Harmonic Interaction of Multiple DG Sources with Power Distribution System

Pradipta kumar Tripathy, *Student member, IEEE*; Elham Makram, *Senior member, IEEE*; Durgesh Manjure, *Member, IEEE*

***Abstract*: Depletion of fossil fuels due to their constant usage and a threat to global warming has necessitated the use of renewable resources such as sun, wind and water for energy production. Solar and wind power can be replenished, are emission free and do not incur fuel cost to generate electric energy. Moreover, deregulation of power system has allowed individual power producers to produce electric power autonomously for their own usage and for commercial sale in the energy market. This has prompted individual power producers to be self-sufficient and produce power by installing their own generating facility. Photovoltaic (PV) systems and Wind energy (WE) systems have come up as viable choices among the renewable energy sources. An increasing number of small distributed generation (DG) units are being installed to generate power from renewable energy sources like solar and wind power, in conjunction with large conventional power plants. Both PV systems and WE systems invariably involve a power-conditioning system such as converters and inverters, and thus create a concern of harmonic injection. Many residential loads are inherently nonlinear and thus draw nonlinear current and create harmonic distortion. Harmonic distortion, a power quality issue, is a cause of concern to the customer and to the utility. This paper presents the study and analysis of harmonics in a distribution system due to increased DG penetration. A hybrid PV-WE system has been simulated and the interaction of harmonics due to multiple DG sources namely, PV system and WE system has also been presented.**

***Keywords* – PV system, WE system, modeling, hybrid, residential load, harmonics**

I. INTRODUCTION

Interest in PV energy dates back to 1954, when the first PV system was designed. With technological advancement, PV energy started being used in low power applications such as calculators, wrist watches etc. Over the last couple of decades, developments in new low cost PV material, and the low manufacturing cost of PV cells have prompted the usage of PV source for energy production throughout the world [1]. PV systems consist of series and parallel combinations of PV cells in the form of an array and produce DC power from the absorbed solar power. Inverters are used to convert the DC power into AC power. These inverters are known sources of harmonics and introduce significant distortion. PV systems can produce power ranging from small generating units of 5 KW to large installations of 0.1 MW. These PV systems can operate as stand-alone units supplying power to the residential or commercial loads. If the power generated is in excess, then it can be supplied to the utility grid. Various methods have been proposed for modeling PV systems. A self-commutated photovoltaic inverter system has been presented in [2]. Modeling and dynamic performance of a line-commutated inverter system has been presented in [3]. Hashimoto et al have presented a novel high performance utility interactive photovoltaic inverter system in [4]. Study and investigation of harmonic distortion from utility integrated photovoltaic systems and other nonlinear loads has been presented in [5], where the source of harmonics has been investigated and techniques to limit the harmonics have been discussed. Study results of harmonics due to a utility integrated PV system has been presented in [6], where it has been concluded that harmonics due to PV system are not significant in comparison to the harmonic distortion caused due to various nonlinear loads.

Harnessing wind power dates back to the 17th century, when people used it for pumping water, sawing wood etc. The modern use of wind power in the form of rural electrification started in the middle of twentieth century. Technological advancement has enhanced the usage of wind energy for generating electric energy with the wind turbine rotor size ranging from a meter to hundred meters and power output ranging from watts to several kilowatts [7]. WE systems typically consist of a turbine, which rotates by wind power and a generator coupled to the turbine, which converts the wind power to electrical power. Both synchronous and asynchronous generators are used in WE systems [8]. However, the usage of asynchronous generators such as induction generators (IGs) in WE systems has been wide spread because of their reliability, low unit cost, reduced maintenance and capacity to bear overload conditions. The most prominent feature that IGs offer is the variable speed operation. Thus coupled with a wind turbine, the IG can virtually be run at any prevailing wind speed generating AC power. The WE system can be designed as a stand-alone unit or a grid-connected unit depending upon the location and availability of wind energy [7, 8]. In remote areas, where grid supply is not available, WE system can be operated in stand-alone mode to supply power to the loads locally. When the power generated by the WE system is in excess of the local load demand, then the WE system can be hooked on to the grid and the excess power can be supplied to the grid. Wind turbines are often operated in variable speed constant frequency (VSCF) mode to extract maximum power out of the widely fluctuating wind speed. However, in this scheme, a power electronic interface, usually a converter cascade is used to convert the variable frequency output of the WE system to the grid frequency. The use of converters in WE systems creates a concern of harmonic current injection into the grid.

