Transformer less Intelligent Power Substation Design with 15kV SiC IGBT for Grid Interconnection

Kamalesh Hatua, Sumit Dutta, Awneesh Tripathi, Seunghun Baek, Giti Karimi, Subhashish Bhattacharya
Future Renewable Electric Energy Delivery and Management (FREEDM) System Center, Dept. of ECE,
North Carolina State University, Raleigh, NC 27695, USA

***Abstract*— Basic power topology for a Solid State Transformer (SST) with new 15kV SiC IGBT devices is discussed. It is difficult to build high efficient, light weight, magnetically isolated solid state transformer for high voltage (13.8 kV) grid connectivity with existing Si 6.5kV rated IGBTs and diodes. Existing state of the art high voltage (6.5kV), high speed power devices (IGBT) cause considerable amount of loss (switching and conduction loss). With the advent of SiC devices these limitations are largely mitigated and this provides the motivation for new power topologies. The targeted efficiency of the proposed SST is 98%.Simulation results for a 1 MVA proposed SST topology is presented.**

I. INTRODUCTION

Solid state transformers (SST) are upcoming power electronics devices for replacement of bulky distribution transformers [1]-[4],[7]-[12]. Conventional distribution transformers steps down 13.8kV, 3-phase distribution level voltages to 480V utility grid voltages. They also provide isolation between input side voltage and output side voltage. Though they are efficient (99% at rated load and 96% at light load conditions) but are bulky, are typically oil cooled and require installation cost for pad-mounting. The main motivation for the design of SST is to find an alternative solution for these 60Hz transformers with lighter weight and higher efficiency. SSTs provide bi-directional power flow control and can also compensate unwanted load injected harmonics and can also act as a static VAR compensator at the high voltage side grid to provide voltage regulation and volt-var control in the distribution feeder. Currently the main challenge to build SST is the high voltage limitations of power devices. Thyristors can reliably be connected to the high voltage side grid, but their performances are restricted by their low switching frequency of operation. IGBTs are fast but they are again limited by their voltage blocking capability to 6.5kV devices. With cascaded H-bridge connections they can be connected to the grid but will reduce system efficiency due to larger number of power devices [3]. Moreover switching and conduction losses of IGBTs will be high and reduce the overall system efficiency.

With the advent of SiC devices the practical issues and high-voltage device limitation to build SST will be largely mitigated [5]. HV (12-15kV) SiC-IGBTs can be switched at a much faster rate than HV 6.5kV Si-IGBTs. The turn-on and turn-off time of SiC-IGBTs are expected to be one-order lesser in magnitude than Si-IGBTs and therefore device switching losses will be largely reduced. More importantly they are expected to block 15kV DC voltage. Their expected electrical properties are the prime motivations behind the proposed SST power topology.

The proposed topology is termed as Transformer-Less Intelligent Power Substation (TIPS). The main motivation of the proposed topology is to remove the bulky 60Hz power transformer with the solid state devices. Therefore “Transformer less” (power transformer) acronym is used. The proposed power topology can act as a VAR compensator at both the 13. kV and 480V grid side according to the grid requirement.

Fig. 1 elaborates the basic block diagram for the proposed TIPS topology. In the proposed power topology of SST, the input side AC voltage (13.8kV) is rectified by a 3-level NPC inverter (RECTIFIER MODULE). This converter is designed using 15kV SiC-IGBTs. The switching frequency of the inverter is designed at 3 kHz and operation at 5 kHz with the loss calculations will be investigated. The rectifier DC bus voltage is maintained at 22.5 kV level. This high voltage DC is stepped down to isolated low voltage DC (800V) using a high frequency link DC-DC converter (DUAL ACTIVE BRIDGE MODULE).

