Intelligent Bidirectional Semiconductor Transformer for Smart Power Distribution System

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A B S T R A C T

In general, conventional transformer composed of coil and iron core can change only the magnitude of the ac voltage and the quality of supplying power is totally dependent on that of the input power. So, it cannot be applicable for the smart grid, in which the magnitude and frequency of the operation voltage are various and high-quality power is required. Intelligent semiconductor transformer or solid-state transformer was proposed by EPRI to replace the conventional transformer in railway systems and substations, in which light weight is mandatorily required.This paper proposes a new bidirectional intelligent semiconductor transformer (BIST) for the smart distribution system and smart grid. The proposed BIST consists of high-voltage high-frequency ac/dc converter, bidirectional low-voltage dc/dc converter, and hybrid-switching dc/ac inverter.

1. Introduction

 Power generation, transmission, and distribution are the three main parts of the modern power system, in which the power transformers play a critical role. The power transformers enable the high efficiency and long distance power transmission by boosting the voltage to a higher one in the generation side. In the distribution system side, this high voltage is stepped down for industrial, commercial, and residential use.The development trends of the traditional power transformers are mainly focused on the new magnetic materials, insulation mediums, manufacturing processes, and etc. Conventional transformers which consist of copper winding and iron core can change only the magnitude of the ac voltage and its power quality is totally dependent on that of the input power. So, it's not flexible for the smart grid applications, in which the magnitude and frequency of the operation voltage are various and high-quality power is required. Modern life needs electrical energy: at any place, any time requiring high quality. Increasing demand for electricity – especially in developing countries – and the concerns about global warming are the reasons to push renewable energy sources in many countries. In addition, high efforts are made to reduce power losses wherever possible. The power transformer plays a transformational role to become the interface technology for full integration of critical distributed resource technologies and independent operation of local energy networks. This ability will be an important development in the overall Smart Grid development strategy. The Electric Power Research Institute (EPRI) has developed the concept for a Smart Grid power interface (SPI), which is the result of several years of research to develop a power electronics-based transformer, the Intelligent universal transformer (IUT) or solid state transformer. EPRI had worked towards construction of a laboratory-scale (2.4 kV, class 5 kVA) prototype. EPRI had developed this new interface to the Smart Grid which includes power electronics. Activity in 2010 focused on the development, testing, and demonstration of a utility-class (4 kV, class 25 kVA) field prototype of the IUT system. Major design changes were made from the first-generation, laboratory-scale IUT. The first prototype is now being developed to integrate the energy storage systems and electric vehicle fast charging. It will support industry-grade communication protocols that will enable the IUT to act as a smart node. The IUT system is being designed to also serve as a voltage regulator to facilitate voltage optimization controls. This EPRI's report is the constant inspiration behind the development of the solid state transformer The Intelligent Solid State Transformer (ISST), or an Intelligent semiconductor transformer, also named Power Electronic Transformer

(PET), Electronic Power Transformer (EPT), or Intelligent Universal Transformer (IUT), is a new type of transformer based on high power electronic conversion, introduced by EPRI to replace the conventional transformer in railway systems and substations, in which light weight is mandatorily required. This solid state transformer not only matches the functions of a conventional power transformer, but also provides additional capabilities to mitigate dynamic power quality problems. ISST aims at voltage regulation, power transmission, isolation, and power quality improvement of power grid. It will become an important smart device for the development of intelligent power grid.

Compared with conventional transformer, ISST has no 50Hz line frequency transformer which remains bulky physical size and weight. Instead, ISST will consists of smart control feature by power electronic converters, high frequency transformer and comprehensive controlling technology. It overcomes the problems such as environmental concerns regarding mineral oil, sensitive to harmonics, protection of the system from problems arising at or beyond the transformer, voltage drop on load, etc. In addition, it is convenient to communicate with power grid. IST also can improve power quality and integrate kinds of AC and DC distribution power source with the flexibility of power electronics switching. Consequently, it has better application prospect not only in intelligent power grid but also in the field of telecom andaerospace.

