A Comparison Study of Solid State Transformers Using Different Switching Techniques

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Abstract: ***This paper investigates different switching frequency based pulse width modulation techniques which can minimize the total harmonic distortion and enhance the power quality from solid state transformer. Solid state transformers are important for various power electronics applications such as flexible AC transmission systems, next generation carriers and power system applications. Four methodologies adopting the constant switching frequency, variable switching frequency, constant pulse width modulation and variable pulse width modulation concepts are proposed in this paper. MATLAB/Simulink has been chosen to implement these techniques due its fast proto typing, simple hardware and software design. The simulation and experimental results are presented.***

Keywords: Solid state transformers, Single Phase Matrix Converter (SPMC), PWM technique, MATLAB/Simulink.

1. Introduction

Today's conventional power electronic systems and design practices result in systems that are 10X too large and heavy for various high frequency applications. In electrical power distribution and power electronic applications, a transformer is an indispensable component which performs many functions. At its operating frequency (60/50 Hz), it is one of the most bulky and expensive components. The concept of the solid state transformer introduced has shown considerable reduction in size, weight, and volume by operating at higher frequencies.

2. Solid State Transformers

The solid state transformer combines power electronics with a transformer that is reduced in size due to the operating frequency of the power electronics. Another possible advantage of this technology would allow the output voltage to be better regulated with fluctuations of the input. The development of wide band gap (WBG) semiconductors is presenting a possible paradigm shift in semiconductor power density. WBG devices operate at higher temperatures and require less cooling. They also have higher blocking voltages than conventional silicon devices and operate at higher switching frequencies, thus allowing for the use of smaller transformers.

The increased usage of power electronics raises the concern of poor power factor loads along with possible high harmonic loads. Both of these issues are a burden on the power generation equipment and affect the overall efficiency of the power distribution system. The power requirements may be better managed to enable the generator to achieve a net power factor of 1.0 by utilizing active pulse width modulations.

3. Single Phase Matrix Converter (SPMC)

The Matrix converter (MC) offers an "all silicon" solution for AC-AC conversion, removing the need for reactive energy storage components used in conventional converter system [1]. The topology for MC was first proposed in 1976 [2]. The SPMC was realized and defined by Zuckerberger [3]. Earlier works are in the absence of no safe commutation. This problem needs to be resolved in any PWM type of converters due to absence of natural freewheeling paths [4] as available in other converter topologies. Switching arrangements for safe-commutation strategy has been proposed in 2005 [5] but not properly defined.This topology consists of a matrix of input and output lines with four bi-directional switches connecting the supply input to load output at the intersections as shown in Fig.1.Each of the individual switches is capable of conducting current in both directions whilst at the same time capable of blocking voltage. For this work, the anti-parallel IGBT-diode pair as shown in Fig.2 is used.

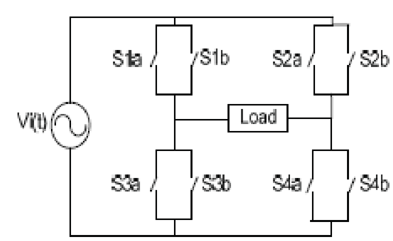


Figure 1: SPMC circuit configuration

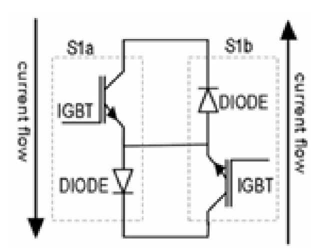


Figure 2: Bidirectional Switch

4. Solid State Transformer Circuit Topology

Fig.3 shows the circuit topology with static converter located at both on primary and secondary side. It contains two main parts, the primary and secondary side converter. Each uses bi-directional switches coupled with high frequency ac transformer that operate synchronously. High frequency current and voltage will be generated at transformer windings due to switching action of the primary converter; the secondary converter on the other hand unfolds the current and voltage into low frequency output. [6]

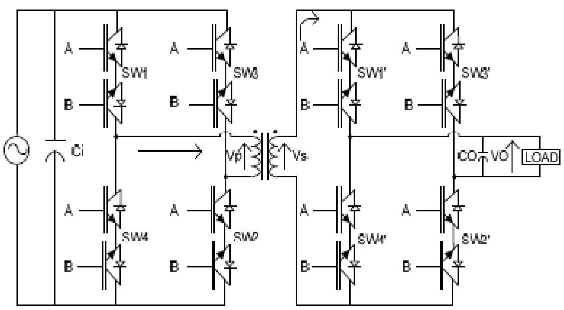


Figure 3: Circuit topology with static converter located at both on primary and secondary side.

