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Three-Port Full-Bridge Converters with Varied Voltage Input for Solar Power Systems

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Abstract: ***A systematic method for deriving three-port converters (TPCs) from the full-bridge converter (FBC) is proposed in this paper. The proposed technique splits the two switching legs of the FBC into two switching cells with different sources and allows a dc bias current in the transformer. By using this systematic technique, a novel full-bridge TPC (FB-FBC) is developed for renewable power system applications which feature simple topologies and control, a reduced no. of devices, and single-stage power conversion between any two of the three ports. The proposed FB-TPC contains of two bidirectional ports and an isolated output port. The main circuit of the converter functions as a buck-boost converter and provides a power flow path between the ports on the primary side. The FB-TPC can adapt to a varied source voltage range, and tight controller over two of the three ports can be achieved while the third port provides the power balance in the system. Also, the energy stored in the leakage inductance of the transformer is utilized to achieve zero-voltage switching for all the primary-side switches. The FB-TPC is analyzed in detail with working principles, design considerations, and a pulse-width modulation scheme (PWM), which aims to decrease the dc bias of the transformer.***

Keywords: Boost-buck, dc-dc converter, full-bridge converter (FBC), Solar power system, three-port converter (TPC).

1. Introduction

Solar power systems, which are capable of harvesting energy from solar cells, fuel cells are establish in many applications such as hybrid electric vehicles, satellites, powering remote communication and traffic lights systems. Since the output power of renewable sources is stochastic and the sources lack energy storage capabilities, energy storage systems such as a battery or a super capacitor are required to improve the system dynamics and steady-state characteristics. A three-port converter (TPC), which can interface with solar sources, storage elements, and loads, simultaneously, is a moral candidate for a renewable power system and has recently attracted increased research interest.

Compared with the conventional solutions that employ multiple converters, the TPC features single-stage conversion between any two of the three ports, higher system efficiency, less components, faster response, compact packaging, and unified power management among the ports with centralized control. As a result of these remarkable merits, many TPCs have been proposed recently for a variety of applications. One way to construct a TPC is to interface several conversion stages to a common dc bus. But this is not an included solution since only a few devices are shared. Power flow control and zero-voltage switching(ZVS) are achieved with phase-shift control between different switching bridges.

Full-bridge TPC (FB-TPC) with single-stage power conversion between any two of the three ports. Furthermore, from a topological viewpoint, because a buck-boost converter is included in the proposed FB-TPC, it can adapt to applications with a varied voltage source range. ZVS of all the primary-side switches can also be achieved with the proposed-TPC. This paper is organized as follows. In Section II, the basic ideas used to generate FB-TPC are proposed. In Section-III, the FB-TPC is analyzed in detail, with operation principles, design considerations, and modulation methods given to verify the proposed method.

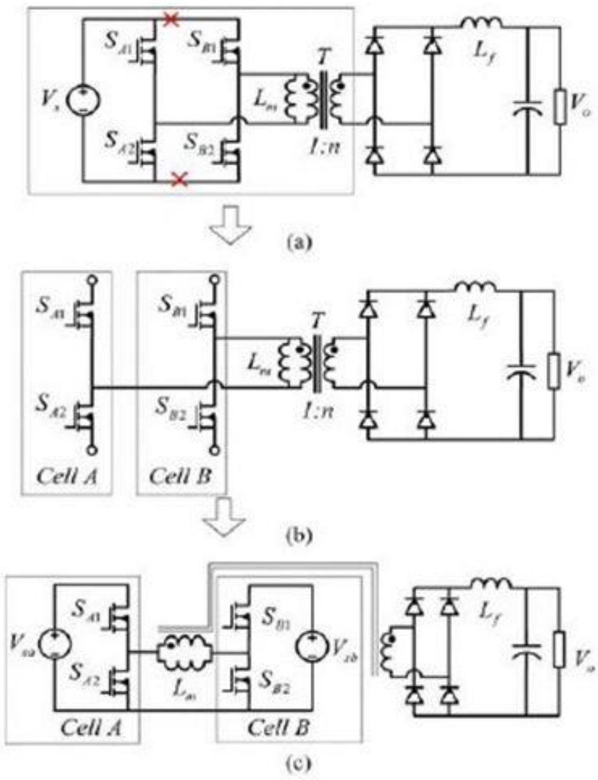

Fig.1 Proposed derivation of full-bridge three-port converter. (a) Full-bridge Converter. (b) Two-switching cells. (c) Three-port Full-bridge converter.