2. Solid state transformer

The transformer has been used throughout the twentieth century. Until now, it has consisted of a configuration of iron or steel cores and copper/aluminium coils, with mineral oil serving as both coolant and dielectric medium. Inherent in this type of construction are regulation, significant weight, losses, environmental concerns, and power quality issues. For the 21st century, a new kind of power electronics transformer is developed one that can be made self-regulating, coil free, and able to correct power quality problems. The solid-state transformer allows add-on intelligence to enhance power quality compatibility between source and load. It is desired to demonstrate the benefits gained by the use of such a device. Recent advancement in semiconductor devices and converter topologies facilitated a newly proposed Solid state intelligent transformer (SSIT), which can isolate a disturbance from either source or load.The solid state transformer is a power electronic device that replaces the traditional 50Hz power transformer by means of high frequency transformer isolated AC-AC conversion technique, which is represented in Fig .1.
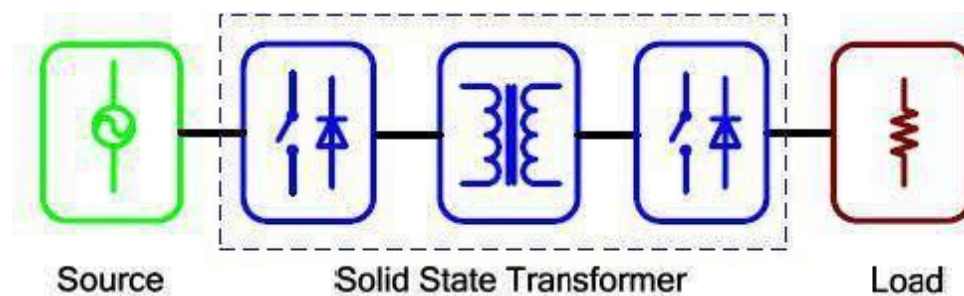
Fig.1 Solid state transformer configuration

The basic operation of the SST is firstly to change the 50 Hz AC voltage to a high frequency one (normally in the range of several kHz to tens of kHz), then this high frequency voltage is stepped up/down by a high frequency transformer with dramatically decreased volume and weight, and finally shaped back into the desired 50 Hz one to feed the load. In this sense, the first advantage that SST may offer is the reduced volume and weight compared with traditional transformers. To reduce the input voltage to a lower one. This was followed in 1995 by a similar EPRI sponsored effort. Both of these efforts yielded working prototypes, but they operated at power and primary voltage levels that were orders of magnitude below utility distribution levels. The ac/ac buck converter is perhaps the most direct approach to single phase ac power conversion. In this arrangement, switches and are bidirectional. Turning a switch on permits it to conduct current in either direction. Conversely, turning it off can block voltage of either polarity. Two devices tied in series indicate an arrangement of some number of semiconductors that would be needed to achieve the desired voltage ratings. (The number of devices required would be a function of voltage level and the type of semiconductor). The bidirectional switches and are alternately turned on at a high frequency relative to the fundamental component of the voltage and current waveforms. Under these conditions, it can be shown that where is the duty cycle (the time the upper switch is on relative to the switching period) and "~" designates the phasor representation of the fundamental component. Although this is the most straightforward approach to ac–ac power conversion, it is problematic in several respects. First, each switch must be able to block full primary voltage and also be capable of conducting full secondary current.

2.1 Necessity of Solid State Intelligent Transformer

With the advancement of power electronics circuits and devices, the all solid-state transformer becomes a viable option to replace the conventional copper-and-iron based transformer for a better power quality. The solid-state switching technologies allow power conversion between different formats such as dc/dc, dc/ac, ac/dc, and ac/ac with any desired frequencies. The term "solid-state transformer" has been defined long back and the main purpose of solid-state power conversion is to convert ac to ac for step-up or step-down with a function same as that of a conventional transformer but with much

reduced size and weight. The key elements of the solid-state transformer are an ac/dc converter and a dc/ac inverter. In recent literature the solid-state transformers were proposed to replace the conventional transformer in the distribution voltage level. Some of them are still relying on low-frequency transformers, but adding electronics to enhance power quality.

A conventional transformer lacks of energy storage capability, and thus the output load can be easily interrupted due to disturbance at the input source. Similarly, when the output load current generates disturbances such as load transients, harmonics and reactive power, the conventional transformer also reflects them back to the input side. To overcome these problems, the modern power electronics technology can be used to serve as the energy buffer in between the source and load to avoid direct impact from either side. In addition, with the flexibility of power electronics switching, it is also possible to provide universal voltage output such as dc voltage or variable frequency ac voltage output to the load