5. Switching Strategies

Both the static converters use different control requirements to achieve the desired output waveforms and it is dependent on the frequency of the synthesized output. In the first stage the frequency is increased from 50 Hz to desired high frequency feeding into the transformer on the primary side. The output of the transformer is then fed to SPMC that reconstructs the high frequency input into 50Hz. Fig.4 shows the operation of primary converter where the input supply of 50Hz produces a synthesized high frequency output waveform.

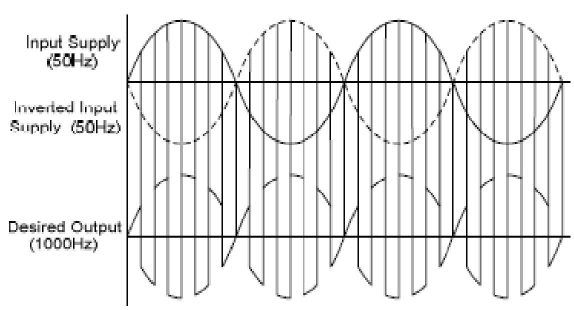


Figure 4: Input supply and the desired output waveform at primary converter.

The output of the primary converter becomes the supply for the secondary converter. The input high frequency will be folded into low frequency 50Hz and can be seen from Fig.5.

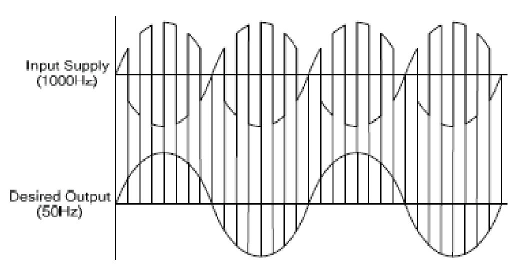


Figure 5: Input supply and the desired output waveform at secondary converter.

The application of safe commutation strategy as proposed by Z.Idris [7] is represented by Fig.6 to Fig. 9.

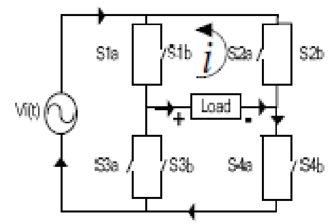


Figure 6: State 1 (positive cycle)

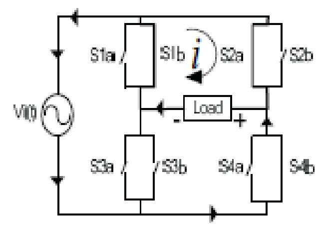


Figure 7: State 2 (negative cycle)

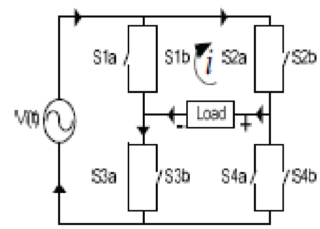


Figure 8: State 3 (positive cycle)

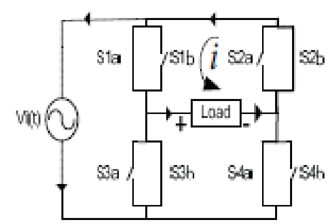


Figure 9: State 4 (negative cycle)

The alternative switching strategy [8] can be seen from Fig. 10 to Fig. 11 where the positive supply same as Fig.6 and Fig.8.

