Sensorless Current Estimation and Sharing in Multiphase Input-Parallel Output-Parallel DC-DC Converters

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***Abstract*—This paper introduces a sensorless current-sharing strategy for multiphase input-parallel output-parallel (IPOP) DC-DC converters. A dual active bridge (DAB) DC-DC converter is chosen as the basic DC-DC converter. With this strategy, by perturbing the duty cycles in (*n*-1) out of *n* phases in turn and measuring the changes of duty cycles respectively, the parameters mismatches among phases are estimated. According to the mismatches, a set of variables, which are proportional to the per-phase output currents, are calculated. Then with a current-sharing regulator, parameter mismatches are compensated, thus achieving current sharing without current sensing. The strategy is verified through both simulation and experimental implementation with a 30V-to-70V, 272W, 20kHz, three-phase IPOP DC-DC converter.**

I. INTRODUCTION

Multiphase DC-DC converters, due to the merits of relatively high power rating with low power rating basic converters, flexibility of power rating and reduced current ripple with multiple interleaved phases, are increasingly studied. For a multiphase DC-DC converter, it is generally desirable that every phase shares the load current equally so that the components possess equal thermal stresses which minimizes component ratings. Otherwise, current imbalance may lead to deterioration of system reliability and even derivation of system stability. Ideally, parameters of phases are designed to be identical, therefore the load current is automatically shared. However, in reality, component parameter errors, component tolerances and some other effects inevitably result in parameter mismatches, so extra current-sharing control is required to compensate these mismatches.

Many current-sharing control strategies are introduced and analyzed in [1-11]. These strategies can be generally divided into two sorts, i.e. droop method [1-4] and active current-sharing method [3-7], with master-slave scheme and democratic scheme. Droop method, by controlling the finite equivalent output resistance of every phase, regulates its output characteristic to realize current sharing among phases. Active current-sharing method uses current sensors to sample output current of each phase, then compares per-phase output current signals with current-sharing bus signal, producing current error signals which are put into current-sharing controller to compensate differences of output currents.

An automatic current-sharing strategy is described in [8]. In this paper, by reducing parameter mismatches among phases to some extent, approximate current sharing with acceptable current differences among phases is achieved using common duty cycle control strategy. This method can only be used where parameter mismatches of phases are less than 10%. In [9], another automatic current-sharing strategy is introduced. In this paper, by utilizing a specific IPOP converter topology, automatic sharing of input and output current is achieved without an extra current-sharing controller even in the presence of parameter mismatches of more than 10%.

With recent development of digital control system, some novel sensorless current-sharing strategies are proposed in [10, 11]. These strategies don't need any current sensor or additional circuit, and merely require measurement of the output voltage. These strategies utilize methods based on perturbation of

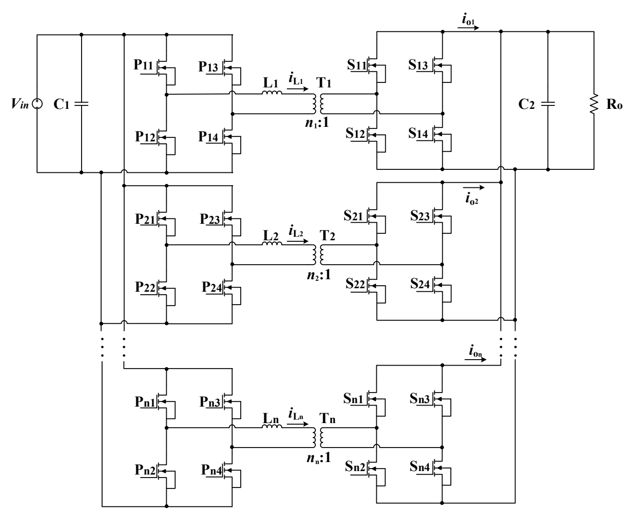

Fig. 1. Topology of multiphase DAB IPOP DC-DC converter

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duty cycle to estimate the parameter mismatches and adjust the duty cycles to compensate the mismatches, therefore realizing current sharing. However, all these strategies are developed only for multiphase buck DC-DC converters.

