Energy Basics: Power Surges

Choosing a Surge Protector

For the items you can't leave unplugged, invest in high-quality surge protectors. They work by monitoring the flow of electricity and diverting excess voltage either back into the system or to the ground.

There are two types of surge protectors - to fully protect your electronics, using both types is a must.

Point-of-use surge protectors

A "point-of-use" surge protector guards individual devices from lower-level internal fluctuations.

You may have equipment plugged into a multi-socket power strip, but it's important to realize that many of these devices function simply as extension cords, providing little or no protection against power surges.

The adage "you get what you pay for" very much applies to surge protectors, with prices ranging from $5 to more than $150.

Did you know?

Many multi-socket "power strips" offer no protection against power surges.

Here's what to look for:

- **Enough connections** to protect all components of a system.
- An **on/off switch** allowing you to shut off power to every component.
- **UL-1449 rating** to ensure adequate testing by Underwriters Laboratories. Look for a specific UL rating, not just a label that says "UL Listed."
- An **indicator light** or **audible alarm** so you know a high-level surge has occurred.
- A **clamping voltage** of 330. This is the level at which the device begins to block the surge - the lower the clamping voltage, the better.
- The **total energy dissipation** - the higher the better.
- A **joule rating** of at least 400 is good; 600 is better. This is a measure of the ability to absorb surges.
- A **response time** of 10 nanoseconds or less.
- Protection between all **three wire combinations**: L-G, N-G, L-N.
- A **warranty** against damage to any connected equipment. Keep in mind that no surge protector will be fully warranted against lightning strikes.
- **Filters** for line noise, also known as electromagnetic interference.

Whole-house surge protectors

To protect against large external power surges, a whole-house protector is key. These devices cost around $150 to $300, and are installed on your meter or service panel by a licensed electrician.

Solutions of EMI Problems From Operation of Variable-Frequency Drives

[Power Quality In Your Home | Power Quality Check List | Understanding Electric Power Characteristics | Notes on Surge Suppressors | Uninterruptible Power Supply | Solution of EMI Problems | Application of Line or DC Link Reactors | Voltage Tolerance Boundary | Power System Harmonics | Telecommunications Interference]

Abrupt voltage transitions on the output terminals of a variable-frequency drive (VFD) are an inherent source of radiated and conducted Electromagnetic Interference (EMI). These voltage transition times are essentially determined by the rise and fall time of the semiconductor devices used in the inverter section of VFDs.

The present tendency among drive manufacturers is to use Insulated-Gate-Bipolar-Transistor (IGBTs) devices which have a much lower power loss and higher switching speed than their predecessors Bipolar Junction Transistors (BJTs). However, these improvements result in voltage transition times that can now be as fast as 100 ns and this high dv/dt produces higher magnitude of common-mode (CM) noise currents in the stray line-to-ground capacitance of motor and cables. These CM noise currents can cause electromagnetic interference and affect control signals, encoder feedback, communication links for programmable logic controllers, including RS-232, RS 484, Remote I/O, and different types of sensors including, ultrasonic sensors, bar code/vision systems, weight and temperature sensors. Conducted ground current also leads to radiated emissions, with the drive cables acting as antennas. AM radio reception, radio-controlled operator devices, and television are the most susceptible equipment to this radiated interference from VFDs. The purpose of this power note is to explain the issues related to EMI problems associated with VFD operation, and to provide recommended guidelines for end-users toward mitigating EMI problems related to VFD operation.

Problem Description

EMI-related problems involve a source of noise, coupling of this noise by conduction or radiation, and circuits/equipment that are susceptible to this noise. The source of noise from VFD operation is the high dv/dt of pulse-width modulated (PWM) output voltage waveforms. As can be seen from Figure 1, the stray capacitance to ground of cables and motors results in high frequency ground currents, the magnitude of which is determined by the equation $I = C\ dv/dt$.

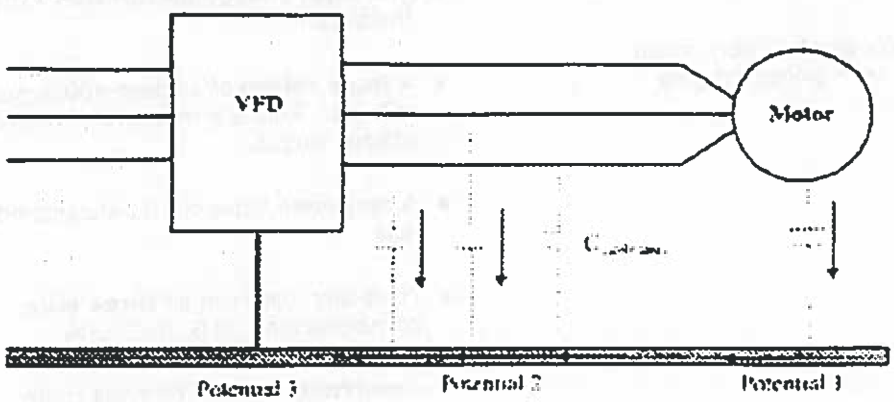


Figure 1 -- Capacitive Coupled Noise Current from Unshielded Phase Conductor of VFD

The high ground impedance at high frequency results in instantaneous voltage differences between two points reputed to be "ground potential." This voltage appears as a common-mode noise voltage that can interfere with control signals and other communication devices. CM noise may also be capacitively coupled onto control signal cables that are in close proximity of unshielded VFD power leads. Conducted ground currents also lead to radiated interference, with the unshielded phase conductor, the stray capacitance, and the ground return path acting as a loop antenna. With the increasing use of VFDs in commercial and residential applications, the possibility of radio interference from VFDs is an issue of concern for end-users. Sometimes this radio interference can affect other customers in the neighborhood of the VFD application.

The rise time of the VFD output waveform and the switching frequency of the inverter determine the frequency of the radiated and conducted noise. The switching frequency, which is typically in the range of 1 kHz to 16 kHz, determines the low-frequency conducted noise spectrum. The rise time of modem IGBT inverters can be in the range of 50 ns to 500 ns. This results in a noise frequency $f_n = 0.318/T_{rise}$, respectively 6 MHz to 600 kHz.

Preventive Measures to Minimize EMI Problems

EMI problems can be minimized to a great degree by adopting preventive measures during the installation phase of VFDs. The most successful preventive measure is to use a shielded power cable to connect the VFD to the motor. This forces the noise current to flow through the shield back to the inverter, before it gets out into the system grid and takes multiple high frequency paths which are difficult to track down in an installation.

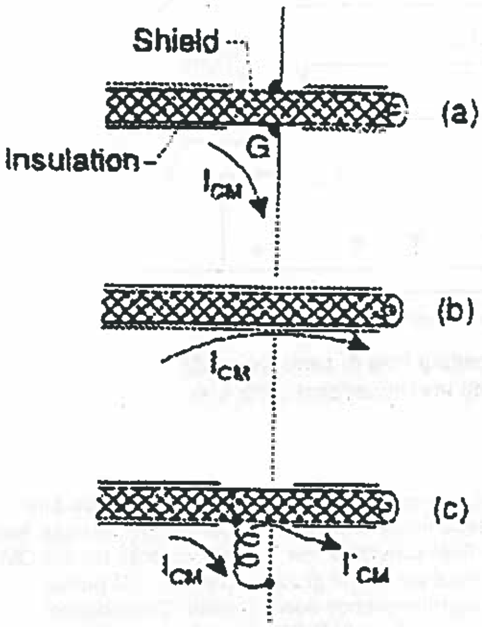


Figure 2 -- Cable shield bonding. Incorrect (a) and (b) Correct (c)

The use of shielded power cables also reduces the area of the loop antenna that is responsible for radiated interference. The shield should be connected to ground at both ends. It is important to ensure good electrical contact from the installation plate through the installation screws to the metal cabinet of the VFD. Cable clamps should be used instead of twisted shield ends (pigtails, see Figure 2), since this ruins the shielding effect at high frequencies.

If a shielded cable is not used, avoid random lay of unshielded cables in cable troughs. Using 3-wire plus ground conductor ("green wire") in a conduit ensures some degree of noise abatement as the conduit and the green wire carry most of the return current. However, accidental contact with grid ground structure due to strap supports, etc. is still a possibility. In contrast, with a shielded cable, this situation can be avoided by using a PVC outer coating.

In addition to the use of shielded power cable, the following noise reduction practices are usually employed for control signal wiring practice:

- Twist the leads to provide a balanced capacitive coupling.
- Use shielded cable to return the noise current flowing in the shield back to the source, instead of through the signal leads.
- Maintain at least 8-inch separation between control and power wires in open air, conduit or cable trays.
- Use a common-mode choke wound with multiple turns of both signal and shield.
- Use optical isolation modules for control signal communications.

EMI Mitigating Devices

Common mode chokes (CMCs) and EMI filters are the two principal mitigating devices commonly used in VFD application for reducing EMI interference. A common-mode choke is an inductor with the three phase conductors wound in the same direction through a common magnetic core, typically torroidal in shape (Figure 3). The CMC, when used on VFD output leads provides a high impedance to any line-to-ground capacitive noise current generated during the fast transition time of the output voltage waveform. The CMC does not affect the line-to-line power circuit and takes up less physical space, in contrast with an output line reactor. The phase-conductor inductance of a line reactor reduces motor phase voltage, lowering the available motor output torque.

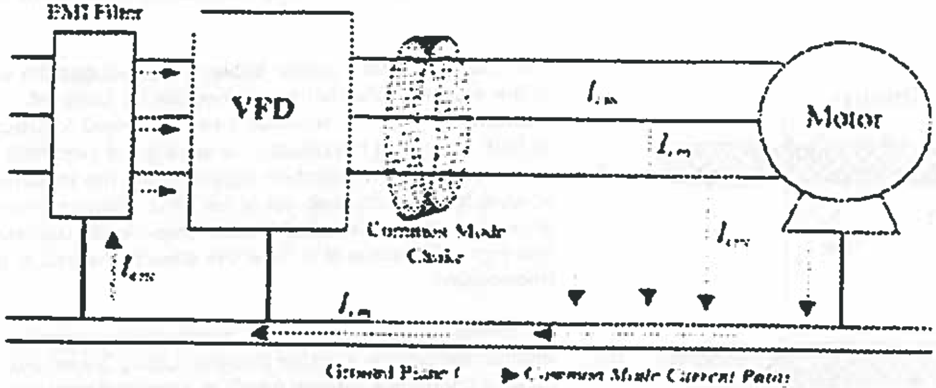


Figure 3 -- Mitigating common mode effects by impeding flow of common mode currents with a Common Mode Choke or by providing low-impedence path with an EMI filter.

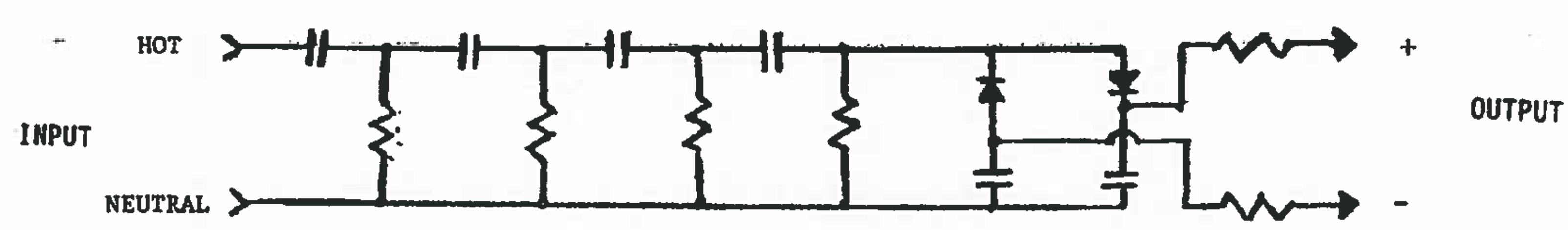
EMI filters for VFD applications are typically structured as low-pass filters with series inductance and bypass capacitors connected in line-to-ground mode. These filters are usually installed on the input leads of the VFD. The line-to-ground by-pass capacitors in the filter provide a low impedance path for the CM noise currents (Icm in Figure 3) to flow back to the VFD input out of the ground. The CM and phase inductors or the EMI filter provide high impedance to the high-frequency noise current. Drive-based equipment that must meet the European CE conformity must use an EMI/RFI filter connected to the drive input.

European Union Basic EMC Standard Applicable for VFDs For new installations, end-users can require the VFD vendor to meet applicable European Union (EU) standards for drives in order to avoid potential EMI problems. These standards set the allowable emission limits for conducted and radiated disturbances. Table 1 presents a summary of these emission limits. Standard EN50081-1, Electromagnetic Compatibility Generic Emission Standard - Part 1: Residential, Commercial and Light Industrial. Standard EN50081-2, Electromagnetic Compatibility Generic Emission Standard - Part 2: Industry.

Frequency Range	Conducted Emissions 50 kHz-30 MHz	
	Residential, Commercial, and Light Industry EN 50081-1 and CISPR 22, Class B	Industry EN 50081-2 and CISPR 11, Class A
150 - 500 kHz	56 - 46 dBµV (Average) 66 - 56 dBµV (Quasi-Peak)	66 dBµV (Average) 79 dBµV (Quasi-Peak)
0.5 - 5 MHz	46 dBµV (Average) 56 dBµV (Quasi-Peak)	60 dBµV (Average) 73 dBµV (Quasi-Peak)
5 MHz - 30 MHz	50 dBµV (Average) 60 dBµV (Quasi-Peak)	60 dBµV (Average) 73 dBµV (Quasi-Peak)

Frequency Range	Radiated Emissions 50 kHz-30 MHz	
	Residential, Commercial, and Light Industry EN 50081-1 and CISPR 22, Class B	Industry EN 50081-2 and CISPR 11, Class A
30 - 230 MHz	30 dBµV/m @ 10m	30 dBµV/m @ 10m
230 MHz - 1 GHz	37 dBµV/m @ 10m	37 dBµV/m @ 10m

COMBINED FILTER AND PEAK DETECTOR



INPUT from POLARIZED UBIQUITOUS AC OUTLET

OUTPUT to DIGITAL DC VOLTMETER with 10 MEGOHM INPUT RESISTANCE

THE FOUR RESISTORS IN THE FILTER ARE 10 kilohms

ALL THE CAPACITORS ARE .01 microfarads

THE DIODES IN THE PEAK DETECTOR ARE 1N4148 diodes

THE PROTECTION RESISTORS IN THE OUTPUTS ARE 270 kilohms

Harmonics and Resonance Issues in Wind Power Plants

IEEE PES Wind Plant Collector System Design Working Group

Contributing Members: M. Bradt, B. Badrzadeh, E. Camm, D. Mueller, J. Schoene, T. Siebert, T. Smith, M. Starke, R. Walling

***Abstract*—This paper presents a summary of the most important issues with respect to harmonics and resonances within wind power plants. An introduction is given to provide an overview of the various power quality related issues encountered when designing, commissioning, or operating a wind power plant, as well as typical characteristics of the components associated with wind power plants. The many variables, which influence harmonics and resonance in wind power plants, will be described with respect to analysis methods, avoidance, mitigation, and compliance with IEEE Std 519-1992 recommended practices.**

Index Terms— Power system harmonics, wind power plants, wind turbines, harmonic penetration, harmonic impedance scan, system resonances, harmonic compliance, harmonic filters.