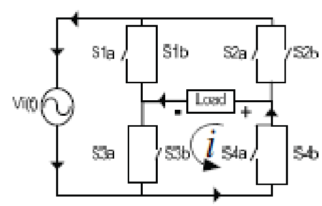


Figure 10: State 2 (negative cycle)

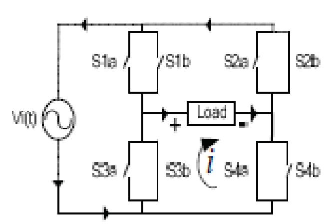


Figure 11: State 4 (negative cycle)

The switching arrangements at both side static converters have been investigated for inductive load applications. Fig.12 shows the alternative switching sequence of the primary converter.Fig.13 shows the alternative switching sequence on secondary converter.

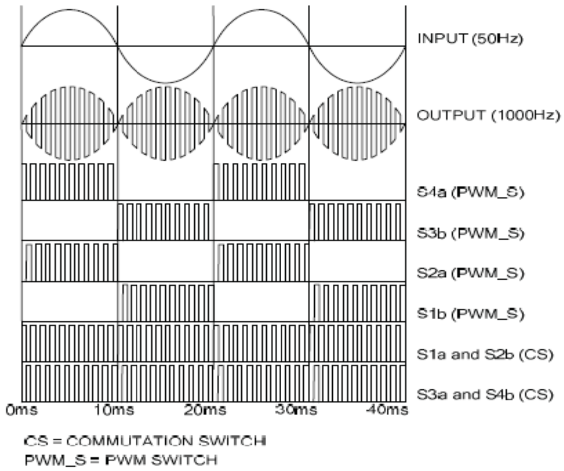


Figure 12: Alternative switching sequence of the primary converter.

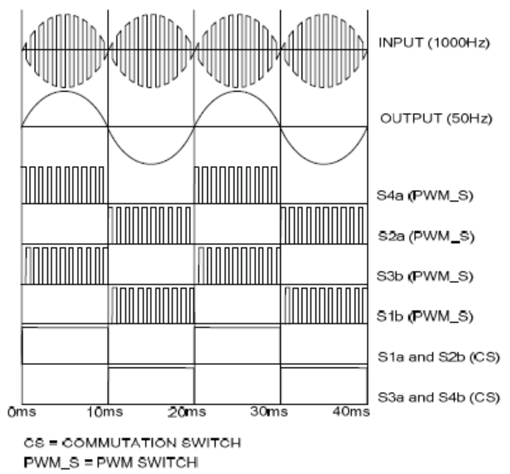


Figure 13: Alternative switching sequence on secondary converter.

6. Switching Techniques and MATLAB Implementation

6.1 Variable Switching Techniques

6.1.1 Variable Switching Frequency

In the timer controller with variable switching frequency technique the switching frequency is varied. In this type of control strategy, the chopping frequency f is kept varied thus by keeping the t_{ON} constant. Even though the frequency is varied the ideal time period that exists between the moment when the input current crosses with the reference current and the converter commutation is always seen to be kept constant and coinciding.

6.1.2 Variable PWM

In order to reduce the inverter switching loss and system noise of motor drives operating in high output torque region, preventing over-heating and demagnetization of the electric motor variable switching frequency PWM (VSFPWM) strategies based on on-line prediction of ripple RMS value this switching strategies are employed [9].

The variation in switching frequency basically causes three main functional problems [10]

(a) Increased high frequency ripple voltage on the output at high modulation index caused by less attenuation of the lower switching frequency's harmonics.
(b) Reduced open loop bandwidth and -loop gain, causing increased distortion as well.
(c) Increase switching losses.

Due to all these functional disadvantages the constant switching techniques are employed.

6.2 Constant Switching Techniques

6.2.1 Constant Switching Frequency

The fundamental idea consists in determining the ideal time period that exists between the moment when the input current crosses with the reference current and the converter commutation. In the timer controller with constant switching frequency technique the switching frequency is constant.[11] In this type of control strategy, the on time t_{ON} is varied but the chopping frequency f is kept constant. The pulses and the switching technique are designed based on the switching shown in figure-13 and 14.