Pradipta Kumar Tripathy (tpradip@clemson.edu), Durgesh P. Manjure (dmanjur@ces.clemson.edu) and Elham B. Makram (elham.makram @ces.clemson.edu) are with the Holcombe Department of Electrical and Computer Engineering at Clemson University, Clemson, SC 29634-0915

Various methodologies have been developed in order to help facilitate the increased usage of wind-energy. The electrical system used for fixed and variable speed operation of a WE system and the power quality issues they can cause, has been presented in [9]. A summary of the state of art regarding generator and power electronic concepts for wind turbines has been presented in [10]. Slootweg et al [11] have presented various topologies for modeling grid connected wind energy systems for dynamic studies. Pena et al [12] have presented a control strategy for a cage induction generator driven by a wind turbine, supplying power to the grid. Z. Chen and E. Spooner [13] have proposed an advanced power electronic interface to minimize the harmonic distortion and voltage fluctuation and to improve the network voltage control. Harmonic distortion caused due to the operation of a variable speed wind turbine has been presented in [14]. Harmonic distortion caused by induction generator in two schemes (i) a variable speed constant frequency scheme and (ii) a slip recovery scheme has been presented in [15]. Apart from distorting the supply voltages and currents, the harmonics also affect the operation of IG in case of a doubly fed IG system, by limiting its active power generation capacity. Harmonics and negative sequence components due to nonlinearity and unbalance may cause severe instability problems in induction generators. Harmonic distortion thus has many adverse effects. Apart from the adverse impacts cited earlier, harmonics in the load current can cause over-heating and damage to the electric equipment. Harmonics injected into the grid can cause problems like interference with power system protection, load unbalance and increase the power loss, as well.

The major contribution to the harmonic injection in the distribution system is due to the increased use of nonlinear loads in household equipment for energy efficiency and conservation. Household loads such as refrigerators, television sets, computers, heat pumps and compact fluorescent lights (CFLs) use power electronic circuitries. Characteristics of some of these loads such as ASDs, television sets, PCs, and CFLs have been presented in [16, 17]. These loads inject harmonic current into the supply resulting in unacceptable level of voltage distortion. The problem of harmonics thus contributes significantly to the power quality issues and it warrants careful attention. Consequently, it has become imperative to investigate the exact cause and nature of harmonics, their quantity and the impact of their interaction with the power system. This necessitates accurate modeling of the power system components and study of power system behavior with respect to harmonics. Harmonic injection due to a grid-connected PV system, supplying power to residential load has been presented in [18]. Harmonic injection due to WE system in various modes of operation, supplying power to a commercial load has been presented in [19].

This paper presents the impact of increased DG penetration on the harmonic distortion in a distribution system. Also, harmonic injection due to the hybrid operation of the DG units supplying power to a residential load has been studied and presented. Various case studies have been done to investigate the harmonic distortion. Finally conclusions have been drawn based on the simulation results.

II. MODELING

A. PV system

In principle, a PV system converts sunlight into electricity. The PV system contains an array of PV cells in series and parallel combination, which upon absorption of sunlight produce electric current (DC), which is then converted to AC current using an inverter to supply power to the AC loads. The circuit model of PV system is simulated using PSCAD software [20] as shown in Fig. 1.

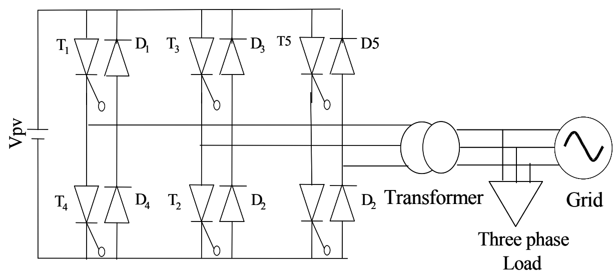

Fig.1. Grid-connected PV system

While performing the computer simulation a DC voltage source (V_{pv}) was used for simulating the output power from the PV array. The DC power is fed to a three-phase, full-wave, line-commutated inverter to produce alternating sinusoidal voltage and current. A control circuit is designed to periodically trigger the GTOs into conduction by a pulse train. Sinusoidal pulse width modulation (PWM) scheme is used to generate the firing pulse to the gate terminals of the GTOs. Details of the PWM scheme and the active and reactive power control through the inverter have been presented in the following section. A transformer at the inverter output provides isolation and prevents the leakage of any DC component to AC side.

