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An SI-MISO Boost Converter With Deadbeat-Based Control for Electric Vehicle Applications

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Abstract—This paper presents a single-inductor multiple-input single-output (SI-MISO) boost converter with a deadbeat-based control method. The proposed deadbeat-based control has the capability to simultaneously conduct the power regulation from multiple inputs and the output voltage regulation for the SI-MISO boost converter. The advantages of the proposed method are less component count, lower system cost, compatibility for arbitrary number of inputs, fast response, and simplicity for implementation. Hence, the SI-MISO boost converter is a promising interface for the regulation of multiple energy sources as a standalone power system, which can be utilized in electric vehicle applications. To verify the performance of the proposed deadbeat-based control method, a laboratorial prototype of the SI-MISO boost converter is built. The steady-state and dynamic operations are investigated based on the prototype. The experimental results demonstrate that input power and output voltage of the SI-MISO boost converter can be effectively regulated by the proposed control method. The comprehensive comparison with the existing methods is conducted to further illustrate the advantages of the proposed deadbeat-based method.

Index Terms—Single-inductor, multiple-input single-output, boost converter, deadbeat control, current observer.

I. INTRODUCTION

VARIOUS research works have been conducted on the multiple-input converters because of their advantages over the conventional single-input converters [1]–[3], i.e., the multiple-input converters can integrate different energy sources as a standalone power system with less components, smaller system size and lower cost. In view of these merits, the adoption of the multiple-input single-output (MISO) converters in electric vehicles (EVs)/hybrid electric vehicles (HEVs) applications has been widely studied in recent years [3]–[5].

Recently, different types of MISO converters have been studied in [6]–[15]. In [6], a zero-voltage-switching technique has been proposed for the dual-input boost converter where the two inputs are serially connected. By regulating an auxiliary circuit

with a small inductor in the discontinuous conduction mode, all switches can be turned on/off softly. A three-port triple-half-bridge bidirectional DC-DC converter in a fuel cell vehicle is presented in [7]. The proposed converter has two current-fed ports for low voltage battery and ultracapacitor. The authors have developed an asymmetrical duty cycle control for the converter, which can obtain the zero-voltage switching with a wide variation range, lower converter peak current, lower root-mean-square (RMS) current and lower RMS loss. In [8], the authors have presented a bidirectional non-isolated multi-input DC-DC converter for the EVs with hybrid energy storage systems, including the battery and ultracapacitor. The multi-input converter is achieved by connecting the input side of multiple cascaded buck-boost converters in parallel and sharing the common output capacitor. Hence, each input source of the proposed converter requires the corresponding separate inductor and switches. A three-input step-up converter has been proposed for the hybrid EVs applications in [9]. The proposed converter incorporates the photovoltaic (PV), fuel cell and battery. The fuel cell acts as the main power supply, battery is the energy storage element, and PV operates in maximum power point tracking mode for charging the battery. To integrate multiple plug-in EVs in the parking lot, a multi-port DC-DC converter has been developed in [10] with two operation modes, vehicle-to-parking mode and parking-to-vehicle mode. The proposed converter enables the response to various power transactions in the same parking lot with less component count and simple topology. A modular MISO boost converter has been proposed in [11]. The module of switching leg and an inductor is assigned for each energy source to achieve the multiple-input topology. As pointed out in [11], the MISO converters in [6]–[11] are achieved by assigning each energy source with an inductor and corresponding module with switches. Hence, when the number of the inputs increases, the component count and system size become large again. To further simplify the topology of MISO converter, the single-inductor MISO (SI-MISO) converters have been developed in [12]–[15].

A nonisolated multi-input multi-output DC-DC boost converter with a single inductor has been proposed for EVs in [12], where the load power demand can be dynamically distributed among different energy sources. The control method for the proposed converter in different operation modes has been designed. In [13], the authors have designed a modified time-sharing switching technique for the single-inductor MISO (SI-MISO) buck-boost converter. The common duty ratio concept is adopted as the unique control variable regardless of the

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number of input legs. In [14], the authors have presented a subproportion control method for the SI-MISO buck converter, and the subproportion term is utilized as a certain proportion of the duty cycle for voltage regulation. The proposed method is able to achieve the seamless and smooth mode transition. In summary, the corresponding methods in [12]–[14] are feasible for the extension of more inputs. However, these methods are all based on small-signal models, which makes the regulation performance easily affected by system operating points. A nonlinear power sharing control strategy has been developed for the dual-input buck-boost converter with single-inductor topology in [15]. Based on the Lyapunov theory, the proposed strategy is capable to regulate the converter regardless of the operating points. The disadvantage of the proposed method in [15] is that it cannot be extended to arbitrary number of inputs.

