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Photovoltaic-Battery Hybrid Power Supply Applied with Advanced-Time-Sharing Switching Technique and Discrete Ripple Correlation Control

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Abstract—Maximum power point tracking (MPPT) is usually desirable in photovoltaic (PV) power applications. The scenario of load demand in excess of power capability that a PV device can provide requires a hybrid power supply (HPS) to employ additional power sources (e.g. AC-line supply or battery power system) for maintaining output voltage regulation (OVR) and MPPT. Such a HPS, in this study, is topologized with a double-input buck conversion circuit which is proven to possess higher efficiency, less component count, lower cost and simpler manipulation, comparing with those conventional parallel-connected single-input single-output converters. Advanced-time-sharing switching (ATSS) scheme for PWM switching function generation is developed and utilized to implement smooth and accurate adjustment to output power produced by power sources, without losing OVR, MPPT, and single-input equivalent circuit analysis convenience. Discrete ripple correlation control is selected to realize MPPT. This paper brings forward the theoretical and mathematical interpretation to the aforementioned procedures as well as the simulation-level verification and performance testing.

Keywords—division multiplexing; multiple-input converters; hybrid system; maximum power point tracking

I. INTRODUCTION

In solar power applications, it is often desirable to track the maximum power point (MPP) of a photovoltaic (PV) array. When the load demand is higher than the power capability of the PV array, a hybrid power supply (HPS) system is required to realize output voltage regulation (OVR) and MPP tracking (MPPT). The additional power source employed in the HPS besides solar power could be an AC-line supply or an energy source device such as a battery bank or an ultra-capacitor bank. Such a HPS should operate through a properly-selected and well-designed power conversion circuit which needs more than one input leg for those power sources.

In the recent decade, multiple-input converters (MICs), topologized as Fig. 1 exhibited (with m -inputs and 1-output), are attracting increasing 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]. In this study, a double-input buck (step-down)

converter (DIBc) ($m = 2$) is utilized to hybridize a battery power system (V_{s1}) and a PV array (V_{s2}).

Time-sharing switching (TSS) technique (or called time division multiplexing technique) is usually used to generate MIC's pulse-width modulation (PWM) switching functions. Generally speaking in HPS control area, more than one switch are allowed to operate within one operating period, T , on the premise of only one of them should conduct at a given instant. With conventional TSS strategies, all switching functions have to share a fixed time interval, inevitably causing switching function coupling [5]. Besides, generation of switching functions in a fixed sharing switching period becomes more difficult as the number of input legs in an MIC increase [6]. In [1], modified-TSS (MTSS) technique was proposed to alleviate the difficulties in controlling and allowing more input legs involved. MTSS transforms the original multiple-input single-output control system into a single-input single-out (SISO) equivalent system for convenience of system analysis and controller design; employs 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 unavailable, which makes an advanced-TSS (ATSS) strategy to control other variable besides the output voltage of a MIC necessary.

Among the several MPPT techniques introduced in the literatures for PV arrays, ripple correlation control (RCC) is well suited for this research because of its simplicity and inexpensiveness in implementation [7]. Discrete RCC (DRCC) uses analog circuits and takes advantage of perturbation that is already present in the system to determine the gradient of a cost function that is considered as its control objective. It does not require any prior information about the PV array characteristics to asymptotically converge to the true MPP, as well as consuming less power to operate in practice [8].

In this paper, a DIBc topology and battery power system are utilized to form a PV-battery HPS with interleaved dual-edge

modulation (IDEM) and ATSS strategy to complete OVR and DRCC-MPPT. The rest of the paper is structured as follows. In Section II, circuitry of the DIbC is briefly introduced. Then ATSS scheme is explained in Section III, combined with MTSS theory. In Section IV, DRCC principle and related functions are extended to ATSS technique, based upon which, simulations are developed in Section V to verify the aforementioned theory and show the HPS's capability and performance. Section VI draws conclusions.