B. Wind Energy system

The basic principle of modeling a WE system using PSCAD software has been presented in detail in [19]. To extract maximum power from the WE system and to be able to operate at nearly all wind-speeds, the WE system is operated in indirect grid connection mode, where the output of the WE system is supplied to the grid through a rectifier-inverter interface. In this mode, the wind generator rotates at variable speeds thus generating AC power at a variable frequency (not necessarily the grid frequency). The diode rectifier converts this variable frequency AC power to DC. This DC power is then converted to AC power with exactly the same frequency as the utility grid by the inverter. The current waveform at the inverter output is observed to be rectangular-shaped due to the alternate switching of the inverters to produce the alternating current. Line reactors are used to smooth out the current. However, some high frequency components, which are multiples of grid frequency, are still left in the output. Fig. 2 shows a grid-connected WE system.

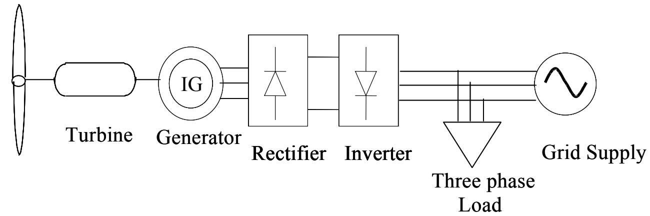

Fig.2. Grid-connected WE system

C. Hybrid PV-wind system

PV system does not produce power in the absence of adequate sunlight; however, a wind energy system can produce power even in the absence of adequate sunshine. So a hybrid PV-WE system with battery backup is a good alternative rather than the PV or WE system alone. In this configuration, both PV system and Wind energy system simultaneously operate and supply power to the residential load. When the power generated by the PV system and the WE system is more than the load demand, then the excess power is stored in the battery. When the total power generated by the PV system and the WE system is less than the load demand then the battery supplies the power deficit. If the load demand is still in excess of the generated power, then power is drawn from the grid. Also the battery storage can help storing the grid power during light loading conditions and transporting power during peak loading. Fig. 3 shows the operation of a hybrid PV-WE system.

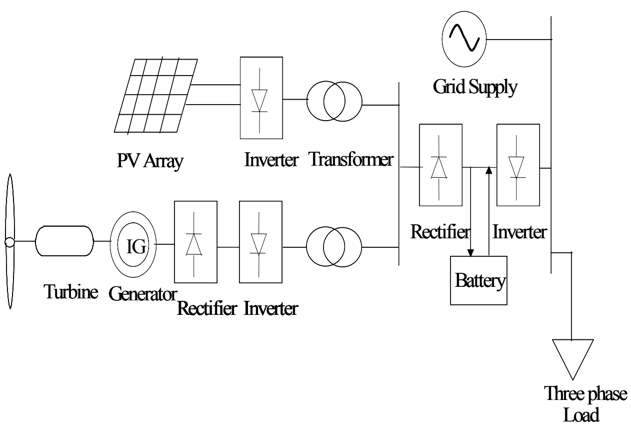

Fig.3. Grid-connected hybrid PV-WE system

III. VOLTAGE REGULATION, ACTIVE AND REACTIVE POWER CONTROL

Rectifier and inverter operation has been discussed in detail in [21]. The variable frequency AC at the wind generator terminals needs to be converted to grid frequency so that it can be connected to the grid. A three phase diode rectifier circuit is used to convert this variable frequency AC power to DC power. An L-C filter is used at the output of the rectifier circuit to hold the DC voltage at the desired value. Fig. 4 shows the rectifier-inverter pair.

