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A COMPREHENSIVE SURVEY ON MULTI-PORT BIDIRECTIONAL DC-DC CONVERTERS FOR RENEWABLE ENERGY SYSTEMS

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ABSTRACT

Renewable energy sources such as fuel cells, photovoltaic (PV) arrays are increasingly being used in automobiles, residential and commercial buildings. For stand-alone systems energy storage devices are required for backup power and fast dynamic response. A power electronic converter interfaces the sources with the load along with energy storage devices. Existing converters for such applications use a common dc link. High frequency ac-link based systems have recently been explored due to its advantages of reduced part count, reduced size and centralized control. Such a high frequency ac link based converter is termed as a multi-port converter in which ports are connected with the energy sources, energy storage devices and the load. It is desirable to have bi-directional, isolated power flow between energy storage devices and the sources. This paper deals about the multi-port bidirectional converters with different topologies either with voltage fed or current fed structure. Bidirectional power flow between the load port and the energy storage devices are achieved in order to maintain the power balance in the system. The power flow between ports can be controlled by suitable control strategy and phase-shifting the square wave outputs of the bridges in combination with pulse width modulation (PWM) control scheme. Moreover the converter also has high efficiency due to soft-switching operation in all the ports. This paper deals about an elaborate review on bidirectional multi-port dc-dc converters for interfacing the renewable sources.

Keywords: photovoltaic array, bidirectional converter, multi-port structure, soft switching operation, photovoltaic, PWM technique, energy management.

INTRODUCTION

Future renewable energy system will need to interface several energy sources such as photovoltaic array, wind energy conversion system and fuel cells with load along with battery backup (Hariharan Krishna swami and Ned Mohan, 2009). A power electronic converter is used as an interfacing device. Basic dc-dc converters such as buck and boost converters and its derivatives do not have bidirectional power flow capability. This limitation is due to the presence of diodes in their structure which prevents reverse current flow. In general, a unidirectional dc-dc converter can be turned into a bidirectional converter by replacing the diodes with a controllable switch in its structure.

Most of the existing bidirectional dc-dc converters fall into the generic circuit structure illustrated in Figure-1, which is characterized by a current fed or voltage fed on one side (Ramya and Jegathesan, 2011; Venmathi and Ramaprabha, 2013). Bidirectional dc-dc converters allow transfer of power between two dc sources, in either direction based on the placement of the auxiliary energy storage, the bidirectional dc-dc converter can be categorized into buck and boost type. The buck type is to have energy storage placed on the high voltage side, and the boost type is to have it placed on the low voltage side. To realize the double sided power flow in bidirectional dc-dc converters, the switch cell should carry the current on both directions. It is usually implemented with a unidirectional semiconductor power switch such as power MOSFET (Metal oxide semiconductor field effect transistor) or IGBT (Insulated Gate Bipolar Transistor) in parallel with a diode; because the double sided current flow power switch is not available. The control technology in bidirectional converter utilizes mostly pulse width modulation (PWM) control technology (Yamamoto *et al*., 2006; Ray and Romney-Diaz, 1992; Hua and Lee, 1995; Kilders *et al*., 2005; Venkatesan, 1989). Because the hard switching PWM technology leads to the reduced efficiency of converter (Ma and Lee, 1996).

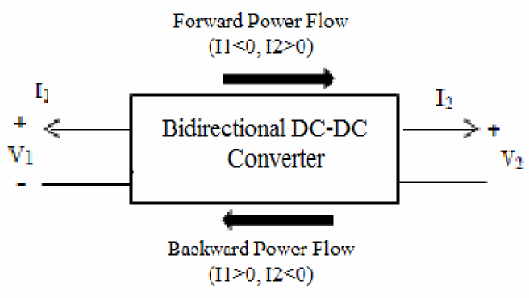

Figure-1. Illustration of bidirectional power flow.

The efficiency, reliability and dynamic performance of the system relies on the operation of the bidirectional converter under different modes of operation, so that individual parts of the system can operate properly. A buck-boost type high performance bidirectional converter is used to charge and discharge the battery. This bidirectional converter is having the following properties which enhance its performance (K. N. Hasan *et al*., 2008), like power flow with large voltage diversity, high step up and step down ratio, soft switching and zero voltage switching, reduced switching losses due to fewer switches, less conduction losses, synchronous rectification, no transformers, no magnetizing current saturation, less weight and volume.