List of Acronyms—

CP	Cumulative Probability
CP95%	CP 95% Level
DFIG	Doubly Fed Induction Generator
EMT	Electromagnetic Transients
HVDC	High Voltage Direct Current
LGIA	Large Generator Interconnection Agreement
PCC	Point of Common Coupling
RLC	Resistor-Inductor-Capacitor
STATCOM	Static Compensator
SVC	Static Var Compensator
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UWIG	Utility Wind Integration Group
VSC	Voltage Source Converter
WTG	Wind Turbine Generator
WPP	Wind Power Plant

I. Introduction

The ideal electrical system sinusoidal waveform is pure, continuous, and of a constant fundamental frequency. Power quality issues are a deviation from this ideal system waveform, and limits have been adopted through various standards and guidelines for maintaining continuity, voltage magnitude, harmonic limits, and transient nature of electric power systems. Two of the most common power quality issues encountered within wind power plants are harmonic resonance and voltage flicker.

Flicker is a variation in the system ac voltage, which can result in observable changes in light output and in some cases become annoying and objectionable. In wind farms flicker is caused by variations in wind turbine generator (WTG) power output due to variation in wind speed, blade pitching, tower shadowing, wind shear or gradient, and WTG start and stop operations. Flicker is usually a concern for interconnections to "weak" systems, such as distribution interconnections in areas of the system where fault currents are very low. The Utility Wind Integration Group (UWIG) has documented this phenomenon very well [1] and it will therefore not be further addressed in this paper.

Resonance issues arise in wind power plants because wind power plants contain both inductive source characteristics and capacitive elements. Wind power plants typically consist of an interconnection substation which transforms from high to medium voltage, several medium voltage underground cable collector system circuits, reactive compensation equipment, wind turbine transformation from medium to low voltage, and wind turbine generators with internal power factor correction capacitors or dynamic power controllers which can also absorb or contribute reactive power. Wind power plants typically have vast underground cable systems, which can result into many series and parallel resonance points. Resonance conditions can be located using frequency domain analysis of impedances and/or amplification factors, recognizing that peaks and valleys of the frequency scan represent parallel and series resonances, respectively.

Feeder line and cable capacitance and the substation reactive compensation equipment, such as medium voltage switched or fixed shunt capacitor banks, can create significant parallel resonance interaction with the main transformer and any associated load tap changing apparatus. Due to the many steps of shunt capacitor steps within the substation capacitor banks, parallel resonance between adjacent capacitors must not be overlooked.

Harmonic sources can be comprised of power system background levels of harmonics and WTGs. One or both of these sources inject harmonic currents that have to be considered when assessing voltage and current distortion compliance requirements.

There are two primary methods for controlling harmonics impacts in wind power plants. (1) The method of avoidance during the design process of the wind plant collector system allows for careful consideration of equipment to prevent resonance problems. (2) Designing harmonic filters based on measurements and simulation results in order to reduce or control series resonance conditions of the wind plant. The later method is the most common mitigation approach, when capacitive compensation is required.

II. Resonance and Frequency Considerations

One objective of a harmonic analysis is to characterize the potential of the wind collector system for series and parallel resonance conditions. Series resonance problems are characterized by series inductance and capacitance driven by background harmonic voltages from the grid (see Fig. 1). Series resonance points are identified by dips in the frequency scan

Please see reference [11] for a discussion of WTG types.

on the high side of the interconnect transformer. The relatively small impedances at the series resonance points can result in high harmonic currents.

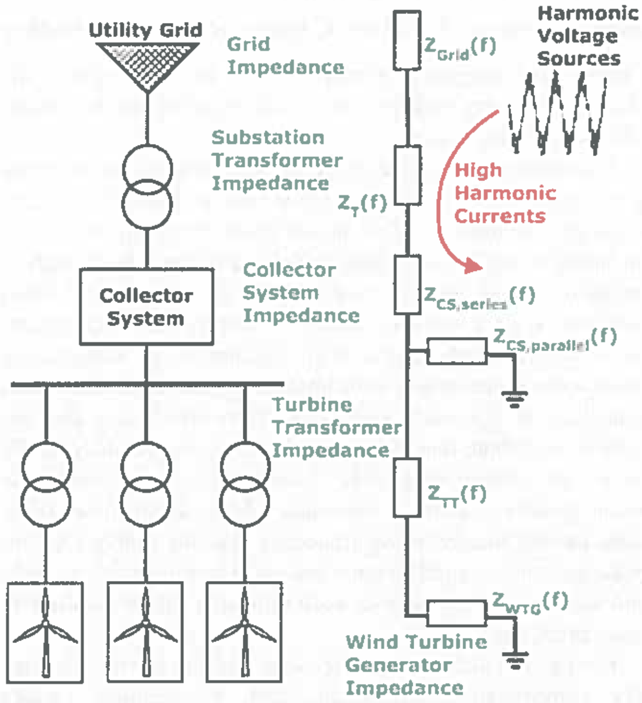


Fig. 1. Illustration of series resonance in a wind power plant

Parallel resonance points magnify voltages and are identified by peaks in the driving point impedance on the medium voltage side of the transformer (Fig. 2). Parallel resonance concerns occur when WTG harmonic current sources excite resonant points (relatively high impedances) resulting in significant harmonic voltages.

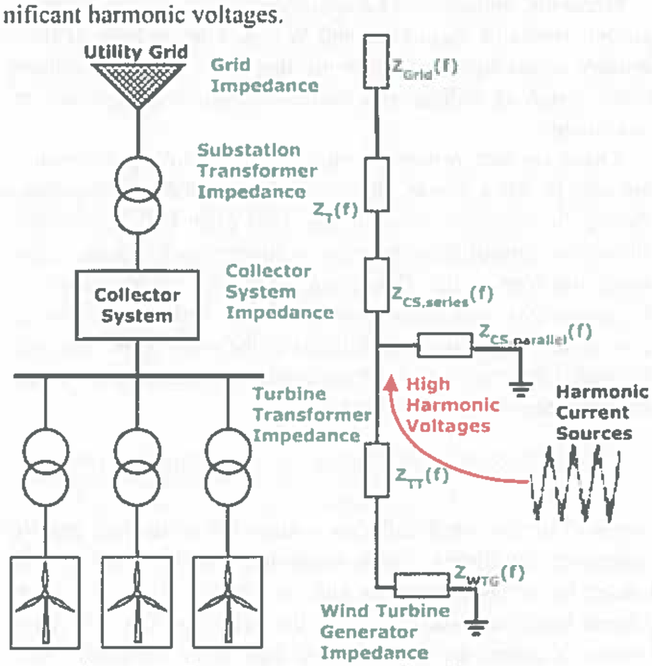


Fig. 2. Illustration of parallel resonance in a wind power plant

When dealing with parallel operation of two wind power plants located within close proximity, it is necessary to also avoid resonance conditions between the two plants and the associated shunt capacitor banks.

A. Frequency Scan Analysis

Frequency scan analysis is a characterization of the system equivalent impedance at a bus in the system as a function of frequency. Figure 3 provides an example of a frequency scan at the main 34.5 kV wind plant bus with over 50 turbines and 30 miles of underground collector cable. In the case where all of the turbines are in operation, the parallel resonance of this example system was near the 10th harmonic frequency (600 Hz).

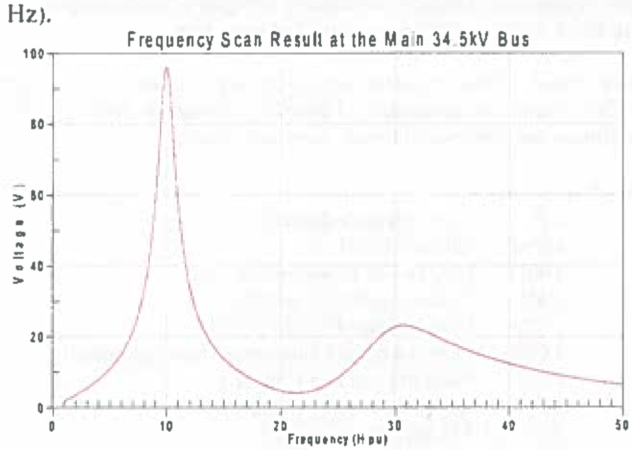


Fig. 3. Example graph of frequency scan results

Frequency scans are performed by system modeling software that injects 1 A sinusoidal currents. The frequencies of the injected currents range from the fundamental frequency (60 Hz for this particular example) up to the largest harmonic frequency of interest to determine the resulting system voltage. In this case the output can alternatively be presented as impedance in Ohms. Often frequency scans are done at various grid locations or at the 34.5 kV collector bus.

An important consideration is that the magnitudes of the frequency scans do not determine the severity of the problem by itself. For harmonic problems, there must also be a sufficient level of harmonic source voltages or currents at or near the resonant frequency to excite the resonance. There is no firm threshold separating impedance magnitudes that might cause trouble, from those that do not cause trouble. A detailed harmonic analysis using harmonic sources specified by measured data and/or turbine manufacturer-provided data is necessary to quantitatively assess potential problems.

A major challenge in assessing the potential for harmonic problems is to cover the large number of different system configurations that can occur during normal operation of the wind plant. The impedance of the system, which can vary significantly, determines the resonance points. Impedance variations are caused by (1) the number of wind turbines in operation, (2) switching of capacitor banks located at the substation, (3) turbine power factor correction capacitors (commonly used in Type 1 and Type 2 turbines), and (4) variations in grid harmonic impedance. In practice, one option to analyze this large number of configurations is using automation to run a frequency scan for various configurations and to display the results in a contour plot.

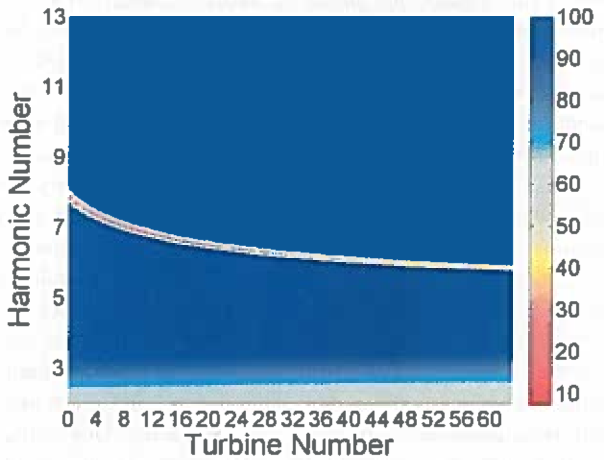


Fig. 4. Contour plot of the driving point series impedance for a large number of system configurations

As an example, Fig.4 shows a contour plot of the driving point series impedance for a large number of system configurations. The harmonic order is displayed on the Y-axis, the number of turbines on line is displayed on the X-axis, and the scale on the right displays the impedance magnitude. A low impedance indicates a potentially hazardous series resonance point. The example contour plot displays results of over 60 simulation runs (one simulation for each turbine number). The contour plot shows that the only odd harmonic frequency for which series resonance points exist is the seventh harmonic. Note that the capacitances of the substation capacitor bank and the turbine power factor correction capacitors were fixed in all simulation runs summarized in the contour plot. Similar contour plots can be created for different system configurations. Furthermore, similar contour plots can be created to determine parallel impedance resonance points.

B. Source Characteristics of Wind Turbine Generators

The frequency scan results for a wind plant collector system are dependent on the type of wind turbine and its representation in the harmonic model. Figure 5 shows an example implementation of a Type 3 (DFIG) turbine for a harmonic study. For both Types 3 and 4 (Full Conversion) turbines, it is important that the high frequency harmonic filters are not overlooked. These filters are often installed on the line side of the voltage source converter (VSC) to shunt the energy from the switching frequency. Even though these filters may only be rated about 50 kvar per turbine, the accumulation of filters for many turbines will shift the natural resonance of the system. Figure 6 provides an example of the effects from these filters.

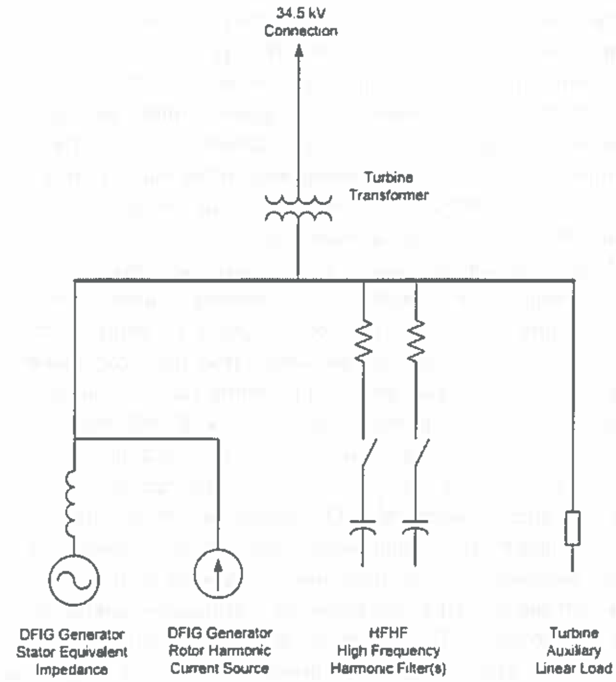


Fig. 5. One-line diagram depicting a Type 3 (DFIG) turbine harmonic model

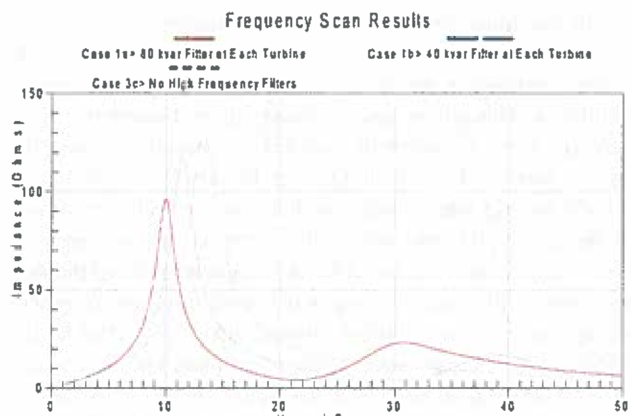


Fig. 6. Frequency scan results showing the impact of turbine high frequency harmonic filters

The typical harmonic analysis practice used in the industry is to consider harmonic-generating devices as ideal current sources. The current injected by an ideal current source is invariant with the driving point impedance of the system to which it is connected, and also invariant regardless of the existence of other sources of harmonic distortion in the grid. When analyzing the influence of other sources, such as background grid voltage distortion, a wind turbine modeled in this way would be considered an open circuit.

Actual harmonic performance of wind plants can differ substantially from the performance predicted by the classical approach. This harmonic analysis practice evolved at a time when the dominant harmonic sources were load-commutated converters and diode rectifiers. For these devices, a constant current assumption has been traditionally used as a reasonable simplification. It has been, however, reported [2] [3] that the harmonic impedances of the current source HVDC converters can affect system resonances, and ignoring them can lead to excessively high harmonic voltage distortion and ineffective harmonic filter designs. The main reason for the oversimplification is the inability of present commercial programs to model the effective converter impedances.

Most wind turbines use a VSC, which have very low harmonic impedance, compared to a current sourced converter. Despite having low harmonic impedance, representation of the VSC by an ideal current source may have considerable inaccuracy, which can lead to misleading results. This is because in reality the harmonic current of VSC will not remain constant, and varies depending on the converter control.