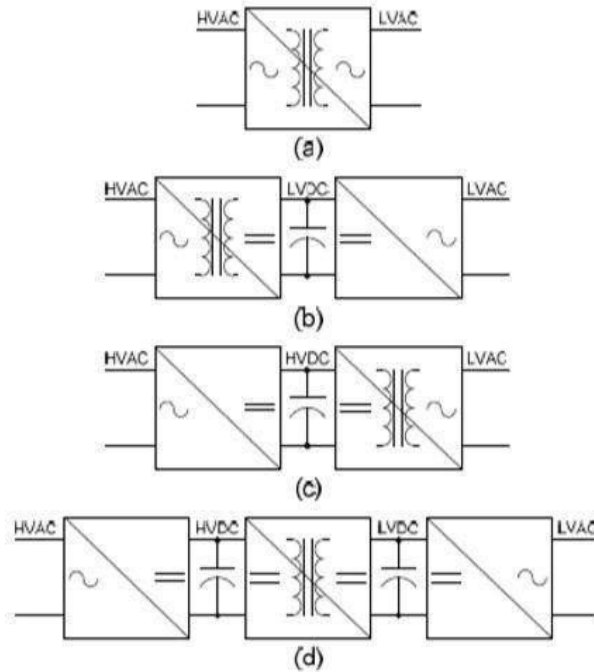## 2.2 Various Solid State Transformer Configurations

Fig.2: Various configurations of solid state transformer

The selection of the appropriate topology for the SST implementation is a key aspect. In order to select these potential topologies for comparison, a number of topologies proposed for SST as well as for general AC-AC power conversion have been surveyed. An approach to classify the SST topologies and select the appropriate configuration according to the specific needs was presented here. In this classification, as seen in Figure.2, four SST configurations that cover all the possible SST topologies are identified: a) single-stage with no DC link, b) two-stage with low voltage DC (LVDC) link, c) two stage with high voltage DC (HVDC) link, and d) three-stage with both HVDC and LVDC links. The DC link of the third configuration is not appropriate for DES and DER integration since it is high voltage and has no isolation from the grid; therefore, topologies under that classification are not practical for SST implementation.

2.3 Basic Solid State Transformer topology

Fig. 2.5 shows the basic topologies for single-phase solid state transformers. In Fig.3.1, switches SW1, SW1 ; SW2, SW2 ; SW3, SW3 ; and SW4, SW4 are operated synchronously and the transformer core is operated at high frequency. The topology shown in Fig. 2.6 employs a multilevel static converter to achieve step down operations. The split transformer core on the primary side ensures equal voltage sharing among the switches employed in the high-voltage primary converter.
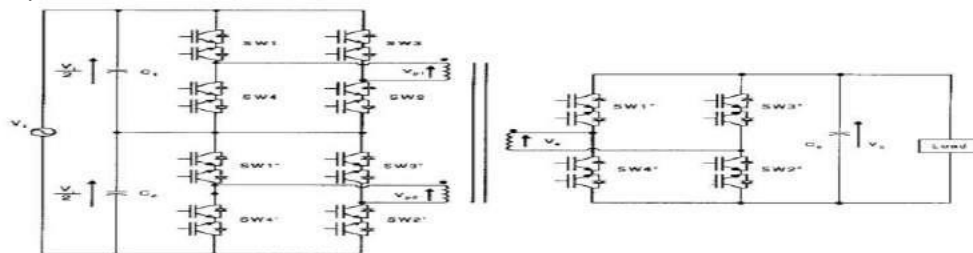

Fig.3: single-phase Solid state transformer

3. AC TO DC CONVERTER TOPOLOGY

One of the first and most widely used application of power electronic devices have been in rectification. Rectification refers to the process of converting an ac voltage or current source to dc voltage and current. Rectifiers specially refer to power electronic converters where the electrical power flows from the ac side to the dc side. In many situations the same converter circuit may carry electrical power from the dc side to the ac side where upon they are referred to as inverters.

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase angle control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf. for commutation and are referred to as the "Load commutated inverter". In phase controlled rectifiers though the output voltage can be varied continuously the load harmonic voltage increases considerably as the average value goes down. Of course the magnitude of harmonic voltage is lower in three phase converter compared to the single phase circuit. Since the frequency of the harmonic voltage is higher smaller load inductance leads to continuous conduction. Input current wave shape become rectangular and contain 5th and higher order odd harmonics. The displacement angle of the input current increases with firing angle. The frequency of the harmonic voltage and current can be increased by increasing the pulse number of the converter which can be achieved by series and parallel connection of basic 6 pulse converters. The control circuit become considerably complicated and the use of coupling transformer and / or interphase reactors become mandatory.

