Design Of Single Phase Power Electronic Transformer For Low Voltage Miniature Synchronous Wind Electric Generator

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Abstract - **Due to environmental effects of carbon emission, depletion of fossil fuel and increasing energy demand, distributed generation (DG) based on renewable sources like wind energy gains importance. This DG concept is realized in smart micro-grid where power is generated at low voltage and consumed locally. India has enough potential for wind electric generation. The problem with roof mounted miniature low voltage single phase synchronous wind electric generator is variable output frequency due to variation in wind velocity. This problem can be overcome by using induction generators. But more penetration of induction based wind electric generators causes voltage instability due to consumption of excess reactive power for producing magnetic field. This paper introduces single phase matrix converter based power electronic transformer for roof mounted miniature low voltage single phase synchronous wind electric generators. Recently steps are taken to reduce the size and weight of transformer. The size of transformers can be reduced by replacing the power transformers with high frequency transformers. Several topologies of PET are available in literature. Matrix converter (MC) based power electronic transformers gains importance recently as it does not require dc link. The proposed single phase PET consists of single phase input matrix converter for converting 50Hz ac to high frequency ac, high frequency step down transformer for galvanic isolation and single phase output matrix converter for converting high frequency ac to 50Hz ac. The single phase MC topology is realized using eight IGBTs and eight diodes. The power electronic transformer topologies proposed in literature have power quality issues like low input power factor, high current harmonics and high voltage harmonics. The proposed PET with the simple controller has unity power factor without harmonic distortion and easy to implement using digital signal processors. The output frequency is kept constant by the controller irrespective of the variation in input frequency. The capability of the device to act as asynchronous tie and maintaining constant output frequency are verified by digital simulation using MATLAB. Power quality analysis is performed using fast Fourier transform (FFT) and it is found that total harmonic distortion (THD) is well below acceptable limits if the input frequency is same as desired output frequency. However its harmonic performance has to be improved if there is fluctuation in input frequency.**

Keywords - **Power electronic transformer, matrix converter, high frequency transformer, power factor, harmonic distortion, low voltage synchronous wind electric generators.**

I. INTRODUCTION

Electricity is the most versatile and widely used form of energy and global demand is growing continuously. Most of today's generation capacity relies on fossil fuels and contributes significantly to the increase of carbon dioxide in the world's atmosphere, with negative consequences for the climate and society in general. The grid in India has losses of 30% on average between generation and distribution. Some of this is due to poor infrastructure and some due to theft. As energy needs for the nearly 1.2 billion people in India increase, we see a tremendous opportunity for smarter energy generation and use. Moreover, because the grid is so unreliable, nearly 1/7th of India's electricity consumption comes from backup diesel generators, according to unofficial statistics, an energy supply, which is both very expensive and polluting. An electrical system has to undergo a major evolution, improving reliability and reducing electrical losses, capital expenditures and maintenance costs. The electrical power system was built up over more than 100 years. A smarter grid is definitely needed to satisfy both the increasing demand for power and the need to reduce carbon dioxide emissions, in a sustainable, reliable and economic way. A smarter grid will provide greater control over energy costs, a more reliable energy supply for consumers, reduced peak demand, integration of more renewable power sources, and reduced CO_2 emissions and other pollutants. Smart grids with capability for integrating low carbon energy sources into power networks will provide more electricity to meet rising demand, increase energy efficiency, increase reliability and quality of power supplies. Smart grids possess demand response capacity to help balance electrical consumption with supply, as well as the potential to integrate new technologies to enable energy storage devices. We believe that, smart micro-grid is the future for electrical systems, as it is designed to meet the four major electricity requirements of our global society: capacity, reliability, efficiency and sustainability. Smart grid is composed of cluster of smart micro-grids. A micro-grid is a mini grid comprising of low voltage generators, mostly renewable generators integrated with energy storage devices, plug-in electric vehicles and loads.

Renewable generation from wind has great potential in India. In smart micro-grid the customers can generate power at low voltage and the excess power generated can be injected into the grid. This solves the power shortage problem and customer can earn money by net metering billing scheme. The consumers can use roof mounted low voltage miniature wind electric generators for power generation. The generation can be at 230V using 5KVA single phase synchronous generators. The problem with synchronous wind electric generator is the variation in output frequency and real power generation due to variation in wind velocities. The magnitude of generated voltage and reactive power generation are controlled using closed loop excitation controllers. In synchronous wind electric generators the output frequency and real power can be controlled by controlling the speed of synchronous generator. But the speed of generator varies with wind velocity. Hence induction generators are preferred for wind electric generation. But the induction generators draw reactive power from the grid to produce magnetic field in the machine. This leads to voltage instability in the grid, if the generation from induction generators exceeds 15% of the total generation capacity of the grid.

The above problems are solved in this research by introducing constant frequency single phase synchronous wind electric generator which uses power electronic transformer interface. Power transformers are an integral part of power system [2]. In many applications weight and space requirements directly influence productivity, and much research effort goes into footprint reduction. Some products, however, have largely resisted this tendency. The size of transformers can be reduced by replacing the power transformers with high frequency transformers [1]. For use of high frequency transformer in power systems, first the low frequency voltages are converted to high frequency by a power electronic converter and then it is stepped up or down by the high frequency transformer and finally the high frequency voltage is converter to low frequency by a second power electronic converter. The whole system is termed as power electronic transformer (PET). The minimum size of a power transformer is essentially determined by the laws of physics, as the core must have certain dimensions to accommodate the magnetic field. In terms of making this component smaller and lighter, the laws of physics fortunately provide some scope for improvement in the form of frequency. The higher this is, the smaller the required core [3]. The nano-crystalline materials used for making high frequency transformers have very low core losses at very high frequencies as compared to 50 Hz power transformers. Also, power devices made of SiC devices are available which can operate at very high switching frequencies with very low switching losses [5]. This principle is used in power electronic transformer and also found in low-power devices such as laptop chargers. Power electronic transformers (PETs) are proposed to replace conventional transformers and perform voltage regulation and power exchange between generation and consumption by electrical conversion. The previous researches show that PETs have a great capacity to receive much more attention due to their merits such as high-frequency link transformation and flexible regulation of the voltage and power. Although many studies have been conducted on application and control of PET in power systems, less attention is paid to the areas of the circuit topologies. The topology of PET can be developed in such a way to achieve multiport electrical system that converts variable input waveform to the desired output waveform. In addition, for higher voltage applications or three phase systems, the topology is expandable as it is modular.