In the past decades, traditional power converter topologies have been evolving in various directions, for example, from single phase to multiphase interleaving and from two levels to multilevel. Nowadays, most dc-dc power converters deal with single input and single output. Recently, attention has been paid to the multi-port converters. Multi-port dc-dc converters are particularly suitable for sustainable energy generation system where diverse sources and storage elements are to be integrated and it can be used in high power application. Compared with the conventional solutions that employ multiple converters, the three port converter features single stage conversion between any two of the three ports, higher system efficiency, fewer components, faster response, compact packaging, and unified power management among the ports with centralized control (Kwasinski, 2011; Jiang and Fahimi, 2009; Jiang and Fahimi, 2011; Tao *et al*., 2008a; Tao *et al.,* 2006). Therefore, multi-port converters are increasingly finding applications in various systems like alternative generation (Tao *et al*., 2005a; Tao *et al*., 2005) Multi-port converter has several ports to which the sources or loads can be connected shown in Figure-2.

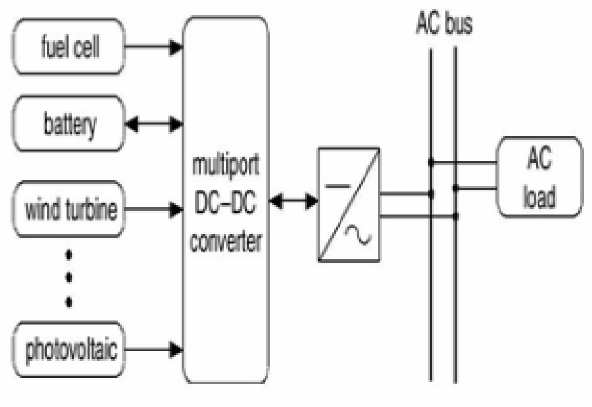

Figure-2. Block diagram of the multi-port structure.

One of the most popular concepts for bidirectional dc-dc converters is the dual active bridge topology (DeDonker *et al*., 1991; Kheraluwala *et al*. 1992; Vangen *et al*., 1992; Peng *et al*., 2004; Xu *et al*., 2004) which utilizes either two full bridges or two half bridges at the primary and secondary sides of a high frequency transformer with phase shift control resulting in flexible power flow control and zero voltage switching (ZVS).

Fuel cell automobiles are considered to be an option for future clean energy automobiles. The primary source will be fuel cells with the power during acceleration and deceleration supplied from batteries. Fuel cells have slow dynamic response and hence energy storage is essential in such an application. Batteries can be charged from fuel cells and during regenerative braking operation.

The advantages of using multi-port structure is that the primary source only needs to be sized according to the average power consumed by the load for a specific application, not necessarily to the peak power. Such operation would avoid oversizing of the primary source and is economically beneficial. Moreover, with the auxiliary storage, not only the system dynamics can be improved, but also the storage acts as a backup energy source in the event of a main source failure. Rooftop solar panels are being widely used to power residential and commercial buildings. Energy storage will be used to store excess power and also as a backup unit to supply vital equipment. Due to cost reasons energy storage is applicable more in off grid applications.

The following sections provide a brief review on the current/voltage fed multi-port converters with different structures.

MULTI-PORT BIDIRECTIONNEL CONVERTER

Multi-port converter has many advantages against conventional structure in terms of the number of power devices and conversion steps which in turn improves the system efficiency was illustrated (Tao *et al*., 2008a). To satisfy the applications where an energy storage element is indispensable, at least one port that connects the storages should be bidirectional. In general, all ports are considered to be bidirectional. Therefore, it is not essential to explicitly distinguish inputs (sources) or outputs (loads). Accordingly, multi-port converter instead of a multi input or multi output converter was used in many applications. Table-1 gives a comparison of the two structures.

Table-1. Comparison of conventional structure and multiport structure.