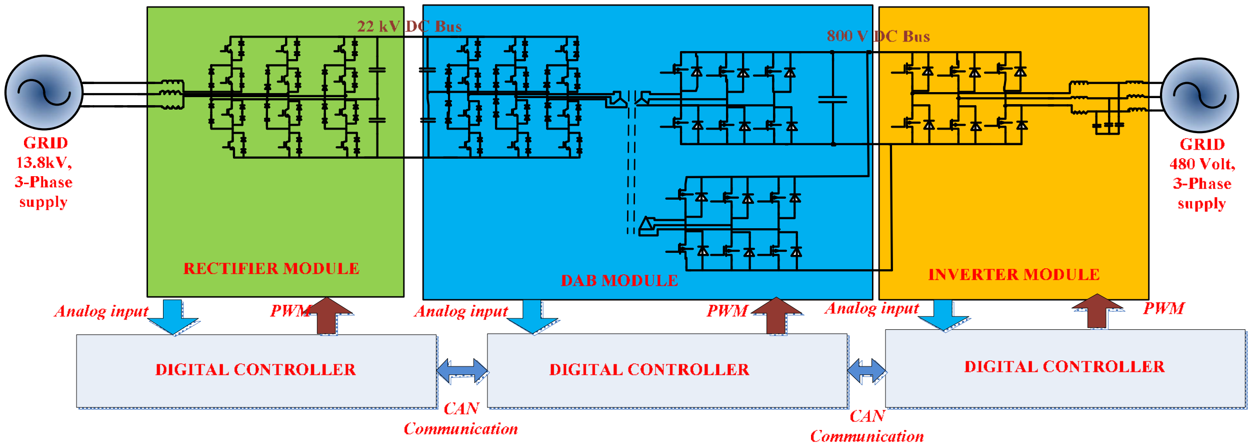

Fig.1. Basic block diagram of TIPS

The primary side of the HF link converter has a three-level NPC converter with 15kV SiC-IGBTs and secondary side is paralleled two-level three-phase inverter. This DC-DC DAB converter module is soft-switched at 20kHz. The input side 3-level converter is built using 15kV SiC-IGBTs. The output side two-level inverters are built using SiC 1200V MOSFETs. The output of this module is a low voltage DC (800V). This DC voltage is converted to 480V 3-Phase AC voltages by paralleled two-level VSIs (INVERTER MODULE). These inverters are switched at 17 kHz using SiC-1200V MOSFETs.

This paper is organized in the following way:
Section II describes the operational overview of the TIPS.
Section III deals with the brief description of the power module and associated control laws. Section IV describes the design of high frequency link transformer. Section V elaborates the anticipated losses for the 1 MVA TIPS. Section VI elaborates the thermal analysis and modeling.
Section VII validates the proposed power topology with experimental results. Section VIII concludes the paper.

II. Operational Overview of TIPS

The TIPS provides a new concept for solid state replacement of a conventional 13.8kV to 480V distribution transformers. Due to the improvement of solid state device technology (15 kV SiC IGBTs) direct connection (without conventional 60 Hz transformer) with 13.8 kV utility grid with TIPS is possible. It is obvious from the structure of the TIPS that it is more compact and lighter in weight compared to a conventional distribution transformer. However, an efficiency and performance comparison is required between TIPS and a conventional distribution transformer.

A conventional distribution transformer has an efficiency of 99% while supplying a 1MVA, 480V feeder. From simulation study of TIPS with SiC devices (IGBT and MOSFET) it is found that while supporting 1MVA load the efficiency of TIPS is around 98%. Of course with varying nature of the load (real and reactive), the efficiency of the TIPS varies. This variation is due to the supply of various amounts of reactive VAR into the grid which will be discussed shortly.

In order to simplify the following discussion, the 1MVA load is partitioned into real power of 800kW and reactive power of 600kVA load. The conventional transformer will supply to the feeder the same amount of load and draws the same real power from the utility grid (13.8kV). The voltage dip at 13.8 kV and increased line loss at the utility grid result from this loading. In contrast to this, a 1 MVA TIPS can support the load at the 480V feeder at fixed voltage without drawing any reactive VAR from the 13.8kV grid. It can only draw 800kW real power from the 13.8kV grid. In addition, it can inject 600kVA leading VAR from the grid, support the voltage sag and also decrease the line loss. In comparison with a conventional transformer, therefore the TIPS is delivering 1.2MVA extra VARs to the 13.8kV grid. If TIPS compensates VAR at the low voltage side grid then another 1.2MVA extra VAR is injected by the TIPS. Therefore a 1 MVA TIPS can supply the same amount of real power (800kW) as a conventional distribution transformer. *In addition, by supplying 2.4MVAR into both the 13.8kV and 480V grids, the 1 MVA TIPS, saves a significant amount of line and operating losses.*

Figure 2 elaborates the power flow diagram of the TIPS and a conventional transformer. For a conventional transformer, the net power (P+jQ) from the 480V grid is drawn from the 13.8kV grid. For TIPS, real power P drawn from the utility grid is supplied by the 13.8kV grid. The reactive power at the 480V grid can be supplied locally at the 480V grid. Even the lagging reactive power can be compensated by injecting leading VAR (jQlv) into the 480V grid (see Fig. 2). Similarly TIPS can support leading VAR into the 13.8kV grid (jQhv) (see Fig. 2). Fig. 3 explains the power flow diagram of TIPS. The behavior of TIPS in the 13.8 kV grid side is studied using *IEEE-34* bus system.

