Case Studies: Interconnection of Wind Turbines on Distribution Circuits

James G. Cleary, Thomas E. McDermott, Jonathan Fitch, David J. Colombo, Justice Ndubah

***Abstract* — Three case studies of proposed wind turbines connected to distribution feeders provide examples of how to efficiently conduct impact studies. In all three cases, the wind turbines are large enough that some engineering analysis was required. To address flicker concerns, power quality monitoring is recommended before and after the wind turbines are connected. Voltage fluctuations can be reduced if the wind turbines absorb some reactive power. Some applications require protective relay functions beyond the minimums identified in IEEE Standard 1547.**

***Index Terms*—power distribution, distributed resources, distributed generation.**

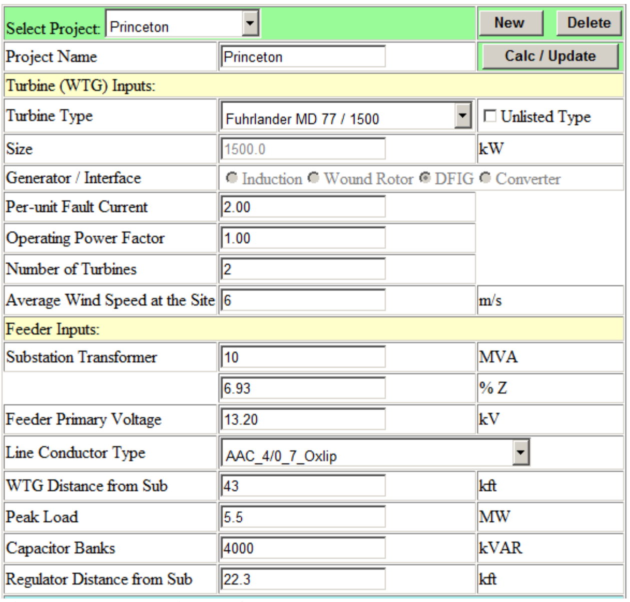
I. NOMENCLATURE

BESC	Berkshire East Ski Center
CCVT	capacitively-coupled voltage transformer
DER	distributed energy resource
DFIG	doubly fed induction generator- wind turbine
DPC	digital phase converter
EMS	energy management system
EMTP	electromagnetic transients program
FERC	Federal Energy Regulatory Commission
LFG	landfill gas
MFR	multi-function relay
PCC	point of common coupling
PMLD	Princeton Municipal Light Department
RTU	remote terminal unit for monitoring output
SGIP	Small Generator Interconnect Procedure
TOV	temporary overvoltage
UL	Underwriters Laboratory
UWIG	Utility Wind Integration Group
WTG	wind turbine generator

II. INTRODUCTION

National Grid needs to perform distributed energy resource (DER) impact studies under regulatory time constraints, with many projects competing for utility engineering resources. IEEE and IEC standards [1-5] define requirements and test procedures for DER projects, but do not spell out how to implement successful interconnections. A guide to DER impact studies is under development by IEEE, but not yet completed. Therefore, the studies reported in this paper were conducted using custom tools [6] provided by the Utility Wind Integration Group (UWIG). These tools are available to many utilities, including municipals and rural electric power cooperatives. A general study outline for distributed wind is presented in [7]. The UWIG tools are efficient, but in some cases the study has to be extended with custom DER modeling in OpenDSS [8], or an Electromagnetic Transients Program such as ATP [9].

The web-based UWIG software first performs a quick project screening, to identify more detailed study requirements. Fig. 1 shows the simplified screening tool inputs, which are sufficient to characterize the wind turbines and the PCC source strength.



Select Project:	Princeton	
Project Name	Princeton	
Turbine (WTG) Inputs:		
Turbine Type	Fuhrlander MD 77 / 1500	☐ Unlisted Type
Size	1500.0	kW
Generator / Interface	○ Induction ○ Wound Rotor ● DFIG ○ Converter	
Per-unit Fault Current	2.00	
Operating Power Factor	1.00	
Number of Turbines	2	
Average Wind Speed at the Site	6	m/s
Feeder Inputs:		
Substation Transformer	10	MVA
	6.93	% Z
Feeder Primary Voltage	13.20	kV
Line Conductor Type	AAC_4/0_7_Oxlip	
WTG Distance from Sub	43	kft
Peak Load	5.5	MW
Capacitor Banks	4000	kVAR
Regulator Distance from Sub	22.3	kft

Fig. 1. UWIG Screening Tool Inputs.