A voltage source converter is better characterized as a Norton equivalent source [4]. The equivalent shunt impedance has real and reactive components that vary by frequency, and phase sequence, in a complex manner defined by the converter's controls as well as the parameters of the converter's physical components. The impact of the source shunt impedance can be very significant, as the magnitude can be a few tenths of the wind turbine's base impedance. As a result, the harmonic current of a wind turbine can vary over a very wide range for the typical range of driving point impedances defined by the collector system and grid characteristics.

Typically, wind turbine generator manufacturers provide test data, defined in terms of current injection, demonstrating compliance with power quality standards and assessing characteristics at the turbine terminals [5]. It should be noted that it is not feasible for a manufacturer to certify compliance at the point of grid interconnection, because the collector system and the particular grid affect the currents at that location. These test data are influenced by the characteristics of the system in which the tests are conducted, both in terms of impedance and in terms of ambient voltage distortion. It is highly difficult to find a test location free of ambient harmonics, and it is also difficult to segregate harmonic current flow caused by the wind turbines and flow caused by grid distortion driving current into the wind turbines and wind plant shunt capacitances. Information on the equivalent source impedance of wind turbines is generally not available.

Modeling the source characteristics of wind turbines is more complex than was initially considered, certainly requiring more complexity than the harmonic current source models used for industrial studies. Practices are still evolving to more sophisticated representations for the WTG harmonic source characteristics. Measurements continue to be an important part of the validation process for harmonics studies, as experience from the field provides a better understanding of what level of detail is necessary in the system modeling.

C. Source Characteristics of Utility Interconnection

The utility grid is characterized by two categories of parameters: The first category is the background, or ambient, voltage distortion present at the point of interconnection without the wind plant connected. The second is the driving-point impedance of the grid at harmonic frequencies.

1) Ambient Voltage Distortion

Ambient harmonic voltage distortion is characterized in terms of the voltage magnitude by harmonic order. This distortion tends to vary over time, due to variations in the harmonic current injected by sources distributed throughout the grid, and also due to variations in the transmission system resonant characteristics, which can amplify distortion at a particular location. Because of the variability in ambient distortion, data used for wind plant harmonic analysis may be statistically characterized. This will allow the plant design to be made on the basis of the appropriate degree of conservatism.

The interconnection utility may have records of compliance with IEEE Std 519-1992 [6] and other power quality standards in regards to power quality limits for their transmission system in general. Availability of ambient voltage distortion characteristics for the particular point of proposed wind plant interconnection, however, is typically not available. This voltage distortion may be characterized with access to operational utility electrical system data from planning, protection, and system operations.

More accurate characterization of ambient voltage distortion levels may require installation of harmonic monitoring equipment at the proposed interconnection point, for an extended period of time.

If the ambient voltage distortion is not available and a harmonic study is being performed the voltage distortion limits contained in Table 11.1 of IEEE Std 519 can be used as a reference for interconnection bus voltage ambient conditions. However, it should be realized that actual distortion might exceed IEEE Std 519 limits. It should also be realized that applying each of the individual harmonic limits collectively might yield unrealistic results. The value of the actual individual frequencies modeled might depend upon local conditions such as other harmonic sources in the area. Some utilities may also provide a planning limit that can be used for studies.

2) Transmission System Harmonic Impedance

Proper representation of the transmission system's impedance at harmonic frequencies is important for both analysis of harmonic currents produced by the wind plant, and interaction of the wind plant with ambient grid distortion.

There are grid representation practices in use for wind plant harmonic studies, which are often less than adequate. Sometimes, the impedance of the transmission system is ignored altogether by assuming the point of interconnection to be an infinite bus or as an ideal voltage source representing ambient voltage distortion. While this simplification is reasonably adequate when the wind plant is small, and connected to a very stiff transmission system, it is not adequate in general.

Another practice is to define the grid impedance as an inductance and resistance defined by the fundamental-frequency short-circuit impedance. This is reasonably accurate for frequencies below the first resonance of the transmission system. Transmission systems, however, often have resonances in the same range of frequencies as the harmonics of greatest interest (i.e., 5th and 7th).

Determination of the harmonic impedance of the transmission system requires detailed modeling. The extent of the transmission system, which must be discretely modeled, depends on the frequency range of most interest, and the required degree of accuracy. Modeling in the lower order harmonic range (e.g., 3rd, 5th, 7th) requires a more extensive transmission model than that needed for similar accuracy in analysis of higher-order harmonics. For a small wind plant in a stiff transmission system, the sensitivity of results to the grid impedance representation is less significant, and thus a less extensive transmission model can be justified.

If a load flow model or a short circuit model, of the transmission system is available, then it is often possible to convert these large models into an electro-magnetic transient (EMT) model or harmonics model using data conversion utilities. The use of an EMT type or harmonic programs allows calculation of the frequency and impedance of each network resonance point.

Harmonic impedance analysis requires that the frequency-dependent characteristics of the external grid components be accurately represented. Damping is an important determinant of resonance severity, and proper representation of grid component damping at harmonic frequencies is essential. For example, a transformer is represented in fundamental-frequency studies as a series inductance and resistance. Such a model, if used for harmonic analysis, would exhibit an X/R ratio that would monotonically increase with increasing frequency, without bound. In reality, a transformer reaches its maximum X/R at a frequency of one or two hundred Hertz, and the X/R decreases continuously for higher frequencies. Thus, the simplified series resistance-inductance representation is clearly inadequate for harmonic analysis. Proper harmonic analysis requires that a model which properly represents damping of transformers and other components be used. Sufficiently accurate models of the network components for harmonic analysis are discussed in [7].

The harmonic impedance of a transmission system can be highly dependent on the specific system configuration. Outages of lines and transformers, even ones that are moderately distant from the point of wind plant interconnection, can significantly change the impedance at certain harmonics. In addition to such contingencies, routine system variations such as the status of capacitor banks and generating unit commitment can also have a large impact. Thus, the transmission system impedance cannot be considered as a single value for each harmonic. The impedance varies over a range in the R-X plane, depending on system condition. Figure 7 illustrates the rather wide range of harmonic impedance and impedance angle for an actual transmission system, over the range of ordinary contingencies and operating conditions. Thorough harmonic analysis of wind plant harmonic performance requires consideration of every possible transmission system impedance. Studies to define transmission system impedance need to consider the range of normal and contingency system conditions. This may result in a large number of possible impedance values to be considered.

To make harmonic analysis manageable, boundaries of the harmonic impedance ranges can be defined as a shape, such as a pie-shaped sector or polygon, in the R-X plane. Figure 8 illustrates a pie-shaped sector, defined by a minimum and maximum impedance magnitude, and a minimum and maximum impedance angle. Critical resonance conditions will always fall on the boundaries of such a shape that surrounds all actual harmonic impedance loci. The application of shapes to define grid harmonic impedance range is a routine practice in transmission technologies where harmonic performance is critical (e.g., HVDC). Some European transmission system operators provide similar harmonic impedance envelopes. This is usually provided separately for the 2nd-5th harmonics and for the 6th and higher order harmonics. For the 2nd-5th harmonics the impedance plot is defined as a square bounded to the area between R_{min}- R_{max} and X_{max}-X_{min}. For the 6th and higher order harmonics the envelope consists of a semicircle with its radius in the origin, and a square to the right of the semicircle.

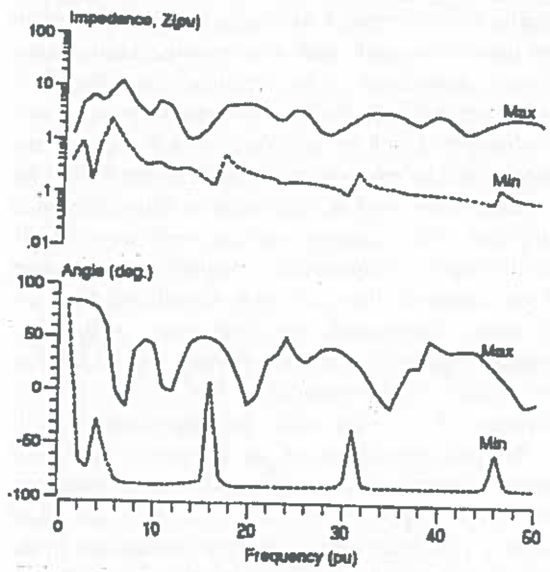


Fig. 7. Range of harmonic impedance at a typical point of interconnection

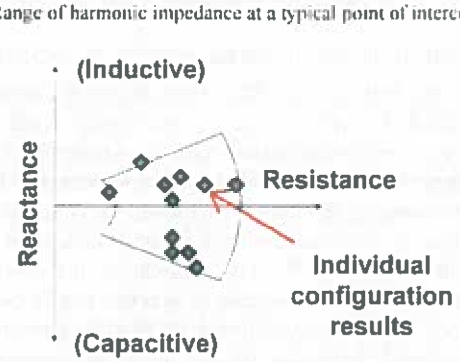


Fig. 8. Harmonic impedance range defined as a sector

Caution and discretion needs to be applied when using harmonic impedance ranges in studies of ambient transmission distortion amplification within wind plants. Ambient voltage distortion, applied as a voltage source behind the transmission system impedance, is usually defined as a maximum, or a range of values, determined from monitoring. High values of ambient distortion may be the result of resonant conditions in the transmission system, that would tend to have a high source impedance. The harmonic impedance range, however, may include low impedance values that are the result of other conditions. The impedance value range is usually defined by system harmonic analysis studies that are performed independent of monitoring used to define ambient voltage distortion magnitude. The correlation between particular background distortion values and particular impedance values is thus not generally known. Use of the highest magnitude ambient voltage distortion combined with a source impedance that results in a worst-case resonance within the wind plant is conservative, but also potentially conservative to an excess degree.

3) Representation of Reactive Compensation Equipment

The representation of the reactive compensation equipment is dependent upon the actual equipment used. If mechanically-switched capacitors and reactors only, these components would typically be represented as single lumped equivalent capacitor or reactor for each bank and various combinations being energized considered in the resonance and distortion analysis. If inverter-based dynamic compensators with mechanically-switched capacitors and reactors are applied, the representation would be expanded to include an equivalent for the step-up transformers and an equivalent ac filter associated with the inverters. The harmonic current contribution of the inverter-based dynamic compensator is negligible in the range of frequencies of interest due to the high modulation frequency typically used. Furthermore, the 'side lobes' of the very high modulation frequency is filtered through the ac filter at the inverter terminals before reaching the MV system. If static var compensators (SVCs) are used, the representation will include the lumped equivalents of the capacitor, filter, and reactor banks, as well as an equivalent current injection source. A STAtic COMpensator (STATCOM) is comprised of a voltage source converter, and as per the discussions made earlier, can be represented by its Norton equivalent circuit.

III. Compliance with Power Quality Standards

In the United States, IEEE Std 519 is the most common industry standard for power quality governing wind power plants although certain limitations apply. Article 9.7.6 of the Standard Large Generator Interconnection Agreement (LGIA), used by many electric reliability organizations, requires generating facilities to limit excessive harmonic distortion in accordance with IEEE Std 519. The application of the IEEE Std 519 limits to wind plants is an area of practice that is evolving. Fundamentally, it is important to realize that the current limits in the recommended practice do not apply to harmonic currents that are absorbed by the wind plant from the background harmonic source of the grid. Series resonance from the collector cable capacitance can easily result in an idle wind power plant absorbing more harmonic current than prescribed by the IEEE Std 519 recommended limits.

Facility compliance is evaluated at the point of common coupling (PCC), and although individual wind turbines may be certified as IEEE Std 519 compliant, the aggregate facility may not meet emission limits. Section 10 of IEEE Std 519 outlines the current distortion limits for individual and total harmonics for various grid voltages as a function of a facilities ratio of short circuit current to the maximum fundamental load current. The current distortion is based upon the maximum demand load current (fundamental frequency). This percentage calculation is referred to as the Total Demand Distortion (TDD). It is often convenient to convert the current limits from percentage values to Amperes, allowing direct comparison with measured values. An example of harmonic current limits at a wind power plant (WPP) is given in Table I.

TABLE I
HARMONIC CURRENT LIMITS AT A WPP INTERCONNECTION

Example Wind Power Plant
Primary Current IL
102.8 MVA
345 kV
172.0 Amps

IEEE 519 (1992) Table 10-5 – Current Distortion Limits for General Transmission Systems >161kV

	<11	11=<h<17	17=<h<23	23=<h<35	35=<h	TDD
Limits (Percent)	2.0%	1.0%	0.75%	0.3%	0.15%	2.5%
Limits (Primary Current Amps)	3.4	1.7	1.3	0.5	0.3	4.3

The maximum current harmonics for interconnecting distributed resources with electric power systems are given in IEEE Std 1547 [8]. The limits indicated for distributed resources are the same as those for large loads specified in IEEE Std 519.

IEC 61000-4-30 [9] prescribes a standard approach for measuring harmonics, where 200 ms windows are used. The data are then aggregated into 10 minute intervals. The 10 minute average values should be used for comparison against the recommended limits. An example trend of the 5^{th} harmonic current at the point of interconnection is given in Fig. 9.

Additionally, voltage distortion limits are also set forth in Table 11.1 of IEEE Std 519 for the corresponding interconnection bus voltage. However, some sites will have harmonic voltage background levels that will exceed these limits, even when the WPP is not in service. The actual voltage distortion contribution from the WPP may be difficult to assess, as the background and WPP harmonic generation will vary over time. The current distortion (Individual harmonics and TDD) may be the most practical measurement for compliance.

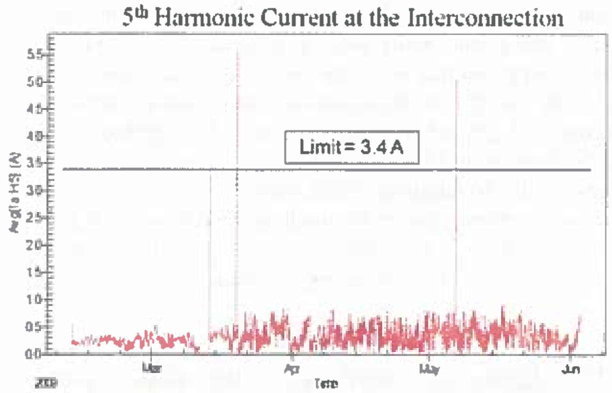


Fig. 9. Example trend showing the 5th harmonic current at a wind power plant point of interconnection (10 minute average values)

When limits are exceeded, they should be evaluated on a statistical basis. The limits should be met by the value that provides a cumulative probability level of 95%. Figure 10 shows an example case that can be considered as compliant, as the limit is met by more than 95% of the measured values. The data block in Fig. 11 (expanded in Fig. 11A), which statistically represents the same data as in the previous trend, shows that the cumulative probability 95% level (CP95%) is 1.42% V_{THD}, which meets the recommended limit.

