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RESEARCH ARTICLE

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IMPLEMENTATION OF SEMICONDUCTOR TRANSFORMER FOR POWER QUALITY ENHANCEMENT IN SMART DISTRIBUTION SYSTEM

G. LOKANATH[1], **P.N. AMRUTHA**[2]

[1]PG scholar, EEE Dept., Srikrishnadevaraya University College of Engineering and Technology, Ananthapur, AP-India

[2]Lecturer, EEE Dept., Srikrishnadevaraya University College of Engineering and Technology, Ananthapur, AP-India

G. LOKANATH

P.N. AMRUTHA

ABSTRACT

The electric distribution system have serious power problems, which affect the safe operation of the system. Therefore the power quality plays a prominent role in electrical systems. The conventional quality transformer does not guarantee the quality of power; it can only vary the magnitude of voltage. A Bidirectional Intelligent Semiconductor Transformer (BIST) is introduced where the power quality is of tremendous importance.

The BIST is capable of bidirectional power flow, compensating voltage sags, swell & harmonics, offers input-output isolation, and occupies less space and light in weight. The Space Vector Pulse Width Modulation (SVPWM) inverter is employed for suppressing the harmonics in the BIST. By using the SVPWM technique the dc bus utilization is also improved. As a result one can output the AC voltage of good power quality. The performance evaluation is done in terms of power quality by using MATLAB SIMULINK environment.

Key Words: Bidirectional dc/ac converter, Bidirectional Intelligent Semiconductor Transformer (BIST), High-voltage ac/dc rectifier, hybrid-switching.

I. INTRODUCTION

The transformer is the one of the main component of electric power distribution systems. The configuration of the traditional transformer usually consists of iron core and it made up of aluminium / copper. The transformer oil serves as coolant and dielectric medium. But, in this type of construction significant weight, losses, environmental concerns regarding transformer oil and poor power quality are inherent. The new transformer is designed to overcome these problems. The transformer made of electronic devices that is coil free, self-regulating and capable of correcting power quality problems can be developed.

The complexity of electrical grid is increasing day by day due to enormous use of renewable energy sources. To cope up with this complexity, for reliable operation and better control, in such areas new topologies of grid components are investigated. One such topology is a bidirectional intelligent semiconductor transformer (BIST). Intelligent universal transformer proposed by the EPRI can address the drawback of traditional transformer. The design features include high frequency operation compact size and no mineral oil [1]. Various topologies of these intelligent universal transformers were investigated

[2]. These offers the compensation to voltage sags and have the capability of addressing drawbacks of traditional transformers [1]-[9]. But some of them do not have bidirectional power flow capability. So, these topologies cannot be employed in micro grids and smart grids [1], [5]-[9]. The topology in [3] introduces a solid state transformer with a three stage configuration [2] based on quad active bridge converter. But it has complexity in the control techniques. This topology introduces load isolation, distributed generation and storage. The charge dynamics in the high voltage semiconductors are investigated [4]. Most of the desired topologies are investigated in [5]-[6]. It has accounted for the benefits and the major problems associated with the solid state transformer [6]. The topologies [7]-[9] suffer from large switch counts and low efficiencies. The power factor cannot be controlled n the topologies [10],[11] through they offer the bidirectional power flow. The topology in [12] can address for power quality problems associated with the critical loads but it employs heavy and bulky line frequency transformers. The SST model in [13] has number switches in each single phase module which results in increased losses and poor efficiency. The topologies introduced in [14]-[17] optimal three stage structure. It comprises of ac/dc converter, active bridge dc-dc converter and an inverter. They suffer from heavy turn off losses in the dc/dc stage and complex control. The topology in [18]-[20] employ a LLC converter as a rectifier which offers at high frequency operation at high efficiency.

This paper proposes a bidirectional semiconductor transformer for power quality enhancement. It can be employed in the areas where the power quality is of major importance.