The screening tool outputs, shown in Fig. 2, include:

1. Wind turbine generator (WTG) size as a percentage of peak feeder segment load. This should be 15% or less to accept the project without further study. If higher, the possibility of unintended islanding exists.
2. WTG fault contribution, which should be no more than 10%. If higher, a protection coordination study should be done.
3. Capacity factor for wind, which is important for the developer to evaluate economic benefits. For the interconnection, a higher capacity factor may increase the risk of unintended islanding.
4. System source strength at the PCC, which is useful in

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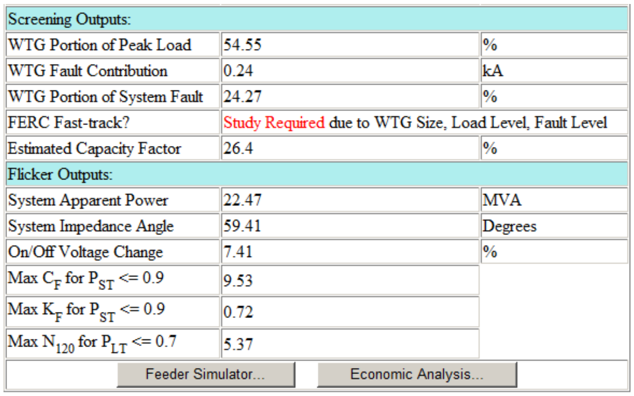
flicker, harmonic, and voltage change evaluation.

5. The maximum steady-state voltage change as the DER cycles between zero and full output. This should be no more than 5%, and some utilities limit the change to 3%. The DER operating power factor affects this value.
6. Flicker severity estimate, or if WTG flicker data is not available, the maximum WTG flicker coefficients [5] to meet the IEEE planning limits in [4].



Screening Outputs:		
WTG Portion of Peak Load	54.55	%
WTG Fault Contribution	0.24	kA
WTG Portion of System Fault	24.27	%
FERC Fast-track?	Study Required due to WTG Size, Load Level, Fault Level	
Estimated Capacity Factor	26.4	%
Flicker Outputs:		
System Apparent Power	22.47	MVA
System Impedance Angle	59.41	Degrees
On/Off Voltage Change	7.41	%
Max C_F for P_{ST} <= 0.9	9.53	
Max K_F for P_{ST} <= 0.9	0.72	
Max N_{120} for P_{LT} <= 0.7	5.37	

Fig. 2. UWIG Screening Tool Outputs.

The UWIG software then creates a skeleton feeder model for more detailed electrical analysis. This tool simulates voltage fluctuations and their impact on voltage regulators and capacitor switching operations, due to variable wind power output. It also simulates overcurrent protection and backfeeding overvoltages for a variety of fault types and locations. The turbine model includes its fault current contribution, its interconnection transformer, and its protection package with overvoltage, undervoltage, overcurrent, and unbalance trip functions. The model can be exported for more detailed analysis using OpenDSS [8].

III. FERC JURISDICTIONAL CIRCUIT

Princeton Municipal Light Department (PMLD) has proposed a 3-MW distributed wind project. The town is supplied by one of National Grid's 13.8-kV distribution circuits. It is a 12 mile long overhead line and serves about 2,000 residential customers including the entire town of Princeton, MA. The wind turbines will be 8.5 circuit miles from the substation on a radial line.

The circuit already has high penetration of DER with 7.2 MW of land-fill gas (LFG) generation exporting onto the feeder. National Grid undertook line re-conductoring to increase thermal ratings, additional relaying, and substation equipment (CCVT) to accommodate reverse flows from the LFG. This LFG project came under FERC jurisdiction (Schedule 23-SGIP Small Generator Interconnect Procedure) because the distribution line already served in a wholesale transaction with sales to the town of Princeton. DER generation exceeds the feeder load and backfeeds to the substation and onto the area 69-kV system routinely.

The same feeder also serves a 5 MW 'winter only' spot load, namely the Mt. Wachusett ski area. Large snowmaking compressors and pumps have been the subject of prior flicker and voltage studies by the utility.

