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A New Control Strategy for Bidirectional Solid State Transformer

Idu Nowshad[1], Raji Krishna[2]

PG Student [Power System and Control], Dept. of EE, Govt. Engg College BartonHill, Trivandrum, Kerala, India[1]

Assistant Professor, Dept of EE, Govt. Engg College BartonHill, Trivandrum, Kerala, India[2]

ABSTRACT: In this paper a new bidirectional solid state transformer with a new control strategy was proposed for smart grid and smart distribution system. The potential to use SST's as enabling technology for smart grid functionalities in electric distribution is much higher. The proposed system consists of a high voltage part and a low voltage part. High voltage part is composed of several half bridge ac/dc converters connected in series through high frequency transformer to cope with high input voltage, while low voltage part is composed of bidirectional half bridge dc/dc converter and dc/ac inverter.

The characteristics of the proposed system are isolation of input output side with high frequency transformer, compensation of voltage swell and sag, bidirectional power flow capability, reduced size and weight, power factor correction and a three phase structure can be realized from three single phase modules. A simulation model of the proposed system along with control strategies was done in MATLAB to check the feasibility of the system.

KEYWORDS: Solid state transformer(SST),High frequency (HF) transformer,Total harmonic distortion (THD).

I. INTRODUCTION

Conventional transformer do not satisfy the requirement of modern grid innovations,so to overcome the problems associated with conventional transformer, bidirectional solid state transformer was proposed. There is a greater demand of power quality and distribution automation in current power utilization scenario; which can be met by smart grid. Smart grid is a modernized electric grid that uses analog or digital information & communication technology to gather information in an automated fashion to improve efficiency,reliability, sustainability of production and distribution of electricity. The problems faced by conventional transformer are reduced power quality, pollution, inability to change the frequency of output voltage etc. A conventional transformer lack energy storage capability and thus the output load can be easily interrupted due to the disturbance at the input source. Similiarly when the output load current generates disturbances such as load transients, harmonics and reactive power, conventional transformer reflects them back to input side.

SST is an element /component consisted of multistage power electronic converters isolated with high frequency transformer, proposed in National Science Foundation (NSF) generation -3 engineering research center(ERC). SST provides ports for the proper integration of distributed energy resources and distributed energy storage, thus enhancing the reliability of the distribution system[1]. Besides the advantage of its reduced size and weight due to its high frequency (HF) transformer[2], the SST makes use of state-of- the-art Power Electronics devices that allows it to provide additional functionalities such as on-demand reactive power support to grid, power quality, current limiting, storage management and a DC bus for end use[3][10]. Poor load power factor and harmonics are isolated from the distribution system, thus improving the overall system efficiency. There are numerous SST topologies, most of them is having unidirectional power flow, so its application in dc distribution and micro grid is limited[7][11].

The paper [1] proposes an Intelligent universal transformer (IUT) circuit,which consists of a set of back-to-back interconnected multilevel converters to serve as both active front- end (AFE) ac/dc and dc/dc converters, a high frequency transformer, and a dc/ac inverter . The input can be tied to high-voltage distribution system, and the output can be tied to low-voltage household applications.The development of a SST based on QAB converter, to integrate distribution generation & storage was done in [4].In that paper QAB converter is used in the implementation of SST dc-

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dc stage,provides isolation for distribution generation & storage through a single four winding HF transformer and control design involves the analysis of only a single converter.Since SST considered here includes grid, load, PV & storage, a four port dc-dc converter as quad active bridge converter is required.In [9] the design of HF transformer isolated bidirectional dc-dc converter modules connected in input series and output parallel for 20 kVA is explained.Input series output parallel structure enables the use of low voltage MOSFET .Phase shift dual active bridge(DAB) converter is used to achieve high frequency galvanic isolation, bidirectional power flow. An adaptive inductor have been introduced as main energy transfer element of phase shift DAB converter.

