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A MPC-based Method for Single-Inductor Multiple-Input Single-Output Boost Converter

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Abstract—This paper presents a MPC-based method to regulate the single-inductor multiple-input single-output (SI-MISO) boost converter. The SI-MISO boost converter is a promising device to integrate different types of renewable energy sources. The proposed method is able to allocate power among the inputs and control the output voltage of the SI-MISO boost converter simultaneously. A laboratorial SI-MISO boost converter prototype is built to validate the performance of the proposed method, and the experimental study cases including steady-state operation and dynamic operation are conducted.

Index Terms—Power sharing, model predictive control, single-inductor, multiple-input single-output.

I. INTRODUCTION

The DC microgrid merges various renewable energy sources (RESs), energy storage systems (ESSs) and loads [1], where the power converters are imperative to connect RESs and ESSs into the DC microgrid. In [2], a single-inductor multiple-input single-output (SI-MISO) buck-boost converter is presented for merging different energy sources with regulated output voltage. In [3], a MISO boost converter is developed to increase energy harvest from the series-connected PV modules during instances of partial shading. The proposed MISO boost converter is achieved by connecting two boost converters in parallel and sharing the same output filtering capacitor.

To further reduce component count and topological complexity, the power converters with single-inductor topology have been proposed. In [4], the single-inductor multiple-input buck converter has been adopted for a 1kW fuel cell/battery hybrid power supply system. The SI-MISO boost converter is reported in [5] for low-power energy harvesting. The authors have proposed the time-multiplexed operation for maximum power extraction from energy sources. However, the converter output voltage is regulated by directly connecting to a battery, so that the output voltage varies when the battery is charged. Hence it is not suitable for applying SI-MISO boost converter in DC microgrid, which requires a stable bus voltage.

The model predictive control (MPC) method has been adopted for power converters [6], including the boost and buck converters [7], [8], and single-inductor multiple-port DC-DC converters [9]–[11]. In this paper, a MPC-based method is developed for SI-MISO boost converter to allocate power among the inputs and control the output voltage simultaneously for integration of RESs with DC microgrid. The features of the proposed method are emphasized as

follows: a) compatibility for arbitrary number of inputs, b) stable output voltage regulation.

II. MPC-BASED METHOD FOR SI-MISO BOOST CONVERTER

In this section, the architecture of the SI-MISO boost converter, the operational principle and control scheme of the proposed MPC-based method will be discussed. Additionally, the state-space model and proposed MPC-based method will be specified.

A. SI-MISO Boost Converter Description

Fig. 1 shows the SI-MISO boost converter. For the inputs, there are n power sources ($v_1, v_2, \dots, v_j, \dots, v_n$) provided by laboratory DC power supplies, which represents the various renewable energy sources. ($i_1, i_2, \dots, i_j, \dots, i_n$) are the corresponding input current for each source. The forward-conducting-bidirectional-blocking (FCBB) switches ($S_1, S_2, \dots, S_j, \dots, S_n$) are regulated by the control signals ($q_1, q_2, \dots, q_j, \dots, q_n$) to achieve the power sharing function. The FCBB structure, including a MOSFET and diode, eliminates the uncertainty power flow between these sources [11]. For the output, the single common inductor is L with current i_L . D denotes the freewheeling diode, and S is the MOSFET switch applied with the control signal q . For the load R , the corresponding voltage, current and capacitor are v_{out} , i_{out} and C respectively.

B. MPC-based Method

1) Operational Principle and Control Scheme

The block diagram of the proposed method is shown in Fig. 2(a). For the i_{th} source, the corresponding average current reference is set as $i_{ref,j}$ based on the power sharing ratio. After the moving average filter (MAF), the average current $\bar{i}_j$ is

Fig. 1. SI-MISO boost converter.

