Multilevel Matrix Converter Interfacing with Generator-grid in Wind Energy System

Kanksshi Agarwal[1], Dr. K. T. Chaturvedi[2]

[1]Research Scholar, [2]Research Guide

Department of Electrical Engineering, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal

Abstract - In the conventional usage of Multilevel converter and Matrix converters when considered separately for heavy industrial and high power applications there are multiple frequencies which occur in the output waveforms of current and voltage that get super imposed with the fundamental frequency. The SIZMC and quasi-Z-source circuits, embedded in the previous reported literature of the converter topologies, they allow interfacing a low-voltage generator with the grid in wind energy systems. The efficiency of the proposed converters was expected to be high due to reduced number of power electronic switches. Noteworthy, is the fact that SIMC and QZMC do not allow bidirectional flows. Thus, the generator couldn't be used for starting the turbine. For providing the bidirectional flow there is a requirement of adding more switches (specifically bidirectional) in the topology. While, in the previous works the concentration was to embed such power electronic devices that could provide a voltage boost, which is typically low for such systems. This was rectified in our thesis work by converting the ultras-parse matrix input stage into a sparse matrix, by adding three more switches (for 3 phase) in the circuit. This work focuses on reconfiguring a matrix converter by hybridizing it with Multi Level Converters in order to reduce the harmonics that are seen due to the DC boost stages which were implemented in order to match the voltage boost requirements of the grid-interfacing. Therefore, the reconfigured topology shown here, has lesser number of harmonics through simulation results produced with the help of SIMULINK/MATLAB. Also, because the topology involves IGBT bidirectional switches it is fit to be used for generator action for a turbine (wind turbines). Proposed topology can be implemented in the future technologies (that can be implemented in smart grids) as it is fully automated and focuses on improving the power quality delivered to the end user.

Key words: Wind turbines, MultiLevel Converters, Matrix converters, Harmonics, bidirectional switches, power quality.

I. INTRODUCTION

Multilevel converters have continuously been the subject of research and development for more than 3 decades and have found various industrial applications. During the beginning of the new Millennium the multilevel converters had demonstrated to have several advantages. For eg: low harmonic, low voltage stress, and high power capability. However, in those times most of the researchers were focused on high power AC-DC and DC-AC applications. During the year 2004, Fan Zhang, F. Z. Peng and Zhaoming Qian [2], presented a paper. This paper presents a number of multilevel DC-DC converters, which were found to useful in the automotive applications and also in high power applications, in non-isolated and isolated applications. Theory analysis was taken as the basis of comparison for diode-clamp, flying-capacitor, and cascaded multilevel inverters, their correlative DC-DC converters were derived. The diode-clamp type converter has lesser redundant switching states and has limitation in DC-DC applications. The flying-capacitor were found to be easier to balance at different applications but more capacitors were used. The cascaded converter has high number of advantages, such as modularized structure and low voltage stress. It is the most suitable type converter for DC-DC applications.

Thus, this result formed the basis for selection of cascaded-converters to be selected in the reconfiguration of Multilevel Converters used in this thesis.

Advancing the M-LMCs a level further was by putting forth the idea of Two-Stage Matrix Converters (TSMCs). There were papers promoting the concept of TSMC in the wind energy systems which was evidently presented by R. H. Zhang, X. Y. Liu, H. T. Wu and Z. C. Wang[3], made a deep analysis to the topology structure of TSMC and took accordingly the PWM space vector to research its control and commutation strategies. TSMC was found to be more suitable for the doubly fed wind energy systems, and this was established by forming a Simulink model which confirmed the feasibility of the control schemes used.

Further, the use of multilevel converters kept on increasing and based on the researches presented by different researchers there was a wave of advancement incorporated in the field of multilevel converters, alongside the concept of Space Vector Modulation being used to modulate the frequencies and waveforms. Thus in 2009, W. Deng, Z. Chen, L. Zhou and Y. Yang [4], presented a paper which drew attention towards the presentation of a novel algorithm for dual space vector modulation for two-stage matrix converters. The three-phase to three-phase matrix converter consists of nine bidirectional switches that allow any output phase to be connected to any input phase. Such is the beauty of a matrix converter and so is the topology that it gives flexibility of wide usage. Matrix converters is nothing but a specific topology that can be incorporated in any of the converters through right understanding. In the discussed paper a Simulink/MATLAB model was built for wind energy conversion system, consisting of doubly fed induction generator and excited by Two-stage matrix converter. The motive was to propose the vector control strategy, decoupling control for active and reactive power generated by DFIG by utilizing grid voltage. Thus, it was concluded that the proposed control strategy promoted dynamic and steady-state performances of WECs.

