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BI-DIRECTIONAL POWER CONTROL USING CONSTANT FREQUENCY HYSTERESIS WITH REDUCED LOSSES

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ABSTRACT
A simple control technique for the bi-directional power flow control between dc source and ac grid is presented. For each 60°of line cycle, the 3-phase bridge is considered as parallel-connected dual buck topology in inverter mode of operation and as a dual boost topology in rectifier mode of operation. Constant frequency hysteresis current control is proposed. Low current distortion and unity power factor are achieved. The magnitude of bi-directional current can be controlled. Simplicity of control circuit, considerable reduction in switching losses with excellent dynamic performance are the salient features of this control technique.

KEY WORDS
Bi-directional power control, hysteresis control, buck topology, boost topology, power system control

1. Introduction

Bi-directional power flow control in a grid interfaced system would be necessary in several areas, the most common application being a regenerative drive system. The power flow in such systems reverses through the front-end grid interface when the machine is braking. In the context of alternative power sources (dc) connected to the grid, such requirements would arise when the dc loads need to be supplied from grid in the event of failure of the alternative source. Increased research efforts have been reported in this area focusing in both, control techniques and circuit topologies.

The approach used in past was to employ back to back connected line frequency thyristor converters [1] in which one converter operates as a rectifier and the second one as an inverter to have bi-directional current flow. In this method the input current has a distorted waveform and power factor is low. Using switched –mode converters the bi-directional power flow with unity power factor can be obtained by controlling the magnitude and phase of the converter voltage [1]. In [2], [3] the authors explain MINNESOTA interface method of 3rd harmonic current injection from the dc source to the neutral of the transformer to obtain a sinusoidal current on ac side with low THD. The generation of the current reference involves calculation of 3rd harmonic and the power circuit contains two controlled switches operated using constant frequency PWM method and a 3-phase line commuted inverter.

Bi-directional power flow control using hysteresis control has been explained in [4]. In this control strategy all the six switches are controlled and the switching frequency is not constant. Using the instantaneous p-q theory, a control method for grid connected dc-ac converter for photovoltaic array, has been discussed [5]. This involves the calculation of instantaneous real and reactive power to generate the current references and the control is using hysteresis control in which all the six switches are controlled at any instant of time. It is well known that the major disadvantage of hysteresis control is the high and variable switching frequencies involved and the consequent high losses.

Constant frequency hysteresis method by controlling all the six switches continuously has been explained for voltage source inverter control [6], [7]. While this makes the system switch at constant frequency, thereby making more efficient use of switching harmonic filters that may be used, losses associated with high switching frequency still persist. Unified constant frequency integration control based on one cycle control has been reported for inverter [8] and rectifier [9] operation of the converter connected between dc source and ac grid. Two switches are controlled at any instant of time. The control structure derivation is, however, involved.

In this paper, constant frequency hysteresis control method is proposed for the bi-directional power flow control (Fig.1). It is shown that, from power flow considerations, the 3-phase bridge configuration may be considered as a dual buck or dual boost configuration, in every 60° interval. It is further shown that these configurations can be controlled simply in a constant frequency hysteresis mode. While control is simple, losses are reduced since only two switches are operated at high frequency at any time. The current on the ac side has low distortion and the system has a good dynamic response. The performance results are presented as simulation studies done using SABER simulator.

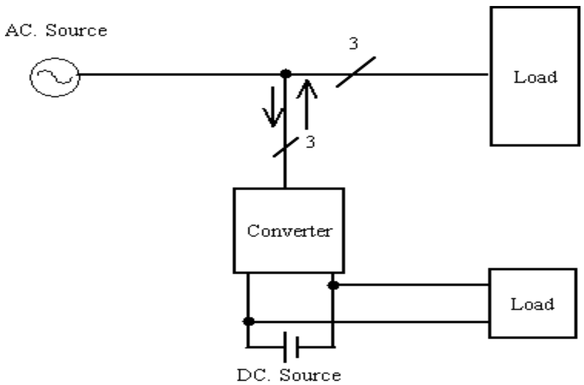

Fig. 1. Bi-directional Power Control

Dual buck and dual boost topologies and their switching patterns are explained in section 2. The proposed controller is presented in section 3 and results are analyzed. Finally conclusion is given in section 4.