Category	Conventional structure	Multiport structure
Need a bus common bus	Yes	No
Conversion steps	More than once	Minimized
Control scheme	Separate control	Centralized control
Power flow management	Complicated, slow	Simple, fast
Transformer	Multiple	Single, multi winding
Implementation effort	High	low

The multi-port structure is promising from the viewpoints of low cost, centralized control and compact packaging. However, a multiport converter is complex and there are more design challenges, e.g. the control system. A three-port energy management system can accommodate a primary source and storage, and combines their advantages by utilizing a single power conversion stage to interface the three power ports is shown in Figure-3. Having the two energy inputs, the instantaneous power can be redistributed in the system in a controlled manner. A number of three-port bidirectional dc-dc converters, which utilize this principle, are reported in (Duarte *et al*., 2007; Zhao *et al*., 2008; Tao *et al*., 2008b; Krishna swami and Mohan, 2008; Liu and Li, 2006). Different topologies to obtain the multiport converter are discussed below.

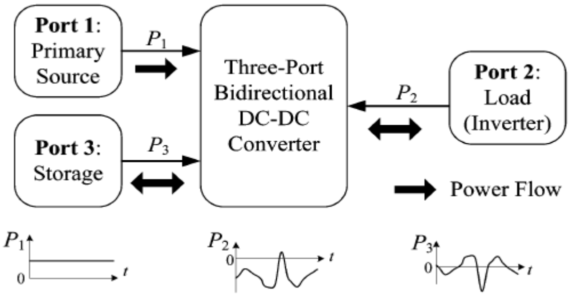

Figure-3. Three-port energy management system.

Full bridge three port converters

A systematic method for deriving three-port converters (TPC) from the full bridge converter (FBC) was proposed in (Hongfei Wu *et al*., 2012). The three port full bridge converter (TP-FBC) was obtained by splitting the two switching legs of the FBC into two switching cells with different sources and allows a dc bias current in the transformer is shown in Figure-4. By using this systematic method, a novel full bridge TPC was developed for renewable power system applications which feature simple topologies and control, a reduced number of devices, and single stage power conversion between any two of the three ports. This FB-TPC consists of two bidirectional ports and an isolated output port. The primary 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 wide source voltage range, and tight control over two of the three ports can be achieved while the third port provides the power balance in the system. Furthermore, the energy stored in the leakage inductance of the transformer is utilized to achieve zero voltage switching for all the primary side switches.

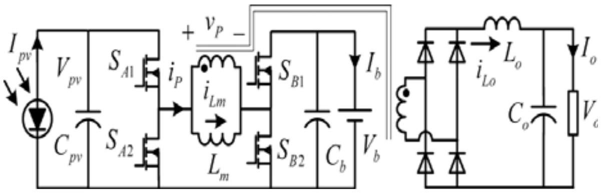

Figure-4. Topology of the full bridge three port converter.

The FB-TPC has three possible operation modes: (1) dual-output (DO) mode, with $P_{PV} \geq$ Po, the battery absorbs the surplus solar power and both the load and battery take the power from PV; (2) dual-input (DI) mode, with $P_{PV} \geq$ Po and $P_{PV} \geq 0$, the battery discharges to feed the load along with the PV; and (3) single-input single-output (SISO) mode, with $P_{PV} = 0$, the battery supplies the load power alone. When P_{PV} = 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 either be treated as DI or DO mode. Since the FB-TPC has a symmetrical structure, the operation of the converter in this state is the same as that of SISO mode, where the battery feeds the load alone. The power management and the control for the TPC were obtained by PWM control scheme. ZVS has also been achieved for all the primary-side switches by utilizing the energy stored in the leakage inductance of the transformer. These result in high conversion efficiency. There are four switching states in one switching cycle. The key wave forms are shown in Figure-5.

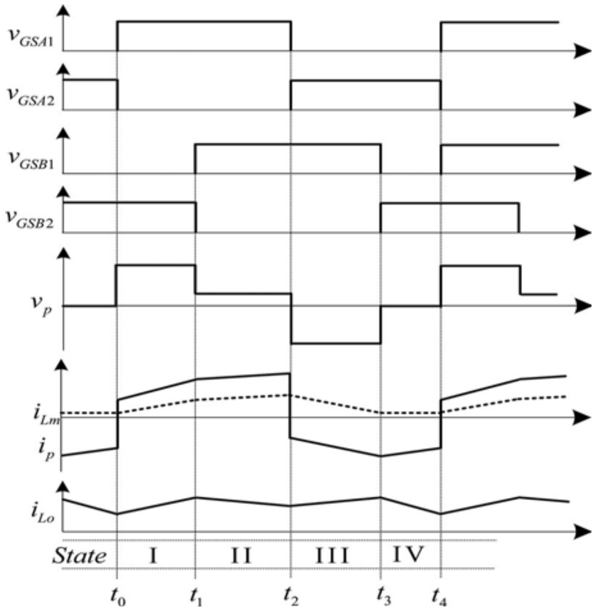

Figure-5. Waveforms of full bridge three port converter in 4 switching states.