II. CIRCUITRY OF DOUBLE-INPUT BUCK CONVERTER

The DIbC topology used in the HPS is retained from Fig. 1. V_{s1} in the circuit denotes the utilized battery power system while V_{s2} denotes the PV array. In steady-state operation, over one T , the average inductor current must equal to zero. If C is sufficiently large, the output voltage V_o can be assumed to be constant, and the following formula is easily to be obtained through steady-state operation analysis of the system [3],

$$V_o = d_1 V_{s1} + d_2 V_{s2}, \quad (1)$$

where d_1 and d_2 are the EDRs of q_1 and q_2 .

The switching frequency of the DIbC, f is used to find the peak-to-peak inductor current ripple as follows [3],

$$\Delta i_L = (d_1 V_{s1} + d_2 V_{s2}) / (Lf). \quad (2)$$

To design the converter, the peak inductor current, if needed, can be found by using a geometrical approach similar to that used in the DIbC circuitry analysis in [3],

$$i_{Lpeak} = V_o / [R(1 - d_1 - d_2)] + \Delta i_L / 2, \quad (3)$$

where R is the resistive load.

More details are accessible in many MIC-relevant literatures [1-4, 6].

III. ADVANCED-TIME-SHARING SWITCHING STRATEGY

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 :

$$N = 2^{N_T}. \quad (4)$$

The instance connection is given in Fig. , showing 8 switch pulses are recombined to yield 3 switching functions, for an equal number of corresponding input-legs of the MIbC with 3 input sources ($m = 3$). Refer to [1] for more details. Then a share factor is defined as

$$\beta_i = N_i / N, \quad (5)$$

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

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

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} , i.e.

$$d_{ieff} = \beta_i d_{CSF}. \quad (6)$$

MTSS's 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, disabling the practical possibilities in smooth and accurate control on power sharing and budgeting among input sources; in other words, only if infinite switching pulses are generated to the MIC, the power extracted from each input source would be possible to be regulated to any required value, thus, the real input power control scheme would be able to be developed.

There will be m -DOF for the system if a m -sourced MIC topology is applied to the controller design [4]. For DIbC, the DOF is 2, and one of them is utilized for OVR, 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 (6) 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 supposed to be constrained by (5). As such in general, d_{ieff} in (6) can be modified to

$$d_{ieff} = \alpha_i \beta_i d_{CSF}. \quad (7)$$

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. We hereby name it "ATSS" strategy. The corresponding demonstration of the 4:4 switching pulses recombination to the schematic given in Fig. 2 is elucidated in Fig. 3. IDEM is applied to generate the switching function. The principle and features of IDEM technique are referable in [9], while details on theory of ATSS and its relevant control approach are accessible in [5].

IV. DISCRETE RIPPLE CORRELATION CONTROL IN ATSS

RCC uses voltage and current ripples to track the MPP of the PV array under changing atmospheric conditions. Unlike many other MPPT techniques, RCC is simple and inexpensively implemented using analog circuits and does not require any prior information about the PV array characteristics to asymptotically

Fig. 2. Schematic of frequency-division operation and switching-function recombination by using OR-gates.

Fig. 3. Switching pulses recombination of the ATSS strategy based on IDEM with ($N_1 = 4$) and ($N_2 = 4$) for the DIBC system.

converge to the true MPP. The continuous RCC theory, principle, and related equations have already introduced in [7].

However, it will take relative higher power dissipation on analog devices and components to implement the RCC technique with analog circuit. Hence, it is necessary to digitalize it into DRCC technique controlled by low-power micro-controller. By high-frequency sampling, the control law is able to be discretized. From the following function [7]

$$d_{2eff}(t) = -k \int \dot{p}_{s2} \dot{v}_{in2} dt, \quad (8)$$

one can see the PV array's energy function is p_{s2} ; the control variable is d_2 ; the state variable is v_{s2} .