2. Analysis of Three Phase Bridge Circuit in Inverter and Rectifier Mode of Operation

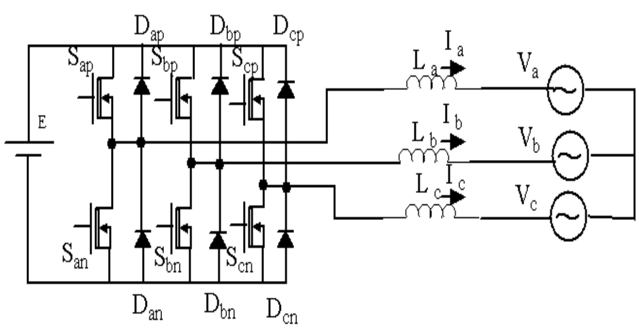

Fig. 2. Three-Phase Bridge Circuit

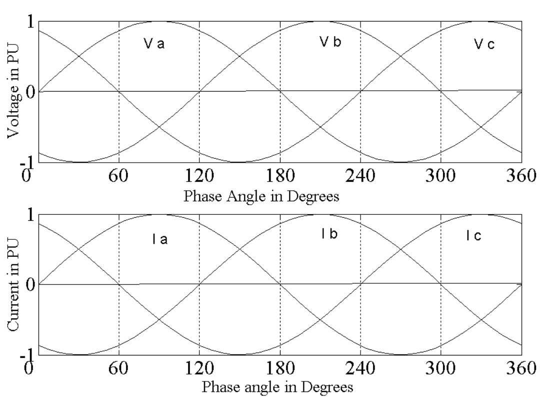

Fig.3 (a) Grid Voltage and injected Current for Inverter Operation

Figure 2 shows the standard 3-phase bridge circuit. The circuit is considered to operate as an inverter or a rectifier interacting with grid, which is represented as voltage source in series with an inductance. Grid interaction is desired at UPF. A three phase three wire system is considered and current directions shown are reference directions for a positive value. When supplying power into the grid at UPF, the current and voltage waveforms (at voltage sources) are shown in Fig. 3(a). The following subsections describe how the topology of the circuit may be simplified to achieve this operation.

A. Inverter mode of Operation

From the grid voltage and injected current polarities, for a power factor angle of 0° (in phase) (Fig.3 (a)), it can be seen that, at any instant of time, the power flows from dc bus to ac grid in all the phases. For example, consider 60º of operation. It may be seen from Fig 3(a) that Ia and Ic are positive while Ib is negative. Controlling the trajectory of Ia and Ic would automatically control that of Ib since the system is 3-wire. Therefore we may conclude that the switch S_{bn} be turned ON to allow for the flow of I_b. Since Ia and Ic are positive, their trajectory may be controlled using switches S_{ap} and S_{cp} alone. This leads to the circuit topology as shown in Fig.3 (b), which is nothing but dual buck converter. Control of the trajectory of Ia and Ic may be simply done using hysteresis control modified for constant frequency operation.

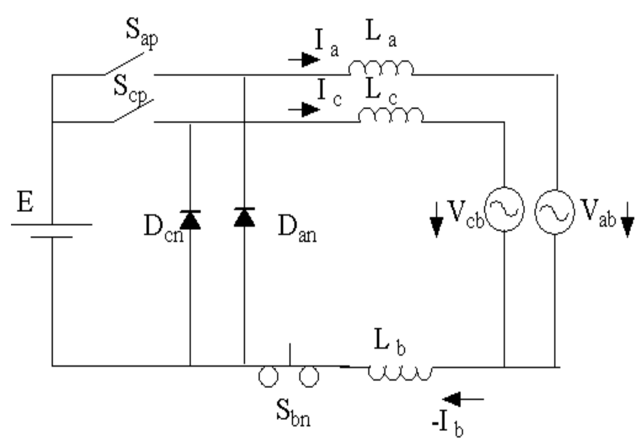

Fig.3 (b) Dual Buck Topology

Similar arguments may be presented for operation in the (60°-120°), (120°-180°), (180°-240°), (240°-300°), and (300°-360°) interval of line cycle and the final switching pattern that emerges is shown in Table 1. Thus we have a switching strategy where only two switches are switched at high frequency at any point of time. This brings down the losses.