3.1. Three Phase Fully Controlled Converter

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig.4
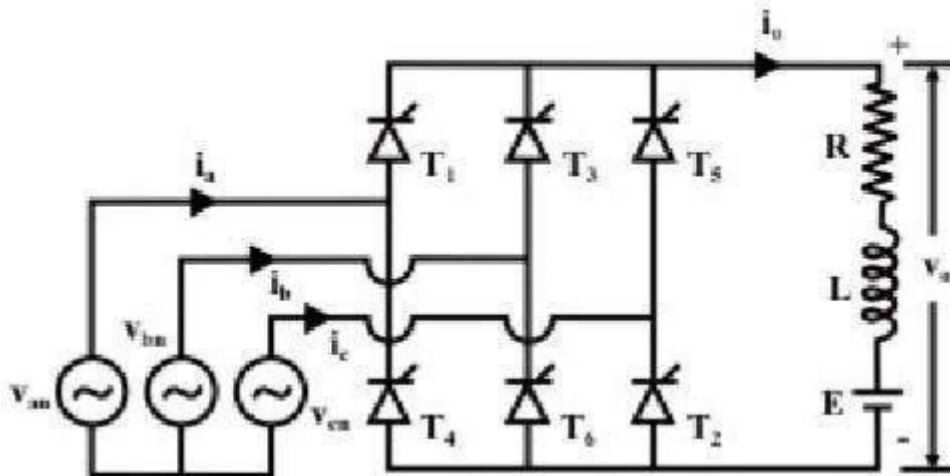

Fig 4. Three phase fully controlled converter

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct. Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Each conduction mode is of 60° duration and appears in the sequence mentioned. For example the thyristor T1 is fired at the end of T5T6 conduction interval. During this period the voltage across T1 was vac. Therefore T1 is fired α angle after the positive going zero crossing of vac. Similar observation can be made about other thyristors. Here all the thyristors are fired in the correct sequence with 60° interval between each firing.

Fig. 3.2 shows the waveforms of different variables (shown in Fig. 3.1). If the converter firing angle is α each thyristor is fired "α" angle after the positive going zero crossing of the line voltage with which it's firing is associated. Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore, this converter is also called the "six pulse" converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.
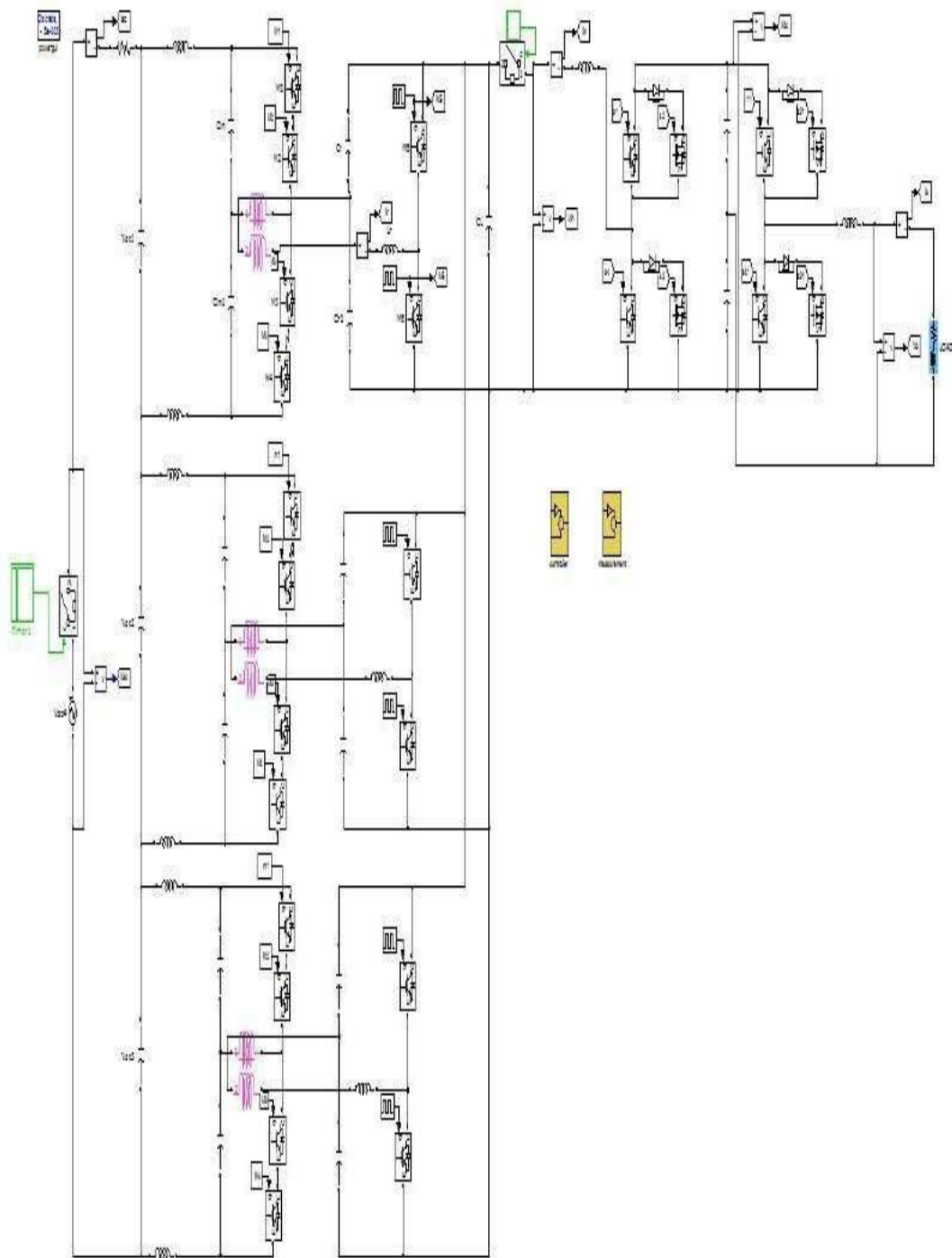
Fig 5 Waveforms of three phase fully controlled converter