There is always a scope of improvement and parallel researches carried out on the interlinked subjects prove the same. Hence, the voracity for betterment led, L. G. Franquelo, J. I. Leon and E. Dominguez [5], to present a paper that focuses on the in-depth analysis of the multilevel approach, moving attention towards high power applications, reviewing different alternatives and approaches. It reviews the current scenarios where power electronic converters are being used. It tries to show that multilevel approaches are a good solution to voltage-high power applications. This paper claimed that M-LCs are the most suitable way to provide power conversion for medium high voltage. There are still few issues to be improved such as the dissemination of the results to more industries for fundamental widespread usage, the reliability and the fault tolerant operation on which the researchers all over the world were focused. However, it was affirmed that the multilevel converters are undergoing a fast growing expansion with a brilliant future for a magnificent number of applications such as the renewable energies integration, storage systems, FACTS, motor drives and electric vehicles.

This paper helped a lot in understanding the mitigation techniques for harmonics, and thus provided a solid base for the thesis work being present here.

Having said about the multiple and expanded usage of the Multilevel Converters, the scope of research expands perniciously. The researchers then started focusing on the multiple applications and exploring the industrial implementation of M-LCs which was studied and presented by S. Kouro*et al*. [6], which was a detailed and systematic insight into the recent advances and contributions in the field of M-LCs, in order to establish the current state of art and trends of new technology. Thus it proved as a milestone in research for it was a comprehensive study of where this technology is used and where it would head in times to come. From new converters to modulation and control techniques, non-traditional applications have been addressed and provided an open space to researches to innovate further ahead to mitigate the short-comings that were highlighted. The indomitable changes and evolution of the industrial processes, and new more demanding standards & regulations will drive and shape the future of multilevel converters.

To support and further the results quoted in [6], the chapter-wise and detailed study presented in the Book published by F. A. Silva [10], on the industrial applications that employ the multilevel converters was a boon. The book focuses on the Neutral Point clamped and diode clamped M-LCs, but forms the basis in the generalized concept of this technology as discussed previously by many authors and work presenters. The book doesn't fails to also include the operation of the flying capacitor multilevel converter, the cascaded bridge multilevel converters, and the hybrid and asymmetric topologies. The noteworthy are the 2 case studies:

1) Application of cascade asymmetric multilevel converters in distribution static compensator (DSTATCOM)

2) A medium-voltage induction motor (IM) drive employing 2 back-to-back connected, 5 level NPC converters.

These particular studies [6] and [10]were a great motivation and provided relevant content for many researches including the thesis work presented in this document.

A different objective of study in the field of Multilevel converters was presented by, S. Mansourpour, H. Ziar, A. Salimi and E. Afjei[7], who presented a novel methodology to produce constant voltage and frequency by using a switching mechanism that implements PWMs to control a matrix converter. Voltage gain with the use of gates was computed and then modulation matrix was formed. The proposed approach proved to be competitive for VSFC Distributed generating application such as wind-turbine and micro-turbines. Simulation results using MATLAB Simulink, for inductive and resistive loads were produced and presented. Fair agreement between the experimental and simulations results shows the validity of this method.

With every step the complexity of study and detailed analysis is bound to increase. The variations in small parameters can also lead to big changes and further a mile of innovation and research. Thus using a matrix converter with newer topologies for newer forms of turbines was taken up and presented in 2012 by, M. Aner, E. Nowicki and D. Wood[8], who proposed to accelerate the turbine to its optimal operating speed in the case of increasing wind speed. This was a complex and a very interesting work, done with the implementation of very sparse matrix which was connected to a grid, where a variable speed wind turbine was experimented to be controlled. Because as the presenters believed that the amount of energy obtained from a wind turbine depends not only on the wind regime but also on the control techniques for governing the turbine. For the case of continuously decreasing wind speed, the turbine decelerates by loading the generator at its maximum torque. This paper shows how the generator torque can be controlled through the backward bidirectional sparse matrix converter where the grid is connected with the rectifier stage, and the generator is connected with the inverter stage. In order to show the accountability of the proposed control technique, a 5.7kW grid-connected variable speed wind turbine was simulated using MATLAB/Simulink.