Table 1. Switching table for Inverter Operation

Voltage Region	S_{ap}	S_{an}	S_{bp}	S_{bn}	S_{cp}	S_{cn}
(0° – 60°)	C	-	-	ON	C	-
(60° –120°)	ON	-	-	C	-	C
(120° – 180°)	C	-	C	-	-	ON
(180° – 240°)	-	C	ON	-	-	C
(240° – 300°)	-	ON	C	-	C	-
(300° – 360°)	-	C	-	C	ON	-

C → Switch is Controlled, ON → Switch is ON,
- → Switch is OFF

B. Rectifier mode of Operation

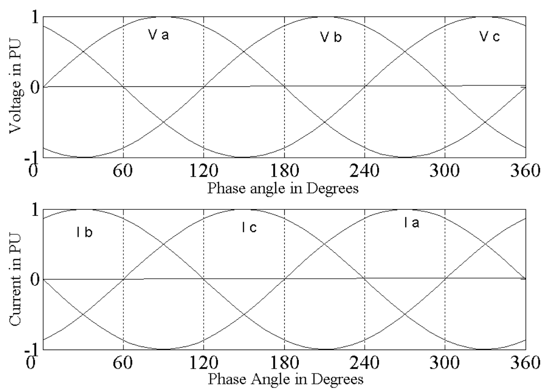

Fig.4 (a) Grid Voltage and injected Current for Rectifier Operation

From the grid voltage and current polarities, for a power factor angle of 180° (lag) (Fig.4 (a)), it can be seen that at any instant of time the power flows from ac grid to dc bus in all the phases. For a 60º of line cycle, it may be seen from Fig. 4(a) that Ia and Ic are negative while Ib is positive. Controlling the trajectory of Ia and Ic would automatically control that of Ib since the system is 3-wire. Since Ia and Ic are negative their trajectory may be controlled using switches S_{an} and S_{cn} alone. The return path for Ib is provided by the freewheeling diode. This leads to the circuit topology as shown in Fig.4 (b), which is called dual boost converter. Control of the trajectory of Ia and Ic may be done using hysteresis control modified for constant frequency operation.

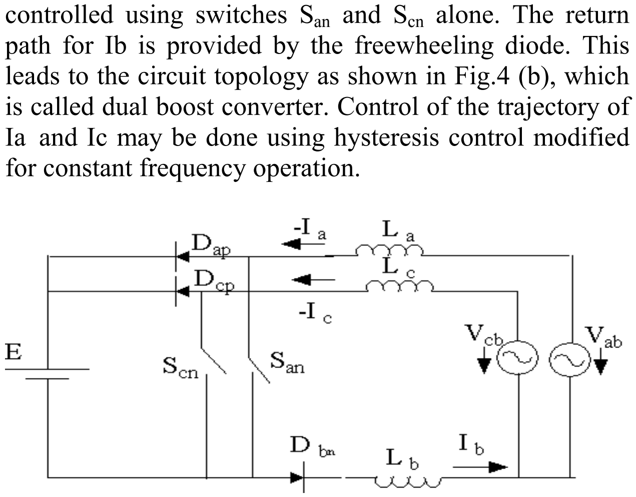

Fig .4(b) Dual Boost Topology

Similar arguments may be presented for operation in the (60°-120°), (120°-180°), (180°-240°), (240°-300°), and (300°-360°) interval of line cycle and the final switching pattern that emerges is shown in Table 2.

Table 2. Switching table for Rectifier Operation

Voltage Region	S_{ap}	S_{an}	S_{bp}	S_{bn}	S_{cp}	S_{cn}
(0º – 60º)	-	C	-	-	-	C
(60º – 120º)	-	-	C	-	C	-
(120º – 180º)	-	C	-	C	-	-
(180º – 240º)	C	-	-	-	C	-
(240º – 300º)	-	-	-	C	-	C
(300º – 360º)	C	-	C	-	-	-

C → Switch is Controlled, - → Switch is OFF

C. The Controlled Switching Algorithm

The switching algorithm for inverter and rectifier mode can be logically combined. Let t_1, t_2, t_3, t_4, t_5, and t_6 represent the region (0º-60º), (60°-120°), (120°-180°), (180°-240°), (240°-300°), and (300°-360°) interval the grid voltage respectively and x represents the mode of operation (x=1 /0=inverter/rectifier) which can be obtained by comparing the dc bus voltage with a reference voltage and x' represent the complement of x.