To solve the aforementioned problems of the previous works, a deadbeat-based control method is developed for SI-MISO boost converter for EV/HEV applications. The deadbeat control strategy has been widely adopted for power electronics devices [16]–[21], including boost converters [17], inverters for wind energy [18], grid-connected converters [19], [20], and the multiple-port converter [21]. The deadbeat strategy has the capability to eliminate the state variable errors in a finite number of steps, which yields fast dynamic response, simplicity and high control accuracy [19]. Considering the dramatic variations of multiple input voltage magnitudes, the aforementioned features make the deadbeat strategy a suitable choice for the regulation of SI-MISO converters.

Based on the previous discussion, a deadbeat-based control method is designed for the SI-MISO boost converter to achieve the input current regulation and output voltage regulation simultaneously. Hence, the SI-MISO boost converter can be utilized effectively for regulating multiple energy sources in EV/HEV applications.

By using the proposed deadbeat based method, the following advantages can be obtained for the SI-MISO boost converter:

- i) Less component count and lower system cost
- ii) Compatibility for arbitrary number of inputs.
- iii) Fast response to disturbance.
- iv) Simplicity for implementation

The advantages (i) and (ii) are inherited from the single-inductor topology, while the advantages (iii) and (iv) are based on the features of deadbeat control.

The rest of paper is organized as follows: In Section II, the topology of the SI-MISO boost converter is presented. Moreover, the proposed deadbeat-based control method for the SI-MISO boost converter is discussed, including the input current regulation and output voltage regulation. Section III and Section IV present the simulation and experimental results. Finally, Section V concludes the paper.

II. PROPOSED METHOD FOR SI-MISO BOOST CONVERTER

A. Architecture of SI-MISO Boost Converter

The topology of SI-MISO boost converter is presented in Fig. 1. It can be seen that there are n input energy sources ($v_{in,1}, v_{in,2}, \dots, v_{in,i}, \dots, v_{in,n}$), and the corresponding input current

Fig. 1. The SI-MISO boost converter.

and input filter capacitor are $(i_{in,1}, i_{in,2}, \dots, i_{in,i}, \dots, i_{in,n})$ and $(C_{in,1}, C_{in,2}, \dots, C_{in,i}, \dots, C_{in,n})$. The input switches to select the input voltage sources are $(S_1, S_2, \dots, S_i, \dots, S_n)$. The switch S_i consists of a MOSFET switch and a diode, which forms a forward-conducting bidirectional-blocking (FCBB) structure to avoid uncertain power among the input voltage sources [5]. When two or more than two switches are turned on simultaneously, only the energy source with the highest terminal voltage value will be connected to the shared inductor, and the other energy sources are disconnected because the corresponding switches with FCBB structure are reverse biased. Consequently, there is no power flow among these energy sources. In addition, the switches are regulated by the control signals $(q_1, q_2, \dots, q_j, \dots, q_n)$ to achieve the regulation of input power. The shared inductor is L and the corresponding current is i_L . v_{in} is the input voltage between the left terminal of inductor and the ground. D denotes the freewheeling diode, and S denotes the MOSFET switch controlled by the signal q . The corresponding voltage, current and filter capacitor of the load R are v_{out} , i_{out} and C respectively.

B. Deadbeat-Based Control Method

1) *Input Current Regulation:* The illustration of input current regulation is shown in Fig. 2. A moving average filter (MAF) [22] is adopted for the average current calculation for the input current $(i_{in,1}, i_{in,2}, \dots, i_{in,i}, \dots, i_{in,n-1})$. The input current regulation is actually achieved by regulating the average input current of $i_{in,i}$ to follow the corresponding current reference $i_{Ref,i}$. Moreover, according to [22], the MAF can be implemented as a low pass filter with a time window of T_{MAF} , and T_{MAF} can be the integral times of t_s , where t_s is sampling time step of the proposed method.

After the process of MAF, the average current and the corresponding current references $(i_{Ref,1}, i_{Ref,2}, \dots, i_{Ref,i}, \dots, i_{Ref,n-1})$ are sent to the proportion-integration (PI) controllers to generate the pulse-width-modulation (PWM) indices $(\delta_1, \delta_2, \dots, \delta_i, \dots, \delta_{n-1})$. It is noteworthy that the last energy source is utilized to compensate the deficient power, which is not fully supplied by the previous $(n-1)$ energy sources.

Fig. 2. Illustration of input current regulation.