Early works considered the use of thyristor based solutions. The primary side of the high frequency transformer (HFT) consists of two thyristor H-bridges connected in anti-parallel while the secondary side has a single phase forced commutated H-bridge [9]. Thus, there is a cycloconverter at the input (HV side) and voltage source inverter (VSI) at the output (LV side). A slightly different approach is also in practice, where multi-winding HFTs are used. The primary side is again realized with a series connection of H-bridges providing intermediate HV side DC links from which the primary windings of the multi-winding HFT are excited by half-bridge series resonant converters operating at 5 kHz. The secondary side is realized using a single H-bridge converter with bidirectional power flow. In another type, the line side AC waveform is modulated into a High or medium Frequency (HF or MF) square wave using AC/DC converter and DC/AC converter, coupled to the primary of HF (MF) transformer, and again is demodulated to AC form by a matrix converter in the secondary side of HF (MF) transformer [4]. This method however does not provide any benefits such as instantaneous voltage regulation and voltage sag compensation due to lack of energy storage system. A power electronic transformer based on matrix converters (MC) with open ended primary is proposed recently [7]. The open ended primary of the transformer is fed from two power converters MC1 and MC2. These two converters are matrix converters with three bi-directional switches removed, one from each leg. The secondary of the transformer is connected to a third matrix converter MC3. Matrix converter fed sinusoidal input output three winding high frequency transformer with zero common mode voltage is proposed by Nath and et.al. [8]. Most of the above topologies deal with three phase power electronic transformer for various applications and harmonic distortion level are high. Also the input power factor is low. This research proposed single phase power electronic transformer with only two single phase matrix converter and a high frequency transformer with unity input power factor and distortion-less output. Review of control and modulation methods for matrix converters are discussed in [6] which are complex for digital implementation. A simple controller is proposed in this paper which ensures unity power factor and harmonic free output voltage and current.

II. SINGLE PHASE MATRIX CONVERTER

This section explains the operation and capability of single phase matrix converter in frequency regulation and serving as asynchronous tie which is the heart of the proposed single phase PET. Matrix converter is a direct AC-AC power converter employing bidirectional switches. In addition to the basic ability of power converter providing a sinusoidal variable voltage variable frequency to the load, matrix converter has many attractive features: no bulky DC-link capacitor, ability to make sinusoidal input current, high efficiency, compact circuit design and regeneration capability. Matrix converter is an efficient frequency regulator but it suffers from harmonic problems. The proposed single phase frequency regulator is based on single phase matrix converter topology shown in fig.1.

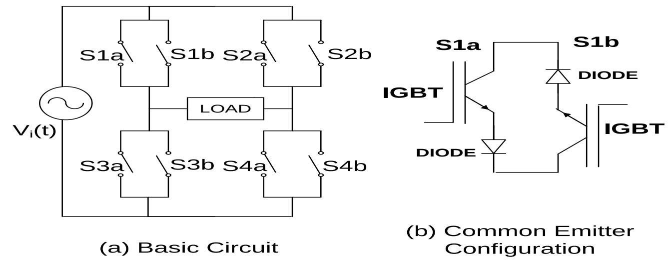

Fig. 1. Topology of single phase matrix converter

The single phase matrix converter has four bidirectional switches with common emitter configuration as shown in figure – 1(b). Each switch has anti-parallel IGBTs in series with diodes. During positive half cycle IGBT ‘S_{ia}’ will be forward biased and during negative half cycle IGBT ‘S_{ib}’ is forward biased. The frequency of output from this matrix converter can be made higher or lower than input frequency. By using certain controller the frequency of output voltage can be kept constant irrespective of the variation in frequency of input voltage. During positive half cycle of input voltage ‘S_{1a}’ and ‘S_{4a}’ has to be closed allowing current in load from source side to output side. The load current can be kept same as earlier even during the negative half cycle of input by closing ‘S_{1b}’ and ‘S_{4b}’. During positive half cycle of input, the direction of load current can be reversed by closing ‘S_{2a}’ and ‘S_{3a}’. The same reverse load current can be maintained even during negative half cycle of input by closing S_{2b} and S_{3b}. The above operation of single phase matrix converter is demonstrated in figure – 7.

Simulink model of the proposed single phase matrix converter is shown in figure - 2. The input is given from a single phase 2KVA, 230V, 50Hz synchronous generator. It is assumed that the synchronous generator is driven by wind turbine. The output of generator is fed to RL load of 10 ohms resistance and 1mH inductance through the single phase matrix converter. As the wind speed varies, the speed of the synchronous generator changes and the frequency of the generated voltage also varies. The matrix converter acts as frequency regulator and maintains the frequency at load side constant at the desired value. In this case the desired frequency is selected as 25Hz to demonstrate the capability of matrix converter to link two circuits at different frequency levels. The generator side is rated for 50Hz and the load side is rated for 25Hz. The frequency regulation capability of matrix converter can be demonstrated by varying the generator frequency. The control objective of frequency regulation is achieved by a simple controller. The simulink model of the controller which is developed based on the above concept is shown in figure – 8. ‘In1’ is the input signal and sine wave is the control signal. The control signal is 25Hz in this case. Relation operator gives output '1' when the desired condition is satisfied. Thus the output frequency is kept constant irrespective of the input frequency.