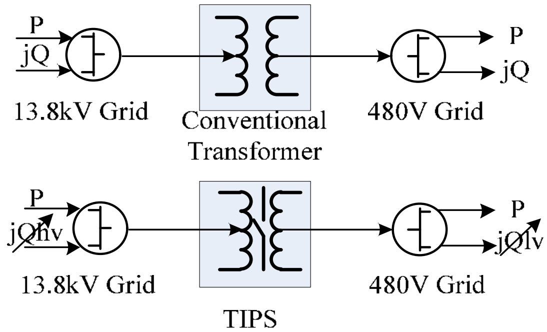

Fig.2. Power flow direction -60 Hz transformer vs. TIPS

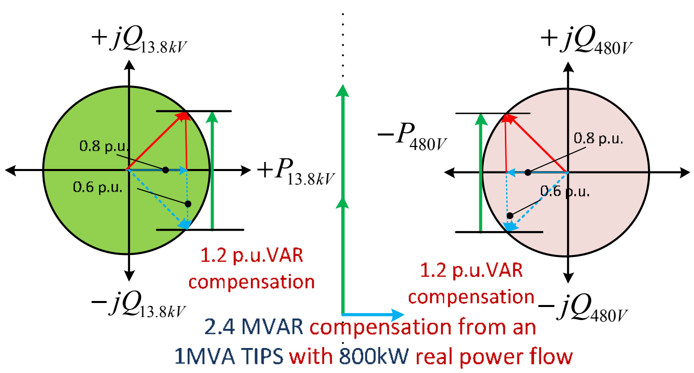

Fig.3. Power flow diagram of TIPS

III. Control and Brief Overview of TIPS Module

The TIPS has three power modules. They are as follows.

A) Rectifier Module.

B) Dual Active Bridge (DAB) Module.

C) Inverter Module.

A. Rectifier Module

The input side rectifier module is built using SiC-IGBT based 3-level inverter. Fig.4. elaborates the power structure for the rectifier. This inverter is switched at 3-kHz switching frequency and connected to 13.8 kV grid. Each IGBT devices are built to withstand 15kV DC voltages and can carry up to 100 A current. The input rectifier is vector controlled and performs the following tasks:

a) Maintains 22.5 kV DC bus at all operating points drawing unity power factor load from the grid following *IEEE*-519 standard.

b) Can supply reactive VAR to the AC grid for maintaining steady voltage profile of the grid.

c) Allows bidirectional power flow with high dynamic performance.

Space vector modulation technique is adopted for maintaining DC bus at 22.5 kV level without going to the over modulation region.

Fig.5. elaborates the basic control block diagram of the rectifier module. The DC bus controller generates the d-axis current controller reference (i_{sd}^*). The q-axis current controller reference (i_{sq}^*) decides the amount of VAR to be supplied to maintain a steady voltage profile in the grid. d-axis and q-axis voltage controllers generate the voltage reference for the 3-level inverter. The unit vectors ($\cos\theta, \sin\theta$) for the controller are generated from the line voltages.