Hence, the PWM index for the n -th energy source is automatically obtained as shown in (1), when the PWM indices of the previous $(n-1)$ energy sources are determined.

$$\delta_n = 1 - \sum_{k=1}^{n-1} \delta_k \quad (1)$$

As discussed previously, when multiple input switches are turned on simultaneously, only the energy source with the highest voltage will be conducted and other energy sources are blocked. This means directly using the PWM indices cannot achieve the successful input current regulation. In other words, the input energy sources should strictly be conducted in sequence and exclusively. To achieve this goal, the accumulated modulation index δ'_i ($i = 1, 2, \dots, n$) is defined in (2) as follows:

$$\delta'_i = \sum_{k=1}^i \delta_k, \quad 1 \leq i \leq n \quad (2)$$

The control signals $(q_1, q'_2, \dots, q'_i, \dots, q'_{n-1}, q'_n)$ can be generated with the accumulated modulation index $(\delta'_1, \delta'_2, \dots, \delta'_i, \dots, \delta'_{n-1}, \delta'_n)$ using the synchronized PWM generator, with a period of t_{PS} , as shown in Fig. 2. The applicable control signals $(q_2, \dots, q_j, \dots, q_n)$ are obtained using the principle expressed in (3).

$$\begin{cases} q_1 = q'_1 \\ q_i = q'_i \text{ XOR } q'_{i-1}, \quad 2 \leq i \leq n \end{cases} \quad (3)$$

In Fig. 2, XOR logical gates are adopted in hardware implementation to achieve the principle in (3). With the control signals $(q_1, q_2, \dots, q_n, \dots, q_n)$, the input current regulation, i.e., input power regulation, can be accomplished. In addition, the selection of input energy sources can help to determine the value of v_{in} , which is given as follows:

$$v_{in} = \sum_{i=1}^n q_i \cdot v_{in,i} \quad (4)$$

The value of v_{in} can assist the output voltage regulation, which will be discussed in detail in the next subsection.

2) Output Voltage Regulation:

a) *Observation of load current:* To implement the deadbeat-based control method for output voltage regulation of the proposed SI-MISO boost converter, information of load current i_{out} is required. However, the measurement of load current via Hall Effect sensor inevitably increases the system cost. To eliminate the load current sensor, this paper proposes a simple load current observer on the basis of the converter model. Mathematically, the proposed SI-MISO boost converter in Fig. 1 can be described by (5) and (6), where d_{db} represents the duty ratio for the control signal q of switch S .

$$L \frac{di_L}{dt} = v_{in} - v_{out} (1 - d_{db}) \quad (5)$$

$$C \frac{dv_{out}}{dt} = i_L (1 - d_{db}) - i_{out} \quad (6)$$

From (6), it is seen that the load current i_{out} can be observed with the knowledge of capacitor voltage v_{out} , inductor current i_L and duty ratio d_{db} . Due to the presence of the derivative term in (5) (i.e., dv_{out}/dt), the observation of i_{out} will be deteriorated by high frequency noises. To solve this problem, a first-order low pass filter is employed as shown in (7), where ω_c is the angular cut-off frequency of the low pass filter and $\hat{i}_{out}$ represents the observed load current.

$$\hat{i}_{out}(s) = [i_L(s) (1 - d_{db}(s)) - sCv_{out}(s)] \times \frac{\omega_c}{s + \omega_c} \quad (7)$$

By applying the bilinear transformation, a discretized observation equation can be derived as (8), where t_s denotes the sampling period and k denotes the k -th sampling instant.

$$\hat{i}_{out}(k) = \frac{2 - \omega_c t_s}{2 + \omega_c t_s} \hat{i}_{out}(k-1) + \frac{\omega_c t_s}{2 + \omega_c t_s} [x(k) + x(k-1)] \quad (8)$$

where $x(k)$ is given as

$$x(k) = i_L(k) [1 - d_{db}(k)] - C \frac{v_{out}(k) - v_{out}(k-1)}{t_s}$$

It is noted that the cut-off frequency is generally selected to be much lower than the Nyquist frequency to reject high frequency

Fig. 3. Illustration of output current observer.

noises, which are given as follows:

$$f_c = \frac{\omega_c}{2\pi} \leq \frac{1}{10} \times \frac{1}{2t_s} \quad (9)$$

In concern of the comparatively slow dynamics of load current, a lower limit of a few hundreds Hz is sufficient for f_c . Moreover, to avoid the delayed estimation of load current when there is a load step change, which further leads to worse dynamic performance, the value of f_c cannot be selected too small. In this paper, $f_c = 400$ Hz is used. Based the discussion in this subsection, an observer of the load current i_{out} is designed for the output voltage regulation as shown in Fig. 3. From Fig. 3, it can be seen that the information of i_L , v_{out} and d_{db} are required, and the generation of d_{db} will be discussed in detail in the following section.

b) Inductor current deadbeat control: In view of its advantages of fast dynamic response, simplicity and reasonably good accuracy, deadbeat control strategy is employed to regulate the inductor current. To implement deadbeat current control, the reference inductor current $i_{L,Ref}$ has to be worked out in the first place. In this paper, $i_{L,Ref}$ is determined with respect to the dynamic energy balance and voltage regulation error.