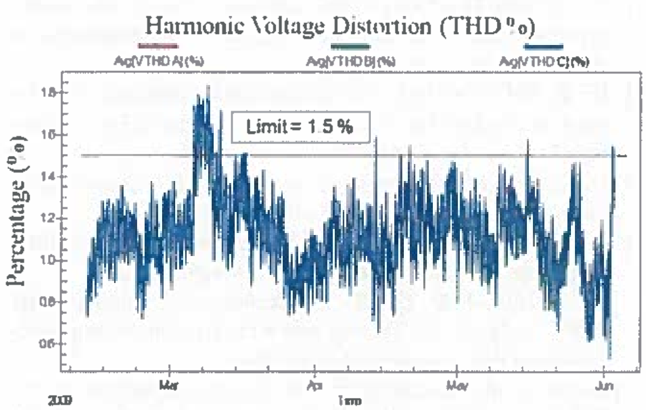


Fig.10. Trend of the harmonic voltage distortion at a wind power plant interconnection

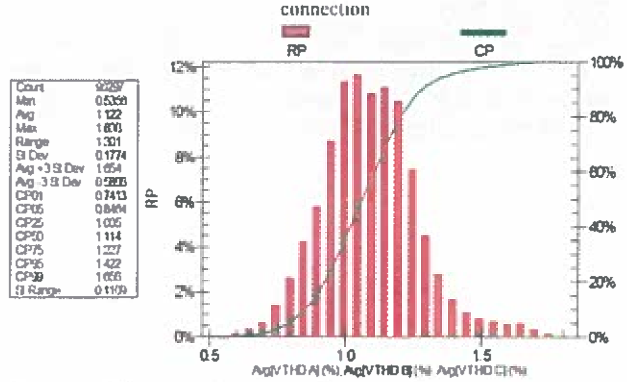


Fig. 11. Statistical analysis of harmonic voltage distortion measurements

In preconstruction, harmonic studies are often commissioned using estimates of background harmonics from the grid and also data provided by equipment manufactures to prevent harmonic issues upon commissioning. Reasonably, it is understood that such studies will not always insure compliance. No harmonic mitigation solution is ideal for every situation and accordingly post construction harmonics monitoring may be need to determine a viable solution should an issue arise. It should also be noted that post-commissioning harmonic measurements might be inconclusive because it is problematic to segregate harmonic currents caused by the wind plant from harmonic current flow into the plant as a result of grid voltage distortion. In the worst case, failure to comply with harmonic limits could result in a default of the terms of an LGIA, which could lead to termination of the agreement if the default is not cured.

IV. Harmonic Filter Overview

Harmonic filters are often used as a mitigation method for preventing unwanted harmonic contributions into a wind power plant. If the WPP includes capacitor banks for reactive power support, frequently these provisions will introduce resonance concerns. Generally, harmonic filters will address these concerns. There are many options for harmonic filter designs; two of the most prevalent methods are the passive notch filter and the band pass filter often called a C-Type harmonic filter. More details on design and performance of the harmonic filters can be found in [10].

The tuned notch type filter is implemented by placing series reactors in an existing capacitor bank, tuned to a single frequency, usually tuned below the 5th harmonic frequency. Advantages of a single tuned filter are that it is a simple design, and multiple stages of reactive power compensation can be designed identically. A disadvantage of the single-tuned filter is that it can lead to sharp resonances at non-characteristic frequencies. Figure 12 shows an example of the effect of a single-tuned filter on a system frequency response.

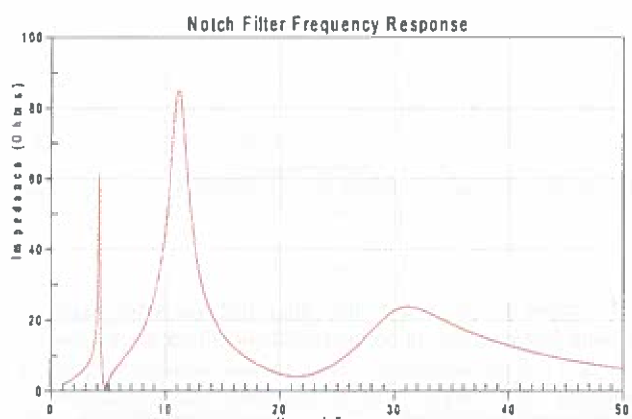


Fig. 12. Example frequency response of a single-tuned (4.7th harmonic) filter on a wind power plant 34.5 kV main bus

A C-Type filter configuration is shown in Fig. 13. It is designed so that the reactor and smaller ("c-stage") capacitor are impedance matched, so that a minimal amount of fundamental frequency power is dissipated across the damping resistor.

While, it presents more complications for the system design and protection, it does have certain advantages. (1) It provides further system damping of unintended resonance conditions over a wide frequency range. (2) It is an excellent choice for capacitors banks installed on transmission systems, especially where there are other banks on nearby buses. (3) It can also be a good choice for 34.5 kV systems, where additional capacitor banks (for reactive power) are installed without harmonic filters.

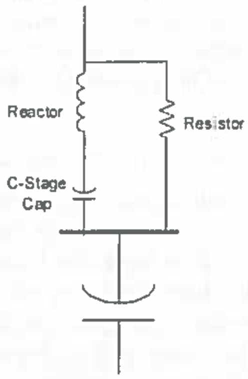


Fig. 13. Oneline configuration of a C-Type harmonic filter

Figure 14 shows an example of the effect of a C-Type filter on a system frequency response.

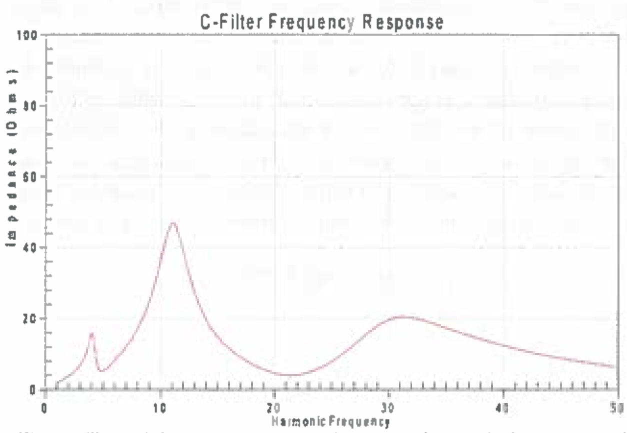


Fig. 14. Typical frequency response of a C-Type harmonic filter at a wind power plant 34.5 kV main bus

V. Conclusion

This paper has presented harmonics and resonance issues for wind power plants in an overview and summary fashion. This included an introduction to series and parallel resonances, frequency scan analysis, and the harmonic source characteristics of WTGs and of utility interconnections. Further, the issue of compliance with the power quality standard IEEE Std 519 was presented, as was an overview of harmonic filters.

The publication of this paper was a minor miracle. It was the result of two years of concerted effort by the authors and the IEEE PES Wind and Solar Plant Collector System Design working group--gathering information, preparing drafts, arguing amongst the interested parties, restarting drafts and arguing some more, and finally coming to agreement. The authors sincerely hope that this and other working group papers are found to be valuable to those who will plan, design, analyze, construct, and operate wind power plants. Recognition is given to the authors and their employers for contributing the resources for the preparation of this work.

For more information on available materials, or to find out how to participate in this working group's activities, please see: http://grouper.ieee.org/groups/td/wind

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Wind Turbines Make Waves: Why Some Residents Near Wind Turbines Become Ill

Magda Havas and David Colling

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Wind Turbines Make Waves: Why Some Residents Near Wind Turbines Become Ill

Magda Havas[1] and David Colling[2]

Abstract

People who live near wind turbines complain of symptoms that include some combination of the following: difficulty sleeping, fatigue, depression, irritability, aggressiveness, cognitive dysfunction, chest pain/pressure, headaches, joint pain, skin irritations, nausea, dizziness, tinnitus, and stress. These symptoms have been attributed to the pressure (sound) waves that wind turbines generate in the form of noise and infrasound. However, wind turbines also generate electromagnetic waves in the form of poor power quality (dirty electricity) and ground current, and these can adversely affect those who are electrically hypersensitive. Indeed, the symptoms mentioned above are consistent with electrohypersensitivity. Sensitivity to both sound and electromagnetic waves differs among individuals and may explain why not everyone in the same home experiences similar effects. Ways to mitigate the adverse health effects of wind turbines are presented.

Keywords

wind turbine, dirty electricity, power quality, ground current, contact current, electrohypersensitivity, noise, infrasound, vibroacoustic disease, wind turbine syndrome

Introduction

With growing concern about climate change, the carbon budget, depletion of fossil fuels, air pollution from dirty coal, radiation from nuclear power plants, and the need for a secure energy supply, more attention and funding are being diverted to renewable energy. Among the various types of renewable energy, wind has received a lot of attention due, in part, to opposition from communities earmarked for wind turbines and from communities that have experienced wind turbines firsthand.

Some people who live near wind turbines report difficulty sleeping and various symptoms of ill health and attribute these problems to noise and shadow flicker—two elements they can perceive. Indeed the U.S. National Research Council (Risser et al., 2007) identify noise and shadow flicker as the two key impacts of wind turbines on human health and well-being.

Not all health agencies, however, recognize that sound waves from wind turbines may cause adverse health effects. Following a review of the literature, the Chief Medical Officer of Health for Ontario (2010), concluded

> that while some people living near wind turbines report symptoms such as dizziness, headaches, and sleep disturbance, the scientific evidence available to date does not demonstrate a direct causal link between wind turbine noise and adverse health effects. The sound level from wind turbines at common residential setbacks is not sufficient to cause hearing impairment or other direct health effects, although some people may find it annoying.
>
> Low frequency sound and infrasound from current generation upwind model turbines are well below the pressure sound levels at which known health effects occur. Further, there is no scientific evidence to date that vibration from low frequency wind turbine noise causes adverse health effects.

What specifically is responsible for the illness reported near wind turbines is controversial; while some of this controversy is scientifically valid, some of it is politically motivated (Phillips, 2010).

It is intriguing that not everyone in the same home experiences symptoms, and the symptoms are not necessarily worse for those nearest the turbines. Indeed, the situation may be much more complex than noise and shadow flicker.

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Why do some people who live near wind turbines become sick while others feel no ill effects? What aspects of wind power generation and distribution are responsible for the health problems? What can be done to minimize adverse human biological and health effects? These are some of the questions addressed in this report.

Wind Turbines Make Waves

What aspects of wind power generation and distribution are responsible for the adverse health effects experienced by those who live near wind turbines?

The short answer to this question is that *wind turbines make waves*. They make pressure waves and electromagnetic waves. The pressure waves (or sound waves) generated by the moving turbines can be heard as noise and/or perceived as infrasound. The electromagnetic waves are generated by the conversion of wind energy to electricity. This conversion produces high-frequency transients and harmonics that result in poor power quality. These high frequencies can flow along the wires (dirty electricity) and along the ground, thereby causing ground current. These four types of waves—noise, infrasound, dirty electricity, and ground current—and shadow flicker are each likely to contribute to ill health among those who live near wind turbines.

Characteristics of Sound Waves and Electromagnetic Waves

Sound waves are longitudinal waves that require a medium for transport. They travel at the speed of sound (340 meters/second) through air and are much slower than electromagnetic waves that travel at the speed of light (300,000,000 meters/second) and can travel through a vacuum. Both sound waves and electromagnetic waves have a frequency (cycles per second) and an intensity (amplitude of the wave).

Frequency refers to the number of waves or cycles per second and is known as pitch for sound. The A above middle C, for example, is set to a frequency of 440 cycles per second (hertz, abbreviated as Hz). The audible range for the human ear is between 20 and 20,000 Hz. Frequencies below 20 Hz are referred to as "infrasound," and, although they cannot be heard, they can still have an effect on the body. Infrasound can travel much greater distances than higher frequency sound waves and could potentially reach and affect a much larger population.

The frequencies of electromagnetic waves, generated by wind turbines, fall within two ranges of the electromagnetic spectrum: extremely low frequency (ELF), below 1,000 Hz; and the lower range (kilohertz [kHz] to megahertz [MHz]) of the radio frequency radiation (RFR) band. Electromagnetic waves can enter homes by various paths: through the air, along wires, through the ground, and via plumbing and other metal structures. Electromagnetic waves travelling across the ground contribute to ground current.

Intensity is measured by the amplitude of the wave and, for sound, is measured in decibels (dB). Vibrations with the same frequency but different amplitude will sound the same, but one will be louder than the other. The decibel scale is logarithmic. A quiet bedroom is at 25 dB, conversation is around 60 dB, a rock group is at 110 dB, and the human threshold of pain is at 140 dB.

The intensity of electromagnetic waves is measured in various ways: electric field, magnetic field, voltage, current, and power density. The biological effects of electromagnetic energy are a function of frequency, intensity, and both the manner and the duration of exposure.

Pressure Waves: Noise

Most people who live near wind turbines and complain of ill effects blame the effects on the noise generated by the turbines (Frey & Hadden, 2007).

> Everything changed . . . when the wind turbines arrived . . . approximately 700 metres away from our property . . . Within days of the windfarm coming into operation we began to hear a terrible noise . . . The noise drove us mad. Gave us headaches. Kept us awake at night. Prevented us from having windows and doors open in hot weather, and was extremely disturbing.
>
> This noise is like a washing machine that's gone wrong. It's whooshing, drumming, constant drumming, noise. It is agitating. It is frustrating. It is annoying. It wears you down. You can't sleep at night and you can't concentrate during the day . . . It just goes on and on . . . It's torture . . . [4 years later] You just don't get a full night's sleep and when you drop off it is always disturbed and only like "cat napping." You then get up, tired, agitated and depressed and it makes you short-tempered . . . Our lives are hell.

The French National Academy of Medicine (Chouard, 2006) issued a report that concludes,

> People living near the towers, the heights of which vary from 10 to 100 meters, sometimes complain of functional disturbances similar to those observed in syndromes of chronic sound trauma . . .
>
> The sounds emitted by the blades being low frequency, which therefore travel easily and vary according to the wind . . . constitute a permanent risk for the people exposed to them . . .
>
> . . . sound levels 1 km from an installation occasionally exceeded allowable limits.
>
> . . . the Academy recommends halting wind turbine construction closer than 1.5 km from residences. (Translated from French)

Noise, especially at night, has been associated with an increase in stress hormones leading to hypertension, stroke, heart failure, and immune problems. It is discussed in greater detail elsewhere in this journal.

Pressure Waves: Infrasound

Repetitive noise can be disturbing, especially at night, when sound seems amplified. However, pressure waves at levels outside the range of human hearing can also have unpleasant side effects.

In Nova Scotia, one family was unable to remain in their home and blamed their loss of sleep and headaches on vibrations from 17 turbines (Keller, 2006).

> The d'Entremont family complained of noise and low frequency vibrations in their house after the wind turbines began operation in May 2005. The inaudible noise deprived his family of sleep, gave his children and wife headaches, and "made it impossible for them to concentrate." They now live nearby; if they return to their home, the symptoms return.
>
> Natural Resources Canada, which oversees funding for wind farm projects, found no problems with low-frequency noise or infrasound. The government report concludes that the measurements:
>
> indicate sound at infrasonic frequencies below typical thresholds of perception; infrasound is not an issue. (cited in Frey & Hadden, 2007)

Gordon Whitehead, a retired audiologist with 20 years of experience at Dalhousie University in Halifax, conducted tests and found similar results but came up with a different conclusion:

> They're [Natural Resources Canada] viewing it from the standpoint of an engineer; I'm viewing it from the standpoint of an audiologist who works with ears . . . The report should read that (the sound) is well below the auditory threshold for perception. In other words, it's quiet enough that people would not be able to hear it. But that doesn't mean that people would not be able to perceive it.
>
> " . . . low-frequency noise can affect the balance system of the ear, leading to a range of symptoms including nausea, dizziness and vision problems. It's not perceptible to the ear but it is perceptible. It's perceptible to people with very sensitive balance mechanisms and that's generally people who get very easily seasick.