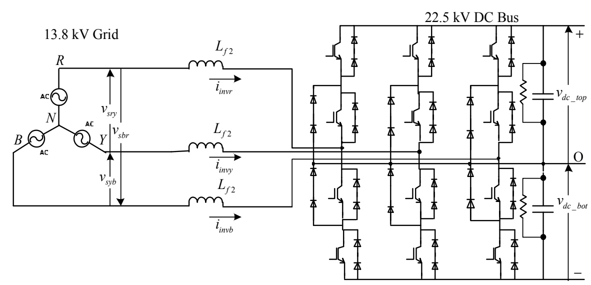

Fig.4. Power structure of the rectifier

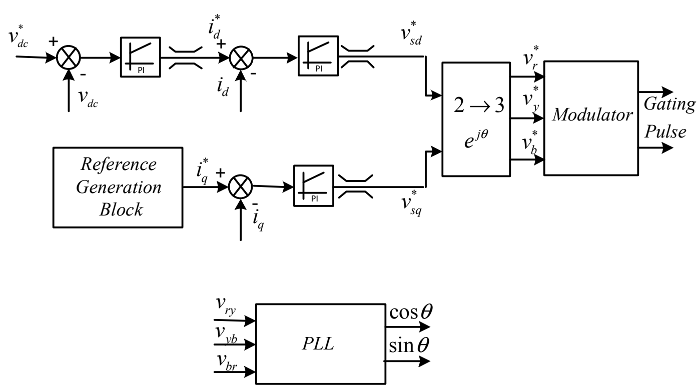

Fig.5. Rectifier Control Block

B. Dual Active Bridge Module

In high frequency link DC-DC converter module 22.5 kV DC bus is stepped down to 800 V DC bus. Fig. 6. demonstrates the power structure of the Dual Active Bridge. The necessary galvanic isolation is provided by a high frequency link transformer. The input side is a three-level inverter and switched at 20 kHz. This inverter is a three-level SiC-IGBT based inverter. This inverter handles high voltage. Output side of this converter is 2-level SiC-MOSFET based inverter. This is a low voltage inverter which handles 800 V DC bus. Secondary side can be built with two paralleled inverters as shown in the Fig. 6. to share the secondary side current. These inverters are connected to a multiple secondary high frequency transformer(Y:Y/Δ).

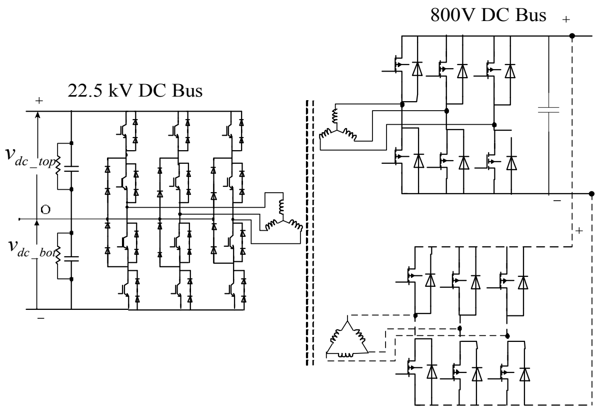

Fig.6. Power structure of the Dual Active Bridge

The two level inverter sets are operated with fixed modulating references and the three-level converter is operated with phase shifted modulator which changes the phase angle of the generated voltages with respect to two level side voltages. Both the two level converter are switched simultaneously. The secondary side Y/Δ transformer with 30º phase shift reduces 5th and 7th order harmonics in the secondary side current to a large extent.

The control block diagram for the DAB control is shown in Fig. 7. The DC bus voltage at the three-level side is maintained at 22.5kV level by the input side rectifier. Controlling the phase angle between the input side 3-level converter voltage and the output side two-level converter sets voltage the power flow is controlled. The DC bus voltage at the low voltage side is maintained at 800 V by a voltage controller. The DC bus voltage controller generates the d-axis current reference (i_d^*) for the DAB unit. The current controller reference generates the amount of phase angle shift (θ_{shift}) between the 3-level and the 2-level converterr sets. The magnetizing current requirement for the high frequency link converter is very less. Therefore no separate q-axis current controller is used.

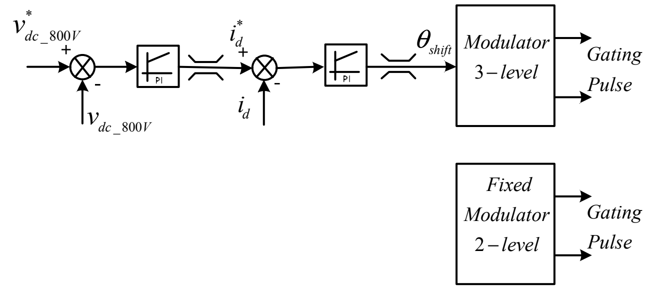

Fig.7. Dual Active Bridge Control Block

C. INVERTER MODULE

In the output side inverter module, three numbers of two-level SiC 1200V MOSFET based inverters are paralleled. The load can be a 480 V grid or a passive load. The output inverters are switched at 17 kHz. The effective switching frequency of this module becomes 51kHz by phase shifting the carrier waveforms for each modules by 120 degrees. The phase shifting of the carrier ensures lighter LC filter at the output side.