II .HIGH FREQUENCY BIDIRECTIONAL AC/DC CONVERTER

The figure shows the topology of the bidirectional high frequency ac/dc converter which is basically a LLC converter. This high frequency bidirectional ac/dc converter is configured with the help of three half modules connected at the input. These modules are connected in series at the input side to operate under higher voltages at the input side.

This converter converts a single phase voltage of 1.6 KV into rectified voltage of into 120V phase to phase voltage. The IGBT switches are both connected in anti-parallel manner at the input side, so as to cope with the low voltage at the output side, these half bridge modules are connected in shunt.

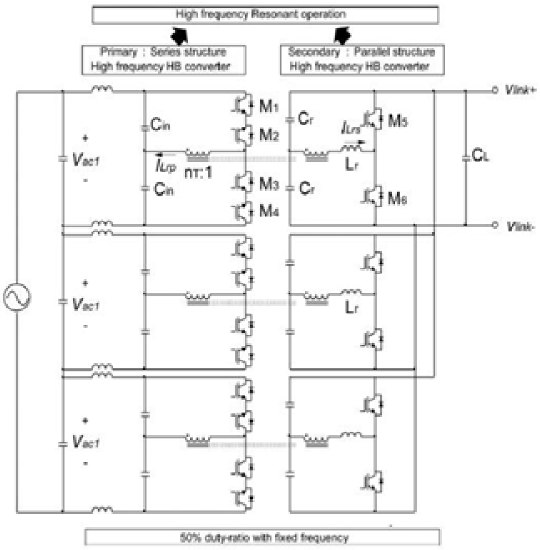

Fig.1 Bidirectional High Frequency AC/DC Converter.

It consists of high frequency transformers to provide high frequency resonance. They also offers better input to output isolation. To reduce the size of the system, switching loss the AC/DC converter is operated at a 50% duty ratio. The resonant stage is a basically a LLC converter.

The LLC resonant converter can operate over a wide range of input voltages at high power density and high power supply efficiencies. Further the zero voltage switching (ZVS) and zero current switching can be achieved through out its operating condition.

The gain of each half bridge module is given by the input given to the each half bridge module $\mathrm{Vac}_1\ \mathrm{Vac} = \frac{\mathrm{Vac}}{3}$. The resonant frequency f_r is equal to switching $\frac{1}{2\pi\sqrt{2\mathrm{LrCr}}}$ resonant inductor L_r and two resonant capacitors C_r .

III. DC/DC CONVERTER: The low-voltage part consists of the dc/dc converter and the dc/ac inverter connected in cascade as shown in Fig. 2. The dc/dc converter changes the full-bridge rectified waveform of 190v peak to peak value into the constant dc voltage of 370 V.

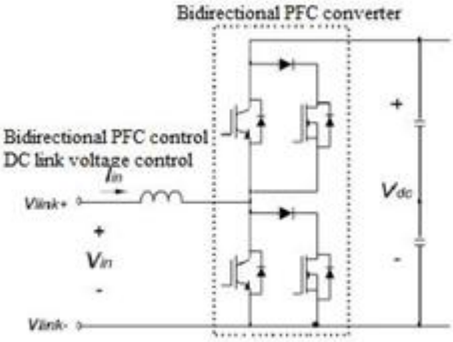

Fig. 2 Configuration of Bidirectional DC/AC converter

The dc/dc converter and dc/ac inverter use a hybrid switch with IGBT and MOSFET connected in parallel. The dc/dc converter and dc/ac inverter are composed of two half-bridges connected in cascade. The dc/dc converter operates to control the power factor and the dc-link voltage, while the dc/ac inverter operates to control the output voltage. As the switching frequency in IGBT increases, the switching loss increases due to tail-current, which critically reduces the system efficiency.