Fig. 2. (a) Block diagram the proposed method. (b) Control scheme of the proposed method.

obtained and sent to the PI controller with $i_{ref,j}$. Sequentially, the pulse-width-modulation (PWM) index δ_j is calculated dynamically, which can be seen in Fig. 2(a), and the period of PWM waveform is t_{PS} as shown in Fig. 2(b). For conducting the sources in order strictly, the accumulated modulation index δ_j' ($i = 2, 3, \dots, n-1$) is calculated as follows:

$$\delta_j' = \sum_{k=1}^j \delta_k, 2 \leq j \leq n-1, 0 \leq \delta_j \leq 1 \quad (1)$$

With the accumulated modulation index δ_j' , the control signals ($q_1, q_2', \dots, q_j', \dots, q_{n-1}'$) can be generated using the synchronized PWM generator. Then the applicable control signals ($q_2, \dots, q_j, \dots, q_{n-1}$) are obtained using the principle as follows:

$$q_j = q_j' \oplus q_{j-1}', 2 \leq j \leq n-1 \quad (2)$$

i.e., q_j is the XOR of q_j' and q_{j-1}' . It is noteworthy in Fig. 2 that q_1 is directly obtained since v_1 is the first source to be conducted, and q_n is the negation of q_{n-1}' because v_n is the power source to make up the unsatisfied load demand, which is not fully supplied by the former ($n-1$) sources. Once the control signals ($q_1, q_2, \dots, q_j, \dots, q_n$) are obtained, they will be also sent to the MPC controller to help determine the input voltage as follows:

$$v_{in} = \sum_{j=1}^n q_j \cdot v_j \quad (3)$$

With the data ($v_{in}, v_{out}, i_{out}, i_L$), the MPC controller is able to generate the optimal control signal q to regulate v_{out} to track the reference v_{ref} as shown in Fig. 2(b).

2) State-Space Model

The equations of the SI-MISO boost converter in continuous-time domain are

$$L \frac{di_L}{dt} = \sum_{j=1}^n q_j \cdot v_j - (1-q)v_{out} \quad (4)$$

$$C \frac{dv_{out}}{dt} = (1-q)i_L - i_{out} \quad (5)$$

Considering MPC is operated in discrete-time domain, a time step t_s is defined. Hence (4) and (5) can be discretized using the forward Euler method [6] with different values of q as follows:

$$i_L(k+1) = \left\{ \begin{array}{l} \frac{t_s}{L} \left[\sum_{j=1}^n q_j(k) \cdot v_j \right] + i_L(k), q(k)=1 \\ \frac{t_s}{L} \left[\sum_{j=1}^n q_j(k) \cdot v_j - v_{out}(k) \right] + i_L(k), q(k)=0 \end{array} \right. \quad (6)$$

$$v_{out}(k+1) = \left\{ \begin{array}{l} \frac{t_s}{C} [-i_{out}(k)] + v_{out}(k), q(k)=1 \\ \frac{t_s}{C} [i_L(k) - i_{out}(k)] + v_{out}(k), q(k)=0 \end{array} \right. \quad (7)$$

$$v_{out}(k+1) = \left\{ \begin{array}{l} \frac{t_s}{C} [-i_{out}(k)] + v_{out}(k), q(k)=1 \\ \frac{t_s}{C} [i_L(k) - i_{out}(k)] + v_{out}(k), q(k)=0 \end{array} \right. \quad (8)$$

$$v_{out}(k+1) = \left\{ \begin{array}{l} \frac{t_s}{C} [-i_{out}(k)] + v_{out}(k), q(k)=1 \\ \frac{t_s}{C} [i_L(k) - i_{out}(k)] + v_{out}(k), q(k)=0 \end{array} \right. \quad (9)$$

With a high sampling frequency, i_{out} in (8), (9) can be considered as a constant [8], so that it is expressed as follows:

$$\frac{di_{out}}{dt} = 0 \quad (10)$$

And the discretization of (10) using the forward Euler method is obtained as follows:

$$i_{out}(k+1) = i_{out}(k) \quad (11)$$

Based on the previous analysis and (6)-(9) and (11), the state-space model is given as follows:

$$\mathbf{x}(k+1) = [\mathbf{A} + \mathbf{B}q(k)]\mathbf{x}(k) + \mathbf{C} \sum_{j=1}^n q_j(k) \cdot v_j, \quad \mathbf{y}(k) = \mathbf{D}\mathbf{x}(k) \quad (12)$$

where $\mathbf{x}(k) = [i_L(k) \ v_{out}(k) \ i_{out}(k)]^T$, $\mathbf{y}(k) = v_{out}(k)$, and the coefficient matrices are

$$\mathbf{A} = \begin{bmatrix} 1 & -t_s/L & 0 \\ t_s/C & 1 & -t_s/L \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 & t_s/L & 0 \\ -t_s/C & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \mathbf{C} = \begin{bmatrix} t_s/L \\ 0 \\ 0 \end{bmatrix}, \mathbf{D} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T$$

Boost converter system is considered as a non-minimum phase system [7], so the long-interval prediction is imperative to guarantee the stability of the closed-loop control for this

Fig. 3. Diagram of enumerated MPC with MBT.

system. The move blocking technique (MBT) is adopted in MPC to achieve the long-interval prediction with low computational requirement [7].