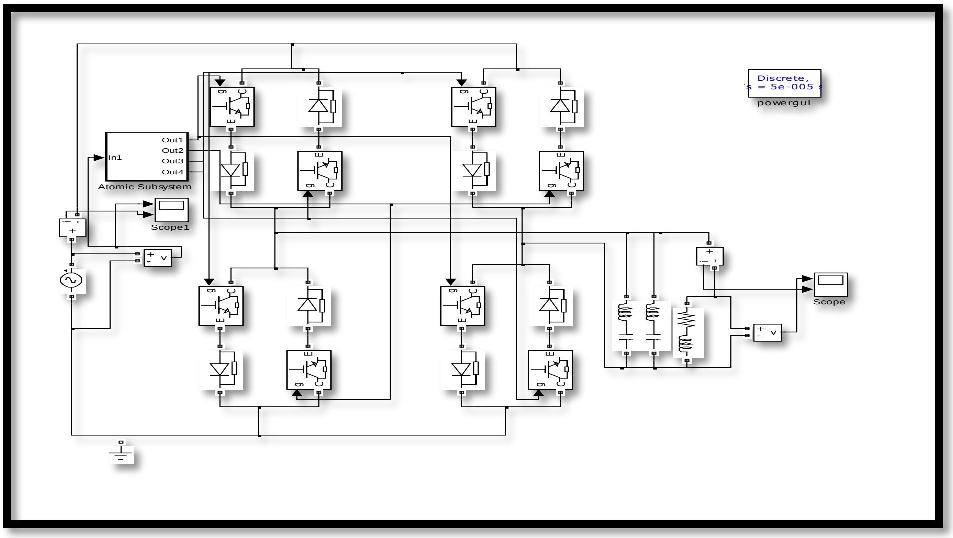

Fig. 2. Simulink model single phase matrix converter

The output current and voltage are highly non-sinusoidal and dominated by third and fifth harmonics where as the input side voltage and current are sinusoidal. The input side voltage and current are shown in figure – 3.

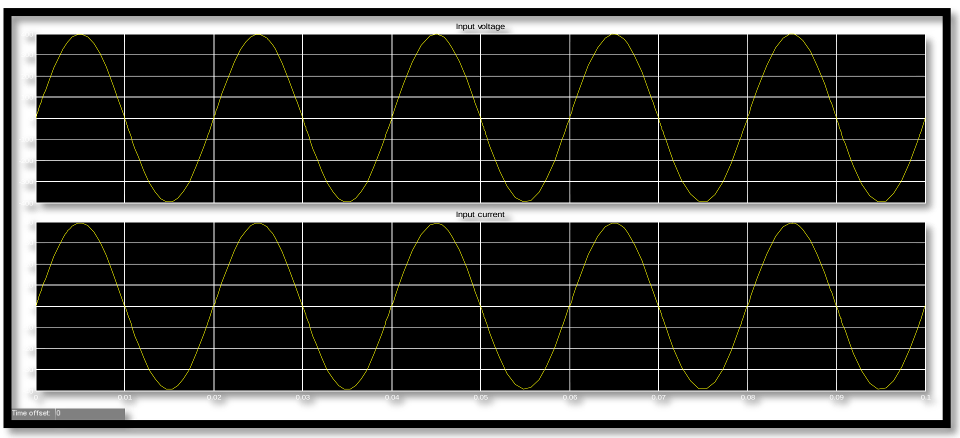

Fig. 3. Input voltage and current

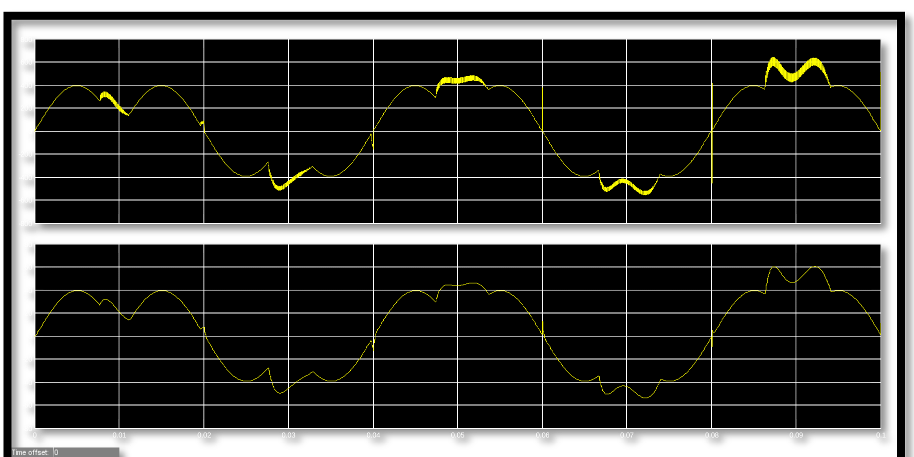

Fig. 4. Output voltage and current

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The input voltage at 50Hz, control voltage at desired frequency of 25Hz and switching pulses for the four operations explained above are shown in figure – 5.

The output voltage and current has harmonics and series tuned passive filters are designed for filtering the third and fifth harmonics. The Xc value is selected as 530 Ω.

$X_c = \frac{1}{2\pi f c}$

Thus $c = \frac{1}{2\pi f X_c} = 120\mu F$

$X_L = \frac{X_c}{h_n^2} = 58.9\ \Omega$ for third harmonic filter and hence,

$L = \frac{X_L}{2\pi f} = 37.5mH$

$X_L = \frac{X_c}{h_n^2} = 2.12\ \Omega$ for fifth harmonic filter and hence,

$L = \frac{X_L}{2\pi f} = 13.5mH$

After implementing the designed passive filter, output side voltage and current are shown in figure – 4. By incorporating active filters the harmonic distortions can be completely eliminated.