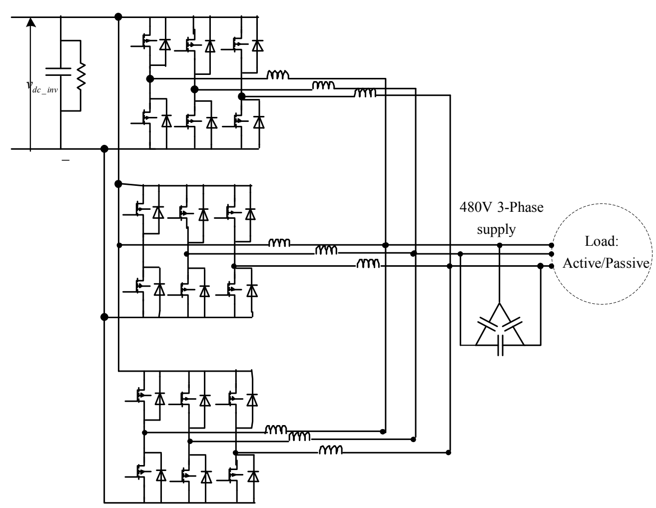

Fig.8. Inverter module

The output side inverters share a common DC bus of 800 Volts. The DC bus voltage is maintained constant by the Dual Active Bridge (DAB) unit. This unit also can inject reactive VAR into the 480 V grids.

IV. High Frequency Link Transformer Design

The high frequency link Transformer of the TIPS transfers power from high voltage side of the DAB to the low voltage side of the DAB. The efficiency and size is the transformer is major trade-off to design this transformer. Transformer losses are usually limited by a temperature rise at the core surface in vicinity of the windings.

The high frequency link transformer used for the TIPS is essentially a three-phase to three-phase transformer. It can have multiple secondary windings according to the requirement.

A high frequency link transformer is designed for the TIPS application. The details of the transformer are given in Table 1. The electrical specification for the transformer is given in the Table 2.

Electrical Specification	***Primary Winding***	***Secondary Winding***
Winding details	3-Phase Y	3-Phase Y
Frequency	20 kHz	
Turns ratio	14.5:1	
Phase V rms	11600 V	800 V
Phase I rms	30 A	435 A
Power	1 MVA	
Bac	0.5 Tesla	
Turns	29	2
Ac	10*10cm^2	
Wa	17*34cm^2(each)	
Length: wire	70 m	
Weight: wire	47 kg	
Core: volume	22236cm^2	
Core: weight	159kg	

Table 1: Transformer details

	Magnetic Inductance	Leakage Inductance
Phase A	46 mH	5 uH
Phase B	71 mH	5 uH
Phase C	46 mH	5 uH
Total weight	183 kg	
Core Loss	2.5 kW	
Winding Loss	Negligible	
Efficiency	99.75%	

Table 2: Electrical specification of the transformer

There are several typical materials of soft magnetics which can be used to build for the high frequency transformer. Even though ferrite cores are most popularly used for high frequency applications, the ferrite material has a low saturation flux density of around 0.3-0.5 T which makes the transformer bulky and heavy. Nanocrystalline exhibits high saturation flux density, typically higher than 1.0 Tesla and 3-4 times less specific losses compared with amorphous and ferrite cores. Therefore, nanocrystalline is apparently the best choice in the frequency range up to several hundreds of kilo hertz. 25kV shielded power cable is used to support 12kV on the primary side. Two copper foils in parallel are used for one turn on the secondary side to minimize the skin effect. The structure of the high frequency link transformer is shown in Fig. 9. Fig. 10. elaborates the flux distribution in the high frequency link transformer. The maximum magnetic flux density (0.4 Tesla) in the designed transformer is kept below half of the saturation level of the nanocrystalline material. It can be observed from the Fig. 10. that the flux distribution is maximum at the edges(red line). The thermal hot spot is created in these regions as the power loss is maximum in these regions.