The grid-connected wind energy generation system has many latent challenges, however the advantages of such systems are marveling. The base paper/reference paper [1] of this thesis used an Indirect Matrix converter interfaced with grid of wind energy system. But a different concept of direct conversion from AC to AC was taken as a subject of study by, O. Abdel-Rahim, H. Abu-Rub, A. Iqbal and A. Kouzou, [9] who highlighted the fact that in case of grid-connected WES, conversion from variable ac voltage into fixed voltage and fixed frequency ac voltage is considered essential and important. Direct matrix Converter (DMC) puts forth a solution for such AC-AC conversion of desired voltage and frequency. His paper proposed to convert five-phase input voltage into three-phase voltage, control the amplitude-range of the output current along with its frequency, and also control input current power factor to be nearly approximate to unity with the supply voltage. Among the existing control techniques, Model Predictive Control (MPC) is considered one of the most effective control techniques. In this paper the use of MPC is prominent to control the 15 switches of the 5-to-3 phase matrix converters. MPC is incorporated to achieve the following control mechanisms: control the O/P current amplitude, (unity power factor). It is done by the means of a cost function which doesn't need a weighing factor. The proposed system was simulated using MATLAB software and also a real time simulation was provided.

In the era of Modular implications the Multilevel Converters are not far from this implementation. Thus, in order to study the application of Modular MCs in wind energy system the experiment was presented by L. Popova, J. Pyrhönen, K. Ma and F. Blaabjerg[11], which talks about Modular multilevel converter (MMC) which is a recently emerged multilevel topology, hence tends to be promising for high-voltage high-power applications. Apparently, in wind power application the performance of the MMC was not deeply investigated. Therefore, they felt incumbent upon them to do so. Hence,their paper presents the application of MMC in wind energy systems. To make the study relevant and applicable the electrical losses of the power devices in the proposed converter are analyzed. The efficiency of the MMC converters, under different P/Q boundaries which are defined by grid codes is investigated and compared with 2-level and 3-level converters.

The researchers concluded certain observations based on the evaluation of 2 solutions of the wind turbine converters using the MMC topology. The first solution has a minimum number of switching modules and needs only 12 IGBT modules. This solution might be more feasible for wind application where the converter is installed in the nacelle and the size is critically small, although in the HVDC application where the space is not a concern the MMCs, with a large number of the Switching modules are popular. The second solution has ten Switching modules in a phase leg and used 60 IGBT modules. This sufficiently analyses the loading of MMCs in WES.

One after the other there were experiments made around Wind energy system. The wind energy is the most potential renewable energy system in current scenario, with national and International references it has become more noticeable and focused. When a wind energy system feeds a AC drive it can use back-to-back converters and matrix converters. We are getting closer to different scenarios where wind energy is used as the generating medium and how the conversion is done to feed a load. To implement this concept, there was a paper presented recently in 2014 by K. N. Kumari, N. O. Gunasekhar and K. V. Thilagar[12], which focused on a small scale wind turbine using self-Excited Induction Generator (SEIG). Which is connected to an Induction machine at the load side through a modified back to back converter (MBBC) and Matrix converter (MC). The proposed converter uses only 8 switches (MBBC) and had the capability of delivering sinusoidal input currents with voltage wave overlapping the current waveform i.e. a unity power factor additionally, to the bi-directional power flow. The Matrix Converter was seen to contribute to the achievement of low volume, sinusoidal I/P current, bi-directional power flow and minimizing of bulky reactive elements. All these reasons lead to the extraneous usage of MC in WECs. The Total Harmonic Distortions for MBBC and MC output voltage are compared by using simulink software, which came out to be better for MBBCs.