In nature, the LC components only store and transfer energy instead of consuming it. Thus, in the case of the SI-MISO boost converter in Fig. 1, the average current flowing through the inductor L (or the average voltage drop across the capacitor C) is generally used to support the load. Meanwhile, the inductor and capacitor are charged and discharged only by ripple current in each switching cycle. In other words, the average inductor current is equivalent to the average load current. With a sufficiently high sampling frequency, the average inductor current and the average load current can be approximated by i_L and i_{out} , respectively. Consequently, $g i_{out}(k) = i_L(k)$ is derived, where g is the ratio of average inductor current over the average load current. Moreover, g can be estimated as the ratio of output voltage v_{out} over input voltage v_{in} . Noticeably, the variation of inductive and capacitive energy storage can be described by (10) due to the fact that changes of energy stored in capacitor are solely delivered by inductor.

$$\frac{1}{2} L i_L^2(k+1) - \frac{1}{2} L i_L^2(k) = \frac{1}{2} C v_{out}^2(k+1) - \frac{1}{2} C v_{out}^2(k) \quad (10)$$

From the perspective of control, $i_L(k+1)$ and $v_{out}(k+1)$ indicate the control targets in the next sampling instant. Therefore, they can be expressed as $i_{L,Ref} = i_L(k+1)$ and $v_{Ref} = v_{out}(k+1)$ respectively. Considering the relation $g i_{out}(k) = i_L(k)$, (10) can be rewritten as (11).

$$\frac{1}{2} L i_{L,Ref}^2 - \frac{1}{2} L g^2 i_{out}^2(k) = \frac{1}{2} C v_{Ref}^2 - \frac{1}{2} C v_{out}^2(k) \quad (11)$$

It implies that the reference inductor current $i_{L,Ref}$ can be determined with the knowledge of the estimated load current $\hat{i}_{out}$, the output voltage reference v_{Ref} and the measured output voltage $v_{out}(k)$ as shown in (12). (12) is derived from (11) on the basis of energy balance with lossless LC components and power semiconductors.

$$i_{L,Ref} = \sqrt{\frac{C}{L} [v_{Ref}^2 - v_{out}^2(k)] + g^2 \hat{i}_{out}^2(k)} \quad (12)$$

In practical applications, there are always energy losses caused by these devices, which can result in small deviations of the determined reference current from its correct value. To compensate for this effect, an integral term of output voltage regulation error is introduced as shown in (13).

$$i_{L,Ref} = \sqrt{\frac{C}{L} [v_{Ref}^2 - v_{out}^2(k)] + g^2 \hat{i}_{out}^2(k)} + \sum K_i v_{err}(k) \quad (13)$$

where $v_{err}(k)$ is given as

$$v_{err}(k) = v_{Ref} - v_{out}(k)$$

The addition of such a term contributes to the minor adjustment of reference current to ensure its convergence to the correct value in steady-states. To this end, the integral gain K_i is generally chosen to be a small positive constant. Generally, there is a saturation current I_{sat} for the practical inductor, and it determines the maximum tolerable current through the inductor. An upper limit for $i_{L,Ref}$ is adopted in this paper, and $i_{L,Ref}$ can be expressed as follows:

$$i_{L,Ref} = \max \left\{ \sqrt{\frac{C}{L} [v_{Ref}^2 - v_{out}^2(k)] + g^2 \hat{i}_{out}^2(k)} + \sum K_i v_{err}(k), I_{sat} \right\} \quad (14)$$

With the presence of reference inductor current, deadbeat current control can be implemented based on the discretization of (5) as shown in (14).

$$d_{db} = \frac{t_s [v_{out}(k) - v_{in}(k)] - L [i_{L,Ref} - i_L(k)]}{v_{out}(k) t_s} \quad (15)$$

However, due to the current derivative term in (5), the generation of d_{db} from (14) is sensitive to measurement noises. In order to eliminate the influence of measurement noises, a non-ideal generalized integrator is utilized as shown in (15), according to the analysis in [23]. This integrator will replace the purely derivative term in s domain with highly accurate approximation and a slight phase error.

$$\frac{1}{s} i_L(s) \approx \frac{\omega_1^2}{s^2 + \omega_2 s + \omega_1^2} i_L(s) \quad (16)$$

In (15), ω_1 and ω_2 denotes the frequency with the largest but finite gain, and the cut-off frequency that helps attenuate the peak gain in frequency response, respectively. In addition, ω_1 is selected as $2\pi \times 20$ k rad/s to provide a broad derivative range, and ω_2 is selected as $2\pi \times 10$ k rad/s in this paper. With (14) and (15), the duty cycle d_{db} can be calculated online without

Fig. 4. Illustration of deadbeat control.