In this paper a new bidirectional solid state transformer is proposed for smart distribution system and smart grid.The proportional integral controllers along with pulse with modulation technique is used as a new control method. The converters are designed and simulated in MATLAB/Simulink platform to validate the design.

II. PROPOSED SEMICONDUCTOR TRANSFORMER

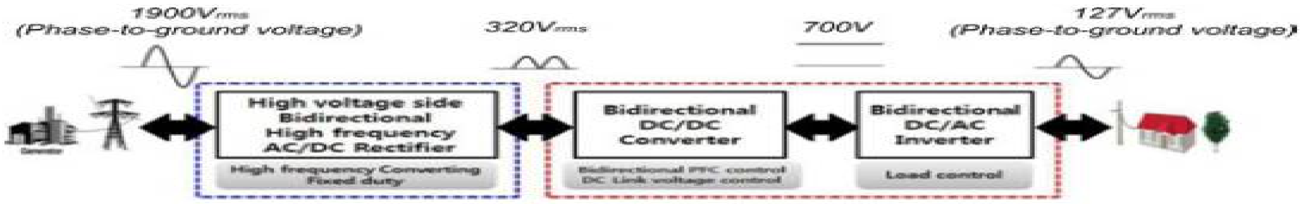

Fig. 1. Conceptual diagram of proposed solid state transformer

Fig. 1 shows a conceptual diagram of the proposed SST which is composed of a bidirectional ac/dc resonant converter, dc/dc converter, and dc/ac converter. In the proposed SST, a single phase input voltage of 1900 V is converted to a full-bridge-rectified voltage of 320 V through the bidirectional ac/dc resonant converter with a fixed duty ratio. The full-bridge-rectified voltage is converted to the constant dc voltage of 700 V through the bidirectional dc/dc converter with a variable duty ratio. The constant dc voltage is converted into a single-phase voltage of 127 V through the bidirectional dc/ac converter. One key issue of SST is system efficiency. The dc/dc converter and dc/ac converter operate in a hard-switching pattern, while the ac/dc resonant converter operates in a soft-switching.

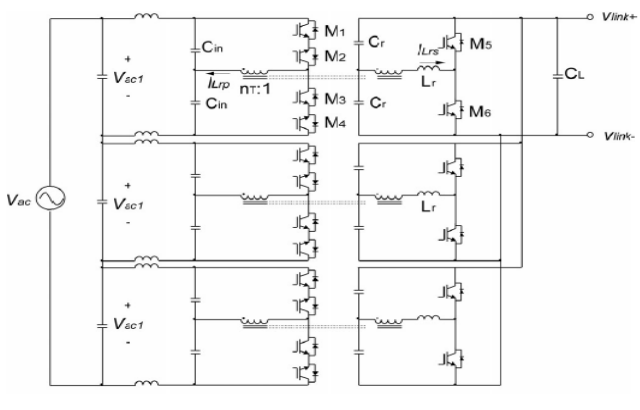

Fig. 2. High frequency rectifier

The power circuit of the rectifier part is shown in Fig. 2. The single phase AC voltage of 1900 V is converted into full bridge rectified waveform of 320 V The ac/dc converter has high-frequency transformers, which offer high-frequency

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resonance and input– output isolation .since the input side is having high voltage ,it is designed with series connected half bridge modules. The low voltage output side is having three half bridge modules connected in shunt. Input to output gain of each resonant converter, that is defined by *v* link /|vac1|, is determined only by its transformer turns-ratio *nT*if the resonant frequency *fr*is equal to the switching frequency *f*sr, where *v*ac1 is the input voltage of each resonant stage and it is equal to *v*ac/3. Since the input and output filter capacitors of *C*in and *CL* are much larger than *Cr* and parasitic capacitances of switches are much smaller than *Cr*, the resonant frequency *fr* which is equal to *f*sr is calculated as 1/[2*π*(2*LrCr*)0.5] with resonant inductor *Lr*and two resonant capacitors of *Cr* . Fig. 3 shows the switching pulses for each switch in a single-module of the bidirectional high-frequency ac/dc converter according to the polarity of the ac input voltage.The magnetizing inductance *Lm* is assumed to be infinity.