In this paper, a novel sensorless current-sharing strategy is proposed. It is used in multiphase DAB IPOP DC-DC converters, as shown in Fig.1, which consists of n phases of dual active bridge (DAB) converters, input-paralleled and output-paralleled. The topology of DAB and its operating principal are analyzed in detail in Section II. In Section III, the sensorless current-sharing strategy, including parameter estimation, current estimation and sharing, is described at length. The simulation and experimental results are demonstrated in Section IV. Finally, conclusions are given in Section V.

II. Dual Active Bridge DC-DC Converter

A DAB DC-DC converter, as shown in Fig.2, is a kind of bidirectional DC-DC converter which consists of a low voltage H-bridge and a high voltage H-bridge, connected through a high-frequency transformer. As researched in [12], DAB has the merits of transferring power in both directions, higher power density with its relatively small size and less power loss due to its ability of zero voltage switching.

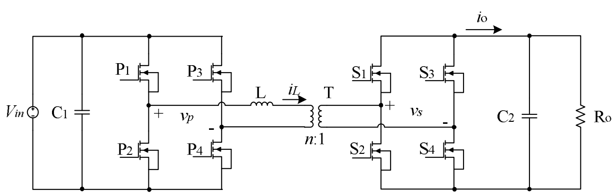


Fig.2. Topology of DAB

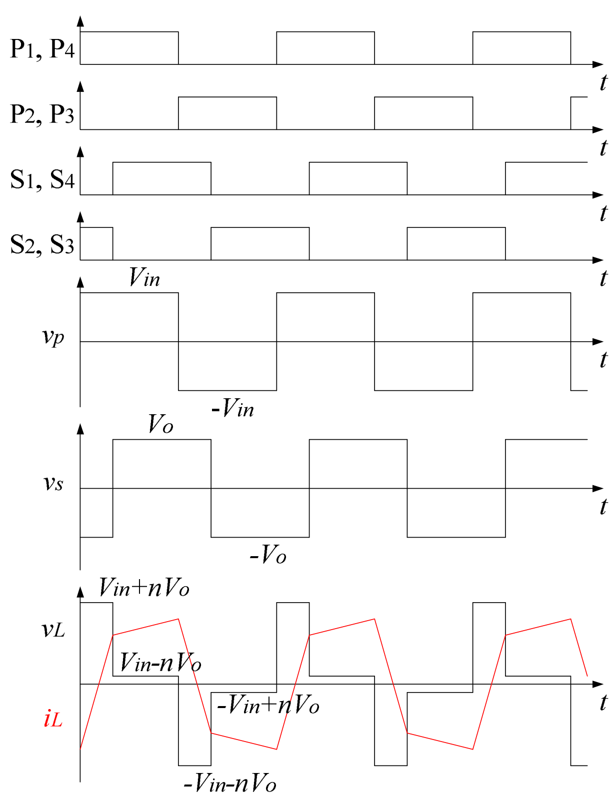


Fig.3. Main waveforms of operating DAB

The main waveforms of operating DAB are shown in Fig.3. In primary H-bridge, the control signals of P_1 and P_4 are identical, with duty cycles of 50%, and the control signals of P_2 and P_3 are identical, complementary to that of P_1 and P_4. Similarly in secondary H-bridge, but with the control signals of S_1 and S_4 lagging that of P_1 and P_4 a phase shifting angle φ. Define ratio of the phase shifting angle φ to half switching period angle as the duty cycle of DAB, which can be expressed as

$$d = \frac{\varphi}{\pi} \tag{1}$$

where $\varphi \in [0, \pi]$, $d \in [0,1]$.

With all these control signals, the transformer's primary voltage v_p, a rectangular wave with its magnitudes of $\pm V_{in}$, and secondary voltage v_s, a rectangular wave with its magnitudes of $\pm V_o$, are generated as illustrated in Fig.3. By controlling the phase shifting angle φ, the voltage v_L of the leakage inductor of the transformer, as well as the leakage inductor current i_L and the active power transferred through the DAB converter, are controlled.