Control equation for the switch S_{ap} can be derived as given below.

$$S_{ap(c)} = x(t_1 + t_3) + x'(t_4 + t_6) \quad (1)$$

$$S_{ap(on)} = xt_2 \quad (2)$$

$$S_{ap} = S_{ap(c)} + S_{ap(on)} \quad (3)$$

Where $S_{ap(c)}$ is the enabling signal to control the switch S_{ap} at high frequency and Sap $_{(on)}$ is the enabling signal to keep it ON. Final enabling signal to this switch is given by $S_{ap.}$ Similarly the enabling signals to all other switches are derived as follows.

$$S_{an(c)} = x(t_4 + t_6) + x'(t_1 + t_3) \quad (4)$$

$$S_{an(on)} = xt_5 \quad (5)$$

$$S_{an} = S_{an(c)} + S_{an(on)} \quad (6)$$

$$S_{bp(c)} = x(t_3 + t_5) + x'(t_2 + t_6) \quad (7)$$

$$S_{bp(on)} = xt_4 \quad (8)$$

$$S_{bp} = S_{bp(c)} + S_{bp(on)} \quad (9)$$

$$S_{bn(c)} = x(t_2 + t_6) + x'(t_3 + t_5) \quad (10)$$

$$S_{bn(on)} = xt_1 \quad (11)$$

$$S_{bn} = S_{bn(c)} + S_{bn(on)} \tag{12}$$

$$S_{cp(c)} = x(t_1 + t_5) + x^{'}(t_2 + t_4) \tag{13}$$

$$S_{cp(on)} = xt_6 \tag{14}$$

$$S_{cp} = S_{cp(c)} + S_{cp(on)} \tag{15}$$

$$S_{cn(c)} = x(t_2 + t_4) + x^{'}(t_1 + t_5) \tag{16}$$

$$S_{cn(on)} = xt_3 \tag{17}$$

$$S_{cn} = S_{cn(c)} + S_{cn(on)} \tag{18}$$

Output switching circuit is realized using these Boolean expressions.

3. Simulation Study

Simulation studies have been carried out using the SABER simulation package. AC grid voltage is taken as 120 V rms and dc source voltage is taken as 350 V. The triangular signal frequency is taken as 30 kHz and this decides the switching frequency, which is constant. Inductors La, Lb and Lc are selected as 2 mH. DC link capacitor is taken as 470 μF. Hysteresis control technique is used. The system is made to work as inverter / rectifier by choosing appropriate switching algorithm, current reference and $Vdc_{(ref)}$. The injected currents in inverter mode and received currents in rectifier mode are at unity power factor with the grid voltages with minimum distortion. The magnitude of the current can be changed by controlling $Vdc_{(ref)}$.