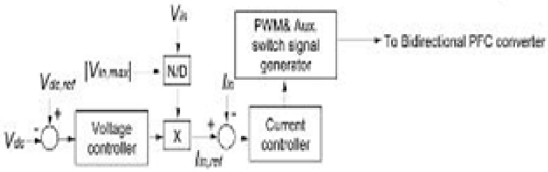

Fig. 3 Control scheme for the bidirectional dc/dc converter

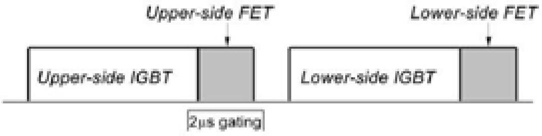

Fig. 4 Gating method for hybrid switch.

In order to improve this switching loss, a MOSFET is connected in parallel to implement a hybrid switch. Fig. 4 shows how to supply the gating signal to the hybrid switch. The MOSFET turns ON a few microseconds ahead when the IGBT switch turns OFF. After the MOSFET turns ON, the IGBT turns OFF immediately and the MOSFET turns OFF at the instant that the IGBT is originally to turn OFF. Hybrid switching offers reduction of recovery loss due to tail-current. If a diode is connected in series with MOSFET, MOSFET destruction due to counter electromotive force can be protected. If resistance is connected in parallel with diode, ringing phenomenon can be reduced

ZERO VOLTAGE SWITCHING (ZVS) OPERATION OF BIST

It is assumed to have infinite magnetizing inductance Lm in the operational mode analysis of BIST, but practically it is not possible. Hence the operational modes are to be analysed more keenly As all operational modes of BIST have similar operation, the ZVS operation is briefly explained for mode 1.

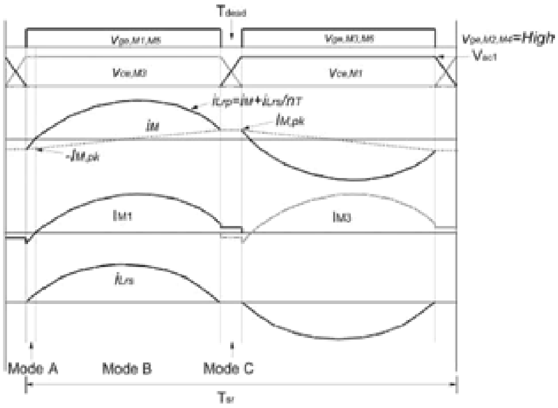

Fig.5 Zero voltage switching operation (ZVS) of mode 1

IV. CONCEPT OF SPACE VECTOR PULSE WIDTH MODULATION INVERTER:

The inverter employed here is a three phase voltage source inverter. Mostly the pulse width modulation (PWM) schemes are employed for this inverter. The major drawback of these PWM techniques is lower dc bus utilization. The space vector modulation technique improves dc bus utilization by 15.5%. This is one of the major advantages of this method.

The structure of a typical three-phase Voltage Source Inverter (VSI) is shown in Fig. 6. The V_a, V_b and V_c are the output voltages of the inverter. Q_1 through Q_6 are the six power transistors that shape the output voltage. These are controlled by a, a', b, b', c and c'. When an upper transistor is switched on (i.e., when a, b or c is 1), the corresponding lower transistor is switched off (i.e., the corresponding a', b' or c' is 0). The on and off states of the upper transistors, Q_1, Q_3 and Q_5 are sufficient to evaluate the output voltage.

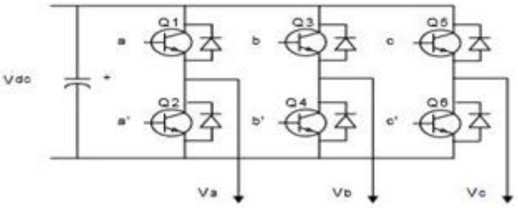

Fig. 6 Three phase voltage source inverter

The relationship between the switching variable vector $[a, b, c]^t$ and the line-to-line output voltage vector $[V_{ab}V_{bc}V_{ca}]^t$ and the phase (line-to-neutral) output voltage vector $[V_aV_bV_c]^t$ is given by equations 1 & 2 below.