Flicker and power quality were of special concern, given the existence of flicker-producing loads at the ski resort. Wind turbine power quality data in IEC Std. 61400-21 format was requested from the vendor, but these tests are expensive and complete results are not always available. Based on the vendor's test report, the PMLD wind turbines are not expected to produce continuous flicker problems from turbine shadowing, blade pitching, wind variability, etc. However, switching flicker data was not available for turbine start-up and shut-down. For many turbines, the switching flicker is more severe than continuous flicker. Similar sized turbine types with available flicker data showed they could produce switching flicker levels above the IEEE Std. 1453 planning limits. Power quality monitoring was required to verify whether a flicker problem actually exists for this installation.

The LFG is interconnected through a wye/delta transformer that provides a ground source and thereby limits temporary overvoltage (TOV) during backfeed conditions, but the wind turbines will not provide a ground source. The WTG are ungrounded, so even with a wye-wye interconnection transformer, the wind project does not provide a ground source. To address these issues, National Grid required a 59N (GV3) trip function that is sensitive to voltage unbalance at the wind turbines. IEEE Std. 1547 only requires under / overvoltage and under / overfrequency trip functions, which are not adequate for this application.

With a feeder load rating of about 10.5 MW and a projected total DER of 10.2 MW interconnected, the penetration level will be nearly 100% at peak load. During light load, up to 9 MW may flow back into the transmission system.

To estimate the likelihood of reverse power flow through East Westminster substation, a typical load duration curve peaking at 10.8 MW was used for the inherent feeder load. Discrete levels of 0, 4800, and 7200 kW were assumed for the LFG output, because it is intended to run continuously and it has high availability. A typical Weibull (k=1.8) wind output distribution was used, with a capacity factor of 0.3. If there were no LFG output, reverse power flow due to PMLD wind alone is estimated at 1.59%, or 139 hours per year. With 4800 or 7200 kW of LFG output, these probabilities increase to 82.56% (7232 hours) and 98.95% (8668 hours), respectively. With 7200 kW * 95% = 6840 kW as the expected LFG output, the probability of reverse power flow is 98.35%, or 8625 hours. Virtually all the time, PMLD wind output will be exported through the substation.

Because of the large DER capacity in relation to the feeder source strength, perceptible voltage changes may appear at PMLD as the DER output varies. Fig. 3 shows a voltage change of about 6% at PMLD as the LFG switches from off to full on, or vice versa, at unity power factor. Presently the LFG output is limited to 4.8 MW, but this will increase to 7.2 MW later. After some time, load tap changers in the substation correct the voltage at PMLD. IEEE Std. 1547 prohibits the LFG from attempting to regulate feeder voltage; that is the utility's responsibility.

Fig. 4 shows the voltage variation at PMLD for a typical 40-minute wind power output variation. Although the wind capacity of 3 MW is smaller than the LFG capacity, the voltage change is still nearly 6% because the feeder impedance is higher at PMLD than at the LFG. However, Fig. 5 shows that the voltage change can be reduced by operating the WTG at leading power factor, which for the generator sign convention, means the WTG absorbs reactive power.

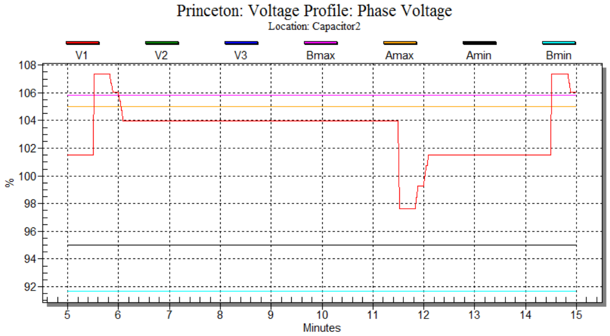


Fig. 3. Voltage Changes at PMLD from Cycling 4.8 MW LFG.

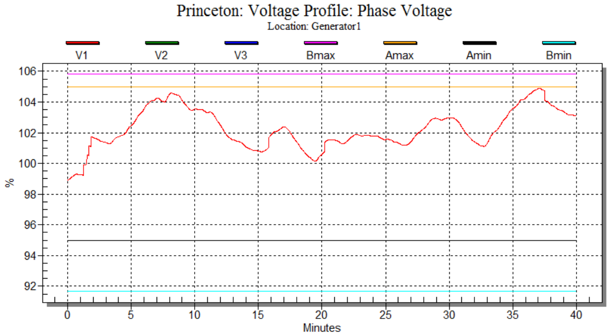


Fig. 4. Voltage Changes at PMLD from Wind, Unity Power Factor.