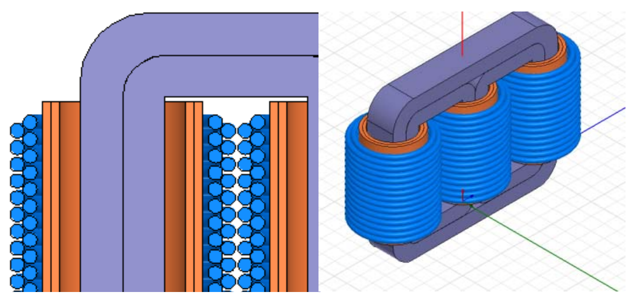

Fig. 9. High frequency link transformer structure

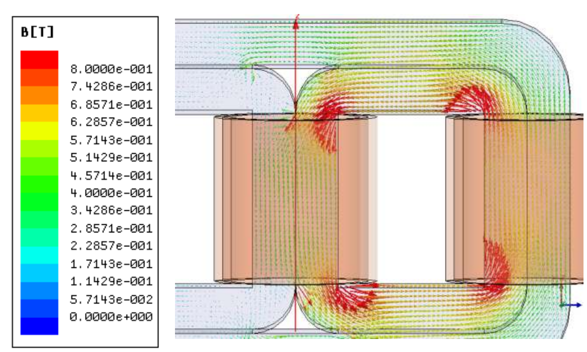

Fig. 10. High frequency link transformer structure

V. Discussion on TIPS Efficiency

The TIPS is an alternative solution for the existing 13.8kV distribution transformer. The proposed TIPS will have expected efficiency of more than 98%. There are two types of devices in the TIPS topology. They are 15kV SiC-IGBTs and SiC 1200V MOSFETs. The SiC-IGBTs are in the design stage and preliminary samples at 12kV/5A are available for device level tests at this point. Therefore the loss data used for the SiC-IGBTs are predicted from the theoretical studies and some initial switching and conduction loss data for 12kV SiC IGBTs. Whereas, the loss calculations for SiC-1200V MOSFETs are based on data from 1200V, 100A SiC MOSFET module (4804 from M.S. Kennedy Corp. and QJD1210006 from Powerex). Table 3. shows the loss distribution for the 1 MVA TIPS. The loss data is calculated when TIPS is supplying 800kW real power and 600kVAR reactive power to the grid. The expected overall efficiency of the TIPS is 98.43% at the above operating condition.

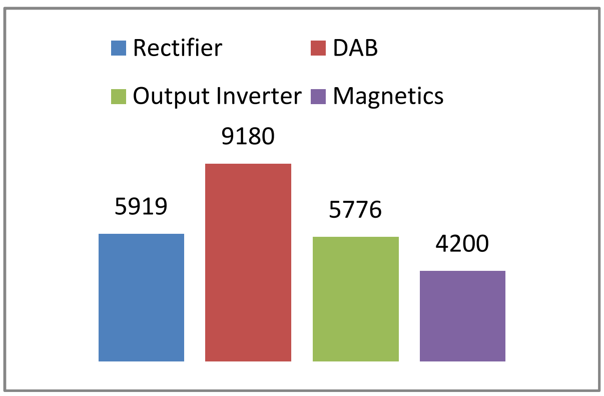

Table 3: Loss Data for TIPS

VI. Thermal Analysis of TIPS

There are two basic inverter modules are present in the TIPS topology. They are 15 kV SiC IGBT based 3-level inverter and 1200 V SiC MOSFET based two level inverter. To test the TIPS concept up to 100kW level, these inverters will be built in the laboratory. Two 3-level inverters with 100kW rating and 5 numbers of 2-level inverter with 35 kW ratings are being developed and will be laboratory tested.

A. Two Level Inverter

Using the loss calculation for the 35 kW 2-level SiC MOSFET based converter, thermal modeling of the low voltage inverter was carried out and a heat sink was selected. The approximate loss taken for the thermal design was 300 Watts. The forced convection air flow rate chosen was 148 cfm and the maximum junction temperature reached upto 106 °C. The ambient temperature chosen was 40°C. Fig. 11. and Fig. 12. show the thermal profile of the heat sink.

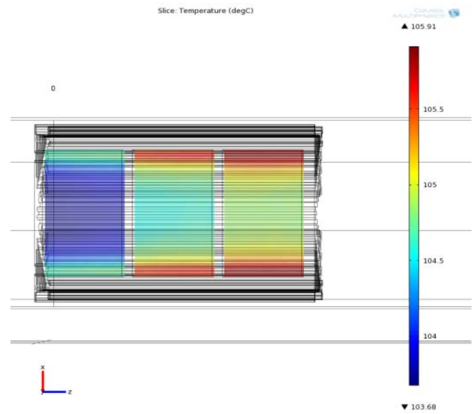

Fig. 11. Thermal modeling analysis of low voltage inverter implemented using three 1200V/100A SiC MOSFET Modules (Top View)