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (2)$$

Here the V_{dc} is the DC supply voltage, or bus voltage. There are eight possible combinations of on and off states for the three upper power transistors. The eight combinations and the derived output line-to-line and phase voltages in terms of DC supply voltage V_{dc}, according to equations (1) and (2), are shown in Table 1.

Table 1 Device On/Off States and Corresponding Outputs of a Three-Phase VSI

A	B	C	V_a	V_b	V_c	Vab	Vbc	Vca
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

SVPWM refers to a special way of determining the switching sequence of the upper three power transistors of a three-phase VSI. Assuming d and q are the fixed horizontal and vertical axes. The vector representations of the phase voltages corresponding to the eight combinations can be obtained by applying the following d-q transformation to the phase voltages

$$\text{Tabc-dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & 1 & 0 \end{bmatrix} \qquad (3)$$

This transformation is equivalent to an orthogonal projection of onto[a, b, c]^t the two dimensional plane perpendicular to the vector [1, 1, 1]^t in a three-dimensional coordinate system, the results of which are six non-zero vectors and two zero vectors as shown in Figure . The nonzero vectors form the axes of a hexagonal. The angle between any two adjacent non-zero vectors is 60 degrees. The zero vectors are at the origin and apply zero voltage to a three-phase load. The eight vectors are called the basic Space Vectors and are denoted here by V_0, V_{60}, V_{120}, V_{180}, V_{240}, V_{300}.

The same d-q transformation can be applied to a desired three-phase voltage output to obtain a value of the corresponding line-to-line voltage with the defined d-q transform.

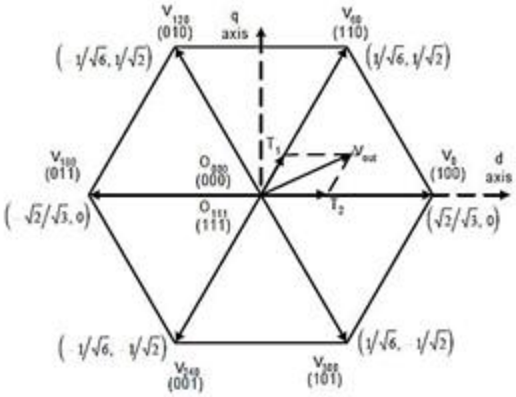

Fig. 7 the Space Vectors Normalized w.r.t. Vdc and Switching States

The advantages of svm are

- Utilization of D.C. link voltage is good and current ripple is low.
- Optimize switching waveforms are flexible.
- Relatively good performance at low modulation ratio.

TRANSFORMER DESIGN

To understand the BIST it is necessary to analyse and derive the expressions. During nth switching period,

The input voltage V_{ac1} [n] = V_{ac1} Sin $\dot{\omega}_n$ T_{sr} ……. (4)

The input voltage V_{link} [n] =V_m Sin $\dot{\omega}_n$ T_{sr}… …. (5)

$\dot{\omega}$ - Angular frequency of V_{ac1}

T_{sr} – switching frequency of resonant converter
n_T- Transformer turns ratio

The resonant waveform can be mathematically expressed as

$i_{Lrp}[n] = \sqrt{2} I_{Lrp,rms}[n] \sin(2\pi f_{sr}(t - (n - 1)T_{sr}) - \phi[n]$..(6)

$i_{Lrs}[n] = (\pi Vac1 \sin(\omega Tsr)/nTR) \sin(2\pi f_{sr}(t - (n - 1)T_{sr}) - \phi[n])$..(7)

where Rb is the effective resistor model of secondary stage

$$R_b = \frac{(Vac\,1.pk/nT^2)}{P_o} \ldots\ldots\ldots\ldots\ldots..(8)$$

Po- output power of each resonant converter. The magnetizing inductance Lm for ZVSoperation is given by

$$L_m = \frac{T_{dead}}{16fsr\,[Ccer\,(Vac\,1) + Cce\,2(nTVac\,1)nT^2]} \ldots\ldots\ldots\ldots\ldots(9)$$

C_{ce1}, C_{ce2} – collector-emitter capacitances of primary and secondary switches respectively.