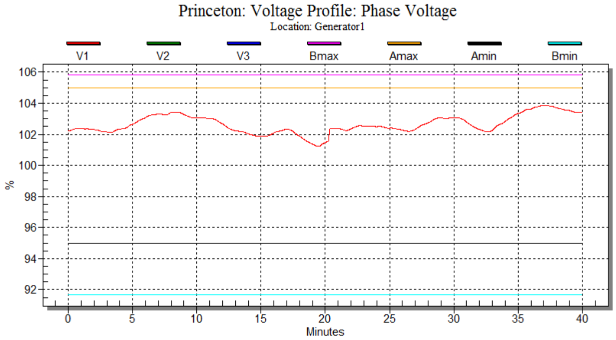


Fig. 5. Voltage Changes at PMLD from Wind, 0.95 Leading Power Factor.

National Grid required real-time monitoring of the wind turbine output, using a remote terminal unit (RTU) integrated into the Energy Management System (EMS) for utility dispatch system operations. The same requirements were imposed on the LFG project.

IV. SKI CENTER WIND TURBINE

Berkshire East Ski Center (BESC) in western Massachusetts has applied to interconnect a 900 kW type 4 (variable speed, full power electronic conversion) wind turbine to another one of National Grid's 13.8-kV distribution feeders. The feeder is lightly loaded with a peak load of 2.1 MW, including a non-coincident winter peaking spot load of 1.9 MW at the ski resort. The minimum feeder load is about 600 kW. Even with a relatively small project size, this feeder will have a wind energy penetration level of about 28% at peak and 150% at light load, so that reverse flows into the transmission system are expected much of the time.

For the originally proposed turbine type, continuous flicker test data was available. The continuous flicker level was estimated at 0.70 at the turbine, 0.63 at the PCC, and 0.2 at the substation. These values are within the IEEE Std. 1453 planning limit of 0.9 for medium voltage. It was not possible to estimate the switching flicker levels due to incomplete data from the turbine vendor. In addition, the WTG vendor selection was changed after the impact study, which often occurs due to high demand for wind turbines. As in the PMLD project, power quality monitoring was recommended.

The relaying scheme should include a trip function that is sensitive to voltage or current unbalance. A 59N (GV3) trip meets this need. The trip time should be set so that the turbine trips before either the substation breaker or mid-line recloser trips, during single-line-to-ground faults. This will preclude high temporary overvoltages.

All existing capacitor banks on feeder should be put on local voltage control, or on local reactive power control. This will prevent the capacitor switch controls from interacting with wind power variations.

The wind turbine should operate at 0.95 leading power factor, to absorb reactive power. This minimizes voltage fluctuation as the wind power output varies, or trips for any reason.

With a delta/wye transformer connection, BESC wind may cause temporary overvoltages (TOV) on two healthy phases, when backfeeding a single-line-to-ground fault. That connection also desensitizes the undervoltage trip function's ability to detect ground faults on the feeder primary. For some types of wind turbine, the TOV can exceed 1.73 per-unit; a very detailed model of the converter, controls, and protection is needed to assess this. For the purpose of this study, it's assumed the TOV will be 1.73 per-unit from the time National Grid's device trips until the wind turbine trips. The UWIG tool often predicts higher values. TOV at these levels can damage surge arresters on the feeder, and other customer load equipment.

Fig. 6 shows an example of the TOV during a single-line-to ground fault on the feeder. The voltage reaches 1.36 per-unit for 0.1 seconds, until unbalance protection trips the wind turbine. Then the TOV decreases to about 1.27 per-unit, as determined by the feeder and substation transformer parameters, until the mid-line recloser trips and clears the fault. These are typical TOV levels and times for effectively grounded feeders. But without unbalance protection tripping the WTG first, the TOV reaches very high levels after the recloser trips. Eventually the multifunction relay (MFR) voltage functions would trip the wind turbine, but this takes longer than the unbalance detection. In the meantime, high TOV is likely to damage utility surge arresters and customer load equipment. National Grid has addressed this by requiring a 59N trip function. It is important to review the tripping times and make sure that 59N trips the wind turbine before the recloser opens.