Fig. 5. Control scheme of the proposed deadbeat-based method.

disturbed by the measurement noises, and it will be compared with a saw waveform with the period of t_s to generate the control signal q , so that the output voltage v_{out} can be regulated at the target value, as shown in Fig. 4.

3) *Control Scheme*: The control scheme of the proposed deadbeat-based control method is presented in Fig. 5. It can be seen that the control signals ($q_2, \dots, q_j, \dots, q_n$) for selecting the input energy sources and input current regulation are generated following the equations (1)–(4). The first step is to generate the PWM indices, which are utilized to obtain the accumulated PWM indices. Consequently, with the XOR logical gates, the selection signals ($q_2, \dots, q_j, \dots, q_n$) are obtained and these signals guarantee the sequential conduction of the input energy sources. Hence, the value of v_{in} varies following the values of ($v_{in,1}, v_{in,2}, \dots, v_{in,i}, \dots, v_{in,n}$), and slopes of i_L change accordingly. Moreover, the output voltage regulation signal q is adjusted based on the data of ($v_{in}, i_L, v_{out}, v_{Ref}$). From Fig. 5, it can be seen that q has a fixed period of t_s and dynamic duty cycles to respond to varying input voltage and maintain the output voltage at targeted value.

III. COMPONENTS DESIGN

The selection of the inductor and capacitors for the proposed SI-MISO boost converter with deadbeat-based method is according to the design guideline from [24], and the corresponding equation are shown below.

$$L = \frac{v_{in,i}(v_{out} - v_{in,i})}{v_{out} f_s \Delta i_L} \quad (17)$$

TABLE I
PARAMETERS OF SI-MISO BOOST CONVERTER

Symbol	$v_{in,1}$	$v_{in,2}$	$v_{in,3}$	C_1, C_2, C_3	C
Value	20V	25V	25, 30V	470 μ F	470 μ F
Symbol	L	R	v_{out}	t_s	t_{PS}
Value	0.5mH	29~58 Ω	50, 55V	40 μ s	80 μ s

$$C = \frac{i_{out,max} d_{db,max}}{f_s \Delta v_{out}} \quad (18)$$

where f_s is the switching frequency of signal q , Δi_L is the ripple of inductor current i_L and Δv_{out} is the output voltage ripple. For Δi_L , it can be estimated in (19) according to [24].

$$\Delta i_L = \lambda \frac{i_{out,max} v_{out}}{v_{in,i}} \quad (19)$$

where λ is a coefficient, which can be set as 0.3 as recommended by [24].

IV. SENSITIVITY INDEX

In order to quantify the performance of the proposed deadbeat-based method for SI-MISO boost, the sensitivity indices are defined according to [25], [26]. The sensitivity to the load step change, i.e., load regulation, is given as follows:

$$S_{i_{out}}^{v_{out}} = \frac{|\Delta v_{out}|}{|\Delta i_{out}|} \times \frac{i_{out}}{v_{out}} \quad (20)$$

Similarly, the sensitivity indices to the input current step change, i.e., input current regulation, and input voltage step change, i.e., line regulation, are expressed as follows:

$$S_{i_{in,i}}^{v_{out}} = \frac{|\Delta v_{out}|}{|\Delta i_{in,i}|} \times \frac{i_{in,i}}{v_{out}} \quad (21)$$

$$S_{v_{in,i}}^{v_{out}} = \frac{|\Delta v_{out}|}{|\Delta v_{in,i}|} \times \frac{v_{in,i}}{v_{out}} \quad (22)$$

V. SIMULATION RESULTS

The parameters of the SI-MISO boost converter and the deadbeat-based method are presented in Table I. The load varies from 29 Ω to 58 Ω . The two output voltage reference values are set as 50 V and 55 V respectively. The values of t_s and t_{PS} are set as 40 μ s and 80 μ s respectively. By substituting the data in Table I into (16), the value of the shared inductor can be estimated as 0.49 mH. Consequently, L is selected as 0.5 mH which is a standard value and available in the laboratory. Similarly, the value of the output capacitor can be calculated as 453 μ F by setting $i_{out,max}$, $d_{db,max}$ and Δv_{out} as 1.7 A, 1 and 0.15 V respectively. According to the standard capacitor values, the output capacitor is selected as 470 μ F. It is noted that the input capacitors are selected same to the output capacitor.

To study the performance of the current observation and the inductor current reference calculation, the simulation has been conducted in Matlab/Simulink and the simulation waveforms of ($i_{out}, \hat{i}_{out}$), ($i_L, i_{L,Ref}$), d_{db} and (v_{out}, v_{Ref}) are presented in Fig. 6.

The initial conditions are $v_{in,1} = 20$ V, $v_{in,2} = 25$ V, $v_{in,3} = 25$ V and $v_{Ref} = 50$ V. A step change in load has been set at $t =$

Fig. 6. Simulation waveforms of the proposed deadbeat-based method including $(i_{out}, \hat{i}_{out})$, $(i_L, \hat{i}_{L,Ref})$, d_{db} and (v_{out}, v_{Ref}) .