An enumerated MPC method with MBT is shown in Fig. 3. In Fig.3, the proposed method is presented as a binomial tree with the depth of (N_c+1) , where N_c is the control horizon in MPC theory. Therefore, the group number of all possible predicted output voltage values is 2^{N_c} as shown in Fig. 3. It can be seen that the prediction is conducted using (6)-(9) based on the value of $q(k+j)$. Because MBT is employed, t_s varies in each prediction step as $n_j T$, where T is the sampling interval restricted by the practical controller. The relationship of n_j follows (13) below.

$$n_1 < n_2 < \dots < n_j < \dots < n_{N_c}, n_j \in \mathbb{N}^+ \quad (13)$$

Based on the state-space model, the 2^{N_c} groups of predicted output voltage values are obtained. If one group of predicted output voltage can minimize the cost function (14), the corresponding set of control actions is the optimal set.

$$J = \sum_{j=1}^{N_c} |v_{ref} - v_{out}(k+j)| \quad (14)$$

The first control action in the optimal set will be applied to the SI-MISO boost converter to regulate v_{out} for tracking v_{ref} .

III. SENSITIVITY INDICES

The corresponding sensitivity is defined to quantify the performance of the proposed method based on the discussion in [10]. The sensitivity to load variations is defined as follows:

$$S_{I_{out}}^{v_{out}} = \left(\frac{|\Delta v_{out}|}{|\Delta i_{out}|} \right) \times \left(i_{out} / v_{out} \right) \quad (15)$$

Similarly, the sensitivity index to input current variations is defined as follows:

$$S_{I_j}^{v_{out}} = \left(\frac{|\Delta v_{out}|}{|\Delta i_j|} \right) \times \left(v_{out} / i_j \right) \quad (16)$$

IV. EXPERIMENTAL RESULTS

A SI-MISO boost converter prototype with three input channels has been built for verification as shown in Fig.4, and the parameters are listed in Table I. It can be seen that the values of v_1 , v_2 and v_3 are different. Hence, v_{in} varies when the

TABLE I PARAMETERS OF SI-MISO BOOST CONVERTER PROTOTYPE

Symbol	v_1	v_2	v_3	C_1	C_2	C_3	L	C
Value	30V	20V	25V	470 μ F	470 μ F	470 μ F	1mH	2200 μ F
Symbol	R	v_{out}	N_c	n_1	n_2	n_3	n_4	T
Value	27-54 Ω	40V	4	1	3	5	7	20 μ s

TABLE II COMPONENTS ADOPTED IN PROTOTYPE

Component	Device
MOSFET	IXFN64N60P
Diode	IXYS DSEI2X61-04C
Voltage Transducer	LEM LV 25-P
Current Transducer	LEM LA 55-P
Controller	DS 1104 Board

Fig. 4. SI-MISO boost converter prototype.

Fig. 5. Steady-state waveforms of v_{out} , i_1 , i_2 and i_3 .

scheduling of v_1 , v_2 and v_3 happens based on (3), which can reflect the variations in the voltage of the RESs in practical situations. The main components used are listed in Table II. Experimental studies including steady-state operation and dynamic operation are conducted. The dSpace 1104 control board is utilized as the controller to implement the proposed method and hardware setup.