A wye / wye interconnection transformer connection would allow the regular undervoltage trip to quickly detect ground faults on the feeder primary. However, it would not limit the TOV levels because the turbine generator windings and the inverter interface are not grounded.

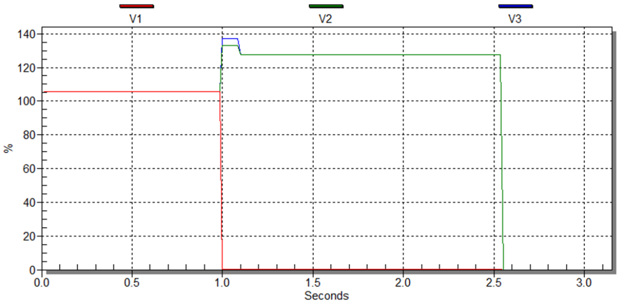


Fig. 6. Temporary Overvoltage (TOV) Limited with Unbalance Detection.

V. Single-Phase Lateral

The third case study involves a smaller 65-kW wind turbine proposed for a single-phase lateral in a remote area. This wind turbine is a type 1 induction generator, with capacitor banks to supply most of the generator's reactive power requirement. The lateral serves only the WTG owner, plus a cell phone tower. The lateral is served from a 34.5-kV three-phase feeder, through a 50-kVA stepdown transformer to 2.4 kV single phase. The existing conductor on the lateral is #6 copper. This DER project requires a number of custom adaptations, so the impact study was done using specialized tools, including transient analysis [9].

Upgrading the lateral to three-phase would be prohibitively expensive. Upgrading the voltage level to 19.9 kV single-phase is also expensive, because the existing conductor would have to be replaced with a larger one to meet current construction standards. The lateral will remain at 2.4 kV, with the stepdown transformer upsized to at least 167 kVA for the WTG output level. The larger stepdown transformer also helps to reduce the expected flicker level. There is a likelihood that flicker will exceed the IEEE planning limits [4], but the exposure to other customers is minimal. The WTG vendor for this project also implemented a soft-start controller to further minimize flicker when the WTG connects.

This project is also unusual in connecting a three-phase WTG to a single-phase lateral. A digital phase converter (DPC) was proposed to transform the phases. The DPC is listed under a UL standard for motor drives, but not to UL 1741-2005 for utility-connected DER. In particular, this DPC does not have the anti-islanding features of a typical photovoltaic or wind turbine inverter. Per IEEE 1547, the WTG must detect an island and trip within 2 seconds, and this application relies on the voltage magnitude and frequency trip settings that are suggested in [1].

Use of the DPC also invalidates flicker testing that was previously done on this WTG model. However, flicker is already addressed in this project with a soft-start controller, and limited customer exposure.

The anti-islanding test for DER simulates a perfectly matched generator output and loading level in the island, which must still be detected within 2 seconds [2]. Because of the several custom aspects to this application, a transient model of the lateral and WTG was built, and tested with a variety of WTG output and load levels. An island could form if the lateral fuse melts, thereby isolating the WTG with loads connected to the lateral.

Fig. 7 shows an example of one case where the frequency trip function detects the island but the voltage trip function does not. Fig. 8 shows another example where the voltage trip function, but not the frequency trip function, detects the island. In all cases tested, the island was detected within 2 seconds. If other capacitor banks are connected to the island, whether owned by the utility or another customer, there is a risk the island would be sustained beyond 2 seconds. The risk was judged acceptable for this particular case. There are no utility-owned capacitors on the lateral, and it's very unlikely that customers on the lateral would own capacitor banks.

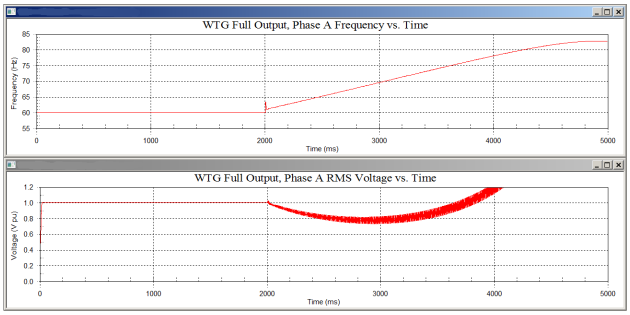


Fig. 7. Island with 65-kW Output, 10-kW Load, Over-frequency Trip in 0.2 s.

