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Testing of Solid State Transformer

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Abstract*: In this paper, a transformer designed for high frequency operation is tested at different frequencies to analyse various aspects of the transformer, with and without load, and a performance comparison is done with the conventional transformer. The same specifications of the transformer are fed into the Matlab/Simulink model of the transformer and results are found to be adequate. A three stage topology of solid state transformer is selected in both software and hardware testing because of its paramount characteristics over the other topologies. The solid state technology led to the reduction in the physical profile of the transformer with power electronic devices on both the sides of the transformer in conjunction with the ancillary services provided by the introduction of power electronic devices into the system. The transformer when operating at higher frequencies (50 – 100 Hz) excelled in the temperature test with very little rise in temperature when compared to the conventional operation at 50 Hz and with suitable cooling system the high frequency operation will prove to be more advantageous. As conventional transformers with copper wound wires on an iron core will not respond to a control signal as power generation becomes distributed and with distributed generation (DG) on the rise, we need electronic based regulated power supply with software based remote intelligence. So, the present power grid has to oblige to solid state technology with the intention of being titled *smart.

***Keywords*: Distributed Generation (DG); High Frequency; Power Electronic Devices (PED), Smart grid; Solid State Transformer (SST); Three stage topology.**

1. INTRODUCTION

With the solid state technology becoming popular, the power distribution can be decentralised [1] in an attempt to increase the efficiency and reliability of power flow i.e. generation, transmission and distribution. This is possible with the DG paradigm that possesses all the required traits that would supplant the present conventional power distribution system, without any kind of compromises. The consumer requirements being a priority, this decentralisation process should be adopted without altering the terms of reliability. The demand control methodologies being followed in the present system are not able to cope with the regular amplification in the load demand. This increases the pressure on the electricity generation operators, not able to meet the load demand because of diminishing natural resources. Distributed generation [2]-[4], which emphasises the use renewable energy sources, will flawlessly eradicate the problem and also help in conservation of natural resources. Solar energy being the ubiquitous of the renewable sources, it is preferred but incomplete without any power electronic conversion techniques. This is the root cause that calls forth the implementation PEDs in the system.

HVDC and EHVDC transmissions are prevalent these days, albeit losses generated with the realisation of PEDs in the system, because of the supplementary benefits offered by these devices [5]. The same reasoning holds good for transformers too. Transformers being the prominent component of any electrical system, they require an immediate changeover to meet the constraints stated above. This led to the design and implementation of SST with different topologies[6]- [8] and it goes way back to the 1970's when the research started [9] and from then it has attracted many researchers to produce more proficient power electronic transformers. Drastic developments have taken shape since then to make SSTs as common as the conventional transformers while providing more benefits to the consumers.

In this work, an attempt has been made to review the available literature on design of transformer at different frequencies, incorporation of power electronic devices (PED) like rectifiers and inverters and integrating them to design and assembly

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(proto type) of an economically viable and energy efficient SST that would radically change the power network and tested on various loads at different frequencies. An analytical loss calculation of SST at different frequencies with appreciable results is also presented.

2. HIGH FREQUENCY TRANSFORMERS

The solid state transformer aims at replacing the traditional 50 Hz power transformer by means of high frequency isolated AC/AC solid state conversion techniques. Due to high-frequency modulation, the volume and weight of SSTs can be much smaller than those of conventional 50 Hz transformers and also allows higher utilization of the magnetic core [10]. Solid state transformers have lower physical contours than traditional 50 Hz transformers and provide active control of power flow. However, they are not as simple as traditional 50 Hz transformers because of the presence of power electronic converters. For a given voltage and number of turns, increasing the frequency allows the cross-sectional area of the core to come down without bringing the core into saturation. The advantage of running an electrical system at 100 to 400 Hz rather than 50 Hz is that the power supplies are smaller and lighter.

Hysteresis loss (W_h) $\propto Bm^{1.6} f \propto (V/f)^{1.6} f \propto f^{-0.6}$ (with constant voltage)

So, whenever frequency is increased, the flux density (Bm) reduces (i.e. for double frequency Bm is halved) and hence there is a significant reduction (around 40%) in W_h.

Eddy Current loss (We) $\propto Bm^2 f^2 \propto (V/f)^2 f^2 \propto V$

i.e., We is constant for any frequency if voltage is constant.

The inverter in the secondary side of the transformer, a part of the three stage topology, can give out constant voltage irrespective of any abruptions in the primary side.

3. THREE STAGE TOPOLOGY

The schematic of three stage topology is shown in fig-1.

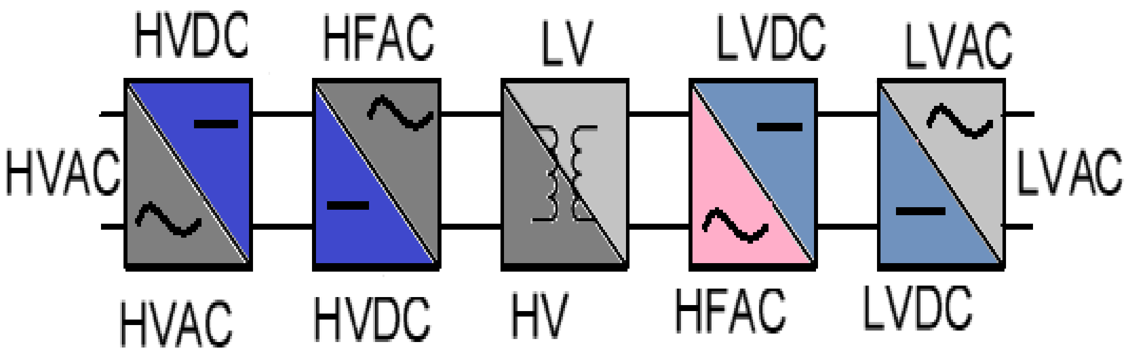

Fig. 1 Three stage topology

A MATLAB/SIMULINK model, fig 2, of the solid state transformer is realized. The three stage topology, as mentioned in [6], is chosen for the implementation. The input is an AC source of 440 Vrms (622 Vpeak) with 50 Hz frequency supplying input to the rectifier 1. Rectifier 1 is a single phase bridge rectifier with RLC filter. The input sinusoidal wave from the supply is first rectified into DC and advances to the primary side inverter. The inverter is an IGBT version with LC filter. The frequency of the operation of the transformer depends on the working frequency of the inverter i.e. the triggering of gate pulse given to the IGBT. The inverter derives the DC supply and produces a 434 Vrms sinusoidal waveform and is fed to the transformer. The inverter, which can control voltage and frequency, delivers the required 100 Hz supply to the isolation transformer. The transformer with a transformation ratio of 1:2 gives out 217 V rms to the secondary side rectifier. The high frequency transformer provides isolation between primary and the secondary side. The same conversion technique, as the primary side, is carried on the secondary side to get the final output of 220 V rms (309.6 V peak) with a Total Harmonic Voltage Distortion (THDv) of 1.56%.

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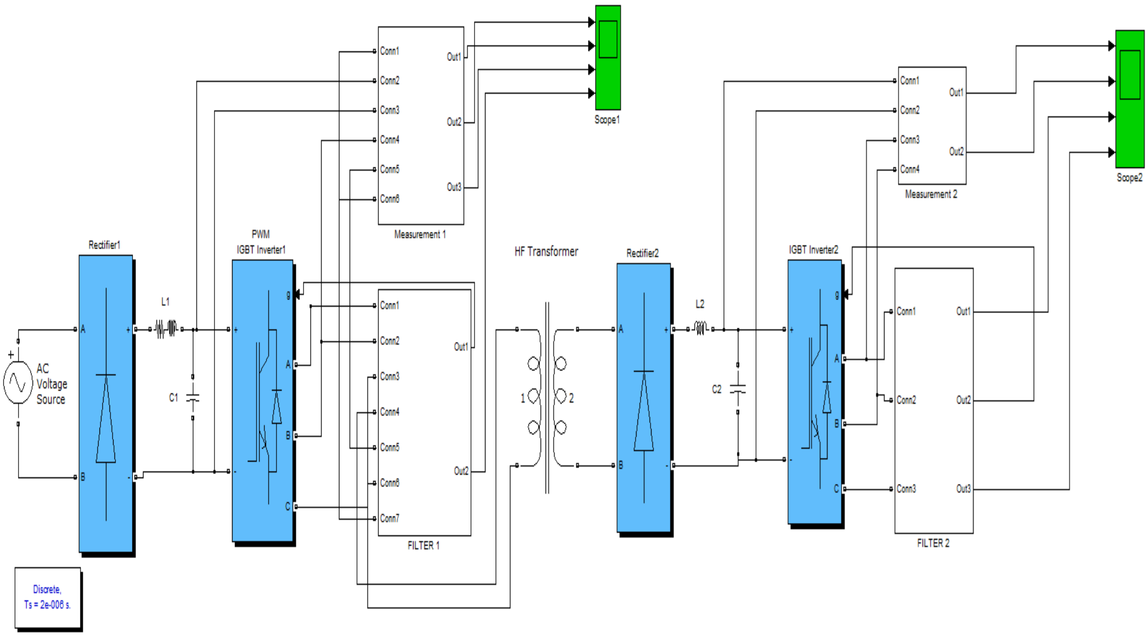

Fig. 2 Simulink model of three stage topology of SST

3.1 Transformer operating at 50 Hz

The input to the transformer is the conventional 50 Hz supply from the inverter. As shown in fig 3, the transformer plot describes a 434 Vrms plot and the final output being 220 Vrms with a THD of 1.56%, which is well below the recommended IEC limit of 5%.

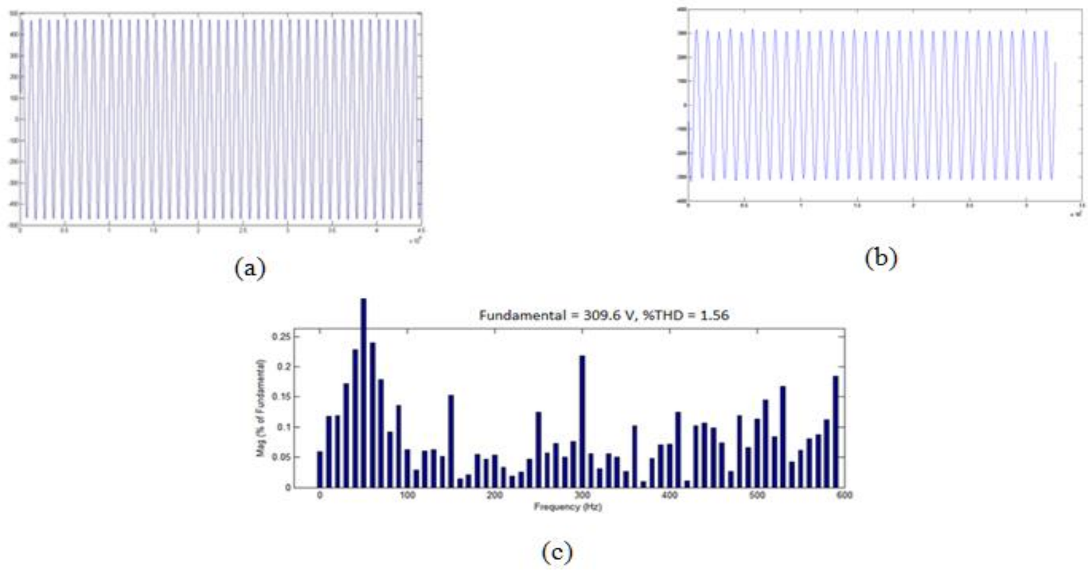

Fig. 3 (a) Transformer input or inverter 1 output (b) Final output or inverter 2 output (c) THDv

3.2 Transformer operating at 100 Hz

Similarly, fig 4 shows the transformer operation at 100 Hz with the same voltage levels as mentioned in 3.1. The transformer properties in Matlab model are altered accordingly for 100 Hz operation. This voltage-frequency control is impeccably achieved through the inverter on the load side. The alleviated THD also ascertains that 100 Hz operation is better than the conventional operation.

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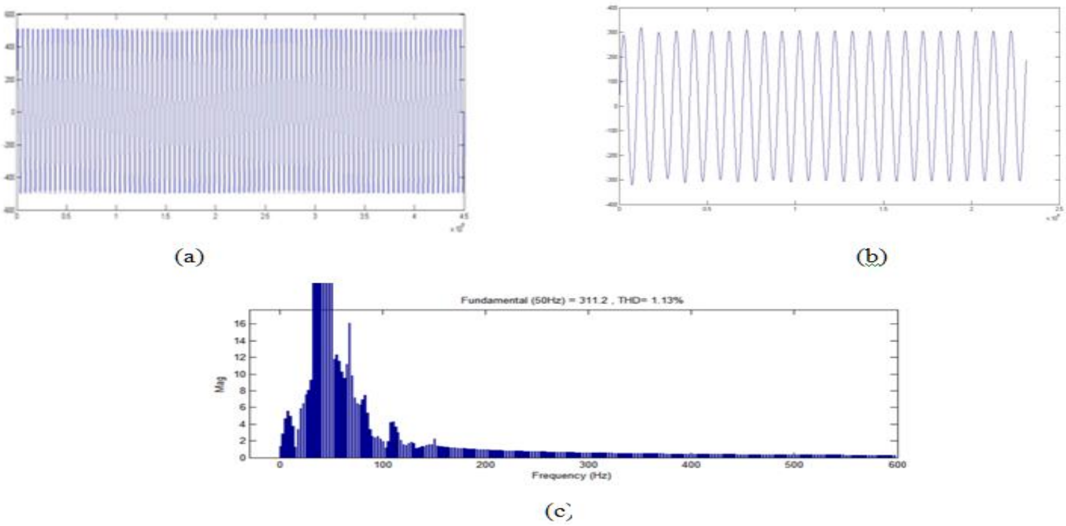

Fig 4 (a) Transformer input or inverter 1 output (b) Final output or inverter 2 output (c) THDv

4. HARDWARE

The proposed model is made ready (fig 5) with the following components (Table-1) and tested at various frequencies for different loads. The results are summarized in 4.1.

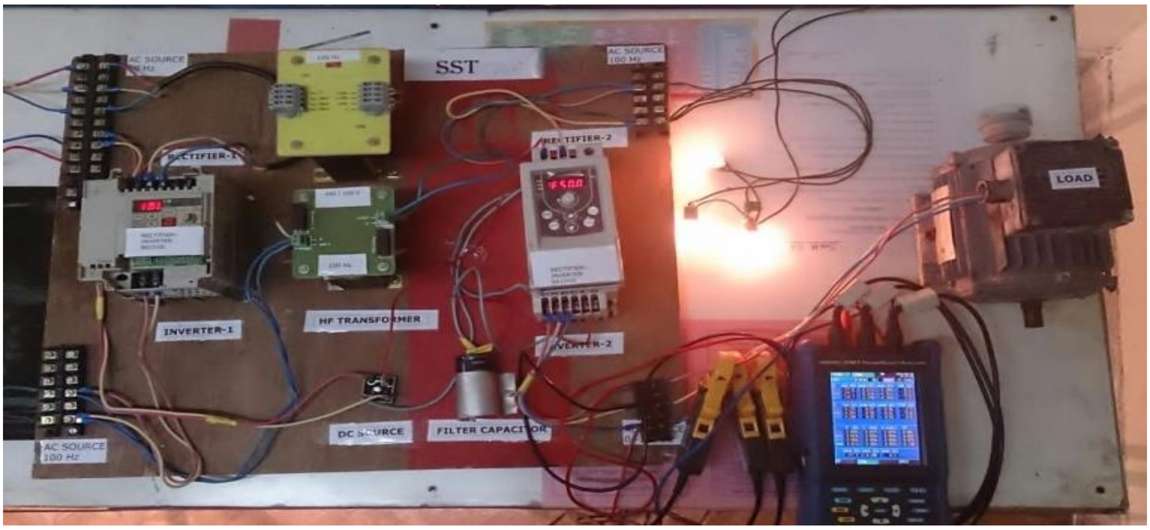

Fig. 5 Hardware model of SST

Table 1

Component	Specification
Rectifiers-1 & 2	Diode Bridge of MEI make, KBPC-3510 (35 A, 700 V, V_f=1.1 V, PIV=1000 V)
Inverters- 1 & 2	H-Bridge of IGBTs: IGW15N120H3 of Infineon make, 1200 V, 25 A)
Transformer	100 VA, 440/220 V
Measurement :	
Power Quality Analyzer	Model: 3197 of HIKIO, Japan
Temperature sensor	Non-contact thermometer (-18 to 275 ^{0}C), Model: 62
Loads	100 W lamps, 65 W ceiling fan and 3 ph, 415V, 50 Hz, 0.37 KW Induction Motor

4.1 Test results

Table 2 shows the complete analysis of the operation of the system. In **I** of the table, transformer operation on no load is evaluated and all the power loss in the system is considered to be iron loss of the transformer. The transformer when working at different frequencies shows a considerable change of iron loss, least being at 100 Hz, because of the changes in flux density which depends on the frequency. The input current is also augmented at 100 Hz which is important in proving that the magnetizing VA of the transformer is alleviated. The secondary voltage depends on the frequency of operation because emf generated which is directly proportional to the frequency.

Table-2

S.No.	Parameter	Conventional-50 Hz		SST (of actual 100 VA Tr.)			
		100 VA	200 VA	25 Hz	50 Hz	75 Hz	100 Hz
I	No-Load :						
1	Primary Volts(V1)	413	413	170	340	405	405
2	Pri. Current(Im)-mA	21	28	11.3	12	9.5	7.8
3	Power loss(=Iron loss)-W	1.8	2.7	3	1.8	1.5	1.0
4	%THD (Pri.)	1.6	1.6	1.65	1.65	1.65	1.65
5	Secondary Volts(V2)	225	225	68	146	177	188
II	Load (100 W Lamp):						
1	Primary Volts(V1): Supply/Tr. input			413/170	413/340	413/405	413/405
2	Pri. Current(I1)-mA :Supply/Tr. input			95/85	190/177.4	209/197	208/196.2
3	Power loss(Iron+copper)-W			5	6	3	3
4	%THD (Pri.)				1.6		
6	%THD(Sec)			8.1	8.02	8.03	8.03
7	Sec. Current(I2)-mA			180	350	404	412
III	Load (2 X 100 lamps=200 W):						
1	Primary Volts(V1): Supply/Tr. input			413/170	413/340	413/400	413/400
2	Pri. Current(I1)-mA :Supply/Tr. input			95/85	190/177.4	209/197	208/196.2
3	Power loss(Iron+copper)-W			5	15	13	13
4	%THD (Pri.)				1.6		
5	%THD(Sec)			8.1	8.02	8.03	8.03
6	Sec. Current(I2)-mA			330	630	740	740
IV	No-Load test of a 3 ph, 415 V, 0.37 KW Induction motor is done by connecting it to Inverter-2 through 100 VA transformer to Grid Supply via Inv-1.						
1	Supply	50 Hz	100 Hz	Grid Supply	Remarks / Observations		
2	Volts to Motor	158.5	193.1	415			
3	%THDv	6.7	NA	3.5	Due to SST supply, No-Load power is reduced with improved power factor and soft starting facility.		
4	Motor Current-mA	270	275	350			
5	Power input to motor-W	32	39	50			
6	Power factor	0.739	0.73	0.2			

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V	To demonstrate UPS, the grid is switched OFF and 220 V DC is extended through a Storage Battery to Inv-2 with an induction motor as load:		
1	Output voltage (Motor Volts)	158.6	Remarks / Observations
2	Output Current (Motor No-Load)-mA	245	
3	%THD	7.6	It is proved that storage battery facility will also equally cater the needs of consumers without disruptions.
4	Frequency - Hz	49.97	
5	Power-W	16	

The voltage also saturated somewhere at 62 Hz, showing that no matter how much the frequency is increased beyond 62 Hz, the voltage levels do not rise abruptly, which is quite an attractive feature of the inverter at the load side.

In case-**II above**, a 100 W lamp load is applied at the load side and the results are shown. The transformer operation is quite normal. The losses observed in this operation will be the total loss of the system i.e. both copper and iron loss. These losses were minimum at 100 Hz.

In **III**, the system load is increased to 200 W to examine the transformer performance and to verify that the transformer can operate at double its rated capacity when the frequency is doubled [11]. The power losses increase, naturally, because the system is loaded to double its capacity. The temperature variations were miniscule when compared with the conventional operation, refer 4.2 for further details.

In **IV**, a motor, without any load on its load end, is introduced in the system and its performance was evaluated. The motor working on grid supply presented substandard results with high power consumption and current and low power factor. Whereas, with the power electronic control in the system, both 50 Hz and 100 Hz operation, there is a drastic improvement in the power factor and power consumption.

In **V**, the grid supply is taken off from the system i.e. the transformer is disconnected from the network. A 220 V DC source from the storage battery is extended through inverter 2. So, the system now encompasses only a battery and an inverter with a motor load. The operation of UPS is demonstrated through results from **V**.

4.2 Temperature Measurement

The conventional transformer of 100 VA is tested at 50 Hz on 100 W load and temperature rise in 1 hour is recorded. Now, 100 Hz supply is given to the transformer and loaded to 200 W and the temperature is recorded again. There is no major rise in temperature and hence concluded that the transformer can be loaded to double the rating at double frequency.

The temperature of the transformer is measured (table 3) at different intervals with the transformer operating at 50 Hz and 100 Hz and all the loads (motor and lamps) connected.

Ambient temperature = 28.2 °C

Table 3

S.No.	Time, t (in minutes)	Temperature (°C) at 50 Hz	Temperature (°C) at 100 Hz
1	0	28.2	28.2
2	5	28.5	28.7
3	7	28.5	28.8
4	10	28.9	29.4
5	15	29.3	29.8
6	60	31.0	32.8

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5. CONCLUSIONS

The solid state transformer performs the duties of the traditional transformer and with power electronics in the circuit several services like power factor improvement, voltage and frequency control, harmonic filtering and reactive power compensation are offered. A simple model has been assembled, with a transformer that can withstand frequency vacillations, and various parameters have been measured with the help of power quality analyser, a true rms meter that can measure values even with frequency variations. The results are motivating, more research options are now available like improving the cooling system, designing even better solid state devices and new construction methodologies of the transformer, with 100 Hz operation possessing the best parameters.

Based on the results, it is proved that high frequency modulation is better with reduced size/weight of the transformer and better control over the system when integrated in to the grid. Further detailed measurement of the temperature rise of transformer confirms that with optimum cooling system the temperature can be controlled.

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