Resonance may explain why infrasound is harmful at low intensities. Different parts of the human body have different resonance frequencies. When the external frequency generated by a wind turbine approaches the resonance frequency of a part of the human body, that body part will preferentially absorb the energy and begin to vibrate. For example, frequencies that affect the inner ear (between 0.5 and 10 Hz) can interfere with balance, cause dizziness or vertigo, contribute to nausea, and be experienced as tinnitus or ringing in the ears. According to the International Standards Organization (ISO Standards 2631), frequencies for the eye are between 20 and 90 Hz, head 20 and 30 Hz, chest wall 50 and 100 Hz, abdomen 4 and 8 Hz, and spinal column 10 and 12 Hz. Some of the symptoms documented at infrasonic frequencies (between 4 and 20 Hz) include general feeling of discomfort, problems with breathing, abdominal and chest pain, urge to urinate, lump in throat, effect on speech, and head symptoms (Frey & Hadden, 2007).

According to a report by the U.S. Air Force, Institute for National Security Studies, acoustic infrasound can have dramatic and serious effects on human physiology (Bunker, 1997).

> Acoustic, infrasound: very low frequency sound which can travel long distances and easily penetrate most buildings and vehicles. Transmission of long wavelength sound creates biophysical effects, nausea, loss of bowels, disorientation, vomiting, potential organ damage or death may occur. Superior to ultrasound because it is "inband," meaning it does not lose its properties when it changes mediums such as air to tissue. By 1972 an infrasound generator had been built in France, which generated waves at 7Hz. When activated it made the people in range sick for hours.

In a paper known as "The Darmstadt Manifesto," published in September 1998 by the German Academic Initiative Group and endorsed by more than 100 university professors in Germany, the German experience with wind turbines is described as follows (cited in Frey & Hadden, 2007):

> More and more people are describing their lives as unbearable when they are directly exposed to the acoustic and optical effects of wind farms. There are reports of people being signed off sick and unfit for work, there is a growing number of complaints about symptoms such as pulse irregularities and states of anxiety, which are known to be from the effects of infrasound [sound frequencies below the normal audible limit].

Infrasound is influenced by topography, distance, and wind direction (Rogers, Manwell, & Wright, 2006) and differs from home to home and room to room because each room is a distinct cavity with its own resonant frequency. Whether a door is open or closed can alter the effect.

The biological effects of low-frequency noise (20-100 Hz) and infrasound (less than 20 Hz) are a function of intensity, frequency, duration of exposure, and direction of the vibration.

Part 4 of 8, Additional information found TheBrainCan.com , SolomonSeries.com, and https://www.youtube.com/solomonseries

Wind Turbine Syndrome and Vibroacoustic Disease

Exposure to low-frequency noise and infrasound may produce a set of symptoms that include depression, irritability, aggressiveness, cognitive dysfunction, sleep disorder, fatigue, chest pain/pressure, headaches, joint pain, nausea, dizziness, vertigo, tinnitus, stress, heart palpitations, and other symptoms. Not everyone has the same sensitivity. Those who experience motion sickness (car, boat, plane), get dizzy or nauseous on carnival rides, have migraine headaches, or have eye or ear problems may be particularly susceptible to low-frequency vibrations.

Two different "diseases" have been associated with low-frequency noise exposure and infrasound. They are wind turbine syndrome—coined by Pierpont (2009) in her book by the same name—and vibroacoustic disease (VAD). VAD is a whole-body, systemic pathology characterized by the abnormal proliferation of extracellular matrices and caused by excessive exposure to low-frequency noise (Castelo Branco & Alves-Pereira, 2004). These two "diseases" differ as described by Pierpont (2009).

> Wind Turbine Syndrome, I propose, is mediated by the vestibular system—by disturbed sensory input to eyes, inner ears, and stretch and pressure receptors in a variety of body locations. These feed back neurologically onto a person's sense of position and motion in space, which is in turn connected in multiple ways to brain functions as disparate as spatial memory and anxiety. Several lines of evidence suggest that the amplitude (power or intensity) of low frequency noise and vibration needed to create these effects may be even lower than the auditory threshold at the same low frequencies.
>
> Vibroacoustic Disease, on the other hand, is hypothesized to be caused by direct tissue damage to a variety of organs, creating thickening of supporting structures and other pathological changes. The suspected agent is high amplitude (high power or intensity) low frequency noise. (p. 13)

VAD seems to be dose dependent, with symptoms becoming progressively worse with continued exposure. Three stages have been identified based on 70 aircraft technicians who, presumably, were exposed to much higher intensities of low-frequency noise than those who live near wind turbines (Castelo Branco, 1999, Castelo Branco & Alves-Pereira, 2004).

Stage 1: Mild, 1 to 4 years, slight mood swings, indigestion, heartburn, mouth/throat infections, bronchitis

Stage 2: Moderate, 4 to 10 years, depression, aggressiveness, pericardial thickening, light to moderate hearing impairment, chest pain, definite mood swings, back pain, fatigue, skin infections (fungal, viral, parasitic), inflammation of stomach lining, pain during urination, blood in urine, conjunctivitis, allergies

Stage 3: Severe, more than 10 years, myocardial infarction, stroke, malignancy, epilepsy, psychiatric disturbances, hemorrhages (nasal, digestive, conjunctive mucosa), varicose veins, hemorrhoids, duodenal ulcers, colitis, decrease in visual acuity, headaches, severe joint pain, intense muscular pain, neurological disturbances

Whatever name is given to the symptoms, the symptoms are real and can be caused by low-frequency sound waves and infrasound.

Electromagnetic Waves

One undesirable consequence of wind-generated electricity is poor power quality due to variable weather conditions, mechanical construction of the towers, and the electronic equipment used (Lobos, Rezmer, Sikorski, & Waclawek, 2008). Electricity in North America has a frequency of 60 Hz and is a sine wave when viewed on an oscilloscope (Figure 1). When a wind turbine generates electricity, the frequency must be converted to 60 Hz by power converters; that conversion generates a large spectrum of current and voltage oscillations leading to poor power quality (Lobos et al., 2008). Wind turbines can generate a wide range of frequencies—from less than 1 Hz (Lobos et al., 2008), with the majority of the frequencies in the kHz range associated with power conversion.

Dirty Electricity

High-frequency transient spikes that contribute to poor power quality, also known as dirty electricity, can flow along wires, damage sensitive electronic equipment, and adversely affect human and animal health.

After wind turbines were activated in Ripley, Ontario, several of the residents complained of ill health. Residents suffered from headaches, poor sleep, elevated blood pressure (requiring medication), heart palpitations, itching, ringing and pain in the ears, watering eyes, and pressure on the chest causing difficulty breathing. These symptoms disappear when the residents leave the area. Some residents were forced to move out of their homes because the symptoms were so severe. Locals complain of headaches and poor radio reception when they drive near these power lines.

One of the authors (DC) measured the power quality near several residences where people were unwell. The primary neutral-to-earth voltage (PNEV) is the electrical potential difference between the earth and the neutral wire on the primary distribution line, as shown in Figure 2. Measurements taken before wind turbines were installed and after they were installed and operating (Figure 3) clearly show the distortion (spikes on the waveform) generated by the wind turbines.

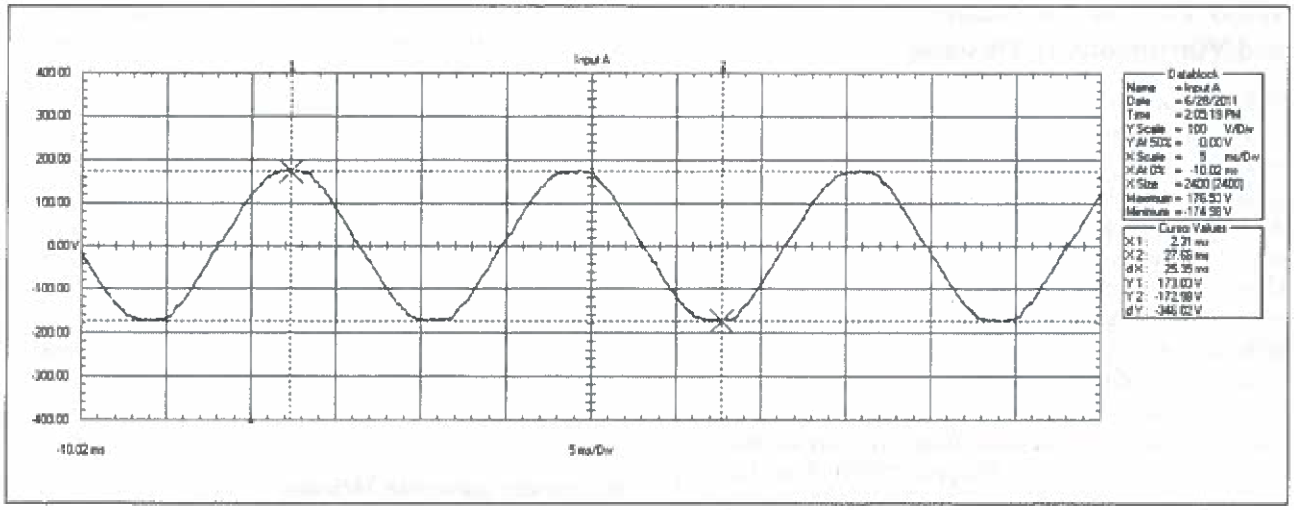

Figure 1. Good power quality exemplified by the 60-Hz sine wave

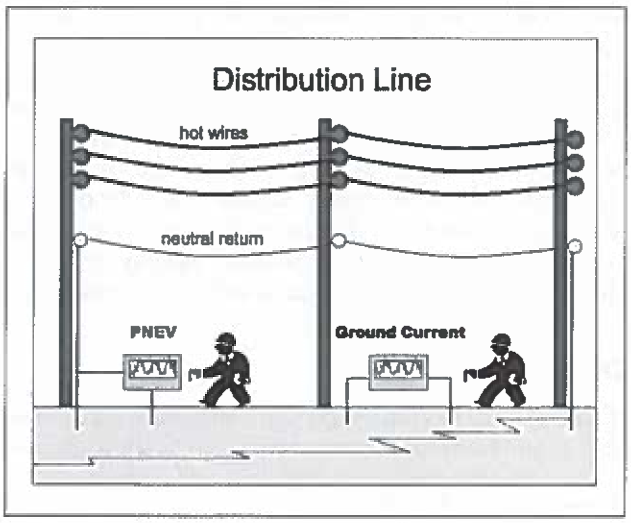

Figure 2. Diagram demonstrating how primary neutral-to-earth voltage (PNEV) and ground voltage measurements are taken

In this area, wind turbines are variable speed and are interconnected. The collection lines connecting the wind turbines to the substation are attached to the same utility pole as the home owners' lines.

According to one of the authors (DC; September 30, 2008),

> We had four families move out of their homes and now if I spend too much time in these homes I get the same symptoms, which is ear aches, ringing in the ears and pressure in the ears. [name removed] eventually buried a portion of the line but have only isolated the lines by insulators so it is better, however there is still some high frequency coming into the houses. The three families that now have buried lines are back in their homes, but things are far from ideal.

Dirty electricity in the kHz range affects human health; this has been shown in schools and homes in both Canada and the United States. Power quality can be improved both on electrical wires by using power line filters (Ontario Hydro, 1998) and inside buildings by using special surge suppressors or power filters that dampen the voltage spikes (http://www.stetzerelectric.com).

In one Wisconsin School that had "sick building syndrome," once power quality was improved, the health of both teachers' and students' improved. According to the school nurse, both staff and students have more energy, fewer allergies, and fewer migraine headaches, and asthmatics rely less on their inhalers (Havas, 2006a).

In a Toronto School, improvements in power quality were accompanied by improvements in teachers' health and students' behavior. Teachers were less tired, less frustrated, less irritable; they had better health and more energy; they had a greater sense of satisfaction and accomplishment; they were more focused and experienced less pain. Students' behavior also improved especially in the elementary grades (Havas, Illiatovitch, & Proctor, 2004). Similar results were reported in a placebo-blinded study in three Minnesota schools (Havas & Olstad, 2008).

Dirty electricity has been associated with increased risk of various types of cancers among teachers in a California school (Milham & Morgan, 2008), with higher blood sugar levels among diabetics, and with exacerbation of tremors and difficulty walking among those with multiple sclerosis (Havas, 2006b). People who are adversely affected by dirty electricity are classified as electrically hypersensitive.

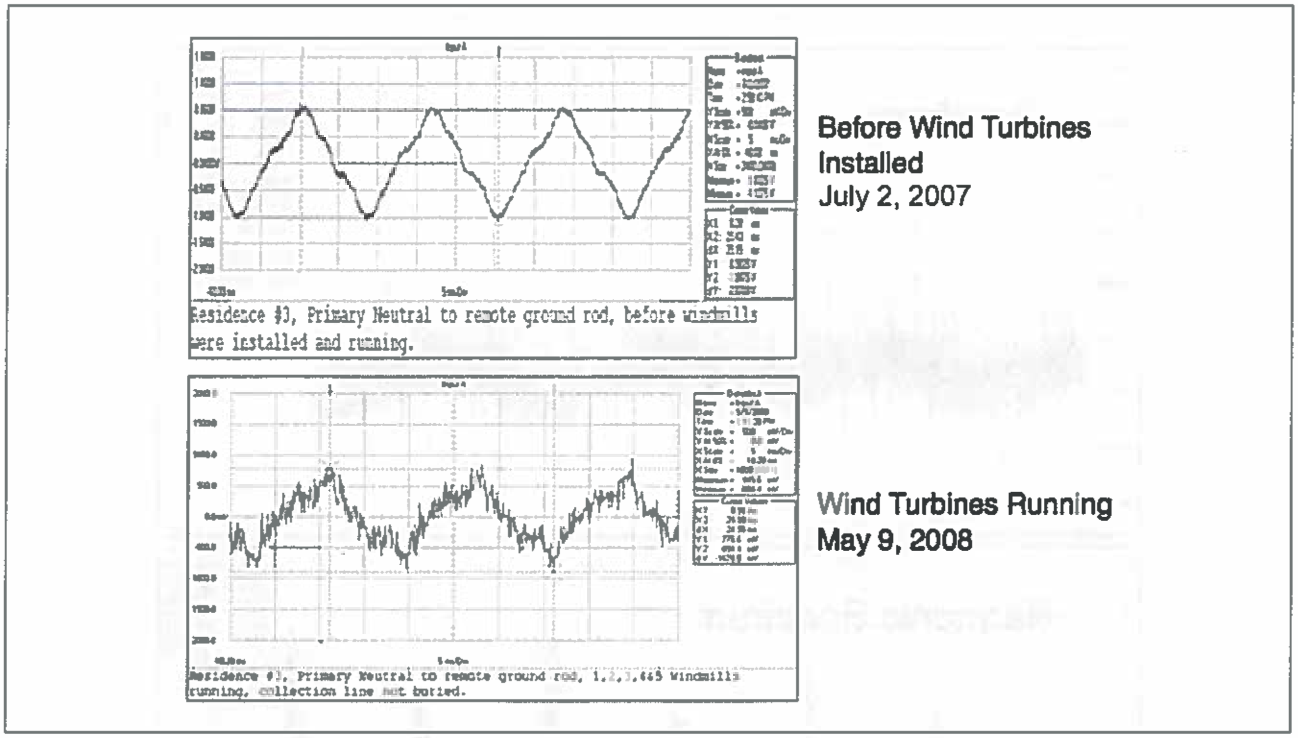

Figure 3. Primary neutral-to-earth voltage (PNEV) at Residence No. 3 in Ripley, Ontario, before wind turbines were installed (July 2, 2007) and when five wind turbines were operating (May 9, 2008)
Note. Collection line was not buried.