6.2.2 Constant PWM

In the constant switching frequency pulse-width modulation (CSFPWM) technique, a triangular carrier signal that consists of the symmetrical negative and positive slopes is compared with a reference signal V_{ref} to obtain PWM switching gate drive as shown in reference [12]. Based on this phenomenon the CSFPWM is designed using discrete PWM generator.

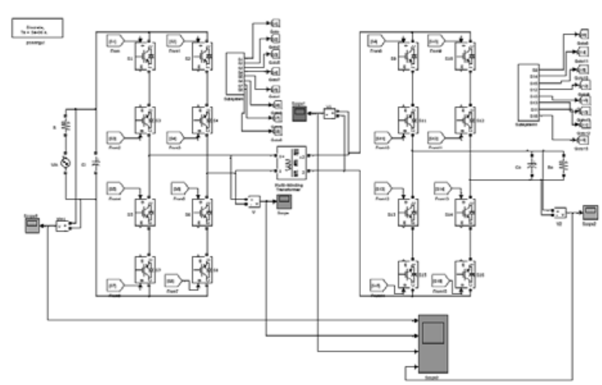
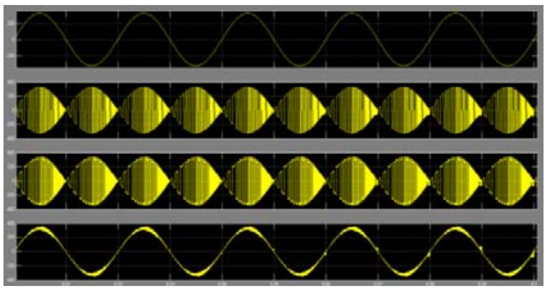


Figure 14: Model of solid state transformer designed in MATLAB

7. Experimental Results

Simulation is performed by MATLAB/Simulink to verify the proposed techniques. The simulation is carried out for the input voltage of 325V (r.m.s). The switching frequency considered as 400 Hz. Fig.15(a) to Fig.18(a) shows the input and output of the converters as well as the primary and secondary sides of the solid state transformers for different proposed switching techniques from these waveforms it is evident of power factor correction. Fig.15(b) to Fig.18(b) shows the FFT analysis of the total harmonic distortion(THD) of all the control techniques, the variable switching frequency technique and variable PWM gives the THD of 4.14 % and 3.37% respectively where as the constant switching frequency technique and the constant PWM gives the THD of 1.66% and 1.64% respectively. The waveforms are shown below. Sample works done in the laboratory by Z. Idris are taken for comparisons [13]. The spikes seen are eliminated using safe commutation techniques.



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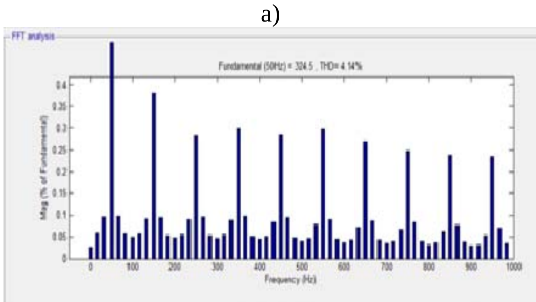
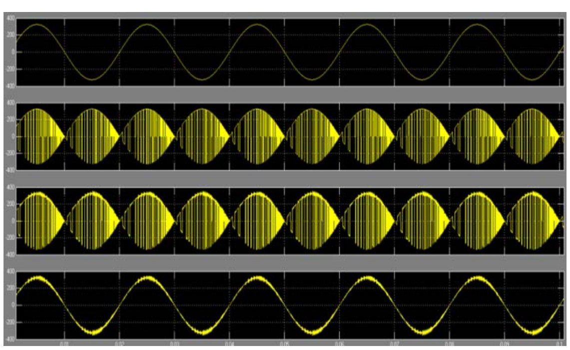


b)

Figure 15: a) Output Waveforms. b) THD values of variable switching frequency technique.