These converters offer the advantages of simple topologies and control, reduced number of devices, and a single stage power conversion between any two of the three ports and increase in the output voltage. Whereas it some limitation like while battery discharges to maintain the power balance in the system which increases the conduction losses there by decreasing the efficiency. Moreover Magnetizing inductor of the transformer also functions as a filter inductor and the energy storage ability of the transformer may limit the power rating of FB TPC. When the same topology was applied for high power application another inductor has to be added which in turn degrade the power density of the converter. The conduction losses can be decreased by using half bridge converter.

Three port triple-half-bridge converter

A three-port triple half bridge (THB) bidirectional dc-dc converter topology is proposed in (Tao *et al*., 2008). The topology comprises a high frequency three winding transformer and three half bridges, one of which is a boost half-bridge interfacing a power port with a wide operating voltage. The three half bridges are coupled by the transformer, thereby providing galvanic isolation for all the power ports. The converter is controlled by phase shift, which achieves the primary power flow control, in combination with pulse width modulation. Because of the particular structure of the boost half bridge, voltage variations at the port can be compensated for by operating the boost half-bridge, together with the other two half bridges as shown in Figure-6, at an appropriate duty cycle to keep a constant voltage across the half bridge. The resulting waveforms applied to the transformer windings are asymmetrical due to the automatic volt-seconds balancing of the half bridges. With the PWM control it is possible to reduce the RMS loss and to extend the zero voltage switching operating range to the entire phase shift region.

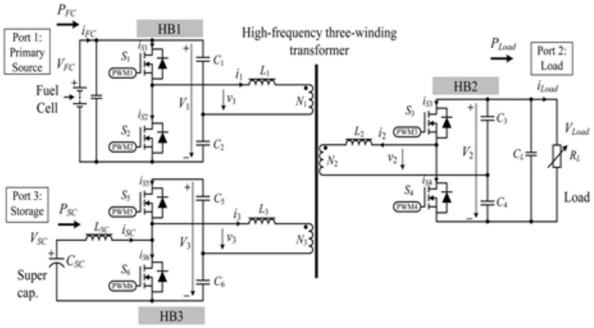

Figure-6. Triple-half-bridge bidirectional dc-dc converter.

In this three-port bidirectional converter interfaces the primary source, load and storage, and manages the power flowing the system. To be capable of integrating the three power ports, the power converter should have the ability of matching different dc voltage levels, have bidirectional power flow, and enable galvanic isolation. In addition to this, soft switching, preferably realized without auxiliary circuits, is desirable in order to increase efficiency. For this THB converter, as long as the dc voltage across each bridge V_1, V_2 and V_3 is kept constant, the operation of the three-port converter is optimal with respect to losses. It is possible to match the different voltage levels of the ports by choosing an appropriate numbers of turns for the windings, given in (1).

$$\frac{V_1}{N_1}=\frac{V_2}{N_2}=\frac{V_3}{N_3} \tag{1}$$

With $V_1 = V_{FC}$, $V_2 = V_{Load}$, $V_3 = V_{SC}/D$, where N_1, N_2 and N_3 and are the numbers of turns of the windings, D denotes the duty cycle of the upper switches S_1, S_3, and S_5 and V_{FC}, V_{SC} and V_{Load} are the voltages of the fuel cell, super capacitor and load, respectively. It is preferable that the fuel cell operates at the maximum power in order to achieve the maximum utilization of the fuel, whereas the load side voltage is regulated. Thus, the operating voltage of V_{FC}, and V_{Load} was assumed to be constant. The operating voltage of the super capacitor, however, varies dynamically in a wide range. This variation can be compensated for by adjusting the duty cycle while keeping V_3 constant and is given in (2).

$$D=\frac{V_{SC}}{V_S} \tag{2}$$

The power flow management and control was obtained by phase shift control in combination with PWM control scheme which is shown in Figure-7, which in turn improves the efficiency. Because of using the current fed structure of the super capacitor ripple current is achieved and ZVS cannot be applied to the converter (current fed ports) when input voltage varies. Hence a three port converter can also be analyzed by using two current fed structures.