III. PROPOSED SINGLE PHASE POWER ELECTRONIC TRANSFORMER

The matrix converter (MC) is an advanced circuit topology that offers many advantages such as the ability to regenerate energy back to the utility, sinusoidal input and output currents and a controllable input current displacement factor. It has the potential for affording an “all silicon” solution for AC-AC conversion and for removing the need for the reactive energy storage components used in conventional rectifier-inverter based systems. The proposed single phase power electronic transformer is based on single phase matrix converter topology shown in figure -1. The frequency of output from this matrix converter can be made higher or lower than input frequency. Simulink model of the proposed single phase power electronic transformer is shown in figure - 6. The input is 230V, single phase 50Hz ac and the output of input matrix converter is 500Hz ac which is stepped down to 50V using 2KVA high frequency transformer as welding power supplies require low voltage high current ac. The 50V, 500Hz ac is converted to 50V, 50Hz ac using output matrix converter and fed to RL load of 10 ohms resistance and 1mH inductance.

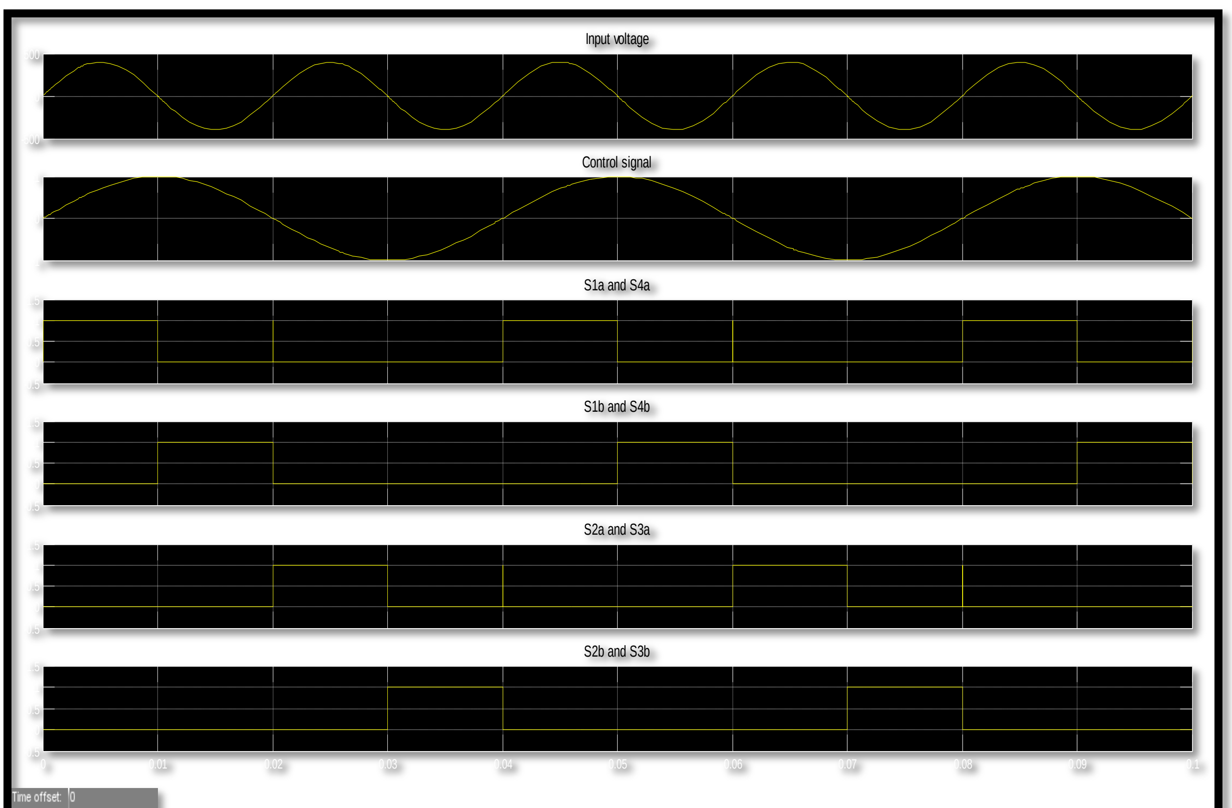


Fig. 5. Input voltage, control signal and switching pulses

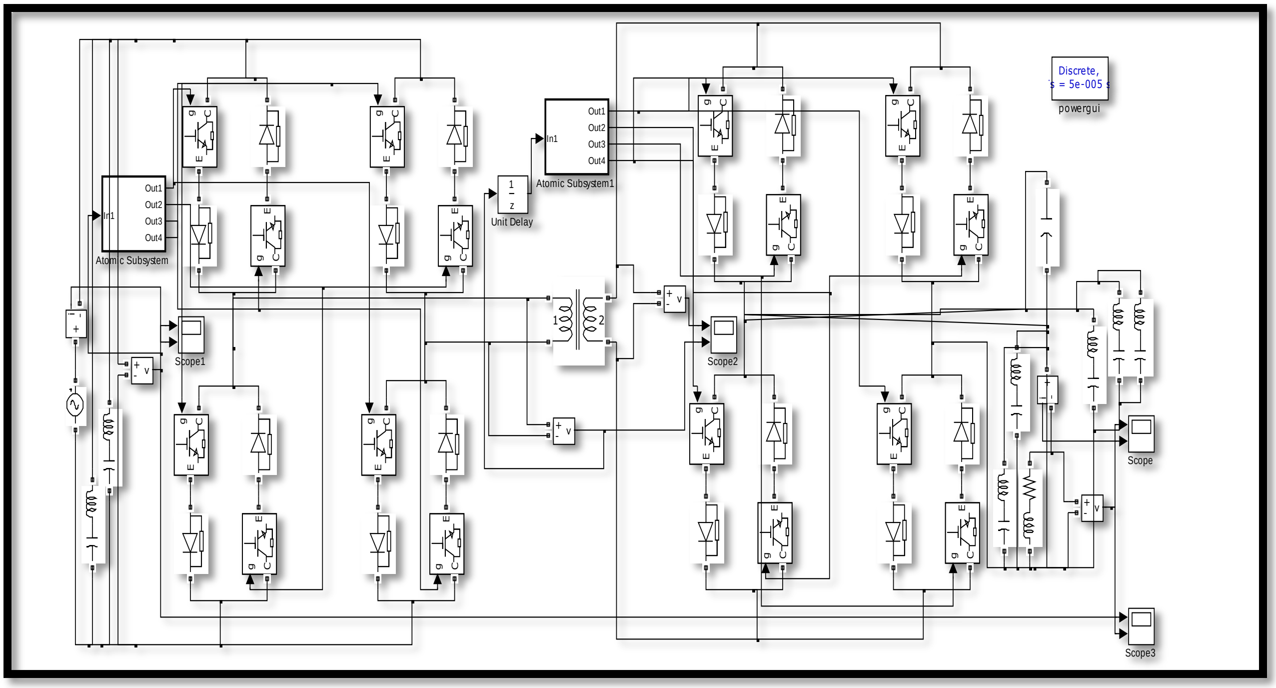
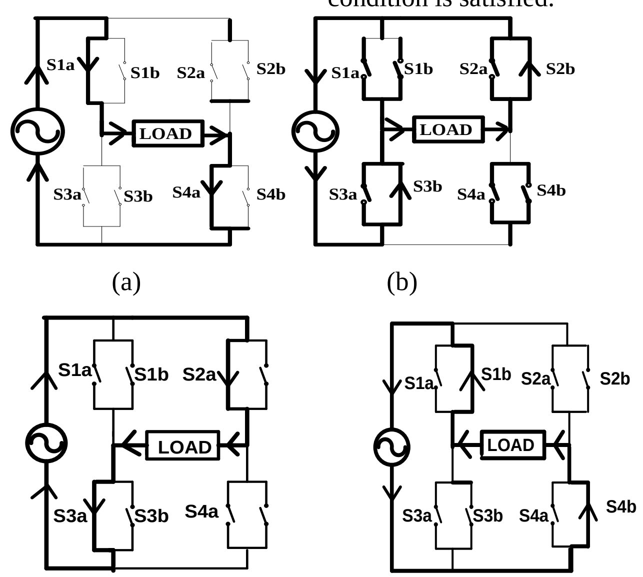