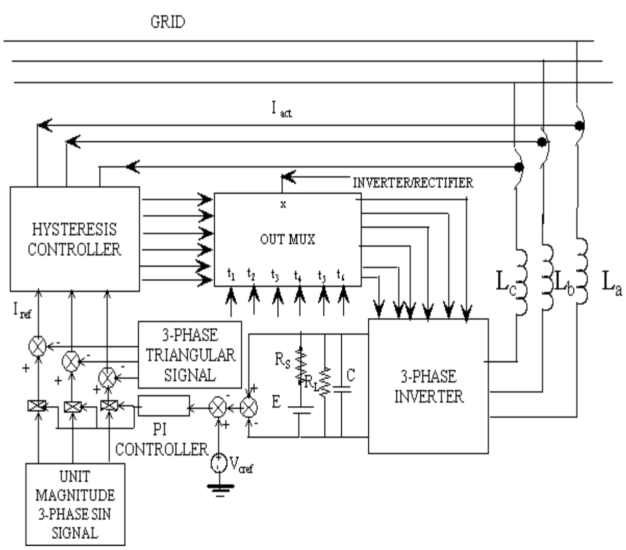

Fig .5. Control Schematic

The schematic of the control scheme is shown in Fig.5. The dc bus voltage is measured and compared with the reference value ($Vdc_{(ref)}$) and the error is given to PI controller. The PI controller output is multiplied with unit magnitude 3-phase sinusoidal signal. 3-phase high frequency triangular wave is subtracted from that to generate the reference current signal (I_{ref}) [6]. Inverter output currents are sensed using current sensors. The Hysteresis controller generates the switching signals and 2% hysteresis band is used. The OUTMUX selects the switching signals based on the Boolean expressions of S_{ap}, S_{an}, S_{bp}, S_{bn}, S_{cp}, and S_{cn} and these are used to control the switching devices. The system has been simulated using SABER. The results are presented in the following sections.

A. Simulation Results

Fig. 6(a), and Fig. 6(b) show the grid voltages and injected currents from dc bus to ac grid for inverter and rectifier operation respectively. It may be noted that in both modes, the operation is at UPF and distortion is minimum.

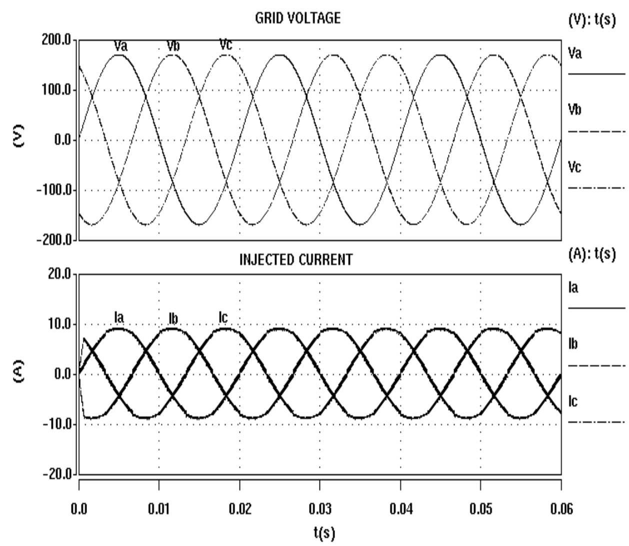

Fig.6 (a) Grid Voltage and injected Currents in Inverter mode

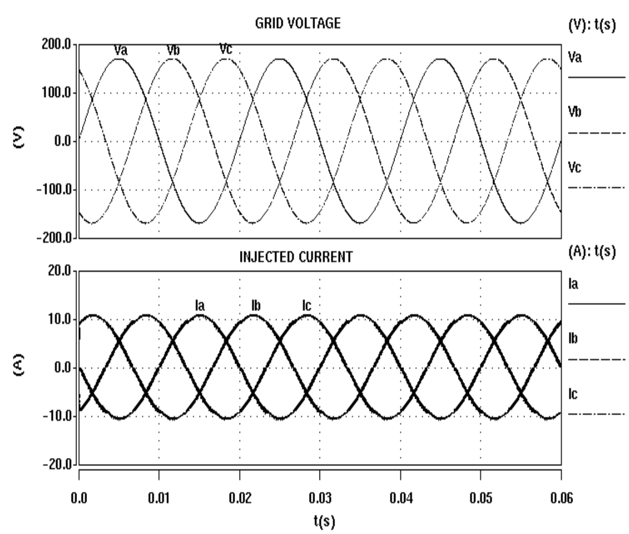

Fig.6 (b) Grid Voltage and injected Currents in Rectifier mode

The switching signal to the switch S_{ap} in inverter and rectifier modes are shown in the Fig. 7. In both cases the switch is controlled at high frequency only for 1/3 period of the line cycle unlike the conventional hysteresis control scheme in which all the six switches are controlled continuously. Thus switching losses would be reduced.

Further it may also be noted that in the rectifier mode the switch is used only for 120^o duration where it is switched at high (constant) frequency. During the remaining time the switch is OFF.