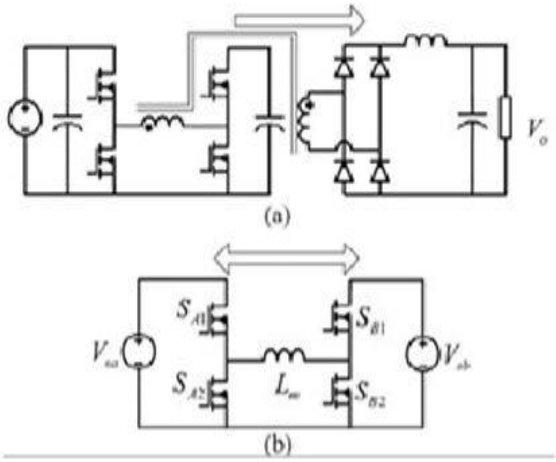

Fig. 2. Equivalent circuits. (a) Between source and load. (b) Between the two sources.

The topology generation method of the FB-TPC is further extended in Section V. Finally, conclusions will be given in Section VI.

2. Derivation Of The FB-TPC From A Full- Bridge Dc-Dc Converter

Referring to Fig. 1(a), the primary side of the FBC consists of two switching legs, collected of SA 1,SA 2 and SB 1,SB 2,in parallel, connected to a common input source Vs.. For the primary side of the FBC, the constraint condition of the operation of the FBC is the voltage-second balance principle of the magnetizing inductor Lm. This means that, from a topological point of view, the two switching legs of the FBC can also be split into two symmetrical parts, cells A and B, if only Lm satisfies the voltage-second balance principle, as shown in Fig. 1(b). The two cells can be connected to different sources, Vsa and Vsb, respectively, as revealed in Fig. 1(c), and then a novel FB-TPC is derived. The voltage of the two sources of the FB-TPC can be arbitrary. Specially, if Vsa always equals Vsb, the two cells can be paralleled directly and then the conventional FBC is derived. Therefore, the FBC can be seen as a special case of the FB-TPC as shown in Fig. 1(c).Close observation shows that the FB-TPC has a symmetrical structure and both Vsa and Vsb can supply power to the load Vo . The equivalent circuit from one of the source ports to the load port is revealed in Fig. 2(a). In addition, a bidirectional buck-boost converter is also included in the primary side of the FB-TPC by employing the magnetizing inductor of the transformer Lm as a filter inductor. Through the bidirectional buck-boost converter, the power flow pathways between the two sources voltage, Vsa and Vsb, can be configured and the power can be transferred between Vsa and Vsb freely. The equivalent circuit among the two sources is illustrated in Fig. 2(b). According to the equivalent circuits shown in Fig. 2, it can be seen that the power flow paths between any two of the three ports, Vsa,Vsb, and Vo, have been assembled. The unique characteristics of the FB-TPC are analyzed and
Summarized as follows.

1) The FB-TPC has two bidirectional ports and one isolated output port. Single-stage power conversion among any two of the three ports is achieved. The FB-TPC is apt for renewable power systems and can be connected with an input source and an energy storage element, such asthe photovoltaic (PV) with a battery backup, or with two energy storage elements, for example the hybrid battery and the super capacitor power system.

2) A buck-boost converter is included in the primary side of the FB-TPC. With the combined converter, the source voltage Vsa can be either higher or lower than Vsb, and vice versa. This shows that the converter allows the sources' voltage varies over a wide range.

3) The devices of the FB-TPC are the similar as the FBC and no additional devices are introduced which means high integration is achieved.

4) The following analysis will specify that all four active switches in the primary side of the FB-TPC can be operated with ZVS by utilizing the energy stored in the leakage inductor of the transformer, whose principle is similar to the phase-shift FBC.

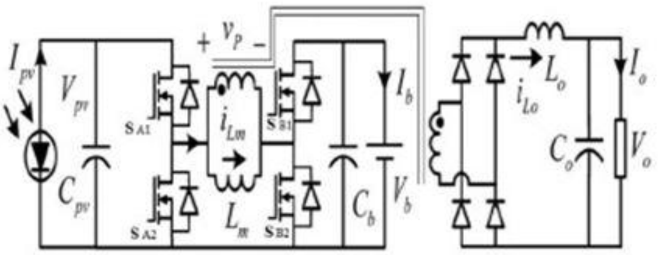

Fig. 3.Topology of the proposed FB-TPC.