Fig. 6. Simulink model of the proposed power electronic transformer

IV. PROPOSED CONTROLLER

The objective of the controller is to produce switching pulses to single phase matrix converter. The control signal is a sine wave of desired output frequency. If both the control signal and input signal are positive, IGBT switches S_{1a} and S_{4a} has to be closed as shown in figure – 7(a). If the control signal is positive and the input is negative, IGBT switches S_{2b} and S_{3b} has to be closed as shown in figure – 7(b). If the control signal is negative and the input is positive, IGBT switches S_{2a} and S_{3a} has to be closed as shown in figure – 7(c). If both the control signal and input signal are negative, IGBT switches S_{1b} and S_{4b} has to be closed as shown in figure – 7(d). The simulink model of the controller which is developed based on the above concept is shown in figure – 8. 'In1' is the input signal and sine wave is the control signal. For input matrix converter control signal is 500Hz and is 50Hz for output matrix converter. Relation operator gives output '1' when the desired condition is satisfied.



(a) (b)

(c) (d)

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Fig. 7. Operation of single phase matrix converter

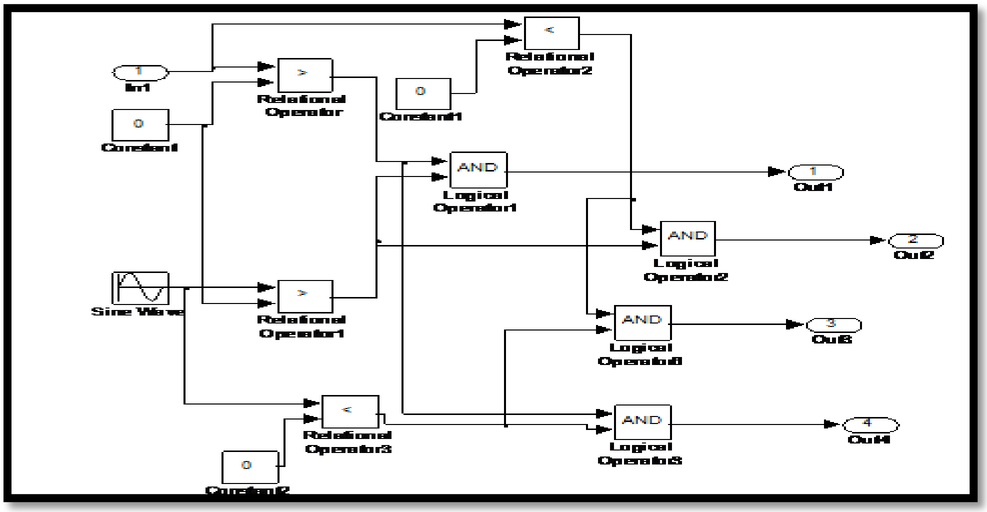

Fig. 8. Simulink model of controller

V. POWER QUALITY ANALYSIS OF THE PROPOSED POWER ELECTRONIC TRANSFORMER

The input voltage and current of proposed PET is shown in Fig. 9. The voltage and current are sinusoidal and they are in phase with each other. Thus the power factor is unity.

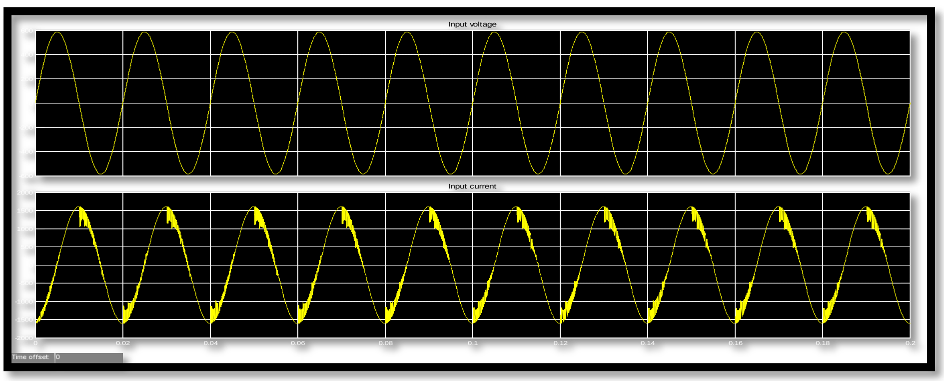

Fig. 9. Input voltage and current

The fast Fourier transform (FFT) of input voltage is shown in figure – 10. The total harmonic distortion (THD) is zero which means there is no voltage distortion.