According to [12], the active power transferred through DAB is written as

$$P = \frac{n \cdot V_{in} \cdot V_o \cdot d \cdot (1-d)}{2L \cdot f_s} \tag{2}$$

where n is transformer ratio, V_{in} is input voltage, V_o is output voltage, L is leakage inductance, f_s is switching frequency, d is duty cycle. Thus the output current of DAB is

$$I_o = \frac{P}{V_o} = \frac{n \cdot V_{in} \cdot d \cdot (1-d)}{2L \cdot f_s} \tag{3}$$

III. Current Sharing

According to (3), in multiphase DAB IPOP DC-DC converters, output current in the ith phase is

$$I_{oi} = X_i \cdot d_i \cdot (1-d_i) \tag{4}$$

where $X_i = \frac{V_{in}}{2f_s} \cdot \frac{n_i}{L_i}$, V_{in} is input voltage, f_s is switching frequency, n_i is transformer ratio, L_i leakage inductance, d_i are duty cycle in the ith phase, i = 1, 2, 3,…, n. Clearly, with a given V_{in} and f_s, X_i is a constant, related to system of the ith phase itself. So define X_i as phase parameter. As shown in (4), load current will be shared among phases automatically as long as the phase parameters are identical and the duty cycles are the same. However, in realistic situation, mismatches among phases are inevitable. In order to achieve ideally current sharing, extra control strategy are required to compensate the duty cycles of phases for the mismatches.

In what follows, a specific procedure for the realization of sensorless current sharing in multiphase DAB IPOP DC-DC converters is described.

A. Parameter Estimation

Firstly, the multiphase converters are controlled by a common duty cycle, which is generated by voltage regulator. The control schematic diagram at this stage is shown in Fig.4. After the system reaches steady state, the duty cycles of all phases are D, expressed as below

$$d_1 = d_2 = \cdots = d_n = D \tag{5}$$

And the output current of the ith phase is

$$I_{oi} = X_i \cdot D \cdot (1-D) \tag{6}$$

Next, the duty cycle of the ith phase is perturbed by subtracting a small constant offset Δd_p from the output of voltage regulator, while the duty cycles of the rest of phases is the output of voltage regulator, with the closed loop voltage regulation. The control schematic diagram at this stage is shown in Fig.5. After the system gets steady, the duty cycle of ith phase is equal to the common duty cycle D minus a small constant offset Δd_{i1}, which is written as

$$d_i = D - \Delta d_{i1} \tag{7}$$

In response to the Δd_{i1}, the second phase duty cycle is equal to the common duty cycle D plus a small constant offset Δd_{i2}, which is written as

$$d_1 = d_2 = \cdots = d_{i-1} = d_{i+1} = \cdots = d_n = D + \Delta d_{i2} \tag{8}$$

Obviously, $\Delta d_{i1} + \Delta d_{i2} = \Delta d_p$. So the output current of the perturbed phase and the other phases is

$$I_{oi} = X_1 \cdot (D - \Delta d_{i1}) \cdot (1 - D + \Delta d_{i1}) \tag{9}$$

$$I_{oj} = X_j \cdot (D + \Delta d_{i2}) \cdot (1 - D - \Delta d_{i2}) \tag{10}$$

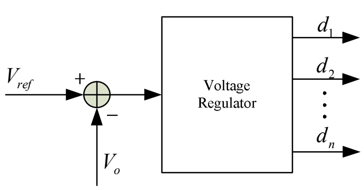


Fig. 4. Control schematic diagram of common duty cycle

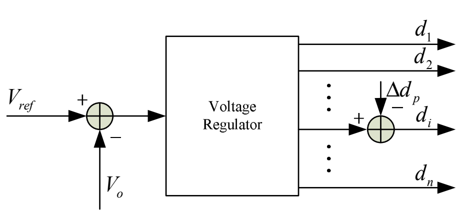


Fig.5. Control schematic diagram of common duty cycle with perturbation

where j=1, 2,…, i-1, i+1,…, n.