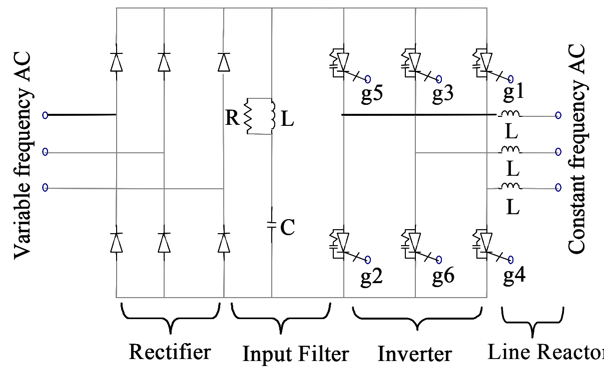

Fig.4. Rectifier-Inverter pair

A three-phase full-wave GTO based inverter circuit has been designed to invert the DC power to AC power at grid frequency i.e. 60 Hz. The voltage at the inverter output terminals can be controlled by controlling the conduction period of the GTOs. In order to achieve this, the GTOs are switched on and off at specific intervals. A control circuit has been designed to generate the firing pulses for switching the GTOs. PWM switching scheme has been used to generate the firing pulses for the GTOs. By this scheme, a reference sinusoidal wave is compared with a triangular carrier wave to generate the necessary turn on and turn off instants of the GTO. The reference wave is synchronized with the output AC voltage of the inverter. The frequency and the amplitude of the carrier wave are maintained constant. Switching frequency of the GTOs is equal to the frequency of the carrier wave. The difference in the set value of the reactive power and the actual value of the reactive power supplied by the inverter, known as the error signal, is fed to a P-I controller to produce the modulation index. Modulation index is defined as the ratio of the peak of the reference signal to the amplitude of the carrier signal. This modulation index gets multiplied with the reference wave and thus the amplitude of the reference wave varies. Consequently, the time period of turning on and turning off of the GTO changes. Thus the reactive power flow sets the magnitude of the voltage at the inverter output. Once the magnitude of the voltage becomes equal to the grid voltage, the output of the inverter is connected to the grid. The active power from the generator is controlled through the interface, by phase shifting the relative angle of inverter voltage with respect to the grid voltage, which allows a current to flow from the WE system to the grid. Inverter output is usually pulse width modulated and so a filter is used at the output of the inverter circuit to smoothen out the voltage and make the shape of the output voltage waveform close to a sinusoidal wave. Firing pulses are applied at the gate terminals g1 through g6 for GTOs 1- 6 respectively, as shown in the Fig.4.

IV. RESULTS

The 13-bus IEEE distribution system [22] shown in Fig. 5 was considered for the case study. A residential load was connected to Node 634 through a 480 V/208 V transformer. The residential load (20 kW) consisted of various linear and nonlinear loads. Incandescent lights have been modeled as linear loads. The nonlinear load consisted of CFLs, TVs and heat pumps, which are typical in a residential system. The PV system was operated at constant power mode at four different power levels such as 5 kW, 10kW, 15kW and 20 kW. Active power, reactive power, line-line voltage and line current were measured on the 208 V side of the transformer. Line current and line-line voltage were measured on the 480 V side. For each of the measured currents and voltages, individual harmonic content at different harmonic frequencies was determined using FFT, and was subsequently used to compute the THD. Similar case studies were performed at each power output levels for WE system. Details of each case study along with the results obtained have been presented ahead.

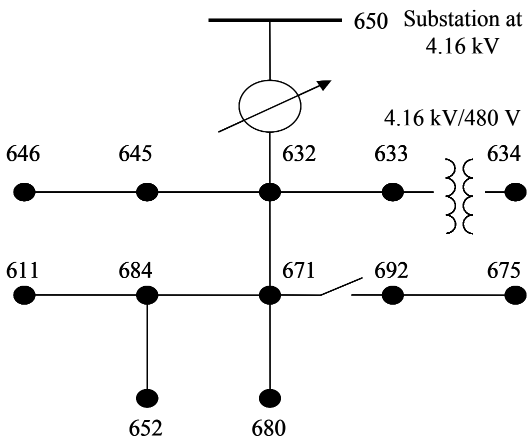

Fig.5. IEEE 13 node test system

A. PV system

PV system was connected to the distribution test system at 208 V. A set of measurements was taken when PV system supplied 5 kW power. The output of PV system was then increased in steps of 5 kW till 20 kW. It was observed that at all the output power levels, the voltage waveforms were sinusoidal shaped on both sides of the transformer (i.e. at 208 V and 480 V) producing a maximum THD of 0.18 %. However, the line current waveforms were distorted on both 480 V and 208 v sides of the transformer. Further, the THD on 4.16 kV side was found to be significantly lower (about 0.39%). Fig. 6 shows the current waveforms on 480 V and 208 V side when the PV system supplied 20 kW. Fig. 7 shows the frequency spectrum of current on 480 V side at this power output. THD of the line current at different output power levels have been presented in Table 1.