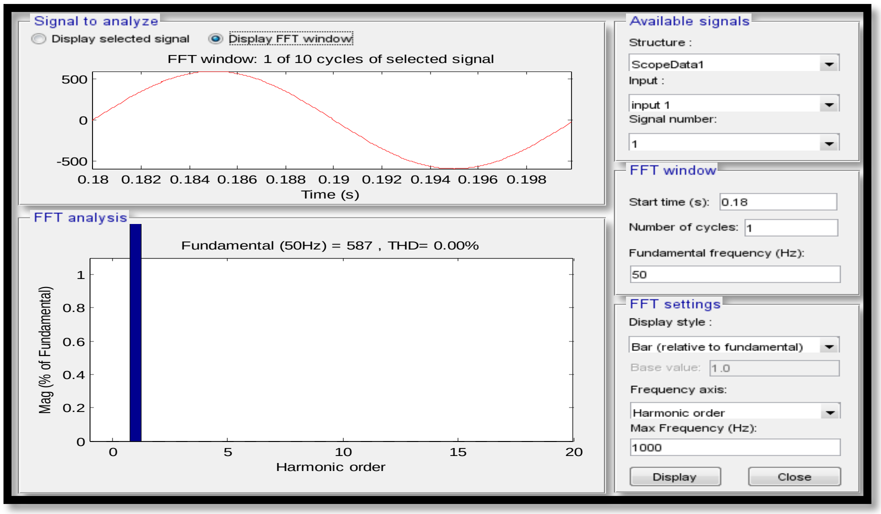

Fig. 10. FFT of input voltage

The fast Fourier transform (FFT) of input current is shown in figure – 11. The total harmonic distortion (THD) is 9.7 % .

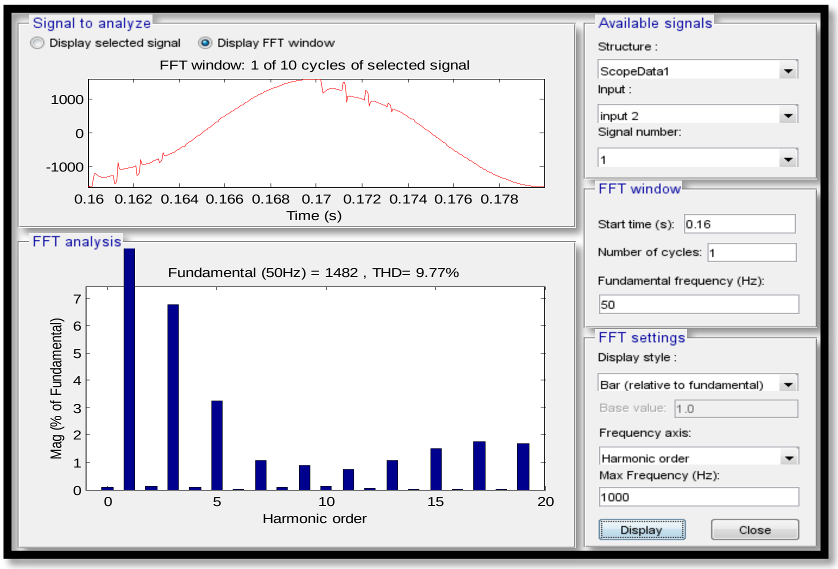

Fig. 11. FFT of input current

The voltage at primary side and secondary side of high frequency transformer is shown in figure – 12. The frequency is 5 kHz, but its envelope follows a sine wave shape. The frequency of the enveloping waveform is same as supply frequency.

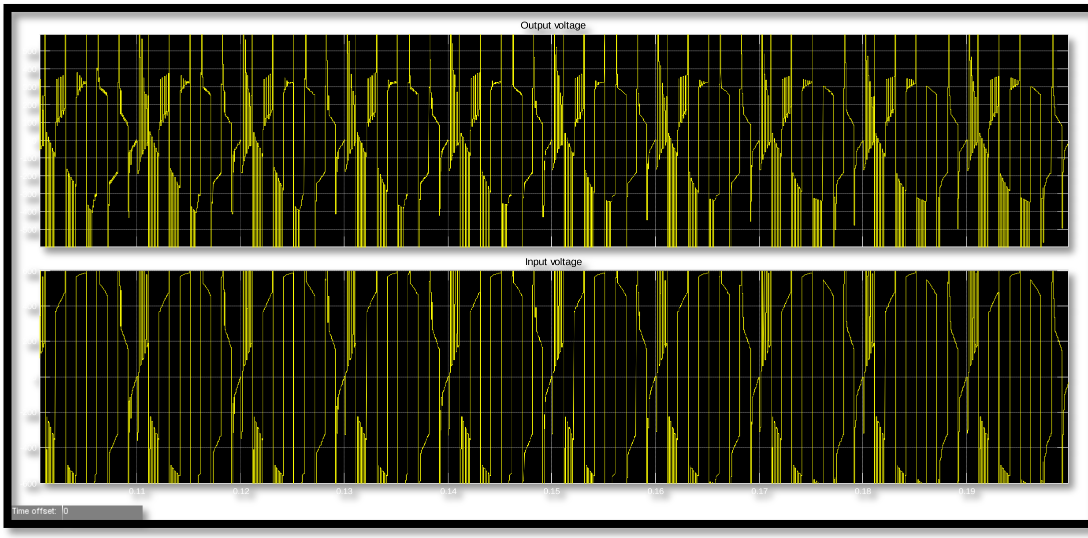

Fig. 12. Voltage at primary side and secondary side of high frequency transformer

The output voltage and current of proposed PET is shown in Fig. 13. The voltage and current are sinusoidal and they are in phase with each other. Thus the power factor is unity.