Ground Current

Just as dirty electricity can flow along wires, it can also flow along the ground resulting in ground current. Ground current (often measured as voltage and called stray voltage or tingle voltage) is a serious problem in certain locations and has been shown to adversely affect the health of farm families and the health and productivity of farm animals, especially dairy cattle.

The Ontario Federation of Agriculture (2007) provides information on symptoms experienced by farm animals, pets, and people who are exposed to tingle voltage as follows:

> Farmers and their families who suffer from immune disorders such as allergies or rheumatoid arthritis find their symptoms worsen or go into remission in close coordination with livestock symptoms. Periods of fatigue increase. Sleep disorders may increase.
>
> Cats leave the farm, become ill, cease to bear litters or have small, unhealthy litters, or die; coats are usually dull and shaggy and eyes are runny.
>
> Horses may paw the ground and shy away from watering or feeding troughs; behaviour and handling becomes more difficult.
>
> Pigs often take to ear and tail biting; mastitis and baby pig scours are common; piglet mortality may increase.
>
> Cattle lap water from the trough or bowl; feed in the bottom of the manger is not cleaned up; milk out is slow and uneven; cows are reluctant to enter the milk parlour and quick to leave; slow growth in calves and heifers; somatic cell counts are high; unexplained spontaneous abortions of calves; bulls become markedly more irritable.

According to the *National Electrical Safety Code (NESC) Handbook* (Clapp, 1997),

> When the earth returns were used in some rural areas prior to the 1960's, they became notorious offenders in dairy areas because circulating currents often cause both step and touch potentials.
>
> In some cases, they have adversely affected milking operations by shocking the cattle when they were connected to the milking machines, and have affected feeding. (p. 152)

According to Lefcourt (1991) in the U.S. Department of Agriculture book titled *Effects of Electrical Voltage/Current on Farm Animals: How to Detect and Remedy Problems*:

> The effect of a transient voltage superimposed on the regular power voltage (dc or ac) is to cause a momentary

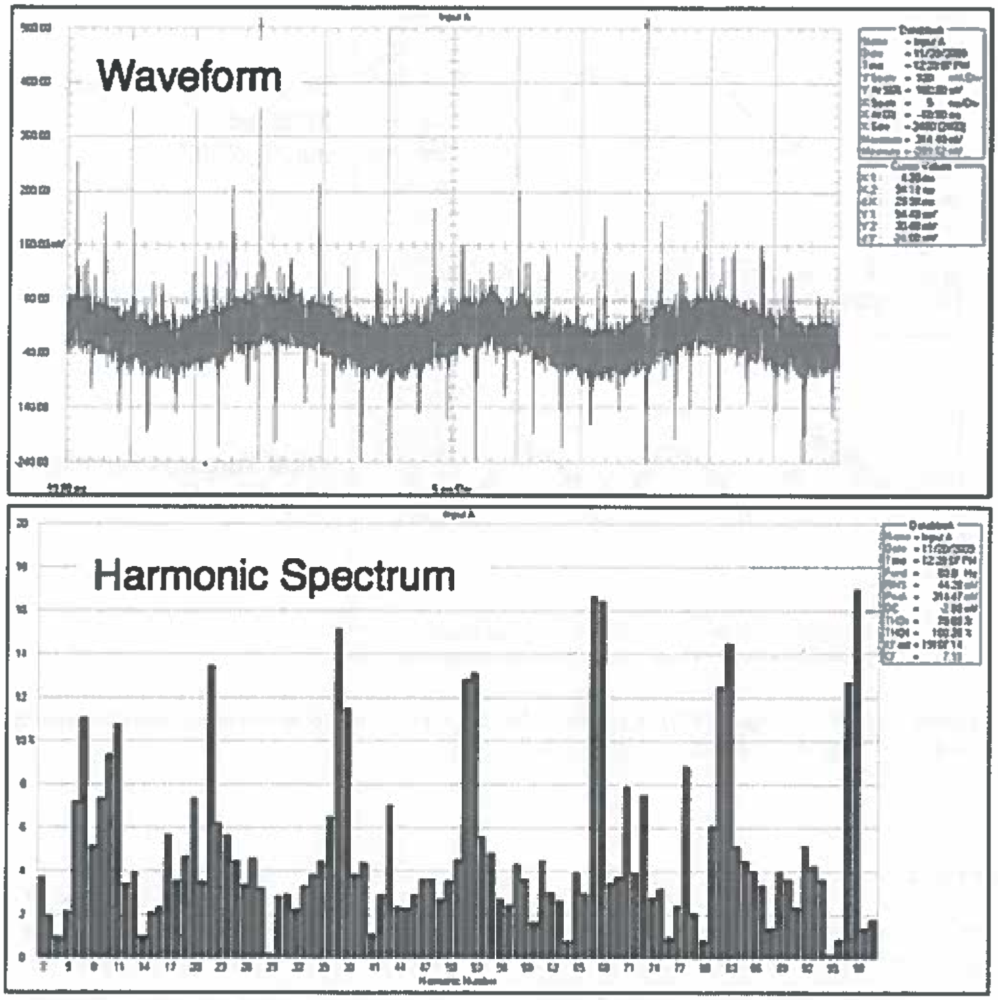

Figure 4. Ground voltage measured at the Palm Springs wind farm in California using 50 feet of copper wire attached to two metal rods in the earth

Note. The top graph shows the distorted 60-Hz waveform, and the bottom graph shows the harmonic frequencies. Data courtesy of Dr. Sam Milham.

> change in the waveform. When the transient causes the momentary voltage to be greater than normal, it may cause a transient current to flow in an animal. If the transient waveform has sufficient energy (magnitude and duration), there may be an animal response. (p. 63-64)

Indeed, dirty electricity flowing along the ground may be more harmful to farm animals than the 60-Hz ground current (Hillman et al., 2003):

> Cows were sensitive to harmonic distortions of step-potential voltage, suggesting that utility compliance with IEEE standards on dairy farms may need to be addressed.
>
> Power quality varied greatly from farm to farm and day to day. Milk production responses to changes in power quality varied inversely with the number of transient events recorded with event recorders, oscilloscope, and power quality meters. Harmonics often gave better estimates of electrical effects on milk production than voltage *per se*. (p. 19)

Do wind turbines generate ground current? They can if proper safeguards are not taken. Generally, this is a problem with power distribution once the energy leaves the turbine.

Figure 4 shows the waveform of ground voltage near an industrial wind farm in Palm Springs, California (as shown in Figure 5 photographs). The waveform distortion in Figure 3 and 4 are considerable when compared with Figure 1.

Figure 5. Wind farm in Palm Springs, California, showing (A) location of ground voltage readings; (B), view of wind turbines from the ground; and (C) view of wind turbines from the air

Note. Photograph A from Dr. Sam Milham. Photographs B and C from Google maps.

Burying the collection line may not eliminate the ground voltage but can improve power quality, as shown in Figure 6.

Just as animals are adversely affected by dirty ground current, so are people. If ground current enters a home via the plumbing, touching any part of the plumbing (e.g., faucet) induces a current in the body, known as contact current.

In one Ripley home, the frequency fingerprint (relative intensities of various frequencies) on the plumbing (sink to floor measurement) was similar to the PNEV, indicating that the source of the ground voltage was the wind turbines' collection line (Figure 7). In this home, the sink to floor contact current was calculated to be 400 microamperes (peak to peak based on 200 millivolts and 500 ohms), and this value is 22 times higher than levels associated with cancer according to Kavet, Zaffanella, Daigle, and Ebi (2000).

> "The absolute (as well as modest) level of contact current modeled (18 micro Amps) produces average electric fields in tissue along its path that exceed 1 mV/m. At and above this level, the NIEHS Working Group [1998] accepts that biological effects relevant to cancer have been reported in "numerous well-programmed studies." (p. 547)

Wertheimer, Savitz, and Leeper (1995) documented the link between ground current and cancer in Denver, Colorado. They found that leukemia risk increased by 300% among children exposed to elevated magnetic field from ground current that enters the home through conductive plumbing.

Electrohypersensitivity (EHS)

Why do some people who live near wind turbines become sick while others feel no ill effects?

Exposure to both pressure waves and electromagnetic waves is highly variable—spatially and temporally—as is sensitivity to these vibrations. Not everyone in the same home is going to have the same exposure or the same sensitivity. People who have balance problems, experience motion sickness, or have ear or eye problems are more likely to react to low-frequency sound vibrations. Those who are electrically hypersensitive are more likely to suffer from dirty electricity

Part 4 of 8, Additional information found TheBrainCan.com , SolomonSeries.com, and https://www.youtube.com/solomonseries

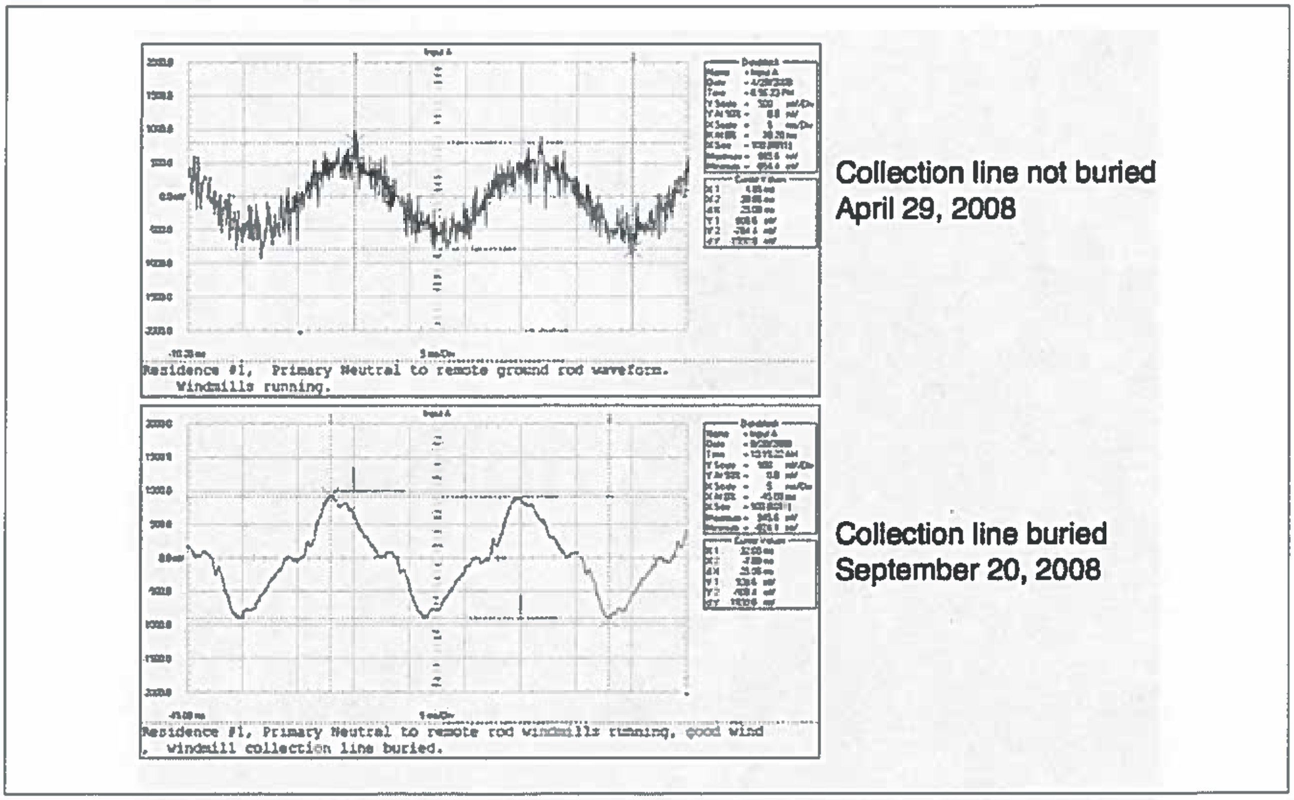

Figure 6. Primary neutral-to-earth voltage (PNEV) at Residence 1 in Ripley, Ontario, when wind turbines were operating
Note. Collection line from wind turbines was buried on September 20, 2008 (bottom graph), but not on April 29, 2008 (top graph).

and contact current. As a result, people living in the same home may have very different sensitivities and may respond differently to these vibrations.

At the Working Group meeting on EMF Hypersensitivity in Prague, the World Health Organization (2004) described electrosensitivity as

> a phenomenon where individuals experience adverse health effects while using or being in the vicinity of devices emanating electric, magnetic, or electromagnetic fields (EMFs).
>
> Whatever its cause, EHS is a real and sometimes a debilitating problem for the affected persons, while the level of EMF in their neighborhood is no greater than is encountered in normal living environments. Their exposures are generally several orders of magnitude under the limits in internationally accepted standards.

Symptoms include cognitive dysfunction (memory, concentration, problem solving); fatigue and poor sleep; body aches and headaches; mood disorders (depression, anxiety, irritability, frustration, temper); nausea; problems with balance, dizziness, and vertigo; facial flushing, skin irritations, and skin rashes; chest pressure, rapid heart rate, and altered blood pressure; ringing in the ear (tinnitus); and nosebleeds. A comprehensive list of the symptoms is provided in Table 1.

In Sweden, EHS is recognized as a functional impairment (not as a disease). Between 230,000 and 290,000 Swedes (about 3% of the Swedish population) may be electrohypersensitive (Johansson, 2006). The number of people complaining of EHS seems to be increasing as is the medication sold to deal with the symptoms of insomnia, pain, fatigue, depression, and anxiety. By 2017, as many as 50% of the population may experience these symptoms (Hallberg & Oberfeld, 2006).

Some individuals may have a predisposition to EHS. Those who have experienced physical trauma to their nervous system (whiplash), electrical trauma in the form of multiple shocks or several severe shocks, and/or chemical exposure to mercury or pesticides are likely to be more electrically sensitive. Children, the elderly, and those with impaired immune systems are also likely to be more electrically sensitive.