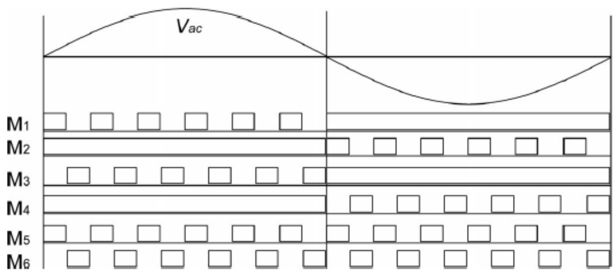

Fig. 3. Waveforms of switching pulse for high frequency ac-dc converter

THE DIFFERENT MODES OF OPERATION OF HIGH FREQUENCY AC-DC CONVERTER IS EXPLAINED BELOW:

Mode 1

The direction of power flow is forward and the polarity of input voltage is positive as shown in Fig. 4(a). In the first stage, the primary current flows through the transistor in*M*1 and the diode in *M*2 when *M*1 turns ON. At this instance,the secondary current flows through diode in *M*5 . In the next stage, the primary current flows through the transistor in *M*3 and the diode in *M*4 when *M*3 turns ON. At this instance, the secondary current flows through the diode in *M*6 .

Mode 2

The direction of power flow is forward and the polarity of input voltage is negative as shown in Fig. 4(b). In the first stage, the primary current flows through the transistor in *M*2 and the diode in *M*1 when *M*2 turns ON. At this instance, the secondary current flows through diode in *M*6. In the next stage, the primary current flows through the transistor in *M*4 and the diode in *M*3 when *M*4 turns ON. At this instance, the secondary current flows through the diode in *M*5 .

Mode 3

The direction of power flow is backward and the polarity of input voltage is positive as shown in Fig. 4(c). In the first stage, the secondary current flows through transistor in *M*5 when *M*5 turns ON. At this instance, the primary current flows through the diode in *M*1 and the transistor in *M*2 . In the next stage, the secondary current flows through the transistor in *M*6 when *M*6 turns ON. At this instance, the primary current flows through the diode in *M*3 and the transistor in *M*4 .

Mode 4

The direction of power flow is backward and thepolarity of input voltage is negative as shown in Fig. 4(d). In thefirststage, the secondary current flows through transistor in*M*6when *M*6 turns ON. At this instance, the primary current flows through the transistor in *M*1 and the diode in *M*2 . In the nextstage, the secondary current flows through the transistor in *M*5 when *M*5 turns ON. At this instance, the primary current flows through the transistor in *M*3 and the diode in *M*4 .