5 ms by setting the value of R from 58Ω to 29Ω . Hence, the waveform of i_{out} has the increment from 0.85 A to 1.7 A and the waveform of i_L is increased accordingly. In addition, the output voltage v_{out} has a sudden drop of 0.38 V. The observed load current $\hat{i}_{out}$ and the calculated inductor current reference $i_{L,Ref}$ are also presented in Fig. 6. It can be seen that an upper limit of 5.0 A is set for $i_{L,Ref}$ to avoid that the inductor current exceeds its saturation current. Based on the comparison between i_{out} and $\hat{i}_{out}$, the effectiveness is confirmed, and i_L tracks $i_{L,Ref}$ tightly. Accordingly, the duty cycle d_{db} can be dynamically calculated as shown in Fig. 6, so that the output voltage can be maintained at the reference value.

VI. EXPERIMENTAL RESULTS

The scaled-down hardware setup has been built for experimental verification as shown in Fig. 7, and the zoomed-in photo of the three-input SI-MISO boost converter prototype is presented. The components, including the MOSFET, diode, voltage/current transducer and controller, adopted in the prototype are listed in Table II. The deadbeat-based control method is implemented in the dSpace MicroLabBox controller, which can be seen in Fig. 7. The MicroLabBox is an all-in-one controller with the ADC for sampling data, DAC for outputting data, and Digital I/O for outputting PWM. It is noted that the host PC in Fig. 7 is for operating the software associated with MicroLabBox rather than the deadbeat-based method, and the proposed method is operated in the digital signal process inside MicroLabBox after compilation.

It is noteworthy that the values of $v_{in,1}$ (20 V), $v_{in,2}$ (25 V) and $v_{in,3}$ (30, 25 V) are different. It results in the variation of v_{in}

Fig. 7. The hardware setup of the SI-MISO boost converter.

TABLE II
COMPONENTS IN HARDWARE PROTOTYPE

Component	Device
MOSFET	IXFN64N60P
Diode	IXYS DSEI2X61-04C
Voltage Transducer	LEM LV 25-P
Current Transducer	LEM LA 55-P
Controller	dSpace MicroLabBox

Fig. 8. Experimental results of steady-state waveforms.

when $v_{in,1}$, $v_{in,2}$ and $v_{in,3}$ connect to the inductor sequentially via S_1 , S_2 and S_3 . The variation of v_{in} can imitate the fluctuation in the voltage of the RESs in practical situations.

A. Steady-State Experimental Results

This section presents the steady-state experimental results including the steady-state waveforms and control signals, as shown in Figs. 8 and 9.

Fig. 9. Experimental results of control signals.

1) *Steady-State Waveforms*: The steady-state waveforms of v_{in} , v_{out} , i_L , i_{out} , $i_{in,1}$, $i_{in,2}$ and $i_{in,3}$ are shown in Fig. 8. The references are $v_{Ref} = 50$ V, $i_{ref,1} = 1.0$ A and $i_{ref,2} = 1.0$ A respectively. It can be observed from Fig. 8 that v_{in} varies due to the different values of $v_{in,1}$, $v_{in,2}$ and $v_{in,3}$. Because of the voltage drop incurred by the switches S_1 , S_2 and S_3 , the values of v_{in} is not exactly equal to 20 V, 25 V or 30 V. In addition, it can be observed that $v_{out} = 50$ V to track v_{Ref} tightly. Hence, i_{out} is 1.7 A with the load $R = 29 \Omega$. The experimental results demonstrates that the proposed deadbeat-based control method is a promising control strategy for the SI-MISO boost converter to integrate the RESs with varying voltages as a standalone HRES or to connect to microgrids. The waveforms of $i_{in,1}$, $i_{in,2}$ and $i_{in,3}$ are obtained via the digital-to-analog of the dSpace MicroLabBox after the process of MAF. Therefore, the $i_{in,1}$, $i_{in,2}$ and $i_{in,3}$ are represented by the voltage signals and the ratio of current and the corresponding voltage signal is one. It can be seen that $i_{in,1}$ and $i_{in,2}$ are regulated to follow the preset references as 1.0 A, so that $i_{in,3}$ is regulated as 2.8 A to compensate the deficient load demand.

2) *Control Signal Waveforms*: The waveforms of control signals q_1 , q_2 , q_3 and q are presented in Fig. 9. Moreover, the related waveforms of v_{in} and i_L are also shown in Fig. 9 to explain the operation of the proposed method. It can be seen that the experimental waveforms in Fig. 8 follows the theoretical analysis in Fig. 4. In addition, it is noteworthy that $v_{in,1}$, $v_{in,2}$ and $v_{in,3}$ are not conducted exactly following the pattern in Fig. 4 because of δ_1 , δ_2 and δ_3 can be 0 occasionally.