In practice, the time derivative of v_{s2} can be expressed in piecewise linear constant: first a positive value ω_+ then a negative value ω_- . Over a time interval from 0 to T ,

$$\dot{v}_{s2} = \begin{cases} \omega_+ & t \in [0, d_2 T], \\ \omega_- & t \in [d_2 T, T], \end{cases} \quad (9)$$

substituting which into (8) leads to the variation of d_2 in T :

$$d_2(T) = d_2(0) - k\omega_+ [\dot{p}_{s2}(d_2 T) - \dot{p}_{s2}(0)] - k\omega_- [\dot{p}_{s2}(T) - \dot{p}_{s2}(d_2 T)]. \quad (10)$$

If a periodic steady-state condition is possible, it requires

$$\begin{cases} p_{s2}(0) = p_{s2}(T), \\ \omega_+ d_2 + \omega_- (1 - d_2). \end{cases} \quad (11)$$

These relationships (11) can be substituted into (10) to yield a control law of

$$d_2(T) = d_2(0) - k\omega_+ [p_{s2}(d_2 T) - p_{s2}(0)] / (1 - d_2). \quad (12)$$

Just as many approximations have been proposed for the analog RCC law (8), there are possible simplifications for (12). Instead of using a gain on the difference between samples of p_{s2} , use a gain on the sign of the difference. If the actuation is quantized, there may be no practical difference between (12) and

$$d_2(T) = d_2(0) - \hat{k} \text{sgn}[p_{s2}(d_2 T) - p_{s2}(0)]. \quad (13)$$

Thus, the input is adjusted in proportion to the sign of the difference between two samples. In periodic steady-state, a generalization is to hold d_2 constant for several cycles nT , then update d_2 based on two samples within a single cycle,

$$d_2(t_0 + nT) = d_2(t_0) - \hat{k} \text{sgn}\{p_{s2}[t_0 + (n-1+ d_2)T] - p_{s2}[t_0 + (n-1)T]\}. \quad (14)$$

As is discussed, in the ATSS strategy, d_2 is determined by d_{CSF} and α_2 . Since d_{CSF} is derived by OVR compensator and without any direct interaction with α_1 and α_2 , the objective of the control law can be transferred to α_2 as

$$\alpha_2(t_0 + nT) = \alpha_2(t_0) - \hat{k} \operatorname{sgn}\{p_{s2}[t_0 + (n-1+d_2)T] - p_{s2}[t_0 + (n-1)T]\}. \quad (15)$$

We hereby name it “DRCC-ATSS” strategy. The key result of this analysis is that all of the information that is needed to drive the operating point to its optimum can be obtained from two samples per switching period, taken at specific times: when the v_{s2} is at a maximum and when v_{s2} is at a minimum.

The advantages of the ATSS strategy allow us to independently design OVR and MPPT for the HPS. The OVR compensator is applied with a conventional PID controller. As for the DRCC design, n is set to 1 for high-accuracy and high-speed of its control performance.

V. SIMULATION VERIFICATION

We modeled this PV-battery HPS based on the DIBC functioned with OVR and DRCC-ATSS MPPT technique on MATLAB/Simulink platform. Its schematic is given in Fig. 4(a), which consists of 30V-battery-bank model served as V_{s1} , 190W-PV-array model served as V_{s2} , input-capacitor-added DIBC circuit [3], changeable resistive load bank, ATSS switching function generation module ($N = 8$, $N_1 = N_2 = 4$), and controller module. The battery model was taken from the library with its nominal voltage 26 V and rated capacity 10 Ah. The PV array mathematical model was based upon [10], where the parameters of a BP-5170-S solar panel was applied to the model. The panel has 72 cells of such kind of solar panel, and its open circuit voltage, short circuit current, voltage and current of the MPP are respectively 45.2 V, 5.62 A, 36.6 V, and 5.2 A. The internal structure of the controller module is specified in Fig. 4(b). The switching frequency of the system was set to 100 kHz. The initial step size for the DRCC module is set to 0.01. The control law of the DRCC-ATSS approach was programed with MATLAB function module. Several tests were then carried out to verify the control performance, stability, and robustness of the proposed DRCC-ATSS MPPT approach, as well as the OVR compensator.

A. Control Performance Test

We designed the two sources of the HPS power the load together with the output voltage V_o keeping at 8 V on any condition and the second source, PV array always operating at MPP. This can only be available when the output power demand is higher than the maximum power that the PV array can provide. Here, the load R_o was set constant to 0.256 Ω , thus making the output power demand 250 W to satisfy this precondition. The calculated constraints α_1 and α_2 were added to the saturation module in the system model as well (see Fig. 4(b)).