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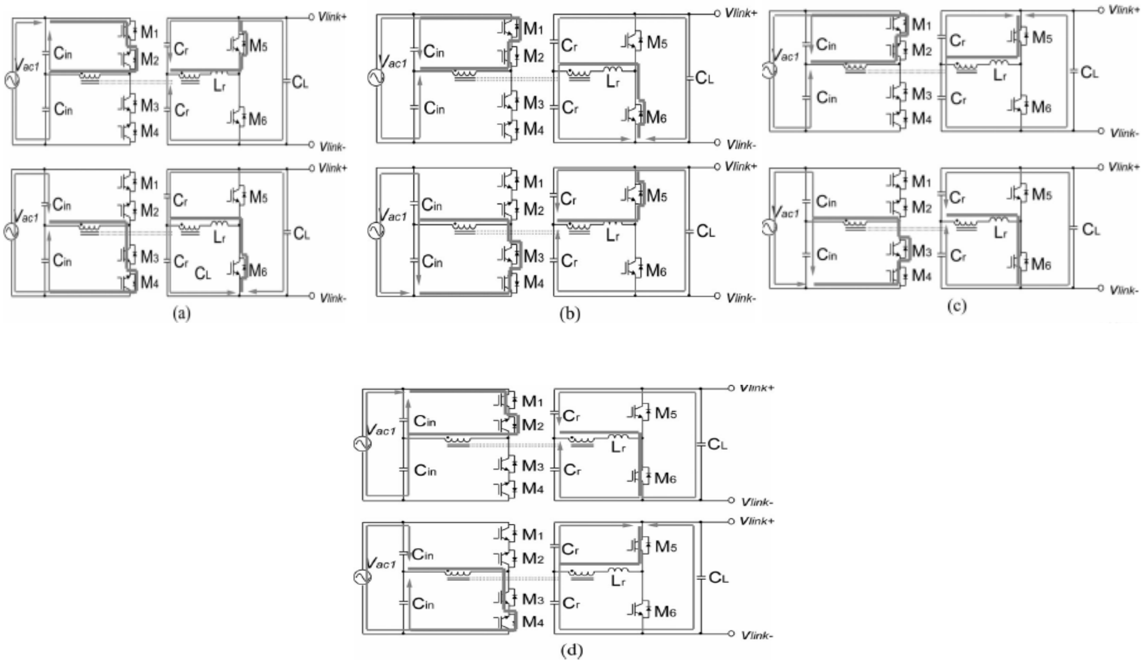

Fig. 4.Current path for each operation mode in the ac/dc rectifier. (a) Mode 1:forward power flow positive input voltage. (b) Mode 2: forward power flow negative input voltage. (c) Mode 3: Reverse power flow positive input voltage.(d) Mode 4: Reverse power flow negative input voltage.

The low voltage part of the proposed semiconductor transformer consists of a dc-dc converter and an inverter is shown in the Fig.5.The rectified waveform of 320 V from the high frequency rectifier is converted to constant dc voltage of 700 V by dc-dc converter .And this constant dc voltage is converted to single phase ac voltage of 127 V by dc-ac inverter. The dc/dc converter and dc/ac inverter are connected in cascade. The dc/dc converter controls the power factor and the dc-link voltage, while the dc/ac inverter controls the output voltage .To reduce the switching losses due to tail current MOSFET is connected in parallel with IGBT to form a hybrid switch thereby improving system efficiency. 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.

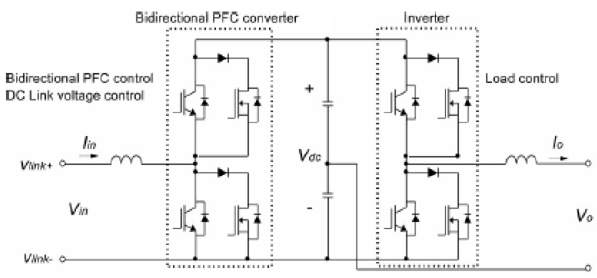

Fig. 5.Configuration of the bidirectional dc/ac converter.

The control implemented is PI voltage controller based pulse width modulated (PWM) control. The highest rating DC output is sensed and is compared with the reference voltage. The error so produced is fed to a voltage controller which

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is then compared with a saw tooth waveform of high frequency. The frequency of the saw tooth wave determines the switching frequency. The resulting PWM pulses controls the duty ratio of the two switches. The two switches should conduct alternatively and it should be ensured that sufficient dead time is provided to avoid shoot through.

III. SIMULATION ANALYSIS

The new bidirectional semiconductor transformer was simulated in MATLAB to check the performance of the proposed semiconductor transformer and its Simulink model is shown. Fig.6 and Fig.7 shows the controls given to high voltage and low voltage side .The first graph shows the input voltage of 1900 V .The second graph shows the rectified output voltage waveform of 320 V .The third graph shows dc link voltage, which maintains constant voltage of 700 V with negligible ripples .The fourth graph shows the output voltage ,current and power waveforms.From the simulation results it can be stated that the proposed bidirectional transformer operates properly as analyzed with the theoretical approach.The total harmonic distortion(THD) is also analyzed in the simulation and is obtained as 3.84% and is shown in Fig .12.