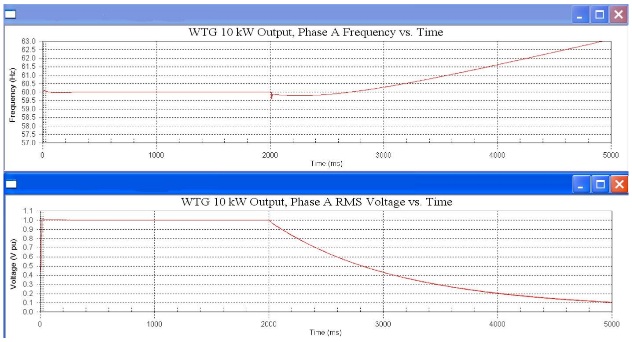


Fig. 8. Island with 10-kW Output, 16-kW Load, Under-voltage Trip in 0.96 s.

VI. Conclusion

With recent interest in distributed renewable energy projects, utilities will have to analyze many such projects efficiently, and this paper illustrates one method of doing so. Based on three case studies, some common elements have been identified:

1. Voltage fluctuations are minimized by operating the WTG at slightly leading power factor, to absorb some

reactive power.

2. A voltage unbalance trip function helps the WTG to reliably detect ground faults on the feeder, and limit both magnitude and duration of temporary overvoltages.
3. Flicker data on WTG is not always available, and even when available, may not match conditions of the project. Power quality monitoring is advisable before and after the DER is connected. Two weeks prior and two weeks post would be sufficient.

VII. REFERENCES

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VIII. BIOGRAPHIES

James G. Cleary received the BSc in Electrical Engineering (’86) and MBA (’91) from Worcester Polytechnic Institute in Massachusetts. Jim has 24 years of Distribution Engineering at National Grid USA in Massachusetts where he is Lead Engineer. His past 5 years have been spent largely on system integration of Distributed Generation on 35 kV systems and below: including solar, wind, hydro, flywheels, co-generation and landfill gas. Jim is currently involved with integration of multi-MW PV (photovoltaic) and wind generation on 15 kV class distribution feeders. His main interests are system impacts due to high penetration Distributed Generation, particularly voltage and power quality. He is a Senior member of the IEEE, PES, IEEE Standards Association, and is a member of CIGRE. He is on the 1547.7 and .8 working groups as well as a member of the T&D PQ Interest and Voltage Quality working group.

Thomas E. McDermott (S 1977, M 1981, SM 1992) is President of MelTran, a power system consulting company based in Pittsburgh. The company specializes in applied R&D for distribution systems and smart grid applications, distributed resource interconnection, custom software development, and electromagnetic transient studies. He is Chair of the Distribution System Analysis Subcommittee of the PSACE committee, Vice Chair of the Working Group on Distributed Resource Integration, and has previously chaired the Pittsburgh Section IEEE and the Working Group on Estimating Lightning Performance of Transmission Lines. He is also a task force leader in Cigre WG C4.502 on system performance impacts of long AC cables. Tom is a registered professional engineer in Pennsylvania. He has a B. S. and M. Eng. in Electric Power from Rensselaer Polytechnic Institute, and a Ph.D. in Electrical Engineering from Virginia Tech.

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Justice Ndubah is a Protection Engineer in National Grid USA. He has been a lead protection engineer in many capital projects for the past one and half years mainly in substation and transmission facilities. He is involved in all phases of the project life cycle. Apart from developing relay protection schemes for the transmission and distribution facilities in National Grid, Justice also does protection impact studies for distributed generation (DG) Interconnection for Western Massachusetts. He has performed impact studies for all forms of DG interconnections ranging between 100kW to 30MW in both distribution and transmission levels. Previously, he worked at Cooper Power Systems, Volta River Authority, and Electricity Corporation of Ghana. Justice received the MSc in Electrical power Engineering (’94) from Vinnitsa State Technical University in the Ukraine and MS in Electrical Engineering (‘2004) from Tuskegee university in Alabama in the USA.