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An Advanced-Time-Sharing Switching Strategy for Multiple-Input Buck Converters

Liang Xian

School of Electrical and Electronic Engineering
Nanyang Technological University
Singapore 639798
LXIAN001@e.ntu.edu.sg

Youyi Wang

School of Electrical and Electronic Engineering
Nanyang Technological University
Singapore 639798
EYYWANG@ntu.edu.sg

Abstract— Multiple-input converter (MIC), which has higher efficiency, less component count, lower cost and simpler control method, is a promising candidate for energy harvesting in hybrid systems, and for power distribution in micro and nano grids. The principle of the proposed advanced-time-sharing switching (ATSS) strategy is that the effective duty ratio of each switch is an integer multiple of a common duty ratio (CDR). CDR is the duty ratio of a common-switching-function (CSF) generated at a higher frequency by frequency division. ATSS transforms the original MIC into an equivalent single-input single-output system, simplifying system analysis, control design and implementation, where CDR is the only control variable for output voltage regulation. Additionally, multiplied by a regulation coefficient α , the fixed CDRs can become the control variables for current limitation, which releases the degree of freedom. By using this technique, smooth and accurate limitation to sources' current is able to be implemented without loss of output-voltage-regulation convenience. Its corresponding circuit modeling, small-signal analysis, controller design, and performance tests have been put forward.

Keywords—time-sharing switching strategy; multiple-input converters; dc-dc power conversion; hybrid system; control systems

I. INTRODUCTION

In the recent decade, multiple-input converters (MICs) are attracting more and more attentions from the areas of power electronics and renewable energy techniques, because of their irreplaceable advantages such as comparative higher efficiency, less component count, lower cost and simpler control method comparing with those conventional hybrid-used converter structures [1-4]. One of the most-commonly-used topologies in the MIC family is multiple-input buck (step-down) converter (MIbC) with m -inputs and 1-output, whose fundamental schematic is given in Fig. 1. As one of the pulse-width modulated (PWM) dc-dc converters, MIC, essentially, belongs to the class of variable-structure time-varying switching system, whose operating principle and dynamic behavior are based on its applied switching functions. Time-sharing switching (TSS) technique (or called time division multiplexing technique) is usually applied to structuring MIC's particular PWM switching functions. In general, it allows more than one switches to operate within

one operating period, T , on the premise of only one of them should conduct at a given instant. However, one of the issues in conventional MICs is switching function coupling, i.e. with conventional TSS strategies, all switching functions have to share a fixed time interval. The generation of switching functions in a fixed sharing switching period becomes more difficult as the number of input legs in an MIC increase. Moreover, the target of closed-loop MIC's output voltage control is required more complicated multiple-input single-output (MISO) control design and added components in order to ensure robustness [5].

In the literature [1], a modified TSS (MTSS) technique was introduced, which alleviated the difficulties in controlling and permit more input legs to be utilized. The contribution of this paper mainly relies on: MTSS transforms the original MISO control system into a single-input single-output (SISO) equivalent system for convenience of system analysis and controller design; employing the toggle flip-flops and the logic gates, instead of using advanced digital signal processor, lowered cost in hardware implementation, and simplified control design process. However, more advanced and systematic TSS strategy and control approach are required if MIC needs to be applicable for operating under a more changeable condition. As the generated effective duty ratios (EDRs) on all the switches equal to each other, a certain number of control degree of freedom (DOF) are actually not in use, which makes an advanced TSS (ATSS) strategy to control other variable besides the output voltage of a MIC possible. In this paper, a regulation coefficient α is applied to be a multiplier for one of the fixed EDRs (d_{1eff} in this paper) to activate d_{1eff} a controllable variable like the common duty ratio (d_{CSF}) for MIC's output voltage regulation. In this case, a compensator is able to be added to realize a required control target via regulating α . We apply it to limit the input current of the 1st source, V_1 to a MIbC in this paper.