3. Analysis Of The Fb-Tpc For The Stand-Alone Solar Power System Application

The FB-TPC, as shown in Fig. 1(b), is applied to a stand-alone PV power system with battery backup to verify the proposed topology. To improved analyze the operation principle, the proposed FB-TPC topology is re-drawn in Fig. 3, the two source ports are connected to a PV source and a battery, respectively, while the output port is linked to a load. There are three power flows in the standalone PV power system 1) from PV to load; 2) from PV to battery; and 3) from battery to load As for the FB-TPC, the load port frequently has to be tightly regulated to meet the load necessities, while the input port from the PV source should implement the maximum power tracking to harvest the most energy. Therefore, the mismatch in power between the PV source and load has to be charged into or discharged from the battery port, which means that in the FB-TPC, two of the three ports would be controlled independently and the third one used for power balance. As a result, two individually controlled variables are necessary.

3.1 Switching State Analysis

Ignoring the power loss in the change,

$$ppv = pb + po(1)$$

Where ppv, pb, and po are the power flows through the PV, battery, and load port, correspondingly. The FB-TPC has three possible operation modes:

dual-output (DO) mode, with ppv ≥ po , the battery absorbs the surplus solar power and both the load and battery take the power from PV;

dual-input (DI) mode, with ppv ≤ po and ppv > 0, the battery discharges to feed the load a long with the PV;

single-input single-output (SISO)mode, with ppv = 0, the battery supplies the load power alone

When ppv = po exactly, the solar supplies the load power alone and the converter operates in a boundary state of DI and DO modes. This state can be treated as DI or DO mode. Since the FB-TPC has a regular structure, the operation of the converter in this state is the same as that of SISO method, where the battery feeds the load alone. The operation ways and power flows of the converter are listed in Table I. The power flow paths/directions of each operation mode have been illustrated in Fig. 4.The switching states in dissimilar operation modes are the same and the difference between these modes are the value and path of iLm, as shown in Fig. 3, which is dependent on the power of ppv and po. In the D_0 mode iLmis positive, in the SISO mode, iLm is negative, and in the DI mode, iL m can either be positive (or) negative. Bring the DO mode as an example to analyze.

Table-I Operation Modes Of The FB-TPC

Operation modes	Power of PV	Power of battery
Dual-output mode	$p_{pv} \geq p_o$	Battery charging, $p_b \geq 0$
Dual-input mode	$p_{pv} \leq p_o, p_{pv} > 0$	Battery discharging, $p_b < 0$
Single-input single-output mode	$p_{pv} = 0$	Battery discharging, $p_b = -p_o$

For simplicity, the following assumptions are made

1) Cpv, Cb, and Co are large enough and the voltages of the three ports, Vpv, Vb, and Vo , are constant during the steady state; and

2) The Vpv≥ Vb case is taken as an example for the switching state analysis. There are four switching section in one switching cycle. The main waveforms and the equivalent circuit in each state are revealed in Figs. 5 and 6, respectively.

State I [t0 –t1]: Before t0, SA 2 and SB 2 are ON and SA 1 and SB 1 are OFF, while iL m freewheels through SA 2 and SB 2. At t0,SA 1 turns ON and SA2 turns OFF. A positive voltage is applied through the transformer's primary winding [see Fig. 6(a)]

a. Modes of Operation

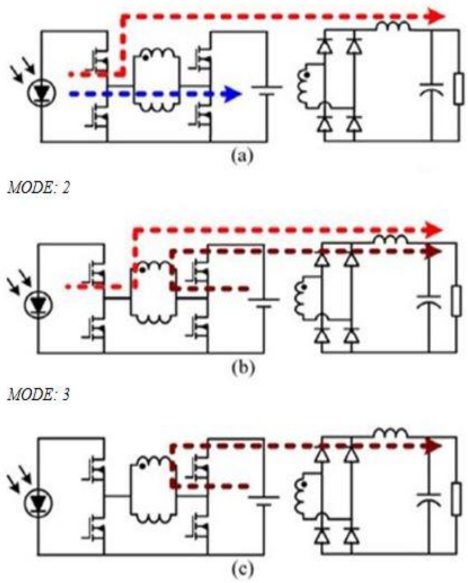

Fig. 4. Power flow paths/directions of each operational mode. (a) DO mode,(b) DI mode,(c) SISO mode.