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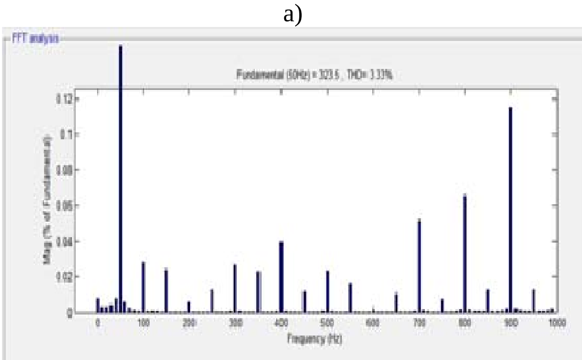
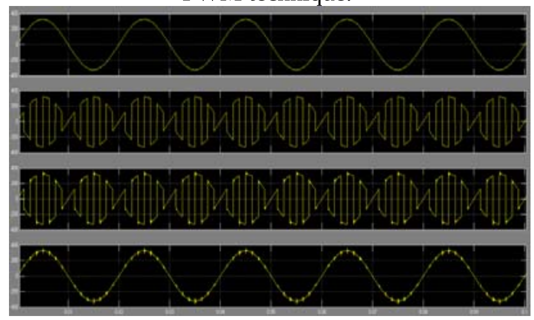


Figure 16: a) Output Waveforms. b) THD values of Variable PWM technique.



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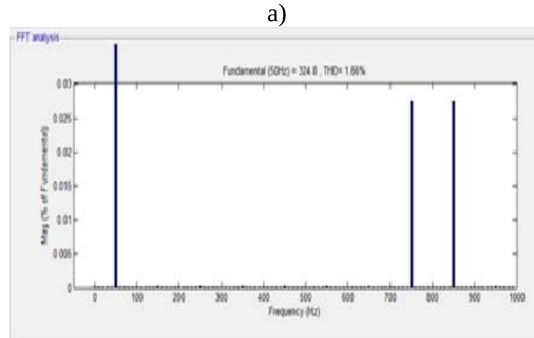
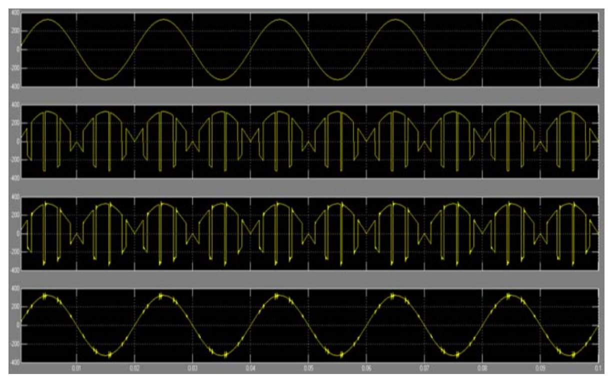


b)

Figure 17: a) Output Waveforms. b) THD values of Constant switching frequency technique.



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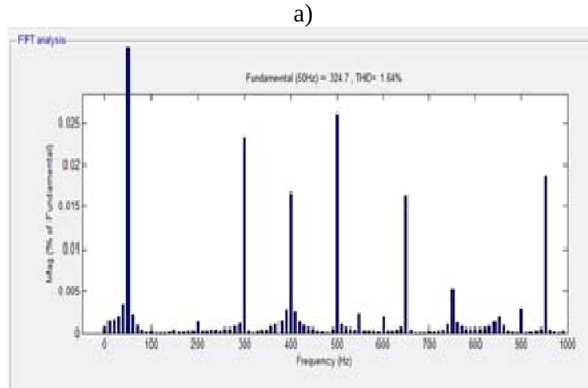

b)

Figure 18: a) Output Waveforms. b) THD values of constant PWM technique

Table.1 Harmonic Analysis

Switching Technique	*THD%*
Variable Switching Frequency	4.14%
Variable PWM	3.33 %
Constant Switching Frequency	1.66%
Constant PWM	1.64%

These THDs are based on the output voltages of the converter-2 i.e. the final voltage of the electronic transformer across the R-load.

8. Conclusion

This paper has discussed the comparison of different PWM techniques. The simulation results are found satisfactory for harmonic elimination with improved output frequency. It can be concluded that the constant PWM technique is optimal and better method for high frequency and high voltage applications.

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