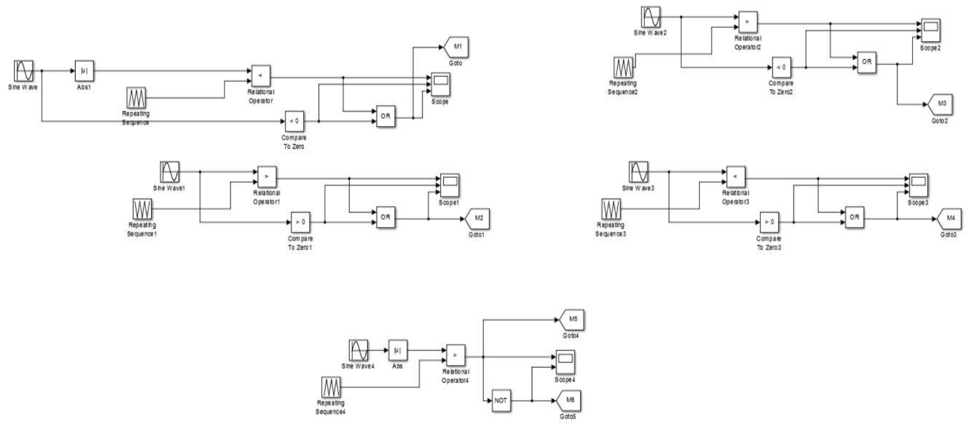

Fig .6 Simulink model of control signals given to ac-dc converter.

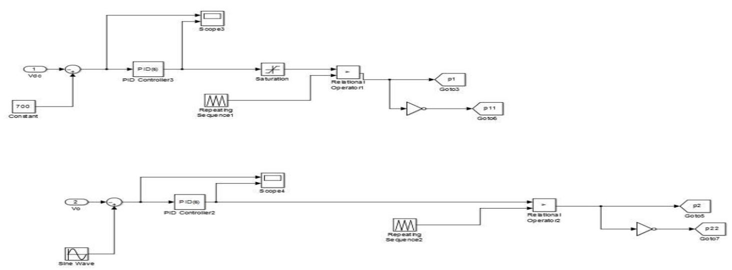

Fig.7 Simulink model of the control signals given to dc –dc converter and inverter.

The control signals given to the ac-dc converter ,dc-dc converter and inverter are shown in the Fig. 6 & Fig .7.Pulse width modulation technique is used as the control strategy for ac –dc converter.PWM signals are obtained by comparing sinusoidal waves with repeating sequence and is shown in Fig.6.The proportional integral controllers are used for the control in dc-dc converters and inverter section. The error signal ,obtained by comparing the output voltage with the reference voltage is given to the PID controllers for generating the control signals for the low voltage part and is shown in Fig.7.

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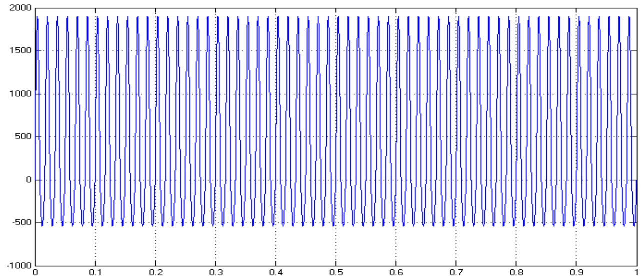