In order to test the steady-state control performance and stability of the HPS, the irradiation for the PV array and the temperature were set to 1000 W/m² and 298 K, respectively. Fig. 5 gives the steady-state results about the electrical characteristics of the PV array and control-related parameters. From the results, one can see that the panel is regulated at its MPP, 197.5 W since the instantaneous power ($v_{s2} \cdot i_{s2}$) passed through the maximum twice in each switching cycle, once while the current was increasing and once while the current was decreasing, which perfectly accords with the DRCC theory [7]. The corresponding averaged voltage and current of the panel were around 37 V and

5.33 A. The values of d_2 , d_{CSF} , α_1 , and α_2 were 0.171, 0.275, 0.81, and 1.24, respectively. It verifies that MPPT for the PV array is able to be realized by applying DRCC technique to ATSS strategy in the DIBC circuit.

B. Stability Test

Fig. 6 gives the steady-state values of the voltage, the current, the power of the sources and the HPS's output. From the results, one can see that V_o was regulated at 8 V while P_{s2} tracked the MPP of the PV array at 197.5 W. The load power demand was 248.1 W and the rest power was compensated by the battery bank P_{s1} . The power conversion efficiency was 82.6%. It proves that the proposed control approach was successful to realize stable and reliable OVR and MPPT of the panel simultaneously in the DRCC-ATSS-based DIBC HPS system.

C. Robustness Test

Finally, the robustness of the HPS system was tested. The relatively large perturbations of the irradiation for the PV array were added. The two step changes of the irradiation for the PV panel were set as (1000 W/m² $\rightarrow$ 750 W/m² $\rightarrow$ 1000 W/m²) at 0.01 s and 0.03 s, respectively, with the rate ramp set to ± 10000 W/(m²·s). Fig. 7 exhibited the HPS's dynamic responses.

In Fig. 7, V_o kept constant at 8 V and its ripple range was limited within ± 0.03 V against irradiation step changes. The settling time to the changes was about 0.015 s. P_{s2} was regulated at its maximum value, 197.5 W under 1000 W/m² and 150.8 W under 750 W/m². P_o kept constant at 248.1 W and its ripple range was limited within ± 2 W against irradiation step changes. P_{s1} compensated 104 W under 1000 W/m² and 151 W under 750 W/m². The results show high-robustness of this HPS system to irradiation perturbations.

VI. CONCLUSION

The advantage of ATSS is that it imports a newly-defined coefficient α to express the power sharing factor of the DIBC based upon the MTSS strategy, which breaks the constraint of the MTSS to single variable control and realize multivariable control without losing any advantage that MTSS contains. The PV/battery HPS system was based upon the ATSS-based DIBC circuit. By taking α_2 as the objective of the control law, the DRCC approach was successful to be applied to the ATSS strategy to realize MPPT of the PV array, simultaneously functioned with OVR via d_{CSF} controlled by the independently-designed compensator. The simulation results about its control performance, stability, and robustness highly supported the aforementioned theory and mathematical deviations, which are positively believed to exhibit highly-valuable information in renewable-energy-related research and pragmatic applications.

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Fig. 4. MATLAB/Simulink models of (a) the PV-battery DIBC HPS functioned with OVR and DRCC-ATSS MPPT and (b) its controller's internal structure.

Fig. 5. Steady-state waveforms of v_{s2} , i_{s2} , p_{s2} , q_2 , d_{CSF} , α_1 , and α_2 in the PV-battery DIBC HPS functioned with OVR and DRCC-ATSS MPPT.

Fig. 6. Regulation waveforms of V_{s1} , V_{s2} , V_o , I_{s1} , I_{s2} , I_o , P_{s1} , P_{s2} , and P_o in the PV-battery DIBC HPS functioned with OVR and DRCC-ATSS MPPT.

Fig. 7. Dynamic responses of V_{s1} , V_{s2} , V_o , I_{s1} , I_{s2} , I_o , P_{s1} , P_{s2} , P_o , d_{CSF} , α_1 , and α_2 in the PV-battery DIBC HPS functioned with OVR and DRCC-ATSS MPPT against the step changes of irradiation ($1000 \text{ W/m}^2 \rightarrow 750 \text{ W/m}^2 \rightarrow 1000 \text{ W/m}^2$).

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