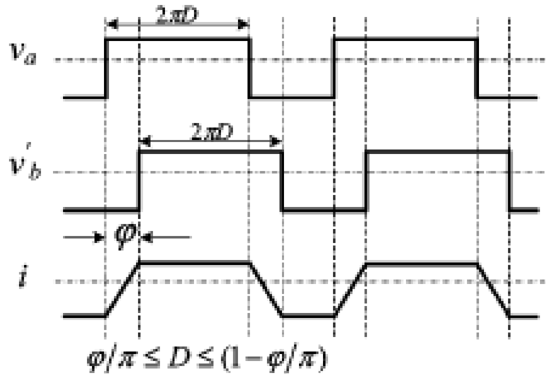

Figure-7. Phase shift and PWM control.

Bidirectional dc-dc converter with two current fed ports

A new asymmetrical duty cycle control method for a three-port bidirectional dc-dc converter with two current fed ports interfacing with low voltage battery and ultra capacitor in a fuel cell vehicle was proposed in (Lei Wang *et al.*, 2012). Along with the phase shift control managing the power flow between the ports, asymmetric duty cycle is applied to each port to maintain a constant DC bus voltage at low voltage side, which as a result will achieve wide zero voltage switching (ZVS) range for each port under varied ultra-capacitor and battery voltages. The ZVS range analyses of different duty cycle control methods as well as the circulation power loss between the ports have been analyzed. In addition, the power flow design featuring the reduced coupling factors between the ports have been developed for the three-port bidirectional dc-dc converter.

Triple half bridges bidirectional dc-dc converters are considered as an appropriate choice to interface the low voltage battery (BU) and ultra capacitor (UC) which contains the current-current-voltage (C-C-V) topology, i.e., two current fed ports and one voltage fed port. Current fed port has the following advantages over voltage fed port when interfacing with energy storage element: (1) smaller current ripple for the BU and UC at steady states; (2)

boosted DC voltage on the transformer primary side reduces the current requirement for isolated transformer design which results in improved transformer efficiency; and (3) the current mode control is available to achieve more control flexibility for this converter, as well as soft current slope for the BU. Therefore, the UC can provide/absorb fast peak power during the load transients, and the BU life cycle can be increased by reducing its current stress. The current mode control can also provide over current protection for the BU and UC and its corresponding interfacing structure is shown in Figure-8.

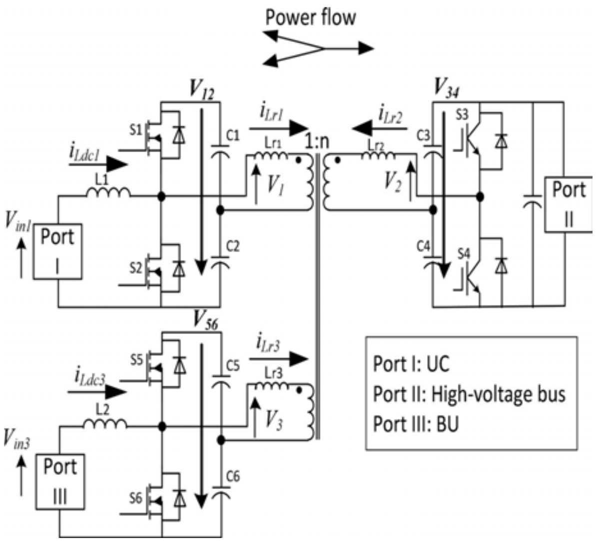

Figure-8. Three port triple half bridge dc-dc converter with two current fed structures.

The power transfer between every two ports in the three-port converter is independent with the third port, and it is the same with the one derived from a two-port converter. Therefore, P_{mk} is given in (3)

$$P_{mk} = \frac{\phi_{mk}\left(\pi - \left|\phi_{mk}\right|\right)}{\pi\omega L_{rmk}} V_m V_k \tag{3}$$