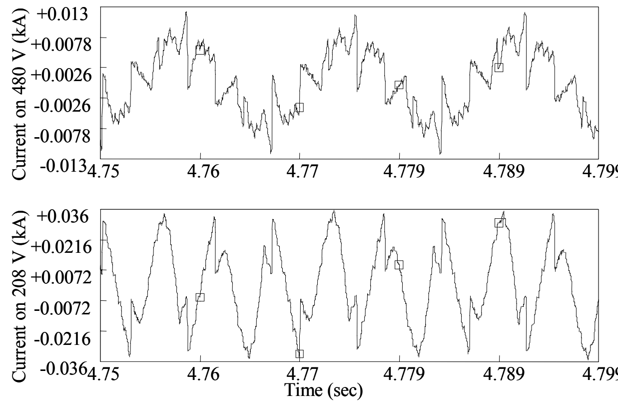

Fig.6. Current waveforms on 480 V and 208 V side

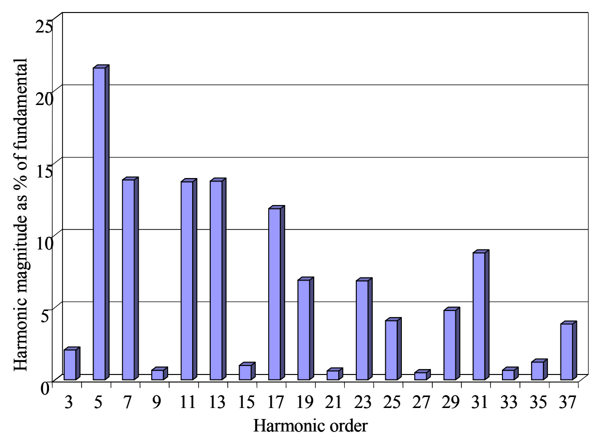

Fig.7. Frequency spectrum of current on 480 V side

TABLE 1 THD IN LINE CURRENT

THD (%)	5 kW	10 kW	15 kW	20 kW
On 480 V side	12.47	17.23	29.8	37.51
On 208 V side	39.83	56.19	103.7	159.8

B. WE system

The WE system was also connected to the distribution system at 208 V and the output was increased from 5 kW to 20 kW in steps of 5 kW. Grid current and voltage were measured and the THD were calculated. As in the case of the PV system, voltage waveforms were found to be sinusoidal on both 208 V and 480 V sides. The maximum THD observed was 0.17 % at all the output power levels. However, the line current waveforms were distorted on both 208 V and 480 V side of the transformer. Further, the harmonics injected into the 4.16 kV side were found to be significantly lower, producing a maximum THD of 0.45%. Fig. 8 shows the current waveforms on 480 V and 208 V side when the WE system supplied 20 kW. Fig. 9 shows the frequency spectrum of current on 480 V side at this power output THD of the line current at different output power levels have been presented in Table 2.

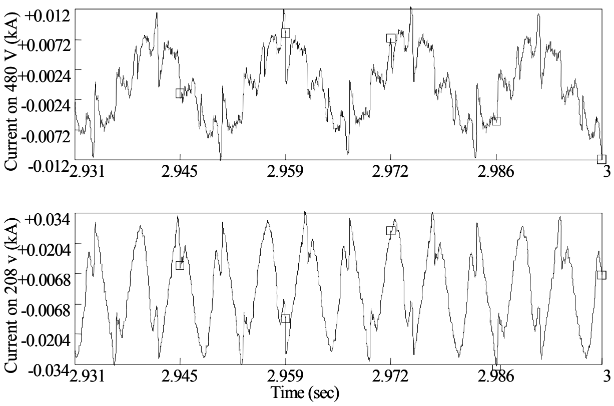

Fig.8. Current waveforms on 480 V and 208 V side

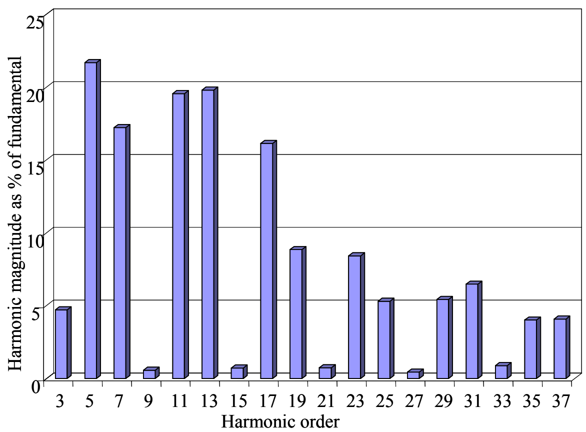

Fig.9. Frequency spectrum of current on 480 V side

TABLE 2 THD IN LINE CURRENT

THD (%)	5 kW	10 kW	15 kW	20 kW
On 480 V side	13.36	17.58	28.9	45.96
On 208 V side	48.2	66.4	123.9	140.1