The rest of the paper is structured as follows. In Section II, the MTSS strategy presented in [1] is briefly introduced, followed by which, the proposed ATSS technique is detailed explained in Section III, including operating principle and small-signal modeling. Based on the closed-loop controller design, simulations are developed to verify the aforementioned theory in Section IV, and cases that source's

Fig. 1. Non-isolated m -input MIBC topologies.

Fig. 2. Switching pulses recombination of the ATSS strategy with $N_1 = 4$ and $N_2 = 4$ for the DIBC system.

input voltage and load changes are tested and analyzed as well. Section V draws conclusions from the results.

II. MODIFIED-TIME-SHARING SWITCHING STRATEGY

In order to take advantage of the conventional TSS strategies and make MICs applicable for renewable energy sources as well as possible, the MTSS technique is proposed in [1], whose principle relies on generating a common switching function (CSF) at a higher switching frequency that is an integer multiple (N) of the desired MIC switching frequency. Frequency division is then performed on the CSF using logic gates and toggle flip-flops; the number of the toggle flip-flops (N_T) is a binary logarithm of N :

$$N = 2^{N_T}. \quad (1)$$

Then, we defined a share factor

$$\beta_i = N_i / N, \quad (2)$$

where N_i is the number of switching pulses of CSF that are channeled to input-leg i . More flip-flops can be used to further divide the CSF's frequency, in which case, the CSF must be supplied at a corresponding higher frequency in order to maintain the same fundamental switching frequency f of individual MIC input-leg switches. With the MTSS strategy presented, the EDR of an input-leg switch (d_i) becomes the product of its corresponding share factor, β_i and the common duty ratio (CDR), d_{CSF} :

$$d_{ieff} = \beta_i d_{CSF}. \quad (3)$$

Although the MTSS has its own advantages on flexibility and efficiency of the circuit, its shortcomings cannot be ignored. The share factor, β_i has its limitation in sharing

ability and application range. The value of $\beta_i N$ is always an positive integer in this MTSS scheme, causing smooth and accurate control on power sharing and budgeting among input sources via a MIC is unavailable in practice; in other words, only if infinite switching pulses are generated to the MIC, the power extracted from each input source is possible to be regulated to any required value, thus, the real input power control scheme is able to be developed. Definitely, it is impossible to be realized by using MTSS strategy only without considering power losses. The proposal of the ATSS strategy breaks a new path for solving this practical problem.

III. ADVANCED-TIME-SHARING SWITCHING STRATEGY

A. Operating Principle

There will be m -DOF for the system if a m -sourced MIC topology is applied to the controller design [4]. For a double-input buck converter (DIBC) ($m = 2$) instant, the DOF is 2, and one of them is utilized for controlling the output voltage of the converter, while another one can be used to control another objective. However, in a m -sourced MTSS-based MIC system, $(m-1)$ DOF are underappreciated. In order to solve this inherent defect, the non-negative coefficient α is introduced to (3) and the product of α_i and β_i provides a new share factor, $\alpha_i \beta_i$, which is controllable. Besides, α_i is an independent control variable and not constrained by (2). As such in general, d_{ieff} in (3) can be modified to

$$d_{ieff} = \alpha_i \beta_i d_{CSF}. \quad (4)$$

The value of β_i is step-adjustable among its possible positive integers by changing the number of N_i channeled to q_i , which is able to realize stepped and coarse control on power sharing. It assists the smooth and accurate controlling behavior of α_i for faster dynamic response time and better control performance.

In this paper, we name it the ATSS strategy. The simplest instance in the MIC family: DIBC is taken for further analysis and discussion, and the average input current of V_1 is set as the DIBC's second control objective, besides the output voltage. A three-flip-flop-based frequency division ($N_T = 3$, $N = 8$) and a 4:4 recombination of the 8 switching pulses are utilized. The corresponding switching function recombination of the ATSS strategy for DIBC system is demonstrated in Fig. 2. The solid lines in q_1 and q_2 are the switching pulses based on the MTSS strategy, the EDRs of which are fixed to $\beta_1 d_{CSF}$ and $\beta_2 d_{CSF}$ respectively once the value of d_{CSF} is determined. By multiplying α_1 and α_2 , it can be seen that the trailing-edges of the switching pulses are moving towards the left side ($\alpha_i < 1$), the right side ($\alpha_i > 1$), or on the side ($\alpha_i = 1$) of the original fixed trailing-edges generated by the MTSS strategy, which are marked with the dashed lines in the figure. As a result, the EDRs of the switching pulses are adjustable through changing the value of α_i even if the value of $\beta_i d_{CSF}$ is predetermined, which restores the DOF of the DIBC system to 2.