3.2 Proposed Control Technique

Fig.6: Proposed control strategy for inverter and dc-dc converter

In this proposed control technique mainly the gating pulses were generated for controlling the bidirectional Dc to DC converter and to the inverter as shown in the fig:5.3. Here mainly the gate pulses are produced to the dc to dc converter stage by comparing the rectified dc voltage to the reference dc voltage signal. The gating pulses are given to the inverter by comparing the output ac with the reference ac voltage.

4. Simulation Model and Results

Fig.6: Proposed circuit model
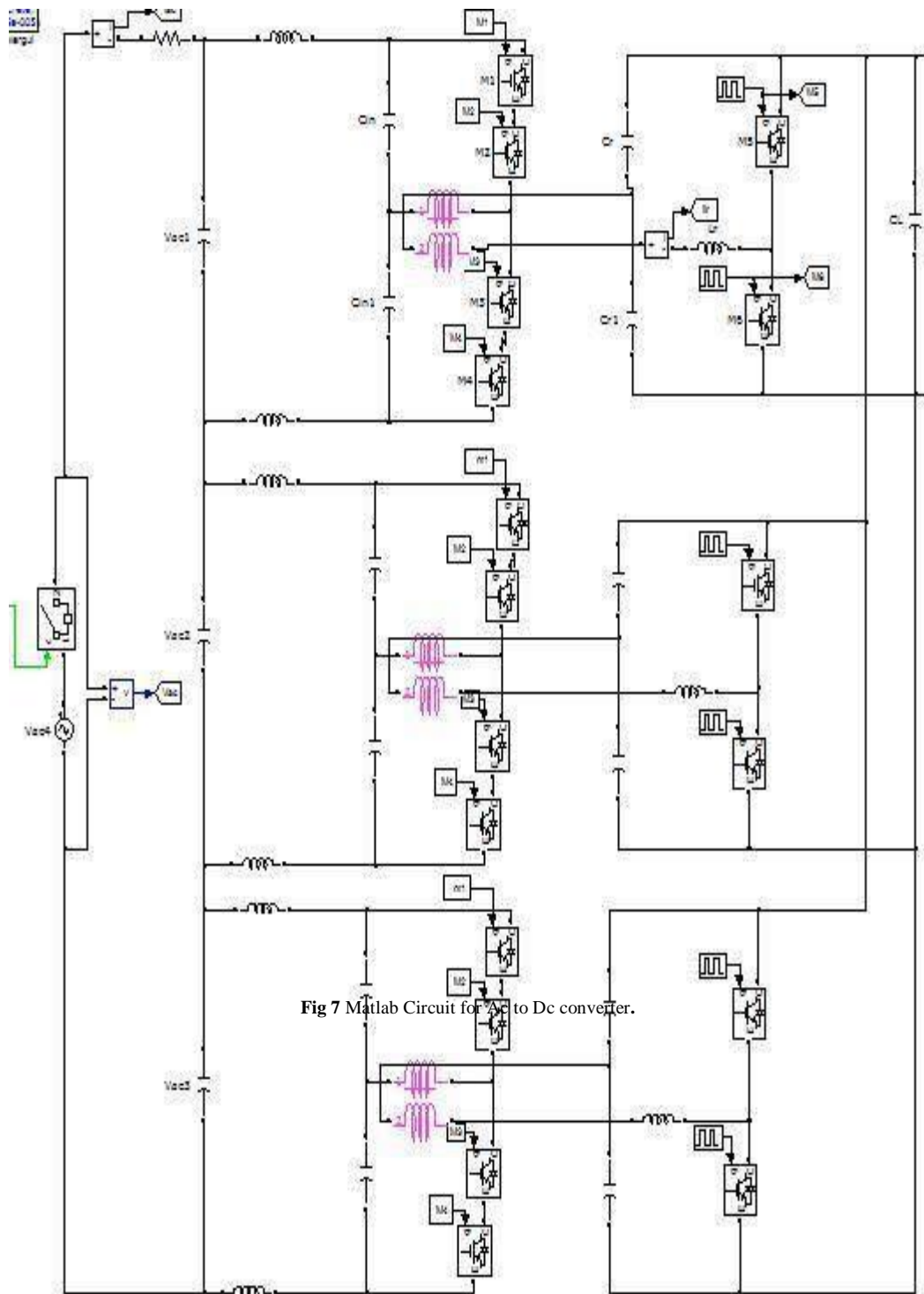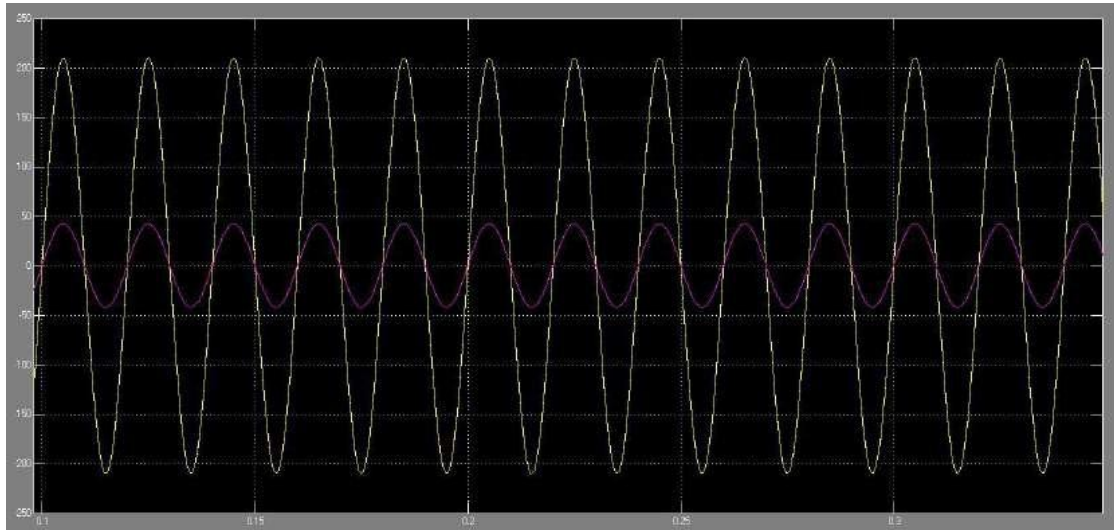
Matlab Circuit for ac to dc converter