It is not possible to determine which factors are contributing to ill health until appropriate monitoring is conducted and steps are taken to reduce exposure to the offending agents. Monitoring of both electromagnetic waves and pressure waves in homes where people report ill health is highly recommended as are the mitigation techniques mentioned below

Part 4 of 8, Additional information found TheBrainCan.com , SolomonSeries.com, and https://www.youtube.com/solomonseries

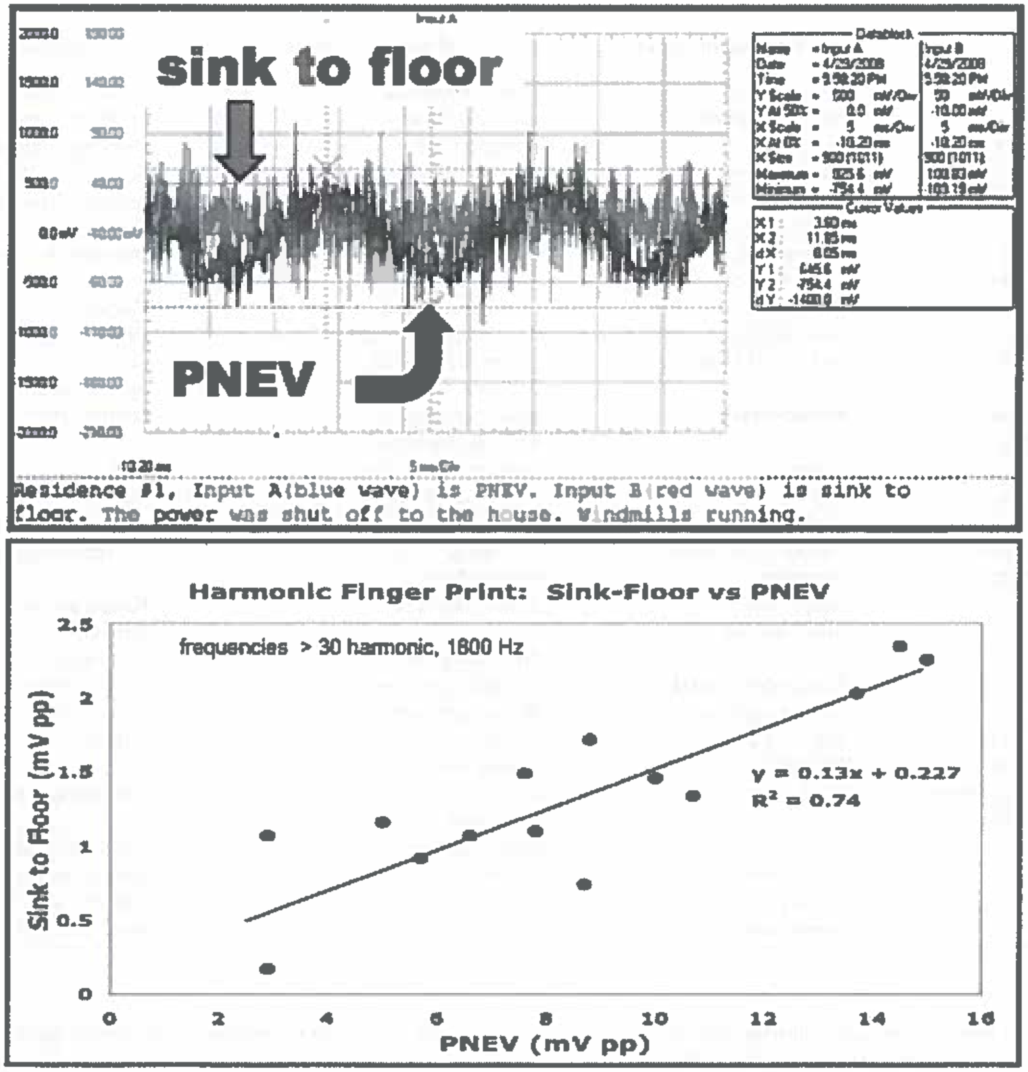

Figure 7. The primary neutral-to-earth voltage (PNEV) and the sink-to-floor voltage for Residence 1 in Ripley, Ontario (top graph), and the harmonic figure print for these voltages (bottom graph).

Recommendations

What can be done to minimize adverse biological and health effects for those living near wind turbines?

One obvious step is to eliminate or reduce exposure to the agent(s) causing the illness.

1. To minimize noise and exposure to infrasound, the following steps should be taken:
   a. Wind turbines should be placed as far away as possible from residential areas. The French National Academy of Medicine (Chouard, 2006) recommends 1.5 km from residential areas.
   b. Buffers can be constructed to disrupt pressure waves and to absorb or deflect sound waves in areas where turbines are closer to homes or where problems have been documented.
2. To improve power quality, the following steps should be taken:
   a. The electricity should be "filtered" at all inverters before it leaves the wind turbine. Ontario Hydro (1998) provides information on power line filters and other ways to improve power quality.
   b. The collector lines from the wind turbines should be attached to utility poles that do not provide power to homes.
   c. Power from the substation supplied by the wind turbines should be filtered before it is distributed to customers.

Table 1. Comprehensive List of Electrohypersensitivity (EHS) Symptoms (Bevington, 2010)

Category	Symptoms
Auditory	earaches, imbalance, lowered auditory threshold, tinnitus
Cardiovascular	altered heart rate, chest pains, cold extremities especially hands & feet, heart arrhythmias, internal bleeding, lowered/raised blood pressure, nosebleeds, shortness of breath, thrombosis effects
Cognitive	confusion, difficulty in learning new things, lack of concentration, short / long-term memory impairment, spatial disorientation
Dermatological	brown 'sun spots', crawling sensations, dry skin, facial flushing, growths & lumps, insect bites & stings, severe acne, skin irritation, skin rashes, skin tingling, swelling of face/neck
Emotional	anger, anxiety attacks, crying, depression, feeling out of control, irritability, logorrhoea, mood swings,
Gastrointestinal	altered appetite, digestive problems, flatulence, food intolerances
Genito-urinary	smelly sweat / urine, urinary urgency, bowel urgency
Musculoskeletal	aches / numbness pain / prickling sensations in: bones, joints & muscles in: ankles, arms, feet legs, neck, shoulders, wrists, elbows, pelvis, hips, lower back, cramp / tension in: arms, legs, toes, muscle spasms, muscular paralysis, muscular weakness, pain in lips, jaws, teeth with amalgam fillings, restless legs, tremor & shaking
Neurological	faintness, dizziness, 'flu-like symptoms, headaches, hyperactivity, nausea, numbness, sleep problems, tiredness
Ophthalmologic	eyelid tremors/'tics', impaired vision, irritating sensation, pain / 'gritty' feeling, pressure behind eyes, shiny eyes, smarting, dry eyes
Other Physiological	abnormal menstruation, brittle nails, hair loss, itchy scalp, metal redistribution, thirst / dryness of lips, tongue, eyes
Respiratory	asthma, bronchitis, cough /throat irritation, pneumonia, sinusitis
Sensitisation	allergies, chemical sensitivity, light sensitivity, noise sensitivity, smell sensitivity

   d. Wind power electrical substations that require power from an external source (electrical distribution network) must ensure that the power quality of this eternal source is not affected as this can result in power quality problems for customers connected to the same external power source.
   e. Nearby home owners may need to install power line filters in their homes if levels of dirty electricity remain high.

3. To reduce ground current/voltage, the following steps should be taken:
   a A proper neutral system (possibly a five-wire system) should be installed to handle the high-frequency return current in overhead lines (Electric Power Research Institute, 1995).
   b. Insulators can be placed between the neutral line and the grounding grid for the wind turbine.
   c. The collection lines from the wind turbine to the substation should be buried if the other techniques to minimize dirty ground current are ineffective.
   d. Local home owners may need to install stray voltage isolators near their transformers until the electric utility can resolve the problem (Hydro One, 2007).

If these steps are taken, improved quality of life and a feeling of wellness may return to some of the people adversely affected by nearby wind turbines.

Conclusions

A subset of the population living near wind turbines is experiencing symptoms of ill health. These symptoms are likely caused by a combination of noise, infrasound, dirty electricity, ground current, and shadow flicker. These frequencies can be highly viable spatially and temporally and are affected by distance; terrain; wind speed and direction; shape, size, and type of dwelling; type of power converters used; state of the electrical distribution line; type and number of grounding systems; and even the type of plumbing in homes. Furthermore, not everyone has the same sensitivity to sound and electromagnetic radiation nor do they have the same symptoms. The following symptoms seem to be quite common: sleeplessness, fatigue, pain, dizziness, nausea, mood disorders, cognitive difficulties, skin irritations, and tinnitus. To help alleviate symptoms in areas where wind turbines have been erected, remediation is necessary to reduce or eliminate both sound waves and electromagnetic waves. More research is required to help us better understand the relative importance of the various factors contributing to poor health. This type of information will enable a healthy coexistence between wind turbines and the people living nearby.

Declaration of Conflicting Interests

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Bios

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White Paper

SOLECTRIA RENEWABLES

Soonwook Hong, Ph. D.
Michael Zuercher-Martinson

Harmonics and Noise in Photovoltaic (PV) Inverter and the Mitigation Strategies

1. Introduction

PV inverters use semiconductor devices to transform the DC power into controlled AC power by using Pulse Width Modulation (PWM) switching. PWM switching is the most efficient way to generate AC power, allowing for flexible control of the output magnitude and frequency. However, all PWM methods inherently generate harmonics and noise originating in the high dv/dt and di/dt semiconductor switching transients. In order to reduce harmonics and switching noise, external filtering needs to be added. The following conceptual figure shows how the AC output voltage is generated at the inverter power stage output using PWM switching.

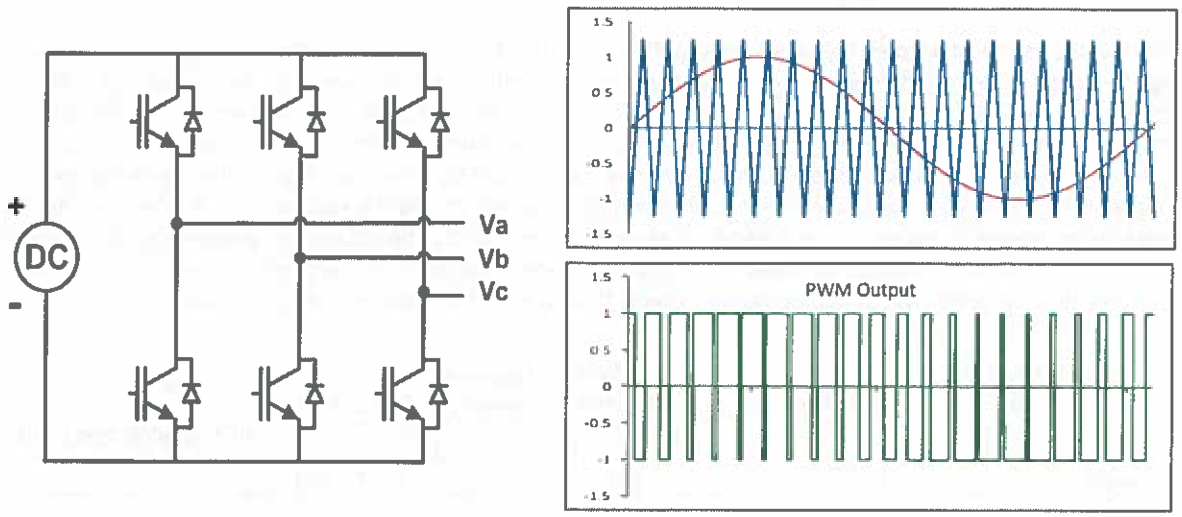


Figure 1. Three Phase Inverter PWM Generation

As shown in Figure 1, the PWM waveform is generated by comparing a reference signal (sinusoidal red trace) and a carrier waveform (triangular blue trace). The PWM waveform controls the Insulated Gate Bipolar Transistor (IGBT) switches to generate the AC output. When the reference signal is bigger than the carrier waveform, the upper IGBT is triggered on (lower IGBT being off) and positive DC voltage is applied to the inverter output phase (A). In the other case, when the reference signal is smaller than the triangular carrier waveform, the lower IGBT is turned on (upper IGBT being off) and negative DC voltage is applied to the inverter output. The reference signal magnitude and frequency determine the amplitude and the frequency of the output voltage. The frequency of the carrier waveform is called the modulation frequency. In order to generate more precise sinusoidal AC voltage waveforms and keeping the size of the LC filter small, high modulation frequencies are generally used.

There are many industrial standards that control the noise and harmonic contents in an inverter system, such as AC motor drives, Uninterrupted Power Supplies (UPS) or other AC power applications. In the case of grid-tied PV inverters, the Institute of Electrical and Electronics Engineers (IEEE) 1547, Underwriters Laboratories (UL) 1741 and FCC Part 15B standards specify the guidelines to control the harmonic contents of the output current and the Electro Magnetic Interference (EMI) generation in the inverter. The guidelines guarantee that:

- The inverters do not generate excessive noise and harmonics, which can contaminate the AC grid voltage.
- The inverters are immune to electrical and magnetic noise from other sources and provide reliable operation in an environment of high electromagnetic noise.
- The inverters do not generate unwanted radiated or conducted noise, which can disturb the stable operation of other equipment coupled either electrically or magnetically.

White Paper

SOLECTRIA RENEWABLES

Most of the PV inverters manufactured in the United States are designed to meet UL 1741 and IEEE 1547 standards. As the capacity of PV generation in power distribution systems grows, utility companies become increasingly concerned that the noise and harmonics from the PV inverter systems will adversely impact the power quality or affect the operation of other equipment and cause it to malfunction or otherwise disrupt the stable operation of the power distribution system.

This article lists the possible sources of the harmonics and switching noise generated by the PV inverter and describes how they can be controlled to meet customer requirements and relevant industrial standards. To present the theoretical and experimental analysis of this phenomenon, a Solectria Renewables PVI 82kW - 480VAC PV inverter system is being used. However, since most PV inverters have similar types of component configurations, the information in this article can be used to understand the harmonics and EMI issues in a variety of inverter systems.

2. PV Inverter System Configuration

Figure 2 shows the block diagram of a Solectria PVI 82kW inverter, including the filters used for attenuating the high frequency noise on the inverter output voltages and currents. There are two main sources of high frequency noise generated by the PWM inverters. The first one is the PWM modulation frequency (2 ~ 20kHz). This component is mainly attenuated by the LC filter and the transformer. The second source originates in the switching transients of the power electronics switching devices (IGBTs). The frequency of the switching transients is dependent on the device switching characteristics, gate drive circuit and the snubber circuit in the inverter, and ranges from several hundred kHz to 100MHz. The series filter and the shunt filter are designed to attenuate the frequency components caused by these switching transients and also the harmonics from other subsystem components such as the switched mode power supply (SMPS) and other inverter control circuitry.