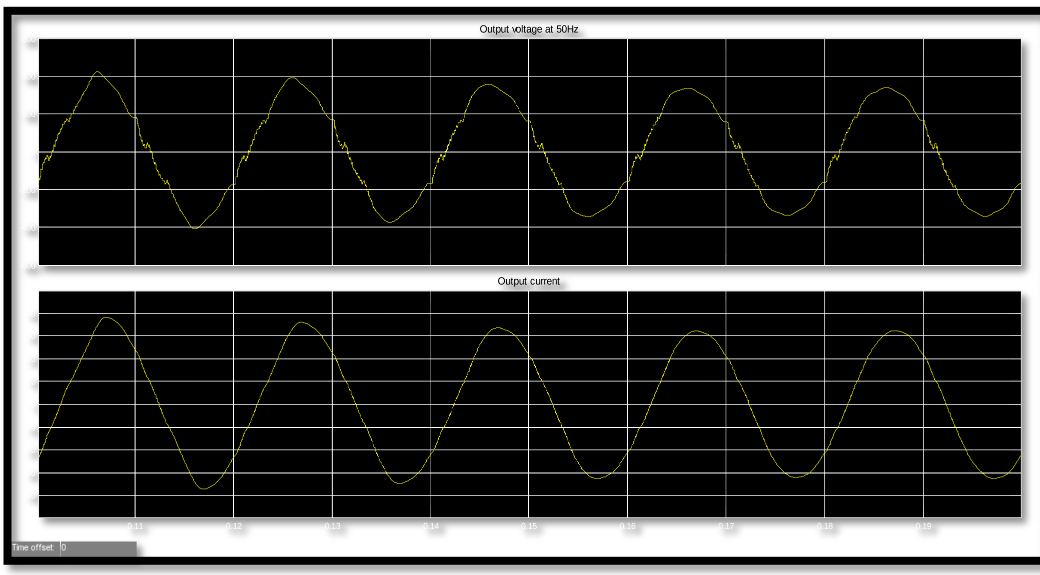

Fig. 13. Output voltage and current

The fast Fourier transform (FFT) of output voltage is shown in figure – 14. The total harmonic distortion (THD) is 4.52% which is less than the standard limits.

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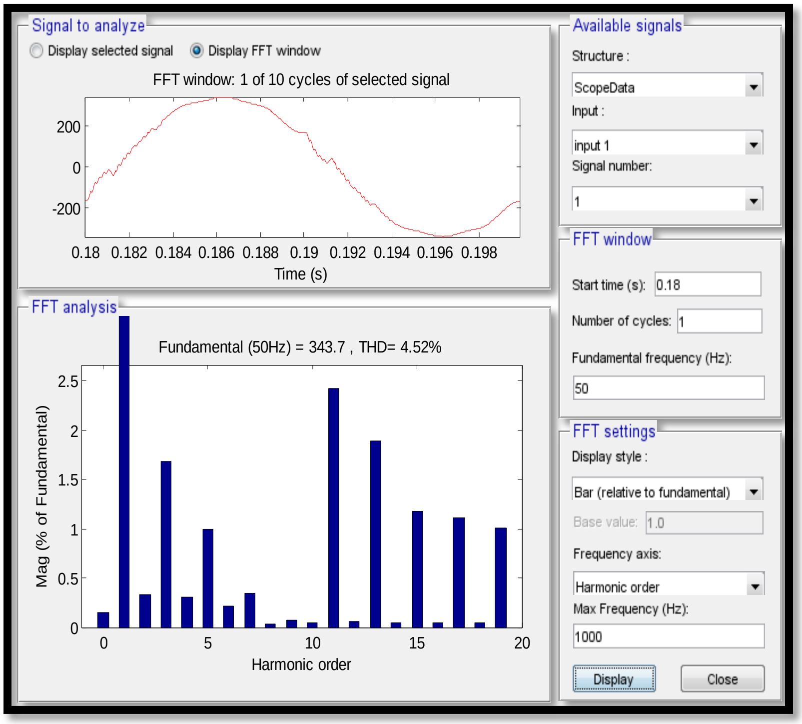

Fig. 14. FFT of output voltage

The fast Fourier transform (FFT) of output current is shown in figure – 15. The total harmonic distortion (THD) is 1.67% which is much less than the IEEE limit.