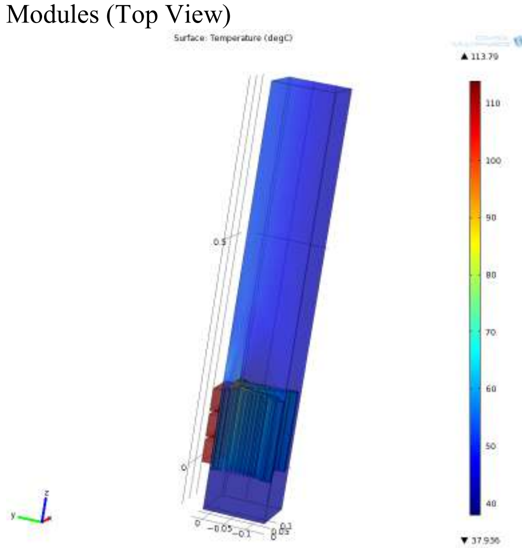

Fig. 12. Thermal modeling analysis of low voltage inverter implemented using three 1200V/100A SiC MOSFET Modules (Orthogonal View)

B. THREE LEVEL INVERTER

Using the loss calculation for the 100 kW 3-level p-type IGBT based inverter, thermal modeling was carried out. The approximate loss chosen per leg for the thermal design was 333 W. Fig. 13. shows the thermal profile of the heat sink for each leg of the 3-level inverter. The forced convection air flow rate chosen was 120 cfm and the maximum junction temperature reached was 102°C. The ambient temperature chosen was 40°C.

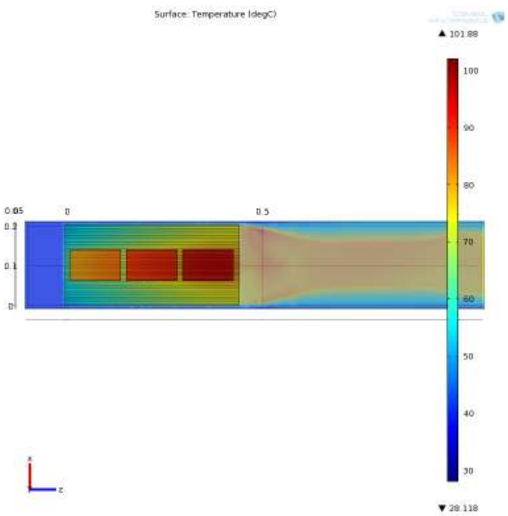

Fig. 13. Thermal modeling analysis of low voltage inverter implemented using three p-type SiC IGBT Modules (Top View)

VII. Simulation Results Of The TIPS

Fig. 14. and Fig. 15. shows the simulation results for the rectifier. The rectifier operates at unity power factor (Fig. 14). In this mode of operation the reactive current drawn by the rectifier is zero. Fig. 15. elaborates the space vector modulating waveforms for all the RYB phase. Fig. 16. shows the simulation results for the DAB. Vm1 is the three-level input voltage and Vm4 is the synthesized two-level voltage waveform. Fig. 17. is the output side line current. As the PWMs for all the three-phases are staggered by 120 degrees the switching harmonics are get cancelled at the resultant output current.