According to (6) (10) (11), the current change in each phase can be written as

$$\Delta I_{oi} = X_i \cdot \left(\Delta d_{i1}^2 + \Delta d_{i1} - 2\Delta d_{i1} \cdot D\right) \tag{11}$$

$$\Delta I_{oj} = X_j \cdot \left(\Delta d_{i2}^2 - \Delta d_{i2} + 2\Delta d_{i2} \cdot D\right) \tag{12}$$

Due to the fact that the output voltage is well regulated, the total output current stays the same before and after perturbation, therefore the reduction of output current in the ith phase is equal to the sum of addition of output current in the rest of the phases, expressed as

$$\Delta I_i = -\left(\Delta I_1 + \cdots + \Delta I_{i-1} + \Delta I_{i+1} + \cdots + \Delta I_n\right) \tag{13}$$

which yields:

$$X_1 + \cdots + X_{i-1} - \frac{(1-2D)\cdot \Delta d_{i1} + \Delta d_{i1}^2}{(1-2D)\cdot \Delta d_{i2} - \Delta d_{i2}^2} \cdot X_i + X_{i+1} + \cdots + X_n = 0 \tag{14}$$

Repeat the procedure described above: perturb the duty cycles in (n-1) out of n phases respectively and measure the changes of duty cycles in the rest of the phases, which yields (n-1) equations accordingly with respect to X_1, X_2, …, X_i, …, X_n. For the simplification of analysis, take for example that the duty cycles of the first to the (n-1)th phase are perturbed in turn. The system of equations derived according to the procedure described above is

$$\begin{bmatrix} -a_1 & 1 & 1 & \cdots & 1 & \cdots & 1 & 1 \\ 1 & -a_2 & 1 & \cdots & 1 & \cdots & 1 & 1 \\ 1 & 1 & -a_3 & \cdots & 1 & \cdots & 1 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ 1 & 1 & 1 & \cdots & -a_i & \cdots & 1 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ 1 & 1 & 1 & \cdots & 1 & \cdots & -a_{(n-1)} & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_i \\ \vdots \\ X_{(n-1)} \\ X_n \end{bmatrix} = 0 \tag{15}$$

where $a_i = \dfrac{(1-2D)\cdot \Delta d_{i1} + \Delta d_{i1}^2}{(1-2D)\cdot \Delta d_{i2} - \Delta d_{i2}^2}$, $i = 1, 2, \cdots, (n-1)$ .The system of equations above can be solved and yield infinite sets of solutions. Given $[k_1, k_2, \cdots, k_i, \cdots, k_n]^T$ is one set of these solutions, it is obvious that k_1, k_2,…, k_i,…, k_n are proportional to X_1, X_2,…, X_i,…, X_n.

B. Current Estimation and Sharing

Assume that $h_1, h_2, \cdots, h_i, \cdots, h_n$ are calculated as:

$$h_i = k_i \cdot d_i \cdot (1 - d_i) \tag{16}$$

According to (4), clearly, $h_1, h_2, \cdots, h_i, \cdots, h_n$ are proportional to the per-phase output current, $I_{o1}, I_{o2}, \cdots, I_{oi}, \cdots, I_{on}$, namely