Where m, k (1, 2, 3), P_{mk} is the power between port m and port k, $L_{rm}k$ is the leakage inductance between m and k port, V_m and V_k are the magnitudes of transformer winding voltages. The duty cycle of each half-bridge can be adjusted to control half bridge DC voltage. There are three types of duty cycle control methods for this C-C-V topology; Fixed duty cycle control (FDC), symmetrical duty cycle control (SDC), and asymmetrical duty cycle control (ADC). The Asymmetrical duty cycle is shown in Figure-9. Both battery and ultra capacitor are low voltage devices in this application. With such low input voltages minimizing RMS loss in the system is equally important to achieving a wide range of ZVS. The proposed asymmetrical duty cycle control not only can achieve a wide ZVS range, but also reduce peak current and RMS current resulting in lower RMS loss. In addition, the circulation current exists in the three-port bi-directional dc-dc converter leading to extra RMS loss. The proposed technology can achieve optimum performance for low and variable voltage, high current application. The reduced coupling factor between phase shift control and duty cycle control was also achieved. But when the input voltage of two current fed ports varies in wide range the dc bus voltage of every bridge also varies in a wide range as a result ZVS capabilities will be lost which can be overcome by using voltage fed hybrid converters.

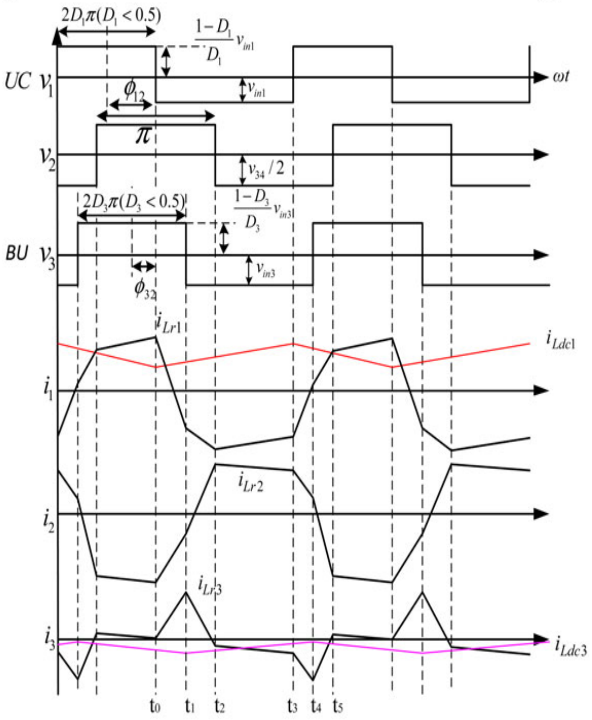

Figure-9. Waveforms of asymmetrical duty cycle control.

Three input dc-dc boost converter

A new three input dc-dc boost converter is proposed in (Farzam Nejabatkhah *et al*., 2012) which interface two unidirectional input power ports and a bidirectional port for a storage element in a unified structure as shown in Figure-10. This converter is interesting for hybridizing alternative energy sources such as PV source, fuel cell (FC) source, and battery. Supplying the output load, charging or discharging the battery can be made by the PV and the FC power sources individually or simultaneously. This proposed structure utilizes only four power switches that are independently controlled with four different duty ratios. Utilizing these duty ratios, tracking the maximum power of the PV source, setting the FC power, controlling the battery power, and regulating the output voltage are provided. Depending on utilization state of the battery, three different power operation modes are defined for the converter. In order to design the converter control system, small signal model is obtained in each operation mode. Due to interactions of converter control loops, decoupling network is used to design separate closed loop controllers.

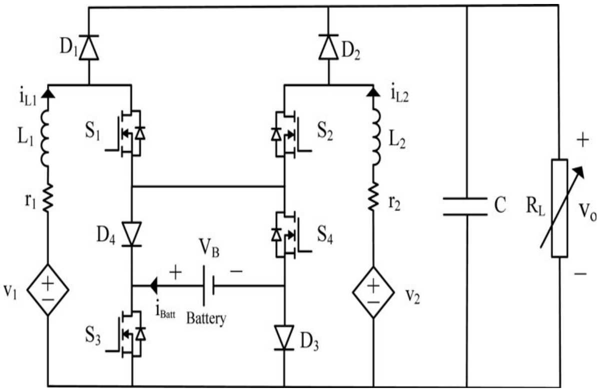

Figure-10. Three input DC-DC boost converter.