B. Small-Signal Modeling Analysis

For further analysis and controller design, the small-signal averaged model of the ATSS-based DIBC system needs to be provided. As for the ($m = 2$) case, there are 3

control variable candidates can be selected to control the pre-selected 2 control objectives v_c and i_1 , which is necessary to be discussed separately.

1) *Case 1 and Case 2*: to choose $d_{CSF}\alpha_1$ ($d_{CSF}\alpha_2$) as control variables, remaining another one constant. Because of the symmetry of Case 1 and Case 2, we only give the derivation results of Case 1 here. The simplified dynamic equations of the small-signal model are

$$\begin{bmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} [d_{CSF}\hat{\alpha}_1\beta_1V_1 + \hat{d}_{CSF}\alpha_2\beta_2V_2 - \hat{v}_c] \\ \frac{1}{C_o} \left(\hat{i}_L - \frac{\hat{v}_c}{R_o} \right) \end{bmatrix}. \quad (5)$$

Then the open-loop control-to-output transfer functions can be derived as

$$\begin{cases} G_{da11}(s) = \left. \frac{\hat{v}_c(s)}{\hat{d}_{CSF}(s)} \right|_{\hat{\alpha}_1(s)=0} = \frac{\alpha_2\beta_2V_{s2}}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{da12}(s) = \left. \frac{\hat{v}_c(s)}{\hat{\alpha}_1(s)} \right|_{\hat{d}_{CSF}(s)=0} = \frac{d_{CSF}\beta_1V_{s1}}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{da21}(s) = \left. \frac{\hat{i}_1(s)}{\hat{d}_{CSF}(s)} \right|_{\hat{\alpha}_1(s)=0} = \frac{(C_o s + 1/R_o)\alpha_1\alpha_2\beta_1\beta_2d_{CSF}V_2}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{da22}(s) = \left. \frac{\hat{i}_1(s)}{\hat{\alpha}_1(s)} \right|_{\hat{d}_{CSF}(s)=0} = \frac{(C_o s + 1/R_o)\alpha_1\beta_1^2d_{CSF}^2V_1}{LC_o s^2 + (L/R_o)s + 1}. \end{cases} \quad (6)$$

It indicates that the plant can be expressed as a coupled DIDO system $G_{da}(s)$ shown in Fig. 3(a).

2) *Case 3*: to choose $\alpha_1\alpha_2$ as control variables, keeping d_{CSF} constant. The simplified dynamic equations of the small-signal model are

$$\begin{bmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} [d_{CSF}\hat{\alpha}_1\beta_1V_1 + d_{CSF}\hat{\alpha}_2\beta_2V_2 - \hat{v}_c] \\ \frac{1}{C_o} \left(\hat{i}_L - \frac{\hat{v}_c}{R_o} \right) \end{bmatrix}. \quad (7)$$