The reason why there has been significant amount of work done on wind energy systems is because it is considered to one of the poor quality energies, mainly due to the variation of the velocity and direction of the wind. Thus there are a lot of propositions given in different researches to rectify this problem by implementing different techniques of power conversion, control strategies and improving the operating system. As these variations increases it increases the fluctuations in the input power and the frequency, henceforth affecting the operations. Using the same basis, there was a paper presented by S. Vaishali and A. Jamna [13], which signifies the usage of Power electronics converters for the purpose of stabilizing the varying parameters, in order to obtain a constant frequency of 50Hz. MBBCs (back to back converters) or AC-DC-AC converters have a lot of disadvantages like being costly and bulky. Through matrix converters constant frequency can be maintained. PWM techniques were used for switching on and off. The wind system was analyzed and simulation results were obtained by MATLAB-Simulink.

In the current scenario, the focus has shifted to improving the operating conditions, reliability, and performance of the renewable energy systems which are usually subjected to several varying parameters due to the sources that drives them. Hence wind energy system have become the guineapig of these experiments, studies and researches that are conducted. Soft-computing techniques is a dynamic field of research and experiment. When such technique is implemented to control the matrix converters the results are expected to be greatly advanced. A paper of simple implementation but major revelations was presented by A. Khodamoradi, H. K. Kargar and A. Nateghi[14], which describes a the new-kind of Wind Energy Conversion System (WECS), where fuzzy logic soft computing techniques and a Matrix Converter model are used to achieve performance enhancement and optimization of efficiency. The Matrix Converters are used as the interface between the Permanent Magnet Synchronous generator (PMSG) and the grid. The power at grid-interface is controlled by MC to ensure that the active power injected into the grid is at its maximum. The system proposed here had a fuzzy logic controller that tracked the angular frequency of the wind velocity and controlled the switching pattern of the matrix converter for extracting maximum power. The complete control system was analysed and validated using MATLAB-SIMULINK modeling.

Recently in 2014 alongside the research conducted for interfacing grid with the Indirect Matrix Converters as discussed in [1], there have been parallel and contemporary researches using different techniques to achieve best performances. As mentioned, the prime focus is to attain best results in terms of performance and power quality by minimizing the distortions due to interference during the transmission or due to the reason of boosting the voltage[1]. One of the researches that helped us was by F. M. Savio, V. R. Rajan, B. ArunKumaran and C. S. A. Sekhar [15], they highlighted the implication of low harmonic indirect matrix converter (IMC) which are used to drive an induction motor fan system. They proposed method to reduce the harmonic level in the load side by controlling the drive system using IMC. The Space Vector PWM (SVPWM) technique has been repeatedly used in all controlling systems including here to control the voltage output of the IMC, and that voltage is fed to the motor terminals. The pulse generated if given vector modulation, it reduces the losses and the harmonics considering the inductive nature of the load. The system designed extended its application to the wind energy conversion system (WECS) using a fixed speed wind turbine, the results are achieved using the mathematical modeling of the proposed system in MATLAB Simulink.

The usage of IMC interfaced with WECs is a potential subject for study. One of the application to achieve certain results was presented by E. Karaman, M. Farasat and A. M. Trzynadlowski, [1], which used Switched-inductor and quasi-Z-source indirect matrix converters. Henceforth, these were proposed as generator-grid interface to wind energy systems and wind turbines in general. All These papers mentioned in this survey gave a basic understanding of the wind systems, their challenges, threats, scope of innovation in future and advancements needed. In this paper of 2014, the Voltage levels of gearless ac generators are low. Therefore, due attention should be given to the voltage boost that can be achieved by the power electronic interfaces used for linking the generator with the grid. Switched-inductor Z-source network has a brief shoot-through state which helps to boost the voltage of inverters. The quasi-Z-source network gives advantages, such as flexibility of lower component ratings, and simpler control strategies. The generator-grid interfaces characterized by the minimum number of semiconductor switches are based on the ultra-sparse matrix topology. The boosting networks are established between the front-end rectifier (that rectifies the signal) and back-end inverter (to supply to a DC load). In [14] the fuzzy logic as a control strategy was used, herewith in [1] the fast Fourier transform analysis for the input/output currents of the converters w.r.t the boost factor implied in the DC Boost stage, is carried out. The simulation results obtained from MATLAB-SIMULINK modeling, and the experimental results verify the effectiveness and relevance of the proposed topologies and control strategies in providing high boosting capability, while the input/output current quality is maintained well.