In Fig. 8, q_1 and q_2 dynamically control $i_{in,1}$ and $i_{in,2}$ based on the corresponding current references, and q_3 is adjusted to regulate $v_{in,3}$ for the compensation to deficient load demand. Consequently, v_{in} varies following the control signals q_1 , q_2 and q_3 . Accordingly, the slope of i_L changes based on the values of v_{in} as shown in Fig. 9.

B. Dynamic Experimental Results

The dynamic experimental results are presented in Figs. 10–13, including the load regulation, input current regulation, line regulation and output voltage regulation.

Fig. 10. Experimental results of load regulation.

Fig. 11. Experimental results of input current regulation.

Fig. 12. Experimental results of input channel number step change.

Fig. 13. Experimental results of line regulation.

1) **Load Regulation:** The load regulation experimental results of the proposed deadbeat-based control method for SI-MISO boost converter are shown in Fig. 10. At beginning, $v_{in,1}$, $v_{in,2}$, $v_{in,3}$, v_{Ref} , $i_{Ref,1}$ and $i_{Ref,2}$ are set as 20 V, 25 V, 30 V, 50 V, 1.0 A and 1.0 A respectively. The step changes in load are achieved by changing the value of R from 29 Ω to 58 Ω , and then back to 29 Ω again. Correspondingly, i_{out} is decreased from 1.7 A to 0.85 A, and then back to 1.7 A. With the control signal q generated by the deadbeat-based control method, the output voltage v_{out} is maintained at 50 V against the changes in load. It also can be seen that the output voltage has Δv_{out} of 1.6 V and 1.2 V due to the load step changes. From Fig. 10, the values of $i_{in,1}$ and $i_{in,2}$ are regulated to track the current reference $i_{Ref,1} = 1.0$ A and $i_{Ref,2} = 1.0$ A tightly. To compensate the deficient power accordingly, $i_{in,3}$ has an decrement from 2.8 A to 0.8 A firstly, and then back to 2.8 A. The load regulation is successfully achieved by the proposed deadbeat-based control method.

2) **Input Current Regulation:** Fig. 11 presents the input current regulation experimental results of the proposed deadbeat-based control method for SI-MISO boost converter. At beginning, v_{Ref} , $i_{Ref,1}$ and $i_{Ref,2}$ are set as 50 V, 1.0 A and 2.0 A respectively. There are two step changes set in $i_{in,1}$ from 1.0 A to 2.0 A, and in $i_{in,2}$ from 2.0 A to 3.0 A respectively. To maintain the output voltage and meet the load demand against the fluctuations in $i_{in,1}$ and $i_{in,2}$, $i_{in,3}$ is decreased from 2.0 A to 1.4 A, then it is decreased to 0.8 A. It can be observed from Fig. 10 that the output voltage v_{out} is always regulated at $v_{Ref} = 50$ V, and there is a voltage variation of 1.4 V and 1.0 V due to the step change of $i_{in,1}$ and $i_{in,2}$. i_{out} is maintained at 1.7 A accordingly. Hence, the proposed deadbeat-based control method is capable to handle the step change in input current references and maintain the output voltage.

3) **Input Channel Number Step Change:** In practical situation, the absence of input energy source occasionally happens. The proposed converter are expected to work when there is an absence of input energy source. Hence, the step change in input

channel number study has been conducted and the experimental results are presented in Fig. 12. The initial setting are $v_{in,1} = 20$ V, $v_{in,2} = 25$ V, $v_{in,3} = 30$ V, $v_{Ref} = 50$ V, $i_{Ref,1} = 1.0$ A, $i_{Ref,2} = 1.0$ A and $R = 50$ Ω respectively.

To change the available input channel number, a step change has been set on $i_{Ref,1}$ from 1.0 A to 0 A, so that the first input energy source is absent for delivering power. Because $i_{Ref,2}$ is fixed as 1.0 A, $i_{in,3}$ is increased from 0.8 A to 1.6 A to compensate the unsatisfied power due to the absence of the first input energy source. It can be the output voltage v_{out} is maintained at the target value of 50 V before and after the step change of input channel number. Therefore, the proposed deadbeat method can solve the input channel number step change very well, and it is feasible for practical implementation of the proposed converter.

4) **Line Regulation:** The potential application of the SI-MISO boost converter with the proposed deadbeat-based control method is to accomplish the integration of multiple RESs. In practical situations, the voltage of RESs always varies due to the changes in ambient conditions. Therefore, the line regulation is conducted to verify the performance of the proposed deadbeat-based control method to respond to the extreme step change in input voltage values.