C. *Hybrid PV-WE system*:

Both the PV system and the WE system were connected at 208 V to the distribution system and shared the residential load supplying 10 kW each. Voltage waveforms were found to be almost sinusoidal as before on both 208 V and 480 V side, producing a maximum THD of 0.17 %. THD in the line current was found to be 40.34 % and 55.9 % on 480 V and on 208 V side respectively.

V. DISCUSSION

From the simulation results, it was observed that, in all the case studies involving PV system, WE system and the hybrid PV-WE system the voltage distortion was pretty low. However the distortion in line currents on both 208 V and 480 V was found significant in all the cases. It was also observed that the magnitude of distortion varies with variation in the output power (both active and reactive) from the DG units. The individual harmonic magnitudes indicate that the odd harmonics are more significant compared to the even harmonics. In case of both PV and WE system, it was observed that 5^{th} harmonic was the dominant one followed by 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} and so on. These harmonics are introduced due to the nonlinear loads present in the residential load. Some higher order harmonics such as 29^{th}, 31^{st}, 35^{th} and 37^{th} were also found to be significant. The higher order harmonics are mostly dependent on the switching frequency employed for the inverter.

As seen in the results, THD in line current on 4.16 kV side was 0.45 %, when the WE system supplied 20 kW power and 0.39 %, when the PV system supplied 20 kW power. The reason being, at node 634, the amount of linear load connected was quite high compared to the amount of nonlinear load down the distribution line. Thus the distortion is attenuated further towards the high voltage side and there is no significant harmonic propagation on the 4.16 kV side. Thus under such scenario, a high penetration of DG also will not effect the harmonic distortion to a considerable amount.

In all the above cases, THD was found to be well within the limits, specified by the IEEE-519 standard (less than 5% in grid voltage and less than 8 % in grid current).

VI. CONCLUSION

This paper presents the harmonics injected into the grid due to the operation of a PV system, a WE system and a hybrid PV-WE system while supplying power to a residential load. From the simulation results obtained, it can be concluded that the operation of DG units do distort the currents on the load side, and the THD is dependent upon the power output of the DG device. However this distortion is not carried over to the high voltage side of the system. As such, the use of these DG devices does not affect the distribution system adversely. The results obtained are for a specific case of (residential) nonlinear loads, and the harmonics scenario could change with a change in the type of load considered.

VII. REFERENCES

1. US Department of Energy, "Photovoltaic energy program overview", Fiscal year 2000
2. Wasynesuk O. and Anwah N. A., "Modeling and Dynamic Performance of a Self-commutated Photovoltaic Inverter System," *IEEE Trans. on En. Conv.,* Vol. 4, No. 3, Sept. 1989, pp 322 -328
3. Wasynesuk O., "Modeling and Dynamic Performance of a Line-commutated Photovoltaic Inverter System", *IEEE Trans. on En. Conv.,* Vol. 4, No. 3, Sept. 1989, pp 337 -343
4. Hashimoto O., Shimizu T., Kimura G., "A novel high performance utility interactive photovoltaic inverters", *Proc. of Ind. App. Conf.*, Vol. 4, Oct. 2000, pp 2255 -2260
5. Stevens John, "The issue of Harmonic Injection from Utility Integrated Photovoltaic Systems Part 1: The Harmonic Source," *IEEE Trans. on En. Conv.,* Vol. 3, No. 3, Sept. 1988, pp 507 –510
6. Stevens John, "The issue of Harmonic Injection from Utility Integrated Photovoltaic Systems Part 2: The Harmonic Source," *IEEE Trans. on En. Conv.,* Vol. 3, No. 3, Sept. 1988, pp 511 –515
7. Web-Page, http://www.wind-power.com/#Wind
8. Web-Page, http://www.windpower.org