This converter can operate in three different power operation modes. Controlling the converter in each operation mode requires different control variables to regulate the powers of input sources and the output voltage. First power operation mode utilizes two active duty ratios, while in the second and third operation modes three different duty ratios are chosen. Therefore, a multi input multi output (MIMO) control system is introduced to the converter. Due to several interaction control loops in the MIMO systems, designing closed-loop controllers for such systems is difficult. However, decoupling network is a proper control method that allows designing separate closed loop controllers for MIMO systems. In order to design closed loop controllers for the proposed MIC, the small signal model of the converter has to be obtained first. This model can demonstrate the converter transient behavior and its stability, and facilitates proper design of the converter controllers. But when it is used to transfer high power switching frequency was reduced which can be overcome by using series resonant tank circuit which has freedom to choose the inductance value independent of the switching frequency.

Three-port series-resonant dc-dc converter

A three-port converter with three active full bridges, two series resonant tanks, and a three-winding transformer is proposed in (Hariharan Krishnaswami and Ned Mohan, 2009) shown in Figure-11. It uses a single power conversion stage with high-frequency link to control power flow between batteries, load, and a renewable source such as fuel cell. The converter has capabilities of bidirectional power flow in the battery and the load port. Use of series resonance aids in high switching frequency operation with realizable component values when compared to existing three-port converter with only inductors. The converter has high efficiency due to soft switching operation in all three bridges. Steady state analysis of the converter is presented to determine the power flow equations, tank currents, and soft switching region. Dynamic analysis is performed to design a closed loop controller that will regulate the load side port voltage and source side port current.

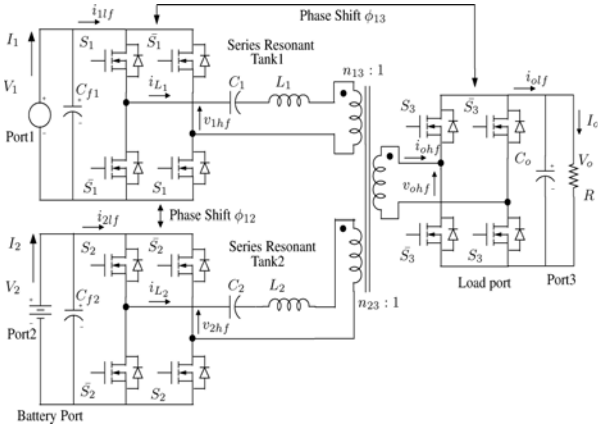

Figure-11. Three port series resonant dc-dc converter.

The output voltage and the primary power flow between the ports are controlled by phase shift in combination with pulse modulation (PWM) which helps in reducing the RMS loss and the zero voltage switching operating range can be extended to the entire phase shift region which is shown in Figure-12.

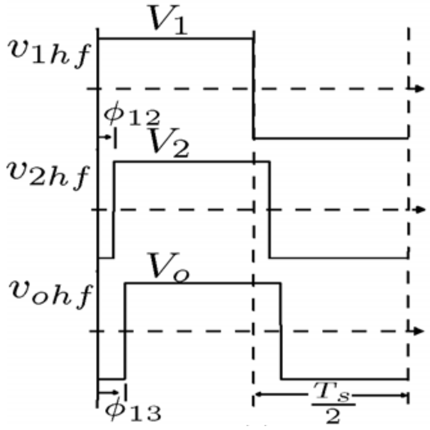

Figure-12. PWM waveforms with phase-shift variables.

Three port bidirectional converters improve the transient response and also ensure the constant power output from the source. The three-port bidirectional series resonant converter has some special features like.

- All ports are bidirectional, including the load port for applications, such as motor loads with regenerative braking.
- Centralized control of power flow by phase shifting the square wave outputs of the three bridges.
- Higher switching frequencies with realizable component values when compared to three-port circuits with only inductors.
- Reduced switching losses due to soft-switching operation. Voltage gain increased by more than two times due to the phase shifting between input and output bridges as opposed to a diode bridge at the load side.

But in this three port series resonant converter the use of too many switches decreases the reliability and performance of the integrated converter.

POWER FLOW IN THREE PORT SYSTEM

The power flow in the three port system has been extensively investigated. A multiport converter integrates diverse sources and would be capable of managing the power flow and other functionality with a sophisticated control strategy. In a practical system, power flow control at each port is implemented to regulate the port current, power or voltage. The power flow can be controlled by proper phase shifts of the voltages applied to the transformer windings. Power is exchanged through the transformer with inductors acting as energy transfer elements.