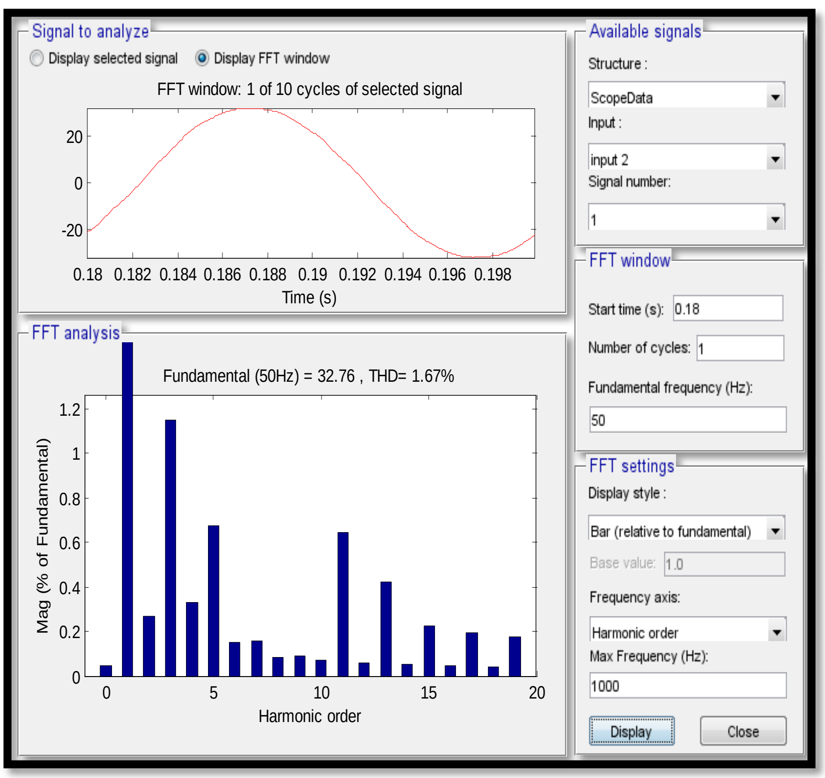

Fig. 15. FFT of output current

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VI. CAPABILITY OF THE PROPOSED DEVICE TO REGULATE FREQUENCY

Thus the proposed single phase matrix converter based power electronic transformer produces harmonic free output. Input voltage at 50Hz and the corresponding output voltage are shown in figure – 16. When the device has to operate as asynchronous tie between two systems operating at different frequencies, the device can operate efficiently and transfer power on either direction depending on the requirements. Also, the device can maintain the output frequency at desired value even when the input frequency varies widely. This is evident from figure – 17, where the input frequency increases to 100 Hz while the output frequency is maintained at desired value of 50Hz. The result shown in figure – 18 indicates the input frequency decreases to 30 Hz while the output frequency is maintained at desired value of 50Hz. This proves the capability of the proposed device in frequency regulation.

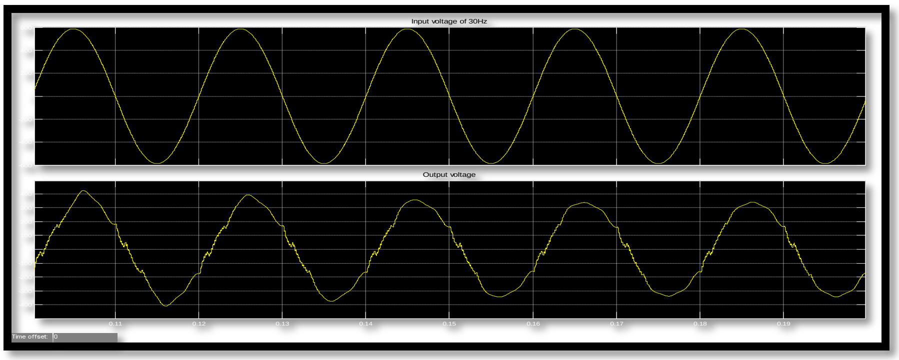

Fig. 16. Input voltage at 50 Hz and corresponding output voltage

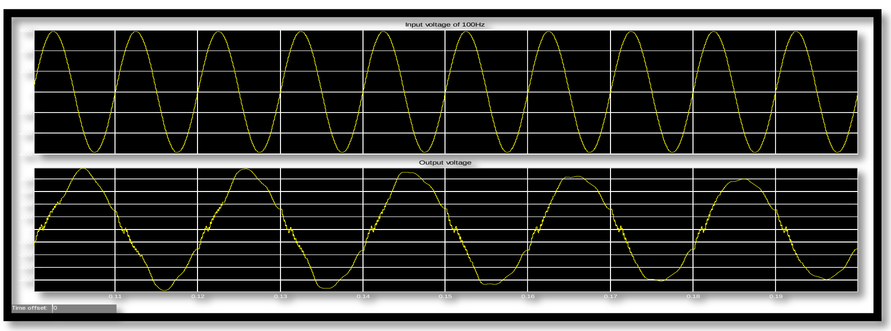

Fig. 17. Input voltage at 100 Hz and corresponding output voltage

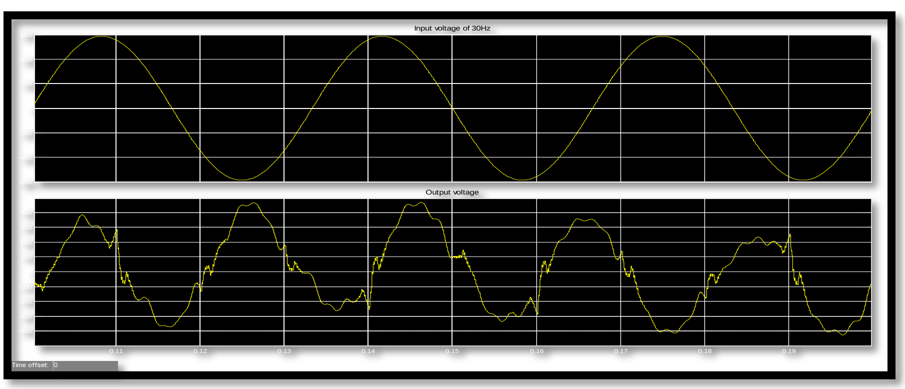

Fig. 18. Input voltage at 30 Hz and corresponding output voltage

VII. CONCLUSION

India has enough potential for wind electric generation. The problem with roof mounted miniature low voltage single phase synchronous wind electric generator is variable output frequency due to variation in wind velocity. This problem is overcome by using induction generators. But more penetration of induction based wind electric generators causes voltage instability due to consumption of reactive power for producing magnetic field. This paper proposes a single phase matrix converter based power electronic transformer for roof mounted miniature low voltage single phase synchronous wind electric generators. Power electronic transformers, providing a reduction in weight and volume accompanied by additional functionalities, are considered a viable solution for the replacement of bulky low-frequency transformers. The problems with existing topologies of PET are low input power factor, voltage and current harmonic distortions. The proposed controller for frequency regulation is easy to implement using digital signal processors. The capability of the device to act as asynchronous tie and maintaining constant output frequency are verified by digital simulation using MATLAB. The proposed controller ensures unity power factor and harmonic free output voltage and current if the desired frequency is same as input frequency. However its harmonic performance has to be improved if there is fluctuation in input frequency. The proposed PET has bidirectional power flow features and it can control power flow between single phase micro-grid and utility grid when used at the point of common coupling (PCC). The proposed transformer can connect single phase micro-grid and utility grid which are operating at different frequencies.

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