Fig .8 Waveform of input voltage

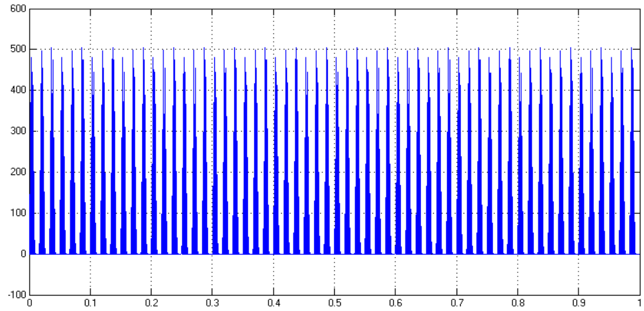

Fig.9 Output waveform of rectifier

An input voltage of 1900V is given to the rectifier and is its waveform shown in Fig .8. The output voltage of the rectifier is obtained as 320 V and is shown in Fig .9. This rectified voltage is given to dc –dc converter.Fig .10 shows the constant dc output voltage of 700 V obtained from the dc-dc converter.The dc link voltage is maintained at 700 V through the voltage control of dc-dc converter.

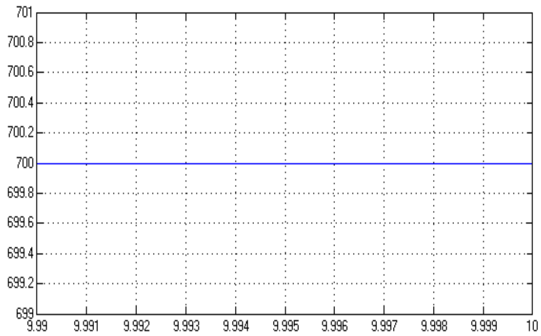

Fig .10 Output ewaveform of dc-dc converter

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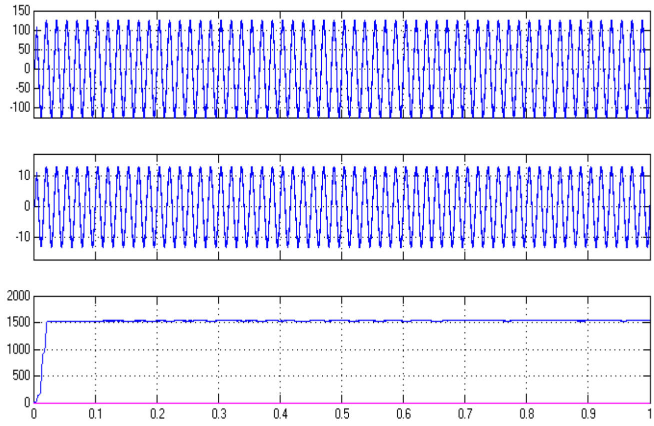

Fig.11 Output voltage,current and power waveforms of inverter.

The output waveforms of the inverter is shown in Fig.11.The first graph shows the output voltage waveform, the second graph shows the current waveform and the third graph shows the power output waveform. The output voltage current and power is obtained as 127 V, 12A &1500W. Fig .12 shows the THD analysis of output current waveform & a THD of 3.84% is obtained .

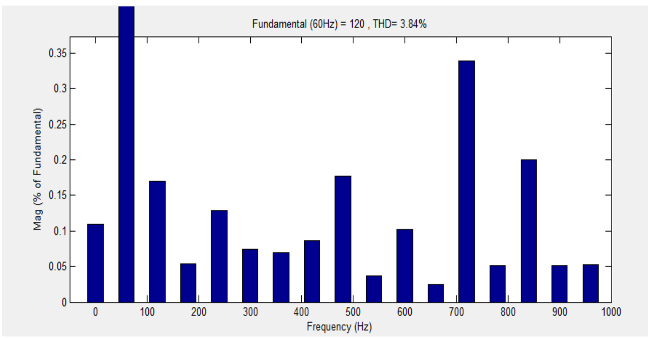

Fig. 12 THD analysis of output current waveform

IV. CONCLUSION

In this paper ,a bidirectional solid state transformer with a new control strategy was proposed.The operational feasibility of the proposed system is verified using MATLAB simulation.The simulation results of the system showed THD below 5% in the input voltage range selected for analysis. The power factor obtained near to unity.Hence the system conforms to standards set by IEEE and IEC. The proposed transformer could be used for implementing the smart grid.

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