While the effectiveness of Boosting was achieved by the proposed topologies, the concern relating to power quality was yet to be addressed. Thus, the work in this thesis was carried out by taking references from all the above mentioned successful works of thesis which focused on one factor at a time and tried to achieve optimized results in that particular domain. Hence, the domain and problem concern of this dissertation is to focus on minimizing the harmonics using a multilevel converter which is interfaced with wind energy system to achieve mitigated harmonics and enhanced power quality and system reliability.

II. PROPOSED METHODOLOGY

Problems of conventional converters:

1. Conventional converters are not optimized and well suited for variable-speed wind energy systems

2. Poor efficiency in the efficiency versus power graph reduces the energy captures

3. At low wind there is a problem of poor converter efficiency.

4. When the generator voltage is reduced, there is a reduction in the converter efficiency.

5. Circulating currents in resonant converters and doubly-fed systems also contribute to these issues.

While in achieving the boosted voltage in a system, the unconcerned part remained was of the harmonics distortions present in the AC/DC waves either taken as input or generated as output to the indirect matrix. The problem concern was of harmonics which affects the system performance, reliability, and power quality and load attendance. Therefore, the work carried out in this work is to reduce the distortions by implementing a reconfigured structure of the converter using a Multi-level Matrix system. The strategy is primarily used in wind energy system, due to the magnificent potential promised in the renewable energy sector and the future scope of the improvement in generating distortion free electricity through renewable energy system.

Proposed Model:

Considering the problem statement taken in this work of thesis, the elimination of harmonics from the delivered power in terms of Output Voltage and Current waveforms to improve the power quality delivered on the load side is taken into account. Thus, the methodology or technique proposed is, to design a new model of Converter Interfaced with the Generator-Grid of the Wind Energy System and **observe** the following-

1. Line to Line input voltages and input phase current
2. Phase output voltages and phase output current
3. Line to Line input and output voltages and output phase current
4. Z-source capacitor voltages and Boost-stage current

The waveforms are observed at different scopes of the Simulink Model of the redesigned model for the generator-grid interfaced to wind energy system using Multi-level Matrix Converters which circumscribes the advantages of both the individual converter topologies that is of: multilevel converters and Matrix converters.

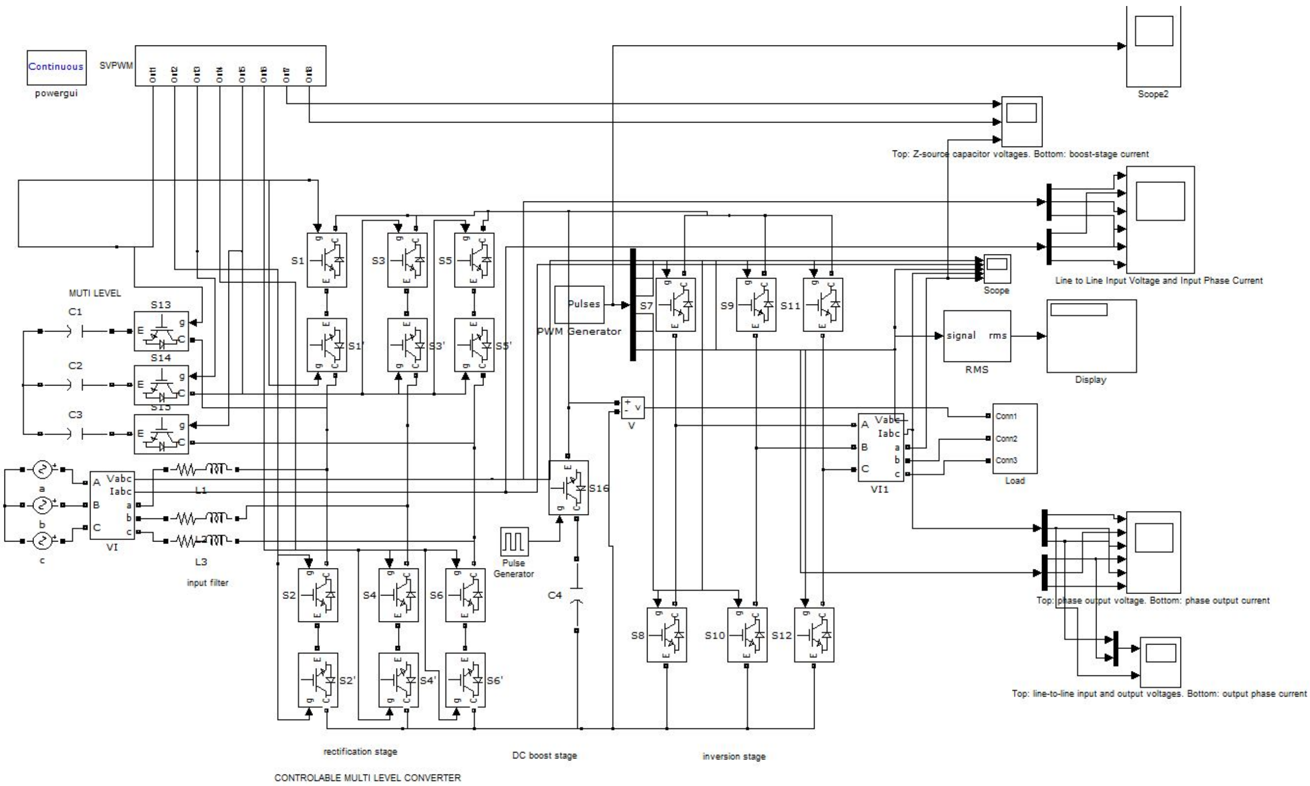

Figure. 2.1- Simulink Model of the Proposed Model

The redesigned model of a Multi-Level Matrix Converter uses following components and stages, to make the design of the interfacing converter with the generator grid, more reliable and efficient in terms of power quality, by eliminating distortions and harmonics-

1. Space Vector Pulse width Modulation (SVPWM and PWM Generator)
2. Wind Energy System as the Renewable Energy source of Electricity generation
3. IGBT Bidirectional Switches (applied on Multiple levels)
4. Filters (Input Filter stage)
5. Rectification Stage (where converter system works as front-end rectifiers)
6. DC Boost Stage (System to boost the Voltage input to the Load)
7. Inversion Stage (Converter system works as back-end inverters)

III. SIMULATION RESULTS

The multi-level matrix converter has several advantages over traditional rectifier-inverter type power Frequency converters. It provides sinusoidal input and output waveforms, with minimal higher Order harmonics and no sub harmonics; it has inherent bi-directional energy flow capability; the Input power factor can be fully controlled. Last but not least, it has minimal energy storage Requirements, which allows to get rid of bulky and lifetime- limited energy-storing capacitors.

The results of the base paper and the work of this thesis have been compared, so as to highlight and emphasize on the scope of improvement and possible extension in the existing works and researches.

The results are compared so as to show the “Reliability of Multi-Level Converters when interfaced with generator-grid of the wind power system”. The power quality as discussed [4.3], is of high importance as it ensures that the generated electricity

The simulations of the Multi-Level Matrix Converter (M-L MC) have been performed for an R-L load which to verify the expected elimination of distortions. The simulated results confirm validity of the proposed system model using Multi-level Matrix converters to reduce the harmonics. Low-pass- RL (C) filters were placed on the input side of the converter to reduce the ripples in the first stage of implemented structure.

This is to show clear improvement and mitigation of the harmonics by comparing the waveforms in the two figures put together.

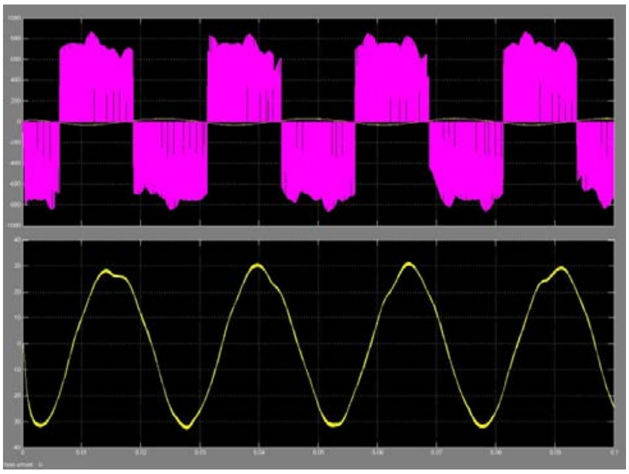

Fig. 3.1 Top: line-to-line input and output voltages. Bottom: output phase current.

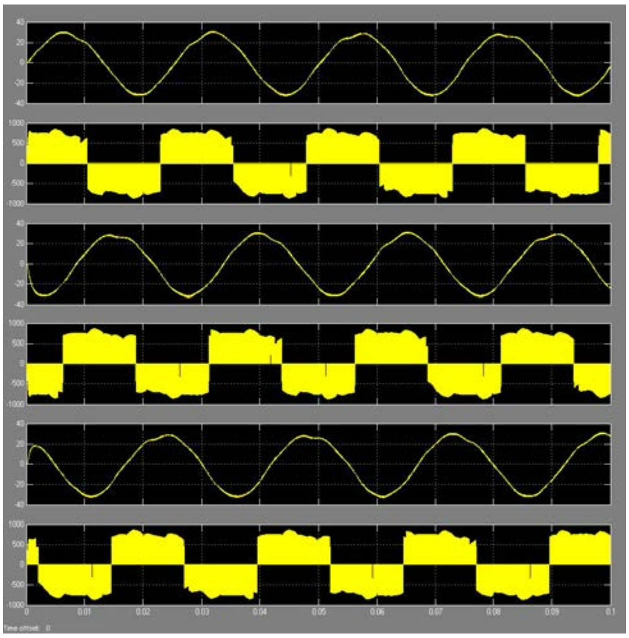

Fig. 3.2 Top: phase output voltage. Bottom: phase output current

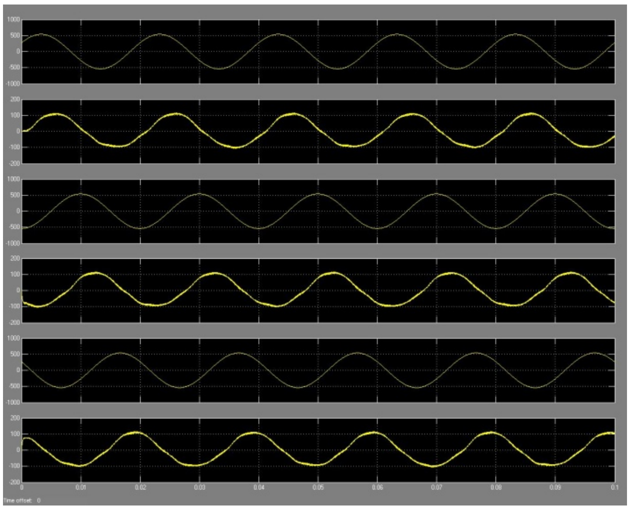

Fig. 3.3 Top: line-to-line input voltage. Bottom: input phase current.

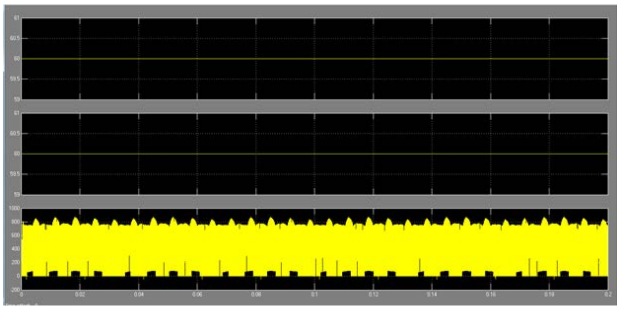

Fig. 3.4 Top: Z-source capacitor voltages. Bottom: boost-stage voltage

IV. CONCLUSION AND FUTURE SCOPE

1. The variable-speed wind power application requires better ac-ac converters having
   - Lower capital cost
   - Improved efficiency over a wide range of wind speeds and generator voltages
   - Better terminal waveforms
2. Electronic power converters having finer structure are becoming feasible:
   - Inexpensive, high performance silicon switches
   - Sophisticated controllers
   - High level of packaging technology
3. Multilevel switching can address the issues of variable speed wind power
   - Reduced switching loss improves efficiency without need for resonant techniques
   - Improved efficiency over wide range of wind speeds
   - Improved waveform quality
4. New modular converter topologies
   - Allow scaling to higher powers and higher voltages
   - Could allow use of advances in packaging and low-voltage silicon in megawatt applications
   - Need additional work in decentralized control and modular topologies

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