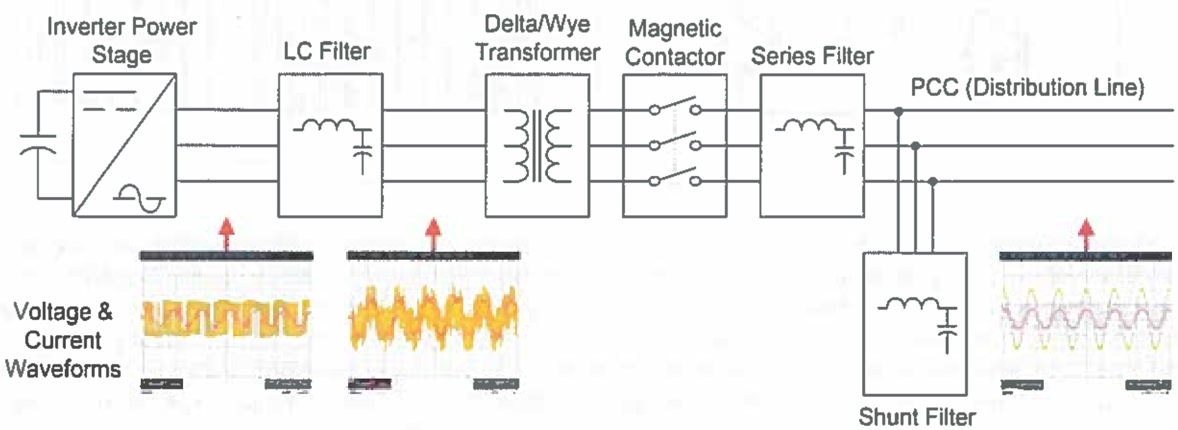


Figure 2. PVI 82kW Inverter Filtering Configuration and V/I Waveforms

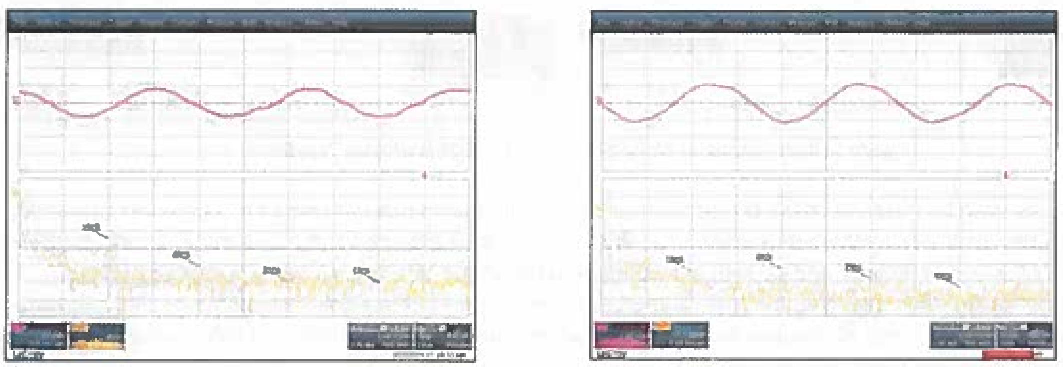
Figure 2 also shows the voltage and current waveforms in each stage of the inverter. Most of the harmonic components in the voltage and current waveforms are filtered out by the LC, series and shunt filters. The inverter output current is in phase with the voltage (unity power factor) and the total harmonic distortion (THD) is less than 5% at rated operation, which is far better than the current THD of most industrial loads, and is comparable to the output current waveforms of an Uninterruptable Power Supply (UPS).

2.1. PWM frequency and LC filter

An LC filter is used to attenuate the PWM modulation frequency and its harmonics in the inverter system. The leakage inductance of the integrated isolation transformer further attenuates the high frequency component so that the output current will be sinusoidal and meet the desired THD limit. A symmetrical PWM scheme is generally preferred to reduce the ripple in the inverter output current. A symmetrical PWM scheme compared to an asymmetrical PWM reduces the effective peak-to-peak ripple current by half when using the same switching frequency.

As shown in Figure 2, the inverter's power stage output voltage waveform is composed of a series of square waveforms and includes high frequency components. The current waveform is relatively smooth and sinusoidal as the inverter output current flows into the inductor in which it cannot change instantaneously.

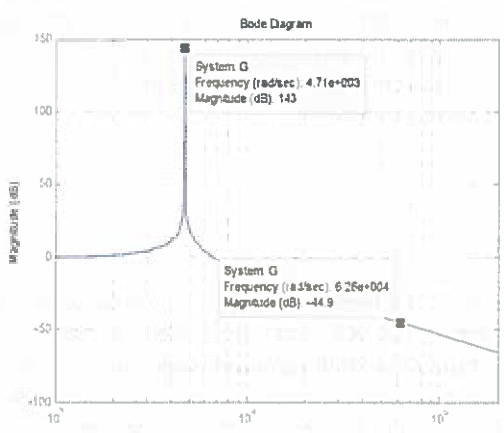
Figure 3 compares the power stage output to the inverter output current. In the time domain, the waveforms do not look very different. However, the Fast Fourier Transformation (FFT) results show that the inverter current after the LC filter has much less high frequency components than the unfiltered power stage output current.



a) Power stage output current waveform and FFT b) Inverter output current waveform and FFT

Figure 3. PVI 82kW Current Harmonic Analysis

This filtering effect can be illustrated in a Bode Plot. Figure 4 (a) shows the LC filter frequency characteristics using the theoretical frequency analysis and the measured harmonic components with a frequency analyzer when the inverter operates at full power. In the example the LC filter resonant frequency is tuned to 750Hz. Assuming a PWM modulation frequency of 10 kHz it would be attenuated to 45dB below the fundamental current component. The actual inverter output current FFT result shows that the 10 kHz ripple component is further attenuated to 60dB below the fundamental component by the shunt filter, which is about 0.1% of the fundamental 60Hz current. Figure 4 (b) shows that all the harmonic component frequencies are well controlled and the overall THD is 2.31%.



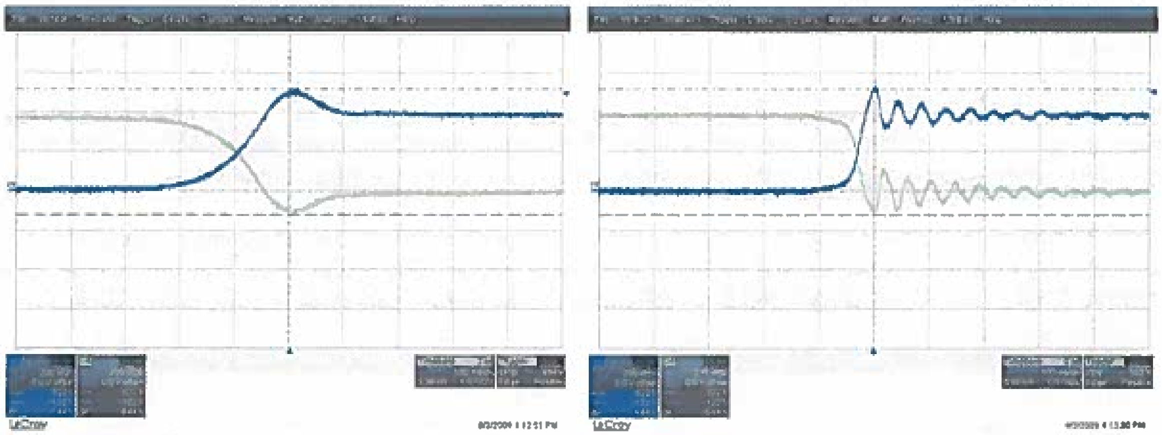
THD	2.31%	12^{th}	0.08%
		13^{th}	0.16%
2^{nd}	0.71%	14^{th}	0.25%
3^{rd}	1.85%	15^{th}	0.05%
4^{th}	0.57%	16^{th}	0.05%
5^{th}	0.52%	17^{th}	0.06%
6^{th}	0.10%	18^{th}	0.04%
7^{th}	0.61%	19^{th}	0.05%
8^{th}	0.07%	20^{th}	0.04%
9^{th}	0.08%	21^{st}	0.05%
10^{th}	0.12%	22^{nd}	0.03%
11^{th}	0.24%	23^{rd}	0.07%

a) LC Filter Bode Plot (Theoretical Result) b) Inverter output current FFT (Test Result)

Figure 4. PVI 82kW System Output Current Harmonics Analysis

2.2. High frequency noise generated by switching transients

When the switching devices are turned on and off, high dv/dt and di/dt cause oscillations during the transients, which contain high frequency noise in the range of 100kHz or higher. Figure 5 shows the switching transients of the IGBT voltage and current with two different gate drive circuit designs.



a) Slow switching transient b) Fast switching transient

Figure 5. High Frequency Noise Generated by IGBT Switching Transients

By using a slow switching transient (a), the oscillation can be minimized but switching losses are increasing due to longer operation of IGBTs in the active region. With a faster switching speed, the switching losses can be kept lower but oscillations in voltage and current are being generated due to the parasitic inductance and capacitance in the inverter stack. This high frequency oscillation falls into the frequency band regulated by FCC. In order to increase the overall efficiency of the inverter and at the same time to minimize EMI, the IGBT switching speed and noise filter design must be carefully coordinated.

There are other sources of switching noise in the inverter system caused by the Switch Mode Power Supplies SMPS and the digital control logic circuits. The noise from these components can reduce the system performance by contaminating internal analog feedback signals, resulting in logic level or communication errors and could also cause EMI interference with the outside world.

The high frequency noise can be further classified into radiated noise and conducted noise. The radiated noise can be controlled in many ways at the board level and at the system level such as shielding, component layout, wiring routing, and signal grouping. The conducted noise can be controlled by grounding or the use of proper filters, carefully designed to eliminate specific frequency components. In Solectria's PVI 82kW inverter, excellent noise levels were achieved by implementing a robust printed circuit board (PCB) layout in combination with hardware and software filters. Noise in signal circuits is solely controlled by ferrite beads and proper grounding. The PVI 82kW inverter also features series and shunt filters in the final output stage of the system. These filters are frequency band limiting and designed to filter out switching frequency transients.

Series Filter

The IGBT switching transients normally last 0.1 ~ 10usec, therefore, the filter should be tuned to between 100kHz and several MHz. Also, the controller uses a SMPS switched at 150kHz. The series filter in the PVI 82kW attenuates both common mode and differential mode noise. It provides 80dB common mode attenuation for the frequencies between 100kHz and 1MHz, and 70dB differential mode attenuation for the frequencies between 200kHz and 3MHz. The filter is selected to eliminate the system specific dominant frequency components, and is not active in the lower PWM modulation frequency range.

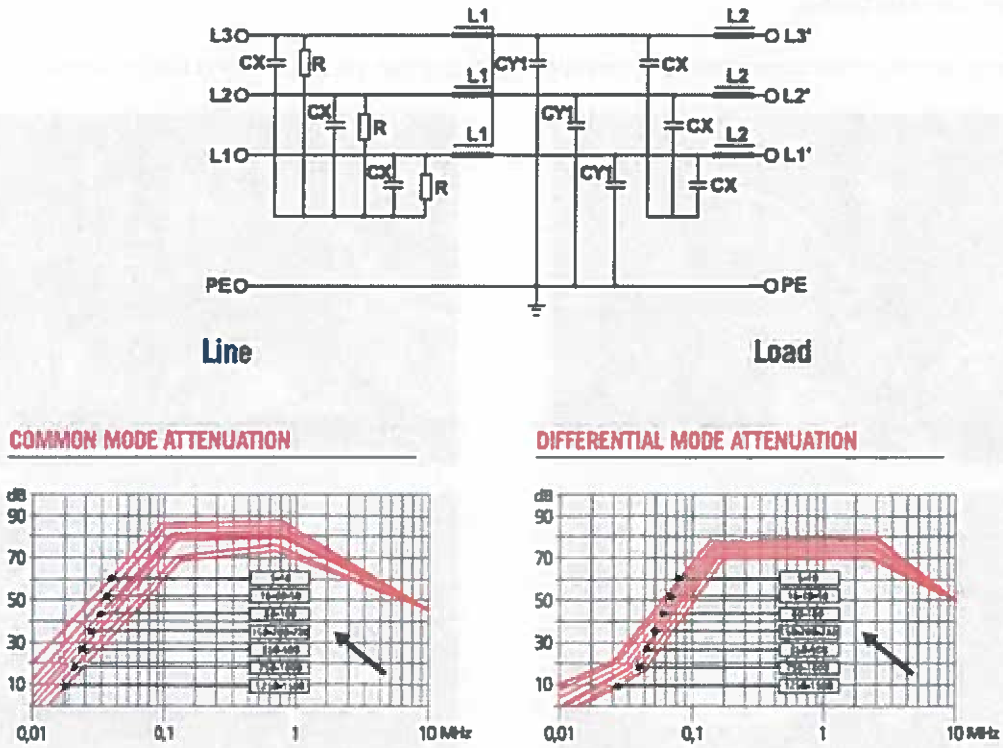


Figure 6. Series Filter Characteristics

Shunt Filter

The selected shunt filter for the PVI 82kW inverter has a resonance point around 150kHz and provides a reduction of noise interference particularly in the frequency range between 50kHz and 5MHz. This filter is added to further reduce the switching noise from the power stage as well as from the switch mode power supply in the inverter control system. The shunt filter also provides a protection circuit against surges of atmospheric origin to the grid, typically caused by lightning and characterized by high current levels of short duration. The filter reacts in a few microseconds to current spikes of a few kA, and protects the system against impulse surges of up to 1000 volts.

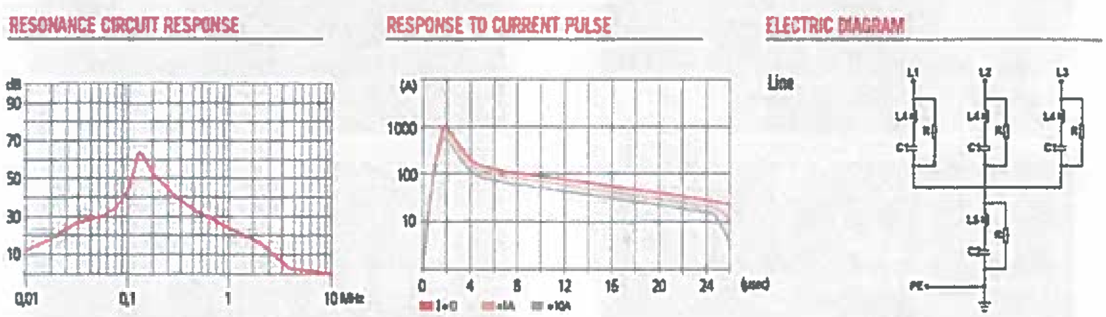
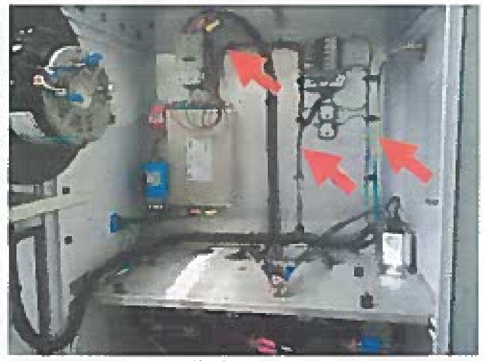


Figure 7. Shunt Filter Characteristics

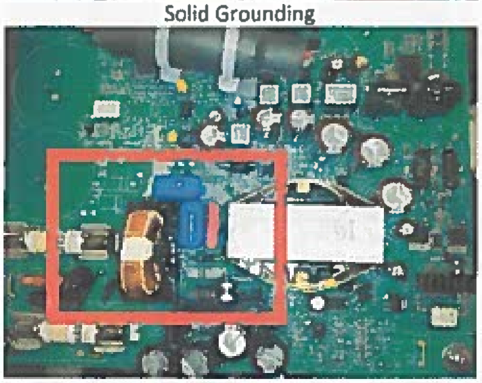
3. System wide EMI Control

The following pictures show some of the EMI reduction strategies that are used in a PVI 82KW inverter.

Solid Grounding

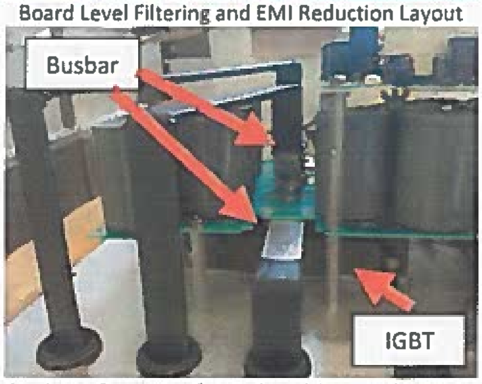


Controlled Wire Routing



Board Level Filtering and EMI Reduction Layout

Wire Twisting



Stack Configuration for Reduced Stray Inductance

Power Electronics Enclosure