V.COMPUTER SIMULATION

The computer simulation using MAT LAB/Simulink software is performed to check the technical feasibility of the proposed BIST. The following fig.8 shows the simulation diagram of BIST The fig. 8 show the operation of BIST during forward power flow and power flow reversal. The waveforms of input voltage, current, resonant current at a frequency of 50 KHz, rectified voltage, rectified current, dc link voltage output voltage and output current shown in fig.9 respectively. It can be observed that though the power flow is reversed at 0.1 ms the output voltage and output current waveforms are free from any kind of distortions. It can be observed that the dc link voltage is constant with negligible ripple and is maintained at 370V.

The waveform of input voltage, input current, rectified voltage, rectified current, dc link voltage output voltage and output current shown in fig.10(a) and fig. 10(b) during voltage sag condition under forward power flow and reverse power flow condition.

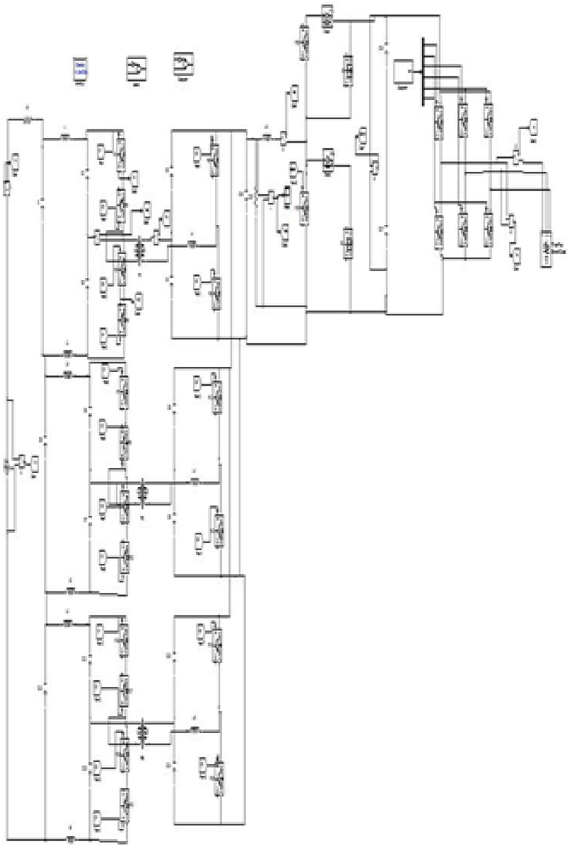

Fig. 8 Simulink model of BIST

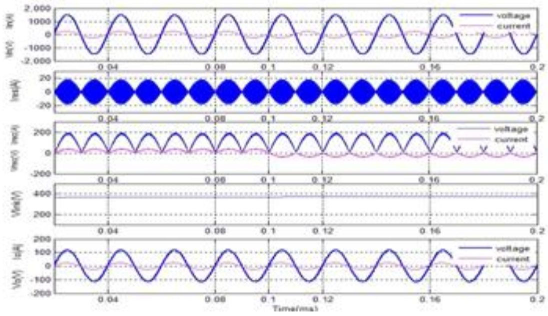

Fig. 9 Simulation analysis of BIST in forward and reverse power flow

It can be observed that the output voltage and output current waves in both the cases (i.e. forward power flow and reverse power flow) are unaffected because the rectified current and input current slightly increases to maintain constant power output.