According to the energy conservation law, the total power generated in the system must be equal to the total power consumed. In other words, the power sourced should be equal to all the power sunk by the ports regardless of system loss, given by (4).

$$\sum_{i=1}^{i=M+N} P_i = 0 \qquad (4)$$

Where P_i is defined as positive when the port is sourcing power and negative when the port is sinking power. Hence at least one of the storages should not be directly regulated in voltage, current, or power. It balances the power flow between the generators and loads automatically as in (5).

$$P_{storage} = -\left(\sum P_{generator} + \sum P_{load}\right) \qquad (5)$$

This is an autonomous system. For instance, in a three-port fuel cell system, the storage matches the load variations while the power of the fuel cell is kept at the same level. In brief, the powers of all the ports except one storage port can be controlled directly by phase shift or duty cycle. To distribute the powers to the generators and loads, the controller needs to set appropriate reference values. By means of magnetic coupling, power flow is controlled by phase shift, whereas by means of dc link, power flow can be regulated by duty cycle.

CONTROL STRATEGY

The control scheme aims to regulate the output voltage and the power of the primary source simultaneously by using the two or three phase shifts as control variables. An arbitrary power flow profile in the system can be achieved by phase shifting the three inverter stages as in the single phase version. The storage supplies/absorbs the transient power difference between the load and the primary source. Since the three-port converter can be viewed as a two input two output first order system, the control system can be implemented with PI regulators based on the dual PI loop control strategy.

Moreover in the three-port system, to draw constant power from the main input source either fuel cell/photovoltaic system while the load power demand varies dynamically. Therefore the storage should sink/ source the transient unbalanced power between the load and the input source automatically. Since the transient load power is hard to predict, the control scheme aims to regulate the output voltage and the source power simultaneously. The proposed controller has two PI feedback loops. There are two independent control variables, namely Φ_{12} and Φ_{13}. With these two angles, any power flow profile in this system can be realised. Figure-13 shows the DSP based control scheme. The output voltage V_{Load} is regulated by Φ_{12}. The input source power P_{FC} is calculated from the measurements of V_{FC} and the average current I_{FC}. The regulation of Φ_{13} keeps the fuel cell power constant. However, the two PI control loops are coupled. The bandwidth voltage control loop is tuned higher than that of the power control loop in order to minimise the interaction and guarantee a fast response to load variations. In addition, merit to the coupling between the SOC and the super capacitor voltage, a SOC manager is integrated in the control scheme by monitoring V_{SC}. For instance, when the super capacitor voltage reaches its limit, by slightly adjusting the fuel cell power reference signal P_{FC}, the control circuit is capable of charging/discharging the super capacitor with an average current.

$$I_{SC} = \frac{P_{FC} - P_{Load}}{V_{SC}} \qquad (6)$$

Where P_{Load} is the power of the load, and I_{SC} and V_{SC} are the current and voltage of the super capacitor, respectively.

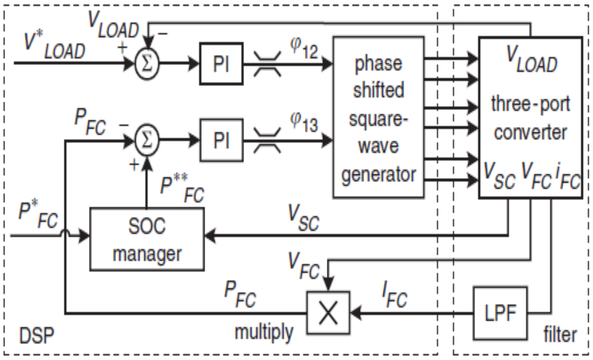

Figure-13. Control scheme for three-port converter.

CONCLUSIONS

A multi-port converter was introduced to interface renewable energy sources and the load, along with energy storage. It was proved that the power flow between ports can be controlled by different topologies of the converters with series resonance and phase shifting the square wave outputs of the active bridges along with the PWM control technique. Each topology has its own limitation. A buck-boost converter which was integrated in the multiport converter configures the power flow path between the two ports on the primary side of the converter, and has capability to handle a wide range of source voltage. ZVS has been achieved for all the primary-side switches by utilizing the energy stored in the leakage inductance of the transformer. With this approach, the operation of the converter is optimized with both current stress and RMS loss being reduced. This results in high conversion efficiency. The converter has bidirectional power flow and soft switching operation capabilities in all ports. Moreover, soft switching conditions for all switches are achievable over the entire phase shift region.

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