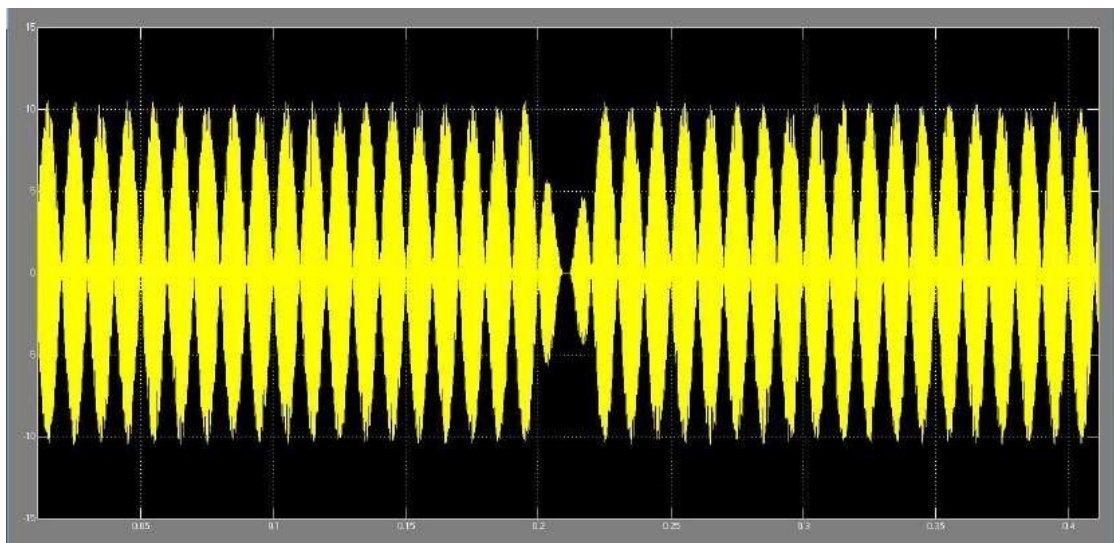**Fig 7** Matlab Circuit for Ac to Dc converter**.**

The above modelling using MATLAB as shown in the fig 6.3 is implemented for AC-DC converter using IGBT's. In this Thesis this converter is referred as high voltage stage.

Simulation Results in Forward and Reverse Power Flow

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INPUT VOLTAGE AND INPUT CURRENT
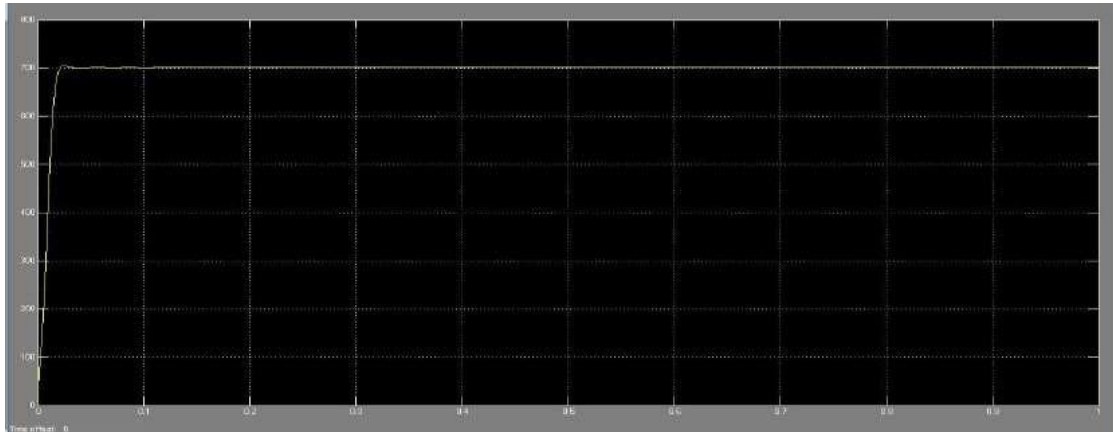
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REASONANT CURRENT