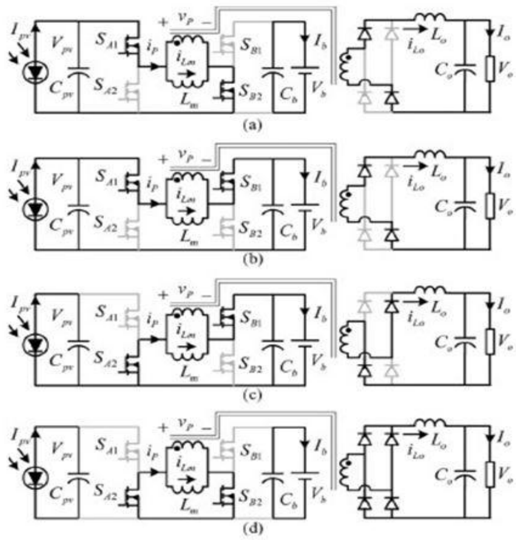

Fig. 5. Equivalent circuits of each switching state. (a) [t0, t1]. (b) [t1, t2],(c) [t2, t3],(d) [t3, t4].

*State II [t1 –t2]:*At *t1, SB* 2 turns OFF and *SB* 1 turns ON. A positive voltage is applied on the primary winding of the transformer [see Fig. 6(b)]

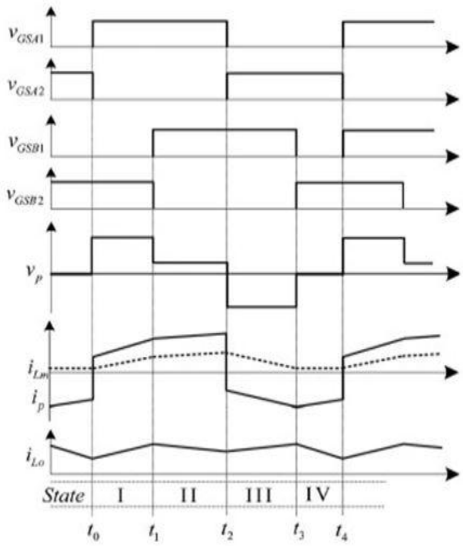

Fig. 6. Key waveforms of the FB-TPC.

State III [t2 –t3]: At t2, SA1 turns OFF and SA2 turns ON. A negative voltage is applied on the primary winding of the transformer [see Fig. 6(c)]

State IV [t3 –t4]: At t3, SB 1 turns OFF and SB 2 turns ON. The voltage across the primary winding is clamped at zero, and iLm freewheels through SA2 and SB 2, [see Fig. 6(d)]

3.2 ZVS Analysis

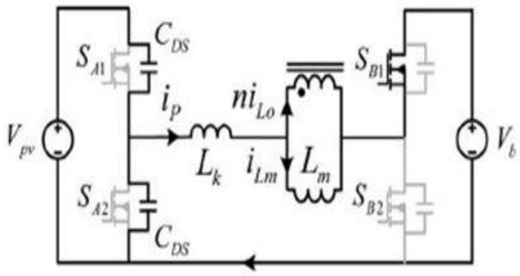

Fig. 7. ZVS analysis of SA2

According to the analysis, the operation of the FB-TPC is similar to the operation of a phase-shift FBC with the two switches SA1 (SB1) and SA2 (SB2), driven with balancing signals. The proposed FB- TPC can utilize the leakage inductance, filter inductance, and the yield capacitors (parasitic drain to source capacitors) of the switches to realize ZVS, zero-voltage turn-on, & zero-voltage turn-off for all the switches. The operation principle is alike to the phase-shift FBC [23], [24]. The only difference is that in the proposed FB-TPC, the magnetizing inductor of the transformer Lm can also help to achieve ZVS of the switches if the direction of iLm is the same as iP. Take SA2 as an example. As shown in Fig. 7, where only the primary circuit is shown for simplicity, considering the leakage inductance Lk , when SB 1 is ON and SA1 is turned OFF, iP = iLm + niLo, the energy stored in Lk and Lm will release to charge or discharge the parasitic drain to source capacitors of SA1 and SA2 . As a result, with a proper dead time, ZVS of SA2 can be achieved if the following condition is satisfied

$$\frac{1}{2}\left[L_k(i_{Lm}+ni_{Lo})^2+L_m i_{Lm}^2\right] > C_{DS}V_b^2.$$

3.3 Design Consideration

As for the semiconductor device stress, the FB-TPC is similar to the old-style FBC. But a key difference between these two converters is that the magnetizing inductance of the transformer Lm is operated as an inductor as well. We also take the Vpv ≥ Vb case as an example for analysis. From (1), in the steady state, is