A. Steady-State Operation

1) Operation Waveforms

The steady-state operation waveforms of v_{out} , i_1 , i_2 and i_3 are shown in Fig. 5. The references are $v_{ref}=40V$, $i_{ref,1}=0.6A$ and $i_{ref,2}=0.4A$. It can be seen that $v_{out}=40.5V$, which tracks

(a)

(b)

Fig. 6. Control signals. (a) Steady-state waveforms of q_1 , q_2 , q_3 and v_m . (b) Steady-state waveforms of q , i_L and v_m .

v_{ref} tightly. Actually, i_j is represented by the voltage signal from the dSPACE after the process of MAF, and the ratio of i_j and the corresponding voltage signal is one. It can be observed that i_1 and i_2 follow the preset reference tightly. i_3 is regulated as 0.9A to make up the unsatisfied load demand.

2) Control Signal Waveforms

In Fig. 6, the waveforms of q_1 , q_2 , q_3 , v_m , q and i_L in steady-state operation are presented to explain the operation of the proposed method. It can be seen from Fig. 6(a) that q_1 and q_2 are dynamically adjusted for regulating i_1 and i_2 to track the corresponding current references. q_3 is utilized to conduct v_3 to make up the unsatisfied load demand. Hence, the waveform of v_m follows the controls signals q_1 , q_2 and q_3 , and it varies with $v_1=30V$, $v_2=20V$ and $v_3=25V$. Additionally, Fig. 5 and Fig. 6(a) indicate that v_{out} tracks v_{ref} well even when v_m dramatically varies due to the scheduling of v_1 , v_2 and v_3 . It demonstrates that the proposed method is capable to achieve the successful regulation of v_{out} when the voltage of RESs, such as solar energy sources, vary in practical situations. Moreover, it should be noticed that because δ_2 and δ_3 are equal to 0 occasionally, v_1 , v_2 and v_3 are not conducted exactly following the pattern shown in Fig. 2. In Fig. 6(b), waveforms of q , i_L and v_m are presented. It can be observed that q is generated by the MPC controller to regulate v_{out} . i_L is increased when $q=1$, and it is decreased when $q=0$. In addition, the slope of i_L changes based on the values of v_m .

B. Dynamic Operation

1) Load Regulation

The load regulation experimental results are shown in Fig. 7. The load step change is realized by changing the values of R

Fig. 7. Waveforms of load regulation.

Fig. 8. Waveforms of step change in input current references.

from 54Ω to 27Ω , so that i_{out} is increased from 0.75A to 1.5A. The influence on v_{out} is $\Delta v_{out}=1.2V$. Based on (15), the sensitivity to load variations $S_{i_{out}}^{v_{out}}$ can be calculated as 3%. Additionally, the average values of i_1 and i_2 follow the corresponding references tightly. Hence, i_3 has an increment from 0.8A to 2.0A to meet the rising load demand. Therefore, the load regulation is successfully conducted by the MPC-based method for the three-input SI-MISO boost converter.

2) Response to Input Current Reference Step Change

The experimental results of response to input current reference step change are shown in Fig. 8. Two step changes have been set in i_1 from 0.6A to 0.3A, and then in i_2 from 0.4A to 0.8A respectively. Correspondingly, i_3 is increased from 0.9A to 1.2A, then it is decreased to 0.8A to meet the load demand. It can be observed the total influence on v_{out} is $\Delta v_{out}=0.5V$ due to the step change in i_1 or i_2 . Based on the definition of $S_{i_j}^{v_{out}}$ in (16), the sensitivities to input current

variations $S_{i_1}^{v_{out}}$ and $S_{i_2}^{v_{out}}$ are calculated as 2.5% and 1.25% respectively. Hence, the proposed method is able to handle the step change in input current reference.

3) Response to Output Voltage Reference Step Change

The experimental results of response to output voltage reference step change are shown in Fig. 9. The v_{ref} is changed from 40V to 45V. Because of the fixed regulation of $i_1=0.6A$ and $i_2=0.4A$, i_3 is increased from 0.9A to 1.4A for boosting the output voltage with the increment of 5V. The experimental results demonstrated that the proposed method has the capability to respond to output voltage reference step change.

Fig. 9. Waveforms of step change in output voltage reference.

V. CONCLUSION

In this paper, a MPC-based method for SI-MISO boost converter has been presented. The method is implemented based on a prototype of three-input SI-MISO boost converter. The steady-state operation and dynamic operation have been verified. The experimental results indicate that the proposed method is capable to control the input power and output voltage based the corresponding references. Moreover, the step changes in load, input current reference and output reference are also successfully regulated by the proposed method.

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