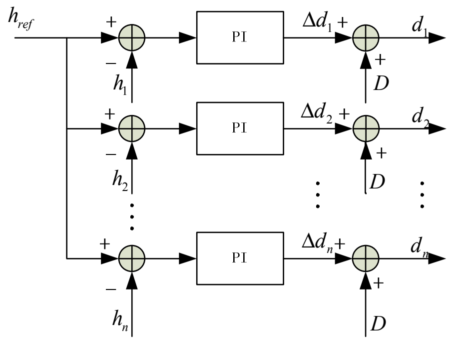


Fig.6. Schematic diagram of current-sharing regulator

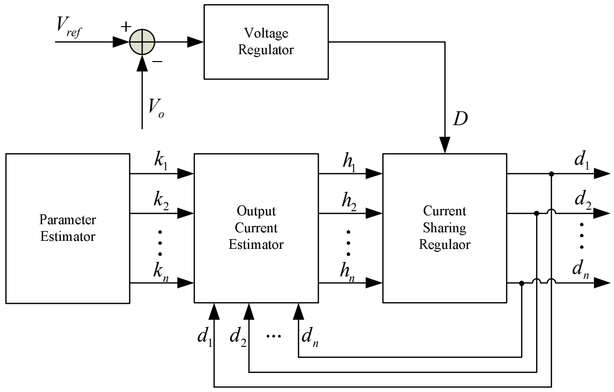


Fig.7. Control schematic diagram of sensorless current-sharing strategy

$$h_i \propto I_{oi} \tag{17}$$

Suppose

$$h_{ref} = \sum_{i=1}^{n} m_i \cdot h_i \tag{18}$$

where gains $m_1, m_2, \cdots, m_i, \cdots, m_n$ are used to achieve certain current-sharing scheme. For example, a master-slave scheme, with which one of the phases is chosen as the master, all the others as slaves, is implemented with gains

$$m_1 = 1,\ m_2 = \cdots = m_n = 0 \tag{19}$$

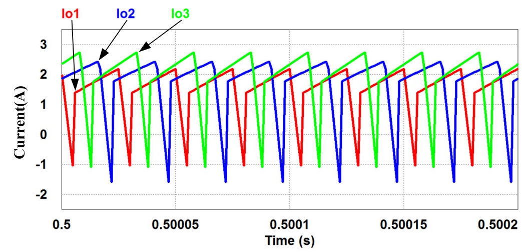
In this design, a democratic scheme is adopted where

$$m_1 = m_2 = \cdots = m_n = \frac{1}{n} \tag{20}$$

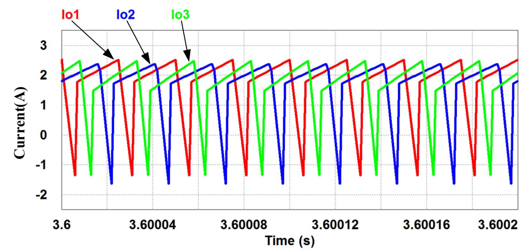
As illustrated in Fig.6, a current error signal for one phase, produced by subtracting h_i from h_{ref}, is transferred through a PI regulator to generate a offset Δd_i to compensate the parameter mismatches, thus achieving current sharing among phases.

IV. Stimulation and Experimental Results

The simulation of a 30V-to-80V, 400W, 20kHz, three-phase IPOP DAB DC-DC converter is implemented by PSIM software. The transformer ratios of three phases are 1:3.1, 1:3.0, 1:3.1, and the leakage inductances are 28.0μH, 25.0μH, 22.0μH respectively.

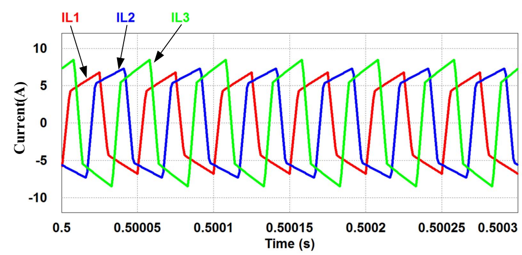


(a) With common duty cycle

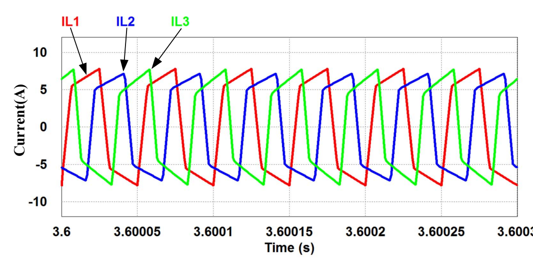


(b) With sensorless current-sharing strategy

Fig.8. Simulation waveforms of output current of the three phases



(a) With common duty cycle



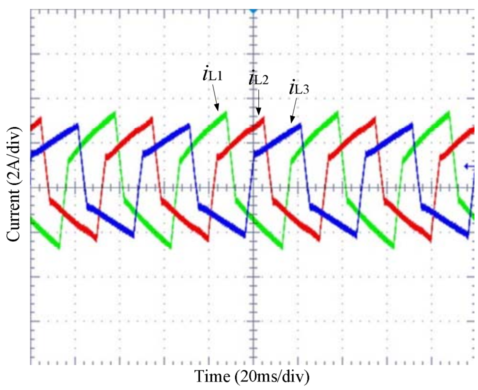
(b) With sensorless current-sharing strategy