9. Larsson Ake, “The Power Quality of Wind Turbines”, Ph. D. Thesis, Department of Electric Power Engineering, Chalmers University of Technology, Sweden 2000.
10. Hansen L.H., Madsen P.H., Blaabjerg F., Christensen H.C., Lindhard U., Eskildsen K., “Generator and power electronics Technology for wind turbines”, *Proc. Of IEEE Industrial Electronics Society (IECON’01)*, 2001, Vol. 3, pp 2000 -2005
11. Slootweg J. G., De Haan S. W. H., Polinder H., Kling W. L., “Modeling Wind Turbines in Power System Dynamic Simulations”, *Proc. of IEEE Power Engineering Society Summer Meeting, 2001,* pp 22 -26
12. Pena R., Cardenas R., Blasco R., Asher G., Clare J., “A cage induction generator using back to back PWM converters for variable speed grid connected wind energy system’, *IEEE Industrial Electronics Society (IECON’01)*, 2001, Vol. 2, pp 1376 -1381
13. Chen Z., Spooner E**., “**Grid power quality with variable speed wind turbines**”,** *IEEE Transactions on Energy Conversion*, Vol. 16, No. 2, Jun 2001, pp 148 -154
14. Larsson, Å., Sørensen, P., Santjer, F., "Grid Impact of Variable-Speed Wind Turbines" *Proc. of the European Wind Energy Conference (EWEC ´99),* March 1-5, 1999.
15. Herrea J.I., Reddoch T. W. and Lawler J.S., “Harmonics generated by two variable speed wind generating systems,” *IEEE Trans. on En. Conv.*, Vol. 3, No. 2, 1998, 267-273.
16. Johnson Karl J. and Zavadil Robert, “Assessing the Impact of Nonlinear Load on Power Quality in Commercial Buildings- An Overview,” *Proc. of the IEEE Ind. App. Society Annual Meeting*, Dearborn, MI, USA, Sept.28-Oct 4 1991, 1863-1869
17. Monsoor A., Grady W. M. et al, “Predicting the Net Harmonic currents Produced by large Numbers of Distributed Single-phase computer Loads”, *IEEE Trans. on Power delivery*, Vol. 10, No. 4, 1995, 2001-2006.
18. Tripathy P. K., Manjure D., Makram E., “Harmonic analysis in selected Distributed Generation devices”, Power system 2002 Conference, March 13-15, 2002, Clemson, USA
19. Tripathy P. K., Makram E., Manjure D., “Harmonic analysis of Wind Energy Systems”, Submitted for publication at Power system 2003 Conference, March 2003, Clemson, USA
20. PSCAD/EMTDC User’s Manual, www.pscad.com
21. Mohan Ned, Undeland Tore M. and Robbins William P., “Power Electronics: Converters, Applications and Design”, Second Edition, John Wiley & Sons, Inc., 1995, pp.121-248
22. Web-Page, http://www.ewh.ieee.org/soc/pes/dsacom/ testfeeders.pdf

VIII. BIOGRAPHIES

Pradipta Kumar Tripathy received his B.E. degree in electrical engineering from Regional Engineering College, Rourkela, India in the year 1997. From 1997 to 2000 he was working as a project engineer in the Network Management Systems group at ABB Asea Brown Boveri Ltd, India. Currently he is pursuing his M.S. degree in electrical engineering at Clemson University, USA. His research interests include modeling of distributed generation systems and harmonic analysis.

Elham B. Makram received her Ph.D., from Iowa State University in 1981. She worked in industry for about 11 years then joined Clemson University in 1985. She is presently a named professor in the Electrical and Computer Engineering Department at Clemson University. She is teaching power courses such as power system analysis, electric power distribution, power system harmonics, and computer applications in power systems. She is a senior member in IEEE Society, member in Sigma Xi, member on Women's Engineering Society, member in CIGRE, and a member in American Society for Engineering Education (ASEE). She is the recipient of the 1991 Alumni Research Award, the 1992 NSF/FAW award, the 1993 SWE distinguished engineering educator award, the 1994 outstanding faculty award at Clemson University, and the 1996 Provost's Award for Scholarly Achievement.
Her research interests include computer simulation of power systems, power system harmonics, and optimal operation and design of power systems.

Durgesh P. Manjure was born in Bombay, India, in 1976. He received his Bachelor of Engineering (Electrical Engineering) degree from the University of Bombay in 1997 and his MS and Ph.D. Degrees from Clemson University, in 1999 and 2002 respectively, both in Electrical Engineering. Currently he is working as a Post-Doctoral Research Fellow at Clemson. His research interests include harmonics analysis, security assessment in deregulated power systems and impact of distributed generation.
He is a Member of the IEEE and the PES, and served as the Secretary for the PES, Clemson Chapter from 1997 to 1999.