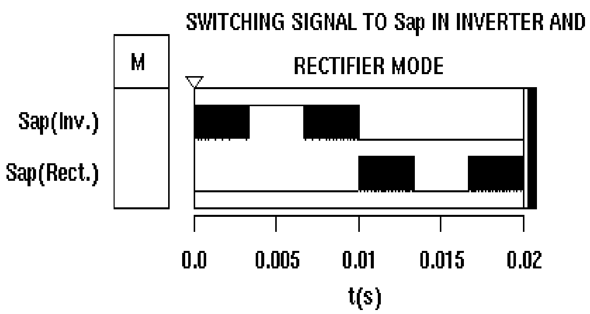

Fig. 7 Switching Signals to the Switch S_{ap} in Inverter and Rectifier mode of Operation.

The device losses for an injected current of 10A(max) in inverter and rectifier mode of operation for modified hysteresis control with constant frequency (proposed algorithm), conventional hysteresis control with constant frequency, and conventional hysteresis control without constant frequency are obtained by simulating these schemes in SABER. The IGBT used is BSP280. Table 3. shows the reduction in losses expressed as a percentage of the losses in conventional hysteresis control (81.6W for the inverter mode of operation and 124.2W for the rectifier mode of operation). While use of constant frequency switching itself increases efficiency, it can be seen that the proposed method further improves it.

Table 3. Reduction in Losses compared to Conventional Hysteresis Control (%)

Mode of operation	Modified hysteresis control with constant frequency	Conventional hysteresis control with constant frequency
Inverter	21.3	9.5
Rectifier	60.8	38.6

4. Conclusion

A simple hysteresis control with constant switching frequency to control the bi-directional power flow between dc source and ac grid is proposed. Switching losses are reduced because only two switches are controlled at any time. Current injected into grid and received from the grid are at UPF in inverter mode and rectifier mode. Current distortion is controllable using hysteresis band. The magnitude of bi-directional current can be controlled. The reduction of switching losses along with simple bi-directional power control makes this scheme attractive for the power control in a grid-interfaced system. Hardware implementation of the scheme is under progress.

References

[1] N.Mohan, Undeland, Robbins, *Power electronics converters, applications and design* (second edition, John Wiley & Sons publication PP 475-500.)

[2] N.Mohan, A Novel approach to minimize Line current Harmonics in Interfacing Power Electronics Equipment with 3-phase Utility Systems, *IEEE Trans. on Power Delivery, Vol.8,* July 1993, pp 1395-1401.

[3] N.Naik, N.Mohan, M.Rogers, Bulawka, A Novel grid interface, optimized for utility-scale applications of photovoltaic, wind-electric and fuel cell systems, *IEEE Trans. on Power Delivery, Vol.10,* Oct.1995, pp 1920-1926.

[4] A.W.Green, J.T Boys, Hysteresis Current-forced three phase voltage sourced reversible rectifiers, *IEE proceedings Vol.136,* May 1998, pp 113-120.

[5] P.G. Borbosa, L.G.B.Rolim, E.H.Wantanabe, R.Hanitsch, Control Strategy for grid-connected DC-AC Converters with load power factor correction, *IEE Proc. Gen., Trans., Distri. , Vol.145* (5), Sept 1998, pp 487-491.

[6] M.Azizur Rahman, Ali M. Osheiba, Azza E.Lashine, Analysis of current Controllers for Voltage-Source Inverter, *IEEE Trans. on Industrial Electronics, Vol.44 (*4), Aug 1997, pp477-485.

[7] David M.Brod, Donald W.Novotny, Current Control of the VSI – PWM Inverters, *IEEE Trans. on Industry Applications, Vol.1A* (21), May1985, pp 562-570.

[8] K.M.Smedley, Chengming Qiao, Three phase Grid Connected Inverter Interface for Alternative Energy Sources with Unified Constant - frequency Integration Control, *Industry Applications Conference, Vol.4,* 2001, pp 2675-2682.

[9] K.M.Smedley, Chengming Qiao, General 3-phase PFC Controller for Rectifiers with parallel connected Dual Boost Topology, *IEEE Trans. on Power Electronics, Vol.17* (6), Nov.2002, pp 925-934.