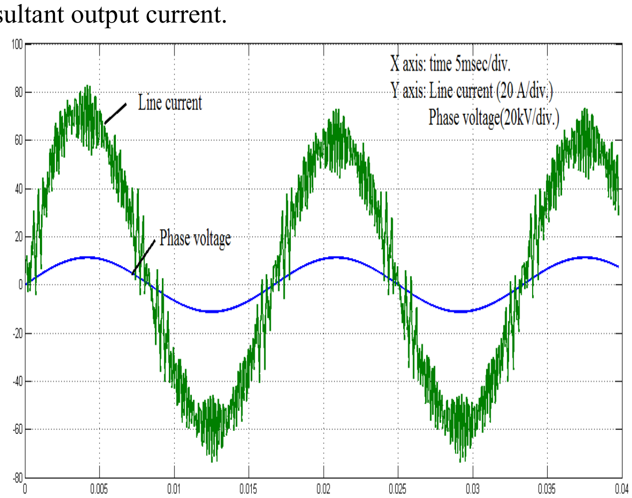

Fig. 14. Line current and Phase voltage of the input side rectifier

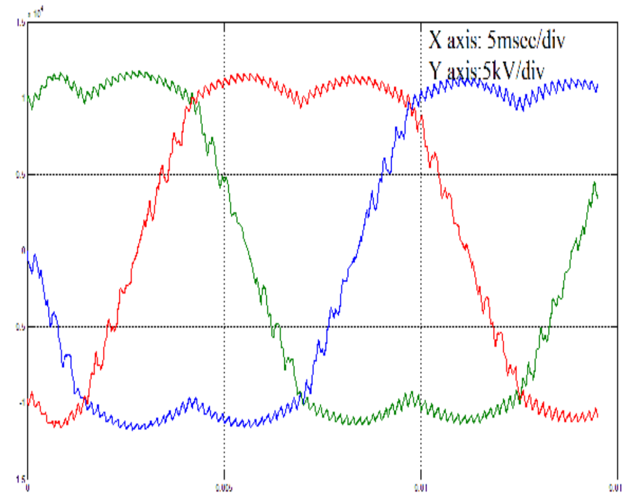

Fig. 15. Space vector modulating waveform

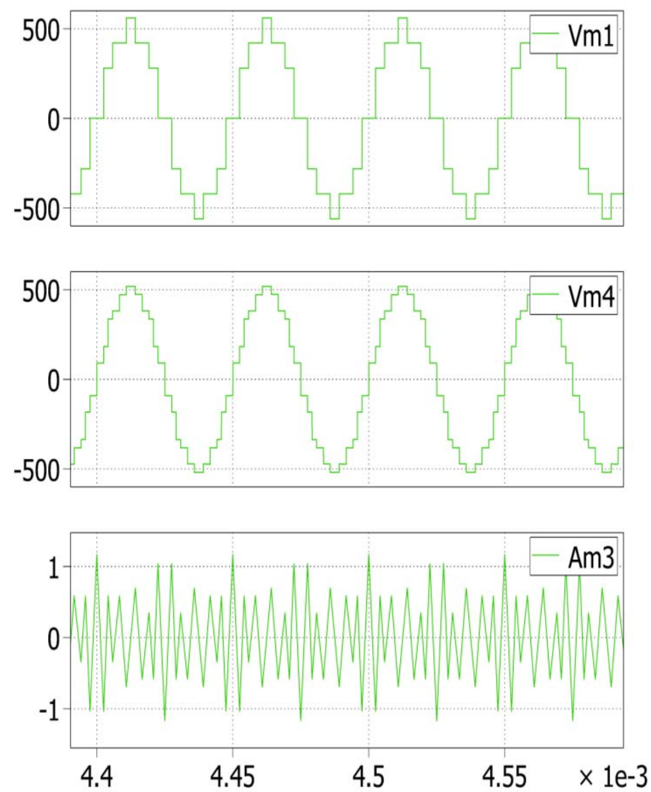

Fig. 16. Voltage and current waveform of DAB

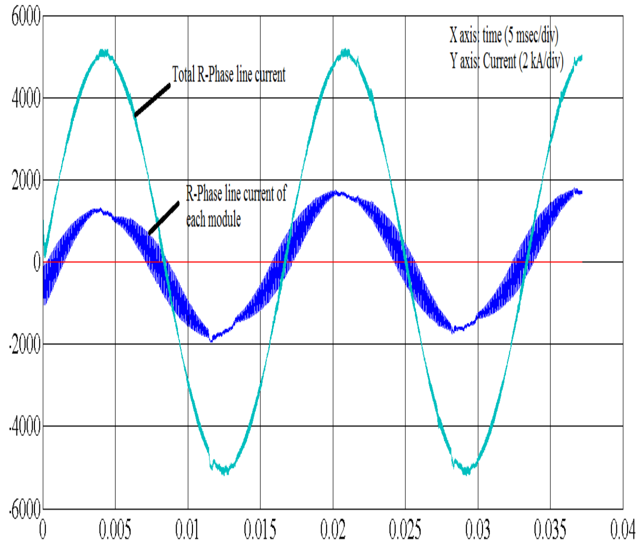

Fig. 17. Output side line current

VIII. CONCLUSION

In this paper an brief overview of TIPS is discussed. The TIPS is expected to be an attractive alternate solution for the distributed transformer. Not only it will transfer the power from the 13.8 kV grid to the 480 V grid but also helps to improve the voltage profile of the feeder. By the advent of SiC-IGBTs the grid interconnectivity with lesser number of switches and with 98% efficiency will be possible.

IX. ACKNOWLEDGEMENT

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