$$VpvIpv = VbIb + VoIo$$

According to the switching states I and II,

$$Ipv = DA1\ (ILm + nIo)$$

Where *ILmis* the average magnetizing current of the transformer, and therfeore

$$ILm = Ipv/\ DA1 - nIo$$

it can be seen that the larger the *DA1,* the smaller the *ILm*.
According to the switching states II and III,

$$Ib = D2\ (ILm + nIo) - D3\ (ILm - nIo)$$
$$= (DB1 - 2D3)ILm + DB1nIo$$

Formerly the average transformer magnetizing current ILm can also be given by the following equation:

$$ILm = (Ib - DB1nIo)/\ (DB1 - 2D3)$$

D3 is determined by Vb and Vo , therefore, the larger the DB1 the smaller the ILm. It is observed that ILm can be reduced by increasing the nominal values of DA1 and DB 1 ; this result is also valid for the Vpv<Vb case by following the same analysis procedure. Consequently, the value of ILm can be decreased with a properly designed modulation scheme.

4. Simulation Results

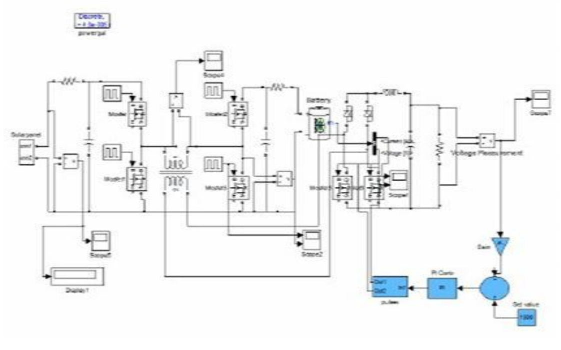

Fig: 8. Simulink model of proposed circuit for R load (closed loop)

In closed loop system, the output will be fed back through the controller to the input. The dc input set to the inductor boost is doubly boost and then given to the resonant cell, which is used to reduce switching losses and diode recovery losses. Then it will given to load, here we are using R load in the closed loop circuit

4.1. Input Voltage

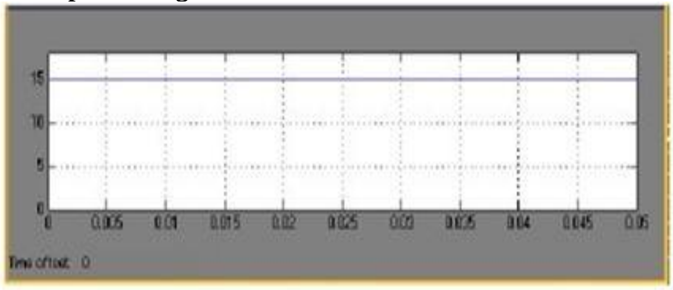

Fig. 9.Vin = *15V (Input voltage)*

The controller used for this circuit is PID circuit. Hence if there is any over distortion or variation in results, the PID controller will given the feedback to input according input varied. It gives better result compared to the open loop R load, since of stable result.

4.2 output voltage

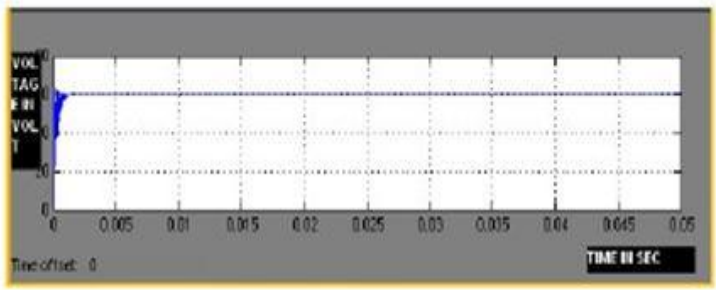

Fig. 10. *Vout = 60V (Output voltage)*

Conclusion

A Full-bridge converter implemented with Three-port Full-bridges has been proposed in this paper. A control method has been presented for achieving soft switching over a wide input range. A PWM control method is applied to the Three- port Full-bridge converter. The particular structure of a boost Full-bridge, interfaces the port having a wide operating voltage, makes it possible to handle voltage variations at this port by adjusting the duty cycle of all the three Full-bridges. With this approach, the operation of the converter is optimized with both current stress and rms loss being reduced. Moreover, soft-switching conditions for all switches are achievable over the entire phase shift region. Control scheme based on multiple PI regulators manages the power flow, regulates the output, and adjusts the duty cycle in response to the varying voltage on the port. Simulation and experimental results were presented, validating the effectiveness of the proposed converter and its control scheme.

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