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This graph shows the 50-kHz resonant current for ZVS when the power flow is reversed from forward to backward at 0.2 ms.
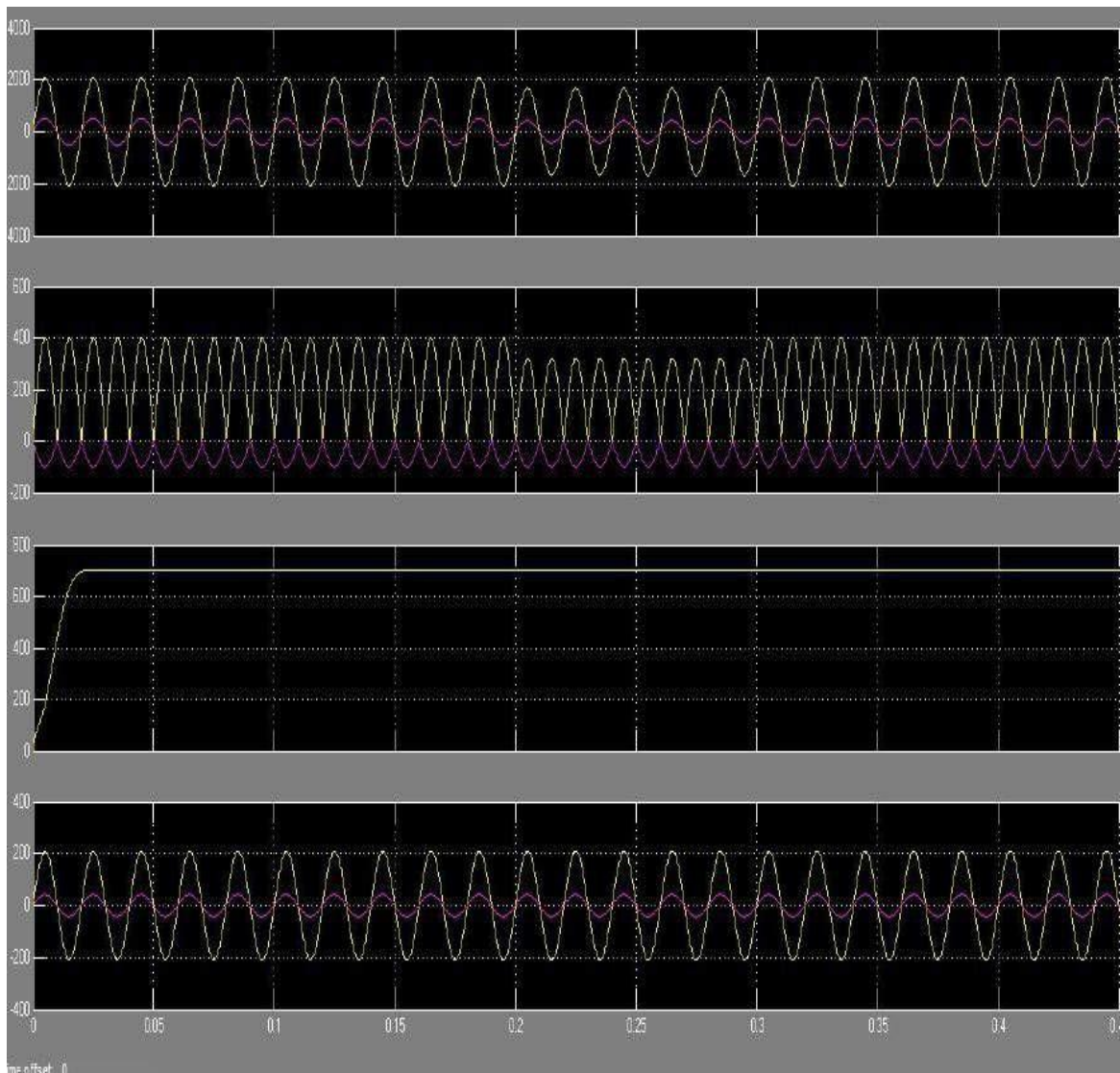
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RECTIFIED VOLTAGE AND RECTIFIED CURRENT

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This graph shows the dc-link voltage, which maintains constant voltage of 700 V with negligible ripples.

Input voltage sag for Reverse power flow

5. Conclusion

Due to the ever increase in the population, the smart grid is the most promising technology, which enables the power system network to work with more quality as well as gives us most optimal solution to many key issues in power system such as voltage fluctuations due to supply disturbances etc., In this project, a new configuration of the ISST was proposed, which has rating of 1.9 kV/127 V, 2 kVA. This proposed SSIT exactly resembles the operation of conventional transformer perhaps with better performance, also it enables us to replace the conventional bulky transformer. This transformer consists of the high-voltage high-frequency ac/dc rectifier, and low-voltage dc/dc and dc/ac converters. The operational feasibility of the proposed transformer was verified by computer simulation with MATLAB software. In this project the simulation was done under both forward and reverse power flow, to ensure the bidirectional power flow capability so that it can be implemented in smart grid environment to in the place of conventional unidirectional transformer. This proposed SSIT was tested in MATLAB for voltage sag as well as swell conditions also. Based on the simulation results,. Using this model, three units of this transformer, a three-phase transformer with rating of 3.3 kV/220 V, 6 kVA can also be built. Therefore, the proposed transformer could be applicable for implementing the smart grid.

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