The experimental results of line regulation are shown in Fig. 13. The initial conditions are $v_{in,1} = 20$ V, $v_{in,2} = 25$ V, $v_{in,3} = 30$ V, $v_{Ref} = 50$ V, $i_{Ref,1} = 1.0$ A and $i_{Ref,2} = 2.0$ A. A step change is set at $v_{in,3}$ from 30 V to 25 V, so that it can be observed from Fig. 13 that the envelope waveforms of v_{in} has a sudden drop. Correspondingly, $i_{in,3}$ is increased from 2.0 A to 2.6 A to provide the same power compensation in the condition of $v_{in,3} = 30$ V. With the deadbeat-based control method, v_{out} , $i_{in,1}$ and $i_{in,3}$ are controlled at the corresponding references against the step change in $v_{in,3}$. Moreover, the output voltage has a variation of 1.2 V due to the step change of $v_{in,3}$. Therefore, the proposed method has the capability to control the SI-MISO boost converter against the variations in input voltage values.

C. Comparison With Other Works

In order to further illustrate the performance of the proposed method for SI-MISO boost converter, the comparison with other works is conducted in this section.

1) **Comparison With MPC-Based Method:** The model predictive control (MPC) is another advanced method [25], [26]. The experiments using MPC-based method for SI-MISO boost converter are conducted, including load regulation, input current regulation and line regulation. The experimental results are shown in Figs. 14–16.

The experimental results of load regulation using MPC-based method are presented in Fig. 14. The step changes in load are implemented, which are similar to those in Fig. 10. It can be seen that the output voltage is maintained at the target value 50 V with Δv_{out} of 1.5 V. Fig. 15 presents the experimental results of input current regulation using MPC-based method. The changes in input current are same to those in Fig. 11. It can be observed that the output voltage is barely influenced, since the value of Δv_{out} is 1.3 V. Similarly, the input voltage step is implemented in $v_{in,3}$ from 30 V to 25 V, and the results are shown in Fig. 16. The

Fig. 14. Experimental results of load regulation using MPC-based method.

Fig. 15. Experimental results of input current regulation using MPC-based method.

output voltage is affected with the variation Δv_{out} of 1.0 V. It can be concluded that the MPC-based method can performance slightly better output voltage regulation than deadbeat-based method, since the values of Δv_{out} in Figs. 14–16 are slightly less than those in Fig. 10, Fig. 11 and Fig. 13.

2) *Comparison With Existing Methods:* The comparison results between the proposed method and the existing methods are tabulated in Table III. With the definitions in (20)–(22), the corresponding sensitivity indices of [13], MPC-based method and the proposed deadbeat-based method are listed in Table III. Based on the values of sensitivity indices, it can be seen that the proposed deadbeat-based method has the similar performance to MPC-based method, but much better than the PI-based method in [13]. Hence, the advanced model-based control strategies, i.e., MPC and deadbeat, are more suitable to control the SI-MISO boost converter compared with the conventional PI-based method.

Fig. 16. Experimental results of line regulation using MPC-based method.

TABLE III
COMPARISON WITH EXISTING METHODS FOR SI-MISO BOOST CONVERTER

References	[13]	MPC-based Method	This Work
Control Strategy	PI	MPC	Deadbeat
$S_{i_{out}}^{V_{out}}$	1.0, 2.0	0.03	0.033, 0.025
$S_{i_{in,i}}^{V_{out}}$	-	0.026	0.028, 0.02
$S_{V_{in,i}}^{V_{out}}$	0.67, 1.0	0.12	0.144
Switching Frequency	Fixed	Varying	Fixed
Complexity	Low	Very High	Medium
Performance	Low	High	High

However, due to varying switching frequency of the MPC-based method, the inductor current varies dramatically compared to that of the deadbeat-based method, and it further leads to apparently increased noises on the output current as shown in Figs. 14–16. The varying switching frequency also makes it difficult to design the values of inductor and capacitor. Another disadvantage of MPC-based method is the very high requirement of computational capability [25], [26], which is much harder to be implemented on microcontrollers than deadbeat-based method.

In summary, the proposed deadbeat-based method is the promising control strategy to regulation SI-MISO boost converter, with better performance than PI-based methods, and implementation simplicity over MPC-based method.

VII. CONCLUSION

In this paper, a deadbeat-based control method is proposed for SI-MISO boost converter for EVs application with the advantages of less component count, lower system cost, compatibility for arbitrary inputs, and fast response and simplicity for implementation. The input current from multiple energy sources can be effectively regulated. Moreover, current observers are designed to further bring down the system cost. Excellent steady state and transient performances of the proposed method are

observed in the experiments carried out on a laboratory hardware prototype. Additionally, the comparison with existing methods is conducted to illustrate the advantages of the proposed deadbeat-based method.

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