Then the open-loop control-to-output transfer functions can be derived as

$$\begin{cases} G_{aa11}(s) = \left. \frac{\hat{v}_c(s)}{\hat{\alpha}_1(s)} \right|_{\hat{\alpha}_2(s)=0} = \frac{d_{CSF}\beta_1V_1}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{aa12}(s) = \left. \frac{\hat{v}_c(s)}{\hat{\alpha}_2(s)} \right|_{\hat{\alpha}_1(s)=0} = \frac{d_{CSF}\beta_2V_2}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{aa21}(s) = \left. \frac{\hat{i}_1(s)}{\hat{\alpha}_1(s)} \right|_{\hat{\alpha}_2(s)=0} = \frac{(C_o s + 1/R_o)\alpha_1\beta_1^2d_{CSF}^2V_1}{LC_o s^2 + (L/R_o)s + 1}, \\ G_{aa22}(s) = \left. \frac{\hat{i}_1(s)}{\hat{\alpha}_2(s)} \right|_{\hat{\alpha}_1(s)=0} = \frac{(C_o s + 1/R_o)\alpha_1\beta_1\beta_2d_{CSF}^2V_2}{LC_o s^2 + (L/R_o)s + 1}. \end{cases} \quad (8)$$

The plane can be expressed as Fig. 3(b) elucidates.

Fig. 3. Open-loop control-to-output transfer functions of the ATSS-based DIBC system with (a) d_{CSF} and α_1 as its control variables while α_2 keeps constant, and (b) α_1 and α_2 as the control variables while d_{CSF} keeps constant.

3) *Case 4*: to choose $d_{CSF}\alpha_1$ with $V_A = V_M$. From Case 1 through Case 3, one can see that the ATSS-based DIBC system becomes a coupled DIDO system and the output voltage of the DIBC is no longer independently determined by d_{CSF} since the second control variable is introduced. As a result, the analysis convenience and controller-designed simplicity of considering the original circuit model of the DIBC system as an equivalent SISO averaged model, existing in the MTSS-based system, is not able to extend to an ATSS-based one. If we still want to maintain the equivalent small-signal stability analysis and controller design process as the case that the MTSS one did, a certain constraint must be imposed on the original dynamic equations to ensure the invariance between the ATSS and the MTSS, i.e., $V_M = V_A$,

where $V_M = \sum_{i=1}^m \beta_i V_{si}$ and $V_A = \sum_{i=1}^m \alpha_i \beta_i V_{si}$. The following relation between α_1 and α_2 can be then derived as

$$\alpha_2 = (V_M - \alpha_1\beta_1V_{s1}) / (\beta_2V_{s2}). \quad (9)$$

In perspective of small-signal model analysis, if the assumption (9) is put into the $d_{CSF}\alpha_1$ model derived in (5), the model will turn back to the MTSS-based small-signal averaged. It means the ATSS-based $d_{CSF}\alpha_1$ small-signal model is decoupled from the control variable α_1 while the relation between d_{CSF} and α_1 obeys the following simple equation:

$$\alpha_1 = i_1 R_o / (v_c \beta_1 d_{CSF}). \quad (10)$$

Fig. 4. Open-loop control-to-output TFs of the ATSS-based DIBC system with d_{CSF} and a_1 as the control variables while a_2 obeying (9).

As a result, the plant can be expressed as Fig. 4 shows.

It can be easily concluded that the equivalent SISO buck averaged model sourced with V_M used in the MTSS strategy can extend to the ATSS-based d_{CSF} - v_c small-signal model without redesigning its compensator, and on the other hand, the value of a_1 is directly dependent on the value of d_{CSF} .

IV. CURRENT LIMIT AND VOLTAGE REGULATION ATSS-BASED DIBC SYSTEM

For conciseness of the control system design process, the transfer functions of the feedback gain, error amplifier gain, and the sawtooth carrier peak value gain of the PWM generators are neglected since their gains are all set as 1 here, plus they do not have any pole or zero to affect the control property of the system.

As is analyzed above, the ATSS strategy provides the system with two control variables, d_{CSF} and a_1 , that are used to regulate v_o and i_1 , respectively. Here, we do only consider the situation that the load requirement is higher than the power that V_1 can afford and both V_1 and V_2 should be operated to power the load. The power drawn from V_1 is controlled fixed to the presetting reference while V_2 compensates the rest. This is the reason we call it the current limit and voltage regulation approach. In this part, the proposed assumption in (9) is proven in simulation to be able to decouple the original coupled ATSS-based DIBC system into a v_c -independent- i_1 -dominated system in the perspective of the small-signal model analysis. Therefore, the compensator with the same parameters as that used in the MTSS-based v_o -controlled DIBC switched model is applied to the d_{CSF} - v_o closed-loop in the ATSS-based DIBC switched model in Case 4 without redesigning. Meanwhile, the simple straightforward i_1 -regulation compensator $G_{Accp}(s)$ via (10) is utilized, which has the following mathematical form:

$$G_{Accp}(s) = R_o / (\beta_1 d_{CSF} v_c). \quad (11)$$

Its control schematic is shown in Fig. 5. The corresponding circuit and the controller parameters are: $L = 680 \mu\text{H}$, $C_o = 1.5 \text{ mF}$, $V_1 = 20 \text{ V}$, $V_2 = 10 \text{ V}$, $R_o = 2 \Omega$, $N_T = 3$, $N = 8$, $N_1 = N_2 = 4$, $\beta_1 = \beta_2 = 0.5$, $d_{CSF} = 8/15$, $f_{CSF} = 100 \text{ kHz}$, $f = 50 \text{ kHz}$.

It is obviously to see, in this control design, only $G_{Avep}(s)$ has given the original system the extra zeros and poles, which technically modifies the property of the system. As a result, the v_c -controlled- i_1 -limited DIBC system is essentially regulated by one compensator. If $G_{Avep}(s)$ is designed for controlling v_c as illustrated here, then to control i_1 is bound to become the passive and following process by d_{CSF} . If, inversely, to regulate i_1 is considered prior to v_c , then $G_{Avep}(s)$ should be redesigned based on the property of

i_1 rather than v_c . In order to prove the above analysis, its stability and robustness in the v_c -preferred control performance against the sudden changes of the source input voltage (V_1) are tested in the switched model of the ATSS-based DIBC system. The relatively large perturbations ($\pm 20\%$) of V_1 around its steady states are considered in the control performance tests. Fig. 6 shows the dynamic responses of the MTSS-based v_o -controlled DIBC switched model against the step changes of V_1 as ($20 \text{ V} \rightarrow 16 \text{ V} \rightarrow 20 \text{ V} \rightarrow 24 \text{ V} \rightarrow 20 \text{ V}$) with 0.05s-intervals.

From the testing results during the first 0.05s-period, one can see the system was controlled very close to the desired equilibrium point. The output voltage of the DIBC, v_o was well-controlled at 8 V against the step changes of V_1 with maximum 0.003V-undershoot in Fig. 6, and with around 0.01s-response time. As for the input current i_1 , the value was well-limited at 1 A against the step changes of V_1 with the maximum 0.02A-overshoot at 0.2 s because of the straightforward structure design of the i_1 -compensator which depends on d_{CSF} . It proved the above-analyzed passive and following property of i_1 in this v_c -preferred control system.

V. CONCLUSION

Based on the MTSS strategy, a novel TSS strategy for MICs, named ATSS, is proposed, with which, the two control variables: v_o and i_1 are successfully under regulation simultaneously. As for a DIBC example, the proposed coefficient a_1 for adjusting d_{1eff} beyond $\beta_1 d_{CSF}$ allows i_1 limited to the preset reference 1A; the corresponding modulation to a_2 applied to d_{2eff} decouples the voltage-regulation-compensator from the current-regulation-compensator, and vice versa. Simulation results verify the ATSS control theory, and conclude ideal regulation effects and dynamic responses.

In our future work, a) experimental verification will be carried out; b) power conversion efficiency will be improved; c) the number and the sequence of the primary switching functions combined with OR-gate are bound to affect the corresponding source's performance, which is meaningful to be studied; d) system-level energy management based on ATSS strategy is necessary to be implemented.

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Fig. 5. Block diagram of the v_c -closed-loop i_1 -straightforward ATSS-based control system.

Fig. 6. Dynamic responses in the v_c -preferred control system of the ATSS-based DIbC switched model against the step changes of V_1 (20 V $\rightarrow$ 16 V $\rightarrow$ 20 V $\rightarrow$ 24 V $\rightarrow$ 20 V).