Fig. 9. Simulation waveforms of leakage inductor currents of the three phases

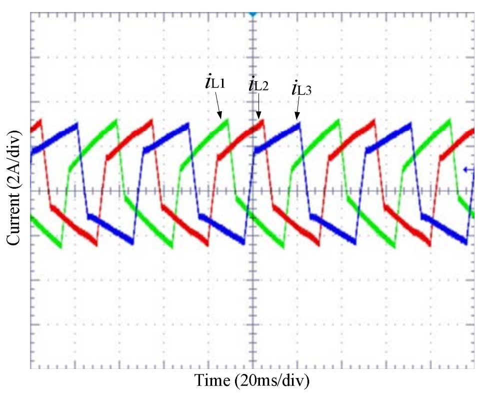
Fig.8 shows the simulation waveforms of output current of the three phases before and after using proposed current-sharing strategy. As shown in Fig.8(a), when common duty cycle is used, the output current is obviously unbalanced. The average values of output current of three phases are 1.44A, 1.65A, 1.91A, respectively. But when the proposed sensorless current-sharing strategy is used, as shown in Fig.8(b), the out-

TABLE I. PROTOTYPE PARAMETERS

Input capacitor	C_1	3300μF
Output capacitor	C_2	4240μF
Transformer ratio in the first phase	n_1	1:3.2
Transformer ratio in the second phase	n_2	1:3.0
Transformer ratio in the third phase	n_3	1:3.1
Transformer leakage inductance in the first phase	L_1	24.0μH
Transformer leakage inductance in the second phase	L_2	27.3μH
Transformer leakage inductance in the third phase	L_3	27.8μH
Input voltage	V_{in}	30V
Output reference voltage	V_{ref}	70V
Switching frequency	f_s	20kHz
Load	R_o	18Ω



(a) With common duty cycle



(b) With sensorless current-sharing strategy

Fig.10. Experimental waveforms of leakage inductor currents of three phases

put current of both phases are all equal to 1.67A. Fig.9 shows the simulation waveforms of leakage inductor current before and after using current-sharing strategy. Also it can be seen that current sharing is ideally achieved with the sensorless current-sharing strategy.

To verify the strategy proposed in this paper, a prototype of a three-phase DAB IPOP DC-DC converter is built. The experimental parameters are listed in Table I. The proposed sensorless current-sharing strategy is programmed and implemented in DSP TMS320F28335 and FPGA EP4CE6E22C8.

Fig.10 shows the experimental waveforms of leakage inductor currents of the three phases before and after using current-sharing strategy. As shown in Fig.10(a), when common duty cycle is used, it can be seen that leakage inductor current of three phases is not equal to each other, therefore the power transferred through phases is unbalanced. But when the sensorless current-sharing strategy is used, as shown in Fig.10(b), significant current-sharing improvement can be realized as expected. The experimental results, as well as the simulation results, are consistent with the above theoretical analysis.

V. CONCLUSIONS

This paper proposes a novel sensorless current-sharing strategy in a multiphase DAB IPOP DC-DC converter. Simulation and experimental prototype of a 30V-to-70V, 272W, 20kHz, three-phase DAB IPOP DC-DC converter are implemented. Some conclusions can be draw from the study with the proposed sensorless current-sharing strategy:

1) The effectiveness of the proposed sensorless current-sharing strategy is verified.

2) With the proposed strategy, current-sharing among phases is achieved hence the reliability of multiphase converters is enhanced.

3) This strategy can be implemented without any current sensors, thus costing less compared with those sensor-required current-sharing strategies.

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