and voltages were 82W and 15.6V respectively, this means that the PV module operated at the maximum power point. Therefore, the PV module can track the MPP continuously in the steady state with the RCC. Figure 17 shows the PV module output voltage and the output voltage of the MI zeta converter in the transient state. The PV output voltage was +48V, which was equal to the reference voltage.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure17}
\caption{PV module output power vs. output voltage.}
\end{figure}

5. Conclusions

This paper presented the power stage of a MI zeta converter using a PV module and a 12V battery for 48V applications. To track the MPP, the PV module used the RCC and to supply the insufficient output power for load, a 12V battery was used with the PI controller. The computer-based simulation results verified the operation mode and control method of the proposed power stage of the MI zeta converter.

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7. References

1. ZEV Program Implementation Task Force, Multi-State Zev Action Plan [Online]. 2014, May. Available from:
http://www.eurelectric.org/Download/Download.aspx?DocumentFileID=90328

2. Dobbs B, Chapman P. A multiple-input dc–dc converter topology. IEEE Power Electron Lett. 2003 Mar; 1(1):6–9.

3. Bae S, Kwasinski A. Maximum power point tracker for a multiple-input Cuk dc–dc converter. Proceedings of IEEE 31st INTELEC; 2009 Oct. p. 1–5.

4. Erickson RW, Maksimovic D. Fundamentals of Power Electronics. 2nd ed. New York: Springer; 2001.

5. Benavides ND, Esram T, Chapman PL. Ripple correlation control of a multiple-input dc–dc converter. Proceeding IEEE PESC; 2005. p. 160–4.

6. Campbell RC. A circuit-based photovoltaic array model for power system studies. 39th North American, Power Symposium NAPS ’07; 2007. p. 97-101.