Magnetically-coupled boostforward converter for high efficiency differential power processing systems

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Abstract: This paper proposes a new switching power circuit topology combining a boost converter and a forward one by integrating the inductor. The target application of the proposed scheme is a photovoltaic (PV) power conditioning system which operates according to the differential power processing architecture. The boost converter delivers the main PV string power to the DC-link, and the forward converter handles a portion of the boost inductor's energy to compensate the power difference among the PV panels. Not only the compensation, but also operates the forward converter the distributed maximum power point tracking (DMPPT) control for each PV panel. Since the input of the forward comes through the transformer coupled with the boost converter's inductor instead of the high voltage DC-link, this converter requires no extremely step-down voltage conversion ratios, which give several benefits such as low device stresses and high conversion efficiency. In the paper, analysis and design procedures are presented and a 200-W hardware is implemented to validate the performance of the proposed topology such as the efficiency and DMPPT control.

Keywords: differential power processing, maximum power point tracking, photovoltaic, coupled inductor, boost-forward converter

Classification: Power devices and circuits

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1 Introduction

Recently, many academic and industrial projects for finding some new circuit topology and system architecture of Photovoltaic (PV) Power conditioning Systems (PCS) are under progress in order to use the energy more efficiently. Compared to centralized architectures, distributed methods result in high energy efficiency as well as the excellent ability to control the PV operation against climate change [1]; however, it contains a complex control structure and higher manufacturing costs than that of centralized systems [2, 3, 4]. For the purpose of overcoming the drawbacks, Differential Power Processing (DPP) architecture has been introduced recently as the representative example of hybrid methods, which hold the advantages of small capacity and high efficiency in distributed structure, along with the low cost of the centralized one. Fig. 1(a) shows a conventional PV DPP PCS circuit which has separate flyback and boost converters. The DPP system can be divided into two functions [3, 5]. In first, the high-efficiency boost converter is responsible for the string current of the PV panels in series to transfer the majority of the total PV power to the load through the DC-link. Secondly, the flyback converters in shunt with their own PV panels are responsible for the current difference among the MPPs of PV panels. The flyback converters process a faction of the total PV power, the power capacity can be small. Also, even under a partial shading condition, PV 1 can operate at the small MPP current with the current compensation of the upper flyback converter for the common string current. However, this conventional scheme still suffers from a poor efficiency because the flyback brings the compensating power from the DC-link which passes through the boost converter [3, 6, 7, 8, 9, 10]. For the solution, this paper proposes a magnetically-integrated boostforward converter topology shown in Fig. 1(b). Instead of DC-link coupled flyback converters, forward converters whose input is a low voltage from the secondary windings of the boost coupled inductor, are introduced for the DPP system. In that case, the compensating power does not come from the DC-link but from the boost





inductor directly, thus the efficiency can be improved. Also, the conventional method requires an extreme step-down voltage ratio in the flyback design leading to a large power loss, whereas that of the forward can be relieved due to the moderate step-down design. The proposed circuit, therefore, has high power conversion efficiency without any cost sacrifice.



Fig. 1. PV Differential Power Processing architectures

2 Operating principles

The proposed DPP PCS circuit operates in distributed maximum power point tracking (DMPPT) control in high efficiency under the grid-connection mode, using a low-cost differential power processor (DPP). Each of the DPP forward converters can control the PV module independently. The forward converters and the boost converter share a magnetic core, to bypass the DPP compensating power through the coupled inductor (N_p , N_{f1} , ..., N_{fn} in Fig. 1(b)), not from the DC-link.

In Fig. 1(b), there are three switches. Q_p is the main switch to control boost converter's inductor (L_b) current (identical to the string current). Q_{f1} to Q_{fn} are main switches to control the forward inductor (L_{m_f1} to L_{m_fn}) current. If MPP current of PV1 is lower than that of PV2 current, the forward converter starts to compensate the PV1 current by switching Q_{f1} to match the string current. When switch Q_{f1} turns on, a potential difference is across L_{m_f1} which induces a current. Since for the potential switch, Q_p needs to turn on first, all the switches $Q_p, Q_{f1}, \ldots, Q_{fn}$ must be synchronized and duty ratio of switch Q_p must be greater than those of switches Q_{f1} and Q_{fn} . The voltage and current stresses of the switches are quite lower than that of the flyback, the forward converter has a higher efficiency. Also, the boost diode D_b current stress is reduced because there is no DPP power during the turn-off of Qp. So, the total efficiency is enhanced.

The system is categorized into two groups for steady-state analysis. Boost converter operates as string converter which determines majority of the system power, and forward converter operates as DPP converter which regulates differential power for achieving each PV MPP. Both converters operate under Continuous Conductive Mode (CCM), and all the components are assumed ideal.

Boost converter input is the PV string voltage. The output is connected to DC link for grid-connection. Therefore, the boost duty cycle D_b is fixed as,





$$M_{boost} = \frac{V_{DClink}}{\sum V_{pv}} = \frac{1}{(1 - D_b)} \tag{1}$$

When forward converter input is considered the PV string, the output is each of the PV module voltage. Therefore, forward converter duty ratio $D_{1(n)}$ is fixed as,

$$M_{forward} = \frac{V_{pv(n)}}{\sum V_{pv}} = D_{1(n)} \frac{N_{f(n)}}{N_p}, \quad \text{where } (N_{f(n)} \text{ is } N_{f1}, N_{f2} \dots).$$
(2)

Also, D_b has to be designed larger than D_1 .

3 Design guidelines

Transformer turn ratio is important in the design guidelines. As the secondary turn $(N_{f(n)})$ is smaller, the forward duty ratio becomes bigger. So, there should be a careful design guideline. From (1), boost duty ratio under CCM is,

$$D_b = 1 - \frac{nV_{pv}}{(V_{DC \ Jink})} \quad (n \text{ is the number of } PV \text{ modules}). \tag{3}$$

From (2), forward converter duty ratio under CCM is,

$$D_{1} = \frac{V_{pv}}{NV_{Lb}} = \frac{V_{pv}}{nNV_{pv}} = \frac{1}{nN} \quad \left(N = \frac{N_{f1}}{N_{p}}\right).$$
(4)

Boost converter duty ratio must be greater than forward converter duty ratio, therefore a condition is summarized as follows,

$$D_1 < D_b, \quad then \ \frac{1}{nN} < 1 - \frac{nV_{pv}}{V_{DC_{link}}}, \quad so \ N > \frac{V_{DC_{link}}}{-n(V_{pn}n - V_{DC_{link}})}.$$
 (5)

Fig. 2(a) shows a design graph of eq. (5) in MATLAB. When PV module number n is equal to 2.5, forward winding ratios become the minimum value. As an example in this paper, the integer n is applied to 2, then the criteria of the turn ratio is N > 5/6.



Fig. 2. (a) Transformer turn ratio graph about the number of PV module (b) Depending on the duty, boost converter minimum inductor value

Then, a design condition (6) is applied for CCM boost converter,

$$L_b \ge \frac{D_b (1 - D_b)^2 \frac{(V_{DC_{link}})^2}{P_{out}}}{2f}, \text{ where } P_{out} \text{ is output power, } f \text{ is switching frequency.}$$
(6)





Fig. 2(b) shows the boost converter's minimum inductor value (L_{b_min}) for operating CCM, according to D_b . If duty is 0.33, it is the largest inductor value. Depending on the graph, inductor value is determined as 300 uH.

Also, nth forward converter's inductance is fixed as (7) for CCM operation.

$$L_{m_{f(n)}} \ge \frac{(1-D_1)\frac{v_{pv}}{\Delta I_{pv}}}{2f} \tag{7}$$

 ΔI_{pv} : The current difference between maximum productive current and the corresponding PV module's current

When ΔI_{pv} is 0.4 A, forward converter's marginal inductance is determined to be 906.3 uH. For the hardware, forward converter inductor value was used as 1 mH.

4 Experimental verification

Fig. 3 is the key waveforms of the drain-source signal at each switch in 200-W hardware prototype. In this operation, PV1 is full radiation (or full power) and PV2 is under a shading (small power). From the figure, it can be seen that the Q_{f1} drain-source voltage (Q_{f1_ds}) is complementary to Q_{p_ds} , which means the flyback converter for PV1 is paused due to the higher power than PV2. Whereas, Q_{f2_ds} waveform tells that when Q_{p_ds} turns on, the flyback switch (Q_{f2_ds}) turns on in synchronization in order to compensate the small PV2 current by that of the flyback converter for PV2 module.

Fig. 4(a) is the efficiency measurement results of the boost converter which steps up the PV string voltage to 200 V DC-link under full radiation. The efficiency is 97.8% to 98.8%. Fig. 4(b) is an efficiency comparison between the proposed boost-forward converter and a conventional boost flyback one according to the variation of ΔI_{pv} . It shows that the proposed DPP topology has a higher efficiency than the previous DPP one. If ΔI_{pv} increases further, then the efficiency gap would increase greater because the conventional architecture has longer compensating power route through the flyback converters than that of the secondary coupled forward converters in proposed scheme.

Fig. 5(a) and 5(b) are simulation and hardware waveforms of the MPPT control with the proposed boost-forward DPP PV system. The MPPT algorithm was Perturb-and-Observe, so V_{pv1} has 3-step perturbations with tracking the MPP of 45 V. Likewise, V_{pv2} has 3-step perturbations with tracking the MPP of 30 V.



Fig. 3. Switching waveforms of each switch in the proposed topology hardware











Fig. 5. MPP current and voltage waveforms of the dual PV module DPP systems (V_{PV1} : PV 1 voltage, V_{PV2} : PV 2 voltage, I_{PV1} : PV1 current, I_{PV2} : PV 2 current)

From the figures, it can be seen that the proposed DMPPT controller works successfully to track each of the MPPs of the dual PV simulator (TerraSAS, ELGAR) individually. Also, the proposed topology has a better performance than that of the conventional separate DPP converter type.

5 Conclusion

In this paper, a magnetically-coupled boost-forward multi-output converter topology has been proposed for the photovoltaic differential power processing (DPP) system. Different from previous DPP systems, the proposed scheme has a bypass conduction path through the coupling to reduce the DPP's compensating power source route. From the feature, the topology has a high efficiency of greater than 97%, even under a 0.8-A current compensating condition with 200-W hardware prototype. This paper also proposed the operating principles and the design guidelines for the proposed scheme. By the implementation of the proposed topology hardware, the distributed maximum power point tracking controller was validated and the high efficiency was achieved successfully.

The proposed DPP system can be utilized for other applications such as multistring LED lighting system or battery charge-equalizing system. The efficiency can also be enhanced by applying other high-efficiency DC topology.