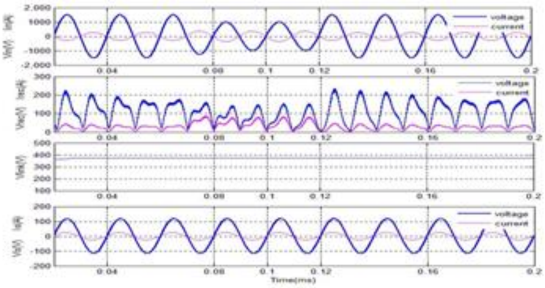

Fig.10 (a) Forward power

Fig 10(b) Reverse power flow

Fig. 10 Simulation analysis against input voltage sag

From the figures 11(a) and 11(b) the voltage output by the BIST with PWM inverter and SVPWM inverter can be compared for the same value of input voltage respectively.

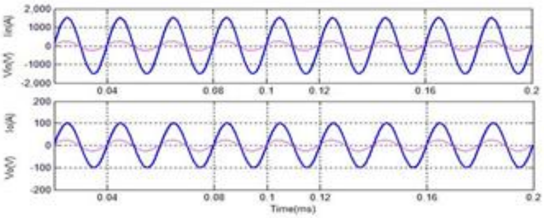

Fig. 11(a)

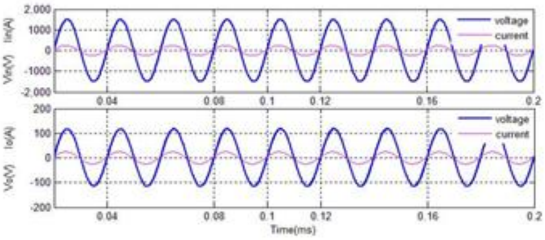

Fig. 11(b)

Fig. 11 Comparison of voltages output by PWM and SVPWM inverters

It can be observed that the voltage output by the BIST with SVPWM inverter is slightly greater than the voltage output by the BIST with PWM inverter for the same value of the given input in both the cases as SVPWM inverter has greater dc bus utilisation factor than PWM inverter.

FFT ANALYSIS

The powergui block can also be used to obtain the frequency spectrum of any signal directly by just clicking the FFT analysis tab. The Fast Fourier Transform (FFT) analysis is used to obtain the frequency spectrum of different waveforms, which are plotted in the form of bar chart between order of harmonics and its magnitude. The FFT analysis is done to study the harmonics of output voltage and current before and after using the SVPWM inverter.

Table 2 Comparison of THD with PWM and SVPWM Inverters

Inverter modulating Technique	THD in Load Voltage (%)
PWM	2.03
SVPWM	0.88

The THD of load voltage by using both PWM and SVPWM are tabulated. The harmonics are reduced in the load voltage by using a SVPWM inverter.

VI.CONCLUSION

In this thesis the concept of a electronic transformer called BIST with new configuration is proposed. It has a rating of 1.6kV/120V. The transformer consists of high voltage ac/dc rectifier, dc/dc converter and a SVPWM inverter. Its Operational feasibility is verified by MATLAB/Simulation.

Though the PWM (Pulse Width Modulation) inverters have better control over output voltage magnitude and result in reduction in magnitude of harmonics, they account for lower magnitude of output voltage. The Space Vector Pulse Width Modulation (SVPWM) Technique can be employed for further reduction of harmonics and total harmonic distortion (THD).

By using the SVPWM technique the THD of the output voltage is reduced to 0.88% from 2.03%.Thus the power quality is further improved. The output voltage is also increased from 100V to 120V.hence the overall efficiency of the BIST is also improved.

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AUTHOR PHOTOS AND BIOGRAPHY

G. Lokanath, received B.Tech (EEE) Degree from JNTU, Anantapuramu in the year 2013. At present pursuing M.Tech in Electrical Power Systems from Srikrishnadevaraya University college of Engineering and Technology, Ananthapuramu, Andhra Pradesh, India.

P.N.Amrutha Lecturer in the Department of Electrical & Electronics Engineering, Sri Krishnadevaraya University college of Engineering and Technology (SKUCET) Anantapuramu, Andhra Pradesh, India. She completed master of technology from JNTU Ananthapuramu and her areas of interest is power system operation and control, Power system stability, Renewable energy resources.