Proceedings of IOE Graduate Conference, 2019-Summer
Peer Reviewed
Year: 2019 Month: May Volume: 6
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Modeling and Analysis of Solid State Transformer

Srijana Shrestha [a], Menuka KC [b], Indraman Tamrakar [c]

[a, b, c] *Department of Electrical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] 070bel340@ioe.edu.np

Abstract
Solid State Transformer (SST), a high frequency transformer controlled by power electronics circuits aims to mitigate the drawbacks of conventional transformer. As compared to conventional transformers, it is small in size, reduces losses accompanied with reactive power compensation for load internally and is insensitive to the harmonics.The power electronic switches used in this model can be controlled in such a way to generate reactive power internally so that separate reactive power compensator is not required providing the zero percent voltage regulation at the load end. In this paper, the optimization of SST is analysed to make it more power efficient.

Keywords
High frequency transformer, Power electronic devices, Reactive power compensation, Power Efficient

1. Introduction

Many renewable energy power plants are becoming popular globally due to their many advantages over conventional power plants like low carbon emission, lower operating costs, never-ending fuel source, etc. However, as these projects are getting more popular, more research and development is required to make them viable and economical. Renewable energy plants like wind power plant requires an additional VAR compensator - most commonly used is Static Synchronous Compensator (STATCOM), in addition to transformer, to inject power to the grid and maintain stability; many micro hydro power plants have induction generators and, hence an additional VAR compensator is required before transmitting power to electrical appliances in homes.

Recent advancements in solid state technology has also given an opportunity to conventional transformer to make it more compatible and economic with different renewable energy technologies. A high frequency transformer with solid state switches, and thus coined as Solid State Transformer (SST), adds more functionality to a transformer than a conventional transformer can, that is, provides required reactive power to the system and therefore, helps in voltage regulation with minimum injection of harmonics in to the source [1, 2] which has become a necessity in present day renewable energy projects. Along with supporting in smooth power flow and voltage regulation in renewable energy projects, SST can be adopted in wide ranges of projects. It can also be used to regulate the voltage in traction system where voltage fluctuation is a major problem that arises during transportation [3]. The conventional transformer performs voltage transformation as well as provides electrical system isolation between two systems: power grid and electric traction system.

In the past few decades, the technological advancement in solid state physics is one of the hopeful solution to deal with the problems of complex power systems. Controllable solid state switches have triggered development of various power electronics converters which find application in both transmission and distribution systems [4].

SST is basically a multi-stage power electronic circuit which achieves voltage transformation via high frequency isolation. The weight and volume of SST is reduced significantly when compared with traditional transformer of same size and capacity. The added power electronic circuitry along with high frequency transformer, not only reduces its size, but also regulates voltage at the load end. One of the most important features is its capability of suppressing the harmonics while injecting or absorbing power from the main grid.

The SST operates in four stage as shown in Figure 1

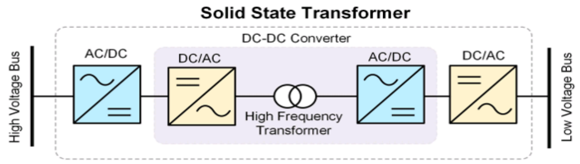

Figure 1: Block Diagram Representation of SST

AC sinusoidal voltage of 50 *Hz* is rectified to pulsating DC wave and a constant DC is obtained across capacitor filter. The DC voltage is then inverted to get high frequency AC square wave normally in the range of several kilohertz as input to the high frequency transformer. The high frequency transformer steps up or down the voltage level to a desired value. As transformer operates in high frequency, its volume and weight decreases significantly. Thereafter, the high frequency AC is rectified to a constant dc across the capacitor. Finally, the DC voltage is again inverted to 50 *Hz* square wave and appropriate filter circuit gives sinusoidal AC voltage which can be fed to the load as desired.

2. Proposed Scheme

Different converter structures can be deployed for realization of AC-AC conversion in SST [5] as shown in Figure 2

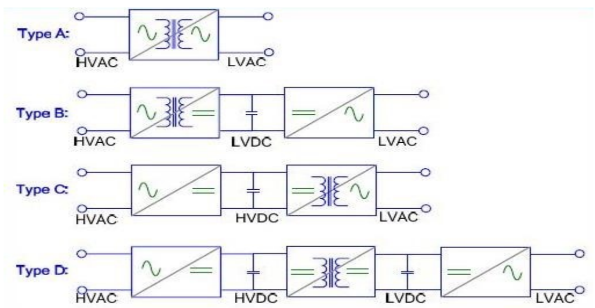

Figure 2: Different Topologies of SST

In this paper, Type-D topology is implemented where 220 V, 50 *Hz* AC source is rectified to DC which is then inverted to 1 *KHz* AC power. High frequency AC power is stepped down/up which is again rectified and then finally shaped back to 50 *Hz* for prospectively adopting SST in power distribution system.

Fig.3 shows the circuit diagram of the proposed scheme with its control logic. The source current is sensed and tracked using hysteresis band current controller where reference current is generated using DC voltage across the filter capacitor across rectifier and passing through PI controller. The signal thus generated is then compared with the input current and gate pulse is generated by hysteresis band current controller.

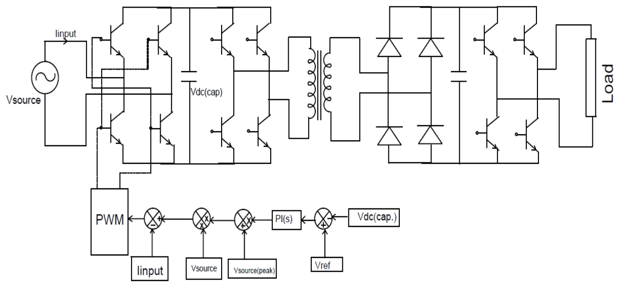

Figure 3: Circuit Diagram of Proposed Scheme

2.1 Control Scheme

2.1.1 Control of Desired Active Power

Control of high voltage rectifier to generate active power demanded by load.

When active power transferred from source is greater than the power consumed by load, filter capacitor gets charged and V_{cp} increases.

When power transferred from source is lesser than the power consumed by load, filter capacitor gets discharged and V_{cp} decreases.

Power transferred from Inverter = Power consumed by load, then V_{cp} remains constant. Hence I_{ref} proportional to Active power to be transferred can be generated.

2.1.2 Control of Input Rectifier:

In this stage, 50 *Hz* sinusoidal 310V peak voltage is supplied by voltage source to high voltage rectifier; the introduction of rectifier with capacitance filter in circuit acts as nonlinear load which draws non-sinusoidal current from sinusoidal voltage source.

The power electronics circuit introduces harmonics in the source current which causes increase in loss eventually reducing the efficiency of the system. Certain vulnerable components can be impaired by overheating of the system. The harmonics also reduces the power factor of the system; the higher order harmonics act as the magnetizing component and thus drawing more reactive power from the source [6].

To lessen these problems, a controlled rectifier is used in the input side controlled by PI controller and gate pulse is generated via hysteresis band current controller.

The voltage across the capacitor V_{cp} (referred to Figure 3 is maintained constant. It means that all the active power required by load is flowing via source to load.

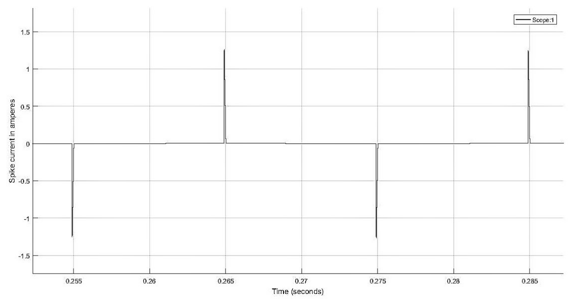

Figure 4: Spikes in Input Current Drawn by Non-Linear Load

The rectified dc voltage is sensed and compared with reference voltage of 310V. 310V is the peak value of ac voltage and at this value V_{dc} should be maintained constant which signifies the constant dc voltage of equivalent ac voltage.

The difference output signal is passed via PI controller. The value of P and I is controlled to generate a signal proportional to the current flowing in the circuit.

This current proportional signal is dc value which is further divided by RMS value of voltage with a gain of $\sqrt{2}$ resulting a signal proportional to inverse of resistance (1/R). Finally, this signal is multiplied by input voltage to make reference current and voltage in phase.

Mathematically,

$$I_{ref} = \frac{(V_{dc} - 310) * (K_p + K_i) * V_m \sin(\omega t)}{V_{rms} * \sqrt{2}} \quad (1)$$

The above equation gives the reference current in phase with voltage which is compared with actual input current and passed via hysteresis band current controller with a band of 5% and the generated gate signal is used to control the switches.

2.1.3 Control of LV Inverter

In low voltage rectifier, the rectified voltage is inverted to a frequency of 50 *Hz*. The gate pulses for MOSFET is generated via sinusoidal pulse width modulation (SPWM). There are various reason for choosing SPWM over HBCC and pulse generator.

2.2 Hysteresis Band Current Controller

A hysteresis band current controller is used to generate gate pulses for the inverter. The inverter is expected to inject the exact replica of reference current ideally but since this is not possible, the best that can be achieved is the injection of an approximated version of the injected current.

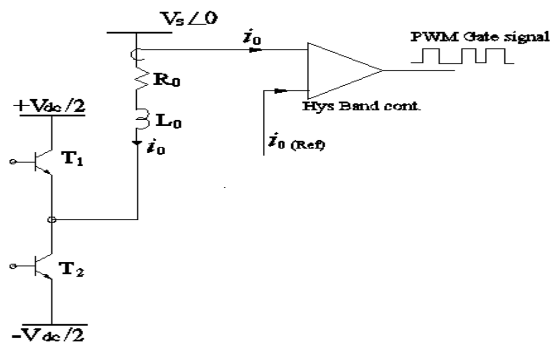

Figure 5: Schematic Diagram of HBCC

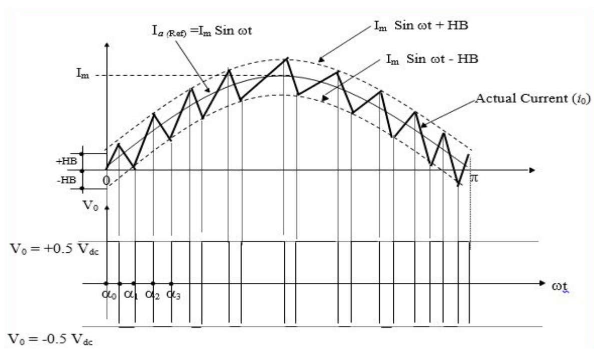

Figure 6: Switching Instants and Waveforms of HBCC PWM Inverter

A comparator is used to compare the value of actual injected current and the reference current to give gate signal as output. Normally, to control the value of some signal, one of the approaches is to use a single threshold value i.e. with no band around the reference signal. The reference current generated by the controller is described by:

$$I_{a(Ref)} = I_m Sin(\omega t) \quad (2)$$

Where, $I_m = \sqrt{I_d^2 + I_q^2}$ The upper and lower limit currents are given by:

$$I_{a(upper)} = I_m Sin(t) + HB \quad (3)$$

$$I_{a(lower)} = I_m Sin(t) - HB \quad (4)$$

When the switch T1 of the bridge inverter is turned on keeping T2 off, the inverter output voltage is +0.5 V_{dc} and the inverter current (i_o) rises up satisfying the following equation.

$$\frac{V_{dc}}{2} - V_s = R_o.i_o + L_o\frac{di_o}{dt} \quad (5)$$

When the actual current exceeds a prescribed upper hysteresis band, the upper switch T1 is turned off and the lower switch T2 is turned on. As a result, the output voltage transits from +0.5 V_{dc} to -0.5 V_{dc}, and the current starts to decay satisfying the following equation.

$$\frac{-V_{dc}}{2} - V_s = R_o.i_o + L_o\frac{di_o}{dt} \quad (6)$$

When the current crosses the lower band limit, the lower switch T2 is turned off and the upper switch T1 is turned on. The actual current wave is thus forced to track the sine reference wave within the hysteresis band by sequential switching of the upper and lower switches as in fig. 6. The inverter then essentially becomes a current source with peak-to peak current ripple, which is controlled within the hysteresis band irrespective of V_{dc} fluctuation. The similar controllers are provided in the other two phases with 120° phase difference. Solution of equation (5) gives the expression for the rising current and when it is equated to $I_m Sin(t) + HB$ gives the solution of the switching instant α_1. Similarly, solution of equation (6) gives the expression for the decaying current and when it is equated to $I_m Sin(t) + HB$ gives the solution of the switching instant α_2 and so on.

2.3 Sinusoidal Pulse Width Modulation

Sinusoidal Pulse Width Modulation (SPWM) is a prominent control method in power electronic inverter circuit. It has various advantages like low switching losses, low power consumption, high energy efficient upto 90%, high power handling capability, no temperature variation-and ageing-caused drifting or degradation in linearity, easy to implement and control, compatible with today's digital microprocessors and the output has fewer harmonic. SPWM makes use of many triangular signals, that are level shifted or phase shifted, and compare with a single sine wave to generate gating signals for the respective switches. The intersection of the sine signal with the various triangular signals will generate the gating signals for the respective switches.

Basically, in this modulation technique there are multiple numbers of output pulse per half cycle and pulses are of different width. The width of each pulse is varying in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The gating signals are generated by comparing a sinusoidal reference with a high frequency triangular signal.

The rms AC output voltage is :

$$V_o = V_s\sqrt{\frac{p\delta}{\pi}} \rightarrow V_s\sqrt{\sum_{m=1}^{2p}\frac{\delta_m}{\pi}} \quad (7)$$

2.4 LCL Filter

LCL filter represents a third order filter giving -60 *dB/ decade* attenuation. This type of filter can reduce the harmonic distortion levels at lower switching frequencies. However, it may cause both dynamic and steady-state input current distortion due to resonance. For the convenience of attenuation of higher frequency at -60 *dB/decade*, LCL filter is chosen for our application [7].

Cut-off frequency is a boundary in the system frequency response at which energy flowing through the system begins to be reduced (attenuated or reflected) rather than passing through. The attenuation characteristics at the cut off frequency (f_c) is one of the critical factors involved in designing a second order filter. The gain near the cut-off frequency could be very large and amplify the noise at that frequency. The relationship between the filter elements and the cut off frequency of a low-pass filter is given by equation

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

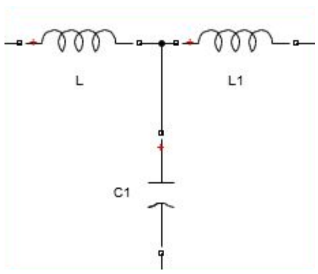

Figure 7: LCL Filter

2.5 Power Factor

PF is cos of ϕ, the phase angle between the voltage and current waveform. However, according to [8] this

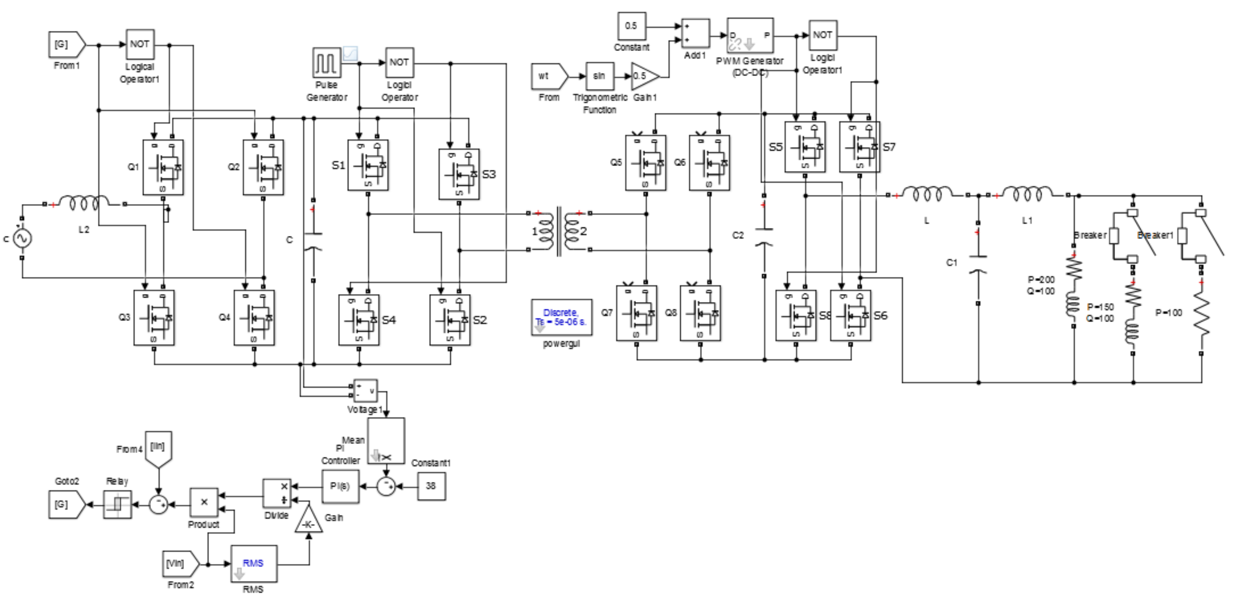

Figure 8: Complete Model of Proposed System

conventional definition is only valid when considering ideal sinusoidal signals for both current and voltage waveforms, and in reality, most off-line power supplies draw a non-sinusoidal current. The P.F. value measured is affected by both the phase lag ϕ and the harmonic content of the input current which is given as :

$$P.F. = \cos\theta . \cos\phi_1 \tag{9}$$

where ϕ_1 is the "conventional" displacement angle (phase lag) between the voltage and the fundamental component of the current, while θ is the distortion angle caused by the harmonic content of the current.

Improving the Power Factor means reducing both elements:
$\phi_1 \to 0$ means $\cos\phi_1 \to 1$: reduction of the phase lag between I and V,
$\theta \to 0$ means $\cos\theta \to 1$: reduction of harmonic content of I.

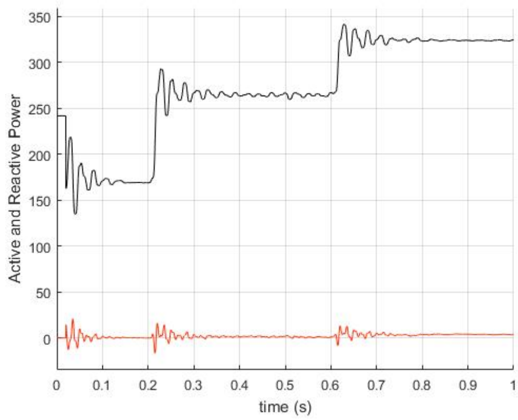

Figure 9: Input Active and Reactive Power

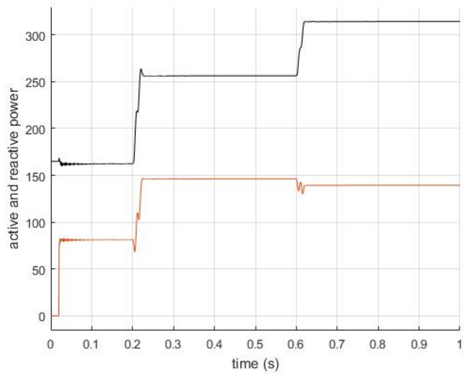

Figure 10: Output Active and Reactive Power

3. Simulation Study

A 500 VA SST with 220 V, 50 Hz input voltage is modeled. The complete diagram of proposed system is simulated in MATLAB/Simulink as shown in Figure 8. Figure 9 shows the active and reactive power flow of input. As it can be seen from figure, the reactive power consumed is zero. However, in Figure 10, it is noticed that the load is consuming reactive power. Figure 11 shows the input voltage and current waveform with phase difference of zero.

As can be seen from Figure 4, the spike current was resulted from non-linear nature of the load. Figure 12 shows the output voltage and current waveform in which current is lagging voltage by some phase difference with harmonics of less than 5%.

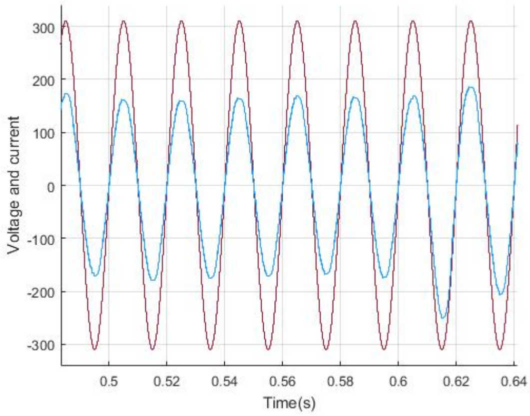

Figure 11: Input Voltage and Current Waveform

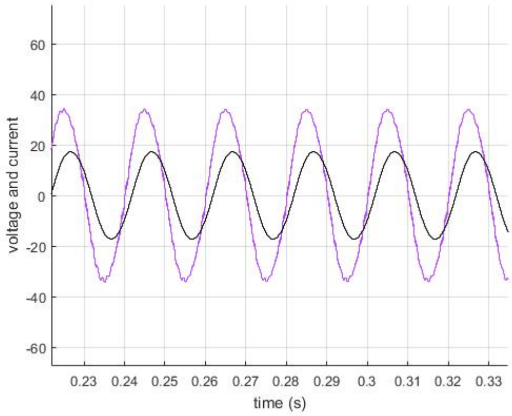

Figure 12: Output Voltage and Current Waveform

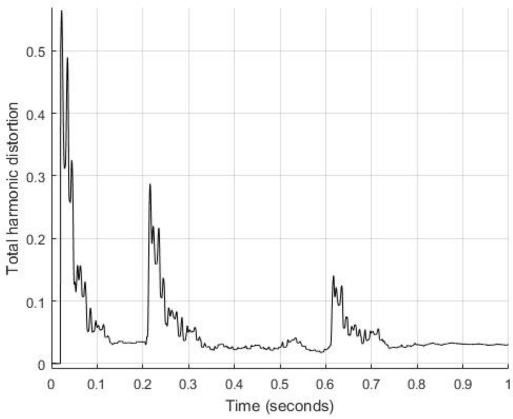

Figure 13: THD in Input Current

It can be seen harmonics in input current is less than 5% from Figure 13 which assures quality to the system.

Figures 14 and 15 show the THD in output current and output voltage.

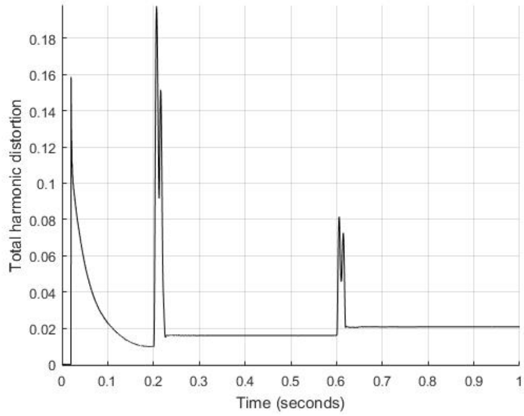

Figure 14: THD in Output Current

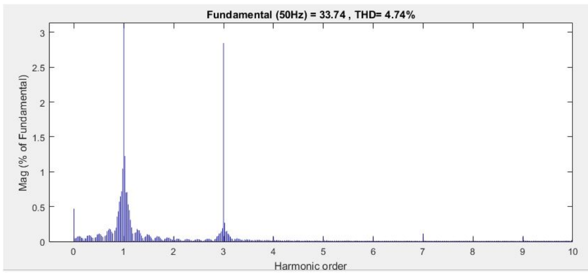

Figure 15: Harmonic Content in Output Voltage

4. Simulation Optimization

As observed in simulation of SST, the power efficiency was greater than 95% which is less in comparison to conventional transformer; as power transformer has maximum efficiency upto 99.9% and distribution transformer has 70%-95% depending upon the load condition which makes SST obliged to have efficiency as maximum as possible. Here, the power losses is occurring in switching inside rectifier and inverter which can be lessen by using power electronic switch made from wide bandgap semi-conductor materials. According to [2], wide bandgap materials such as 4H-Silicon Carbide(4H-SiC) can be adopted as it has larger energy band gap(EBG), which makes it capable of operating at a higher temperature. Additionally, the ten times larger Breakdown Electric Field(BEF) enables the SiC devices to switch at higher voltage than common semiconductors, higher current and higher frequency condition thereby reducing internal power loss in the switches.

Table 1: Characteristics Comparison of 4H-SiC and Si [2]

Material	EBG (eV)	BEF (V/cm)	TC ($W/m.K$)	SEDV ($cm.sec$)
4H-SiC	3.26	2.2(10^6)	380	2.0(10^7)
Si	1.12	2.5(10^5)	150	1(10^7)

5. Conclusions

SST in contrast to the conventional transformer, reduces the size and weight of transformer considerably as well as generates reactive power internally reducing the cost of additional reactive power compensator. To justify objective, variable inductive load has been used and simulated. As seen in the results and analysis section, the power factor of the system was improved to 0.99 and efficiency of greater than 95% was obtained. As well as the load terminal voltage is maintained almost at constant value. As per the objective i.e. reactive power compensation, this simulation model of single phase SST successfully fulfills its objective.

Also, optimization of model can be done by the application of wide bandgap semiconductors such as 4H-SiC which has high energy band gap (EBG) , breakdown electric field (BEF) , thermal conductivity (TC) and high saturated electron drift velocity (SEDV). It can operate at high temperatures, high frequencies and high voltages reducing the internal losses in semiconductors ultimately resulting high efficiency of SST.

6. Recommendation for Future Works

The simulation model was successful in meeting the desired output of reactive power compensation and less than 5% voltage regulation at load end. In future, simulated SST model has high scopes in integrating renewable energy technologies like solar PV system, wind system, tidal power system into the electrical grid or mini grid system. Futhermore, the hardware implementation of the model will result in small and cheaper solution to the existing technologies of transformer and VAR compensator.

Acknowledgments

The authors would like to express gratitude towards the Department of Electrical Engineering, Pulchowk Campus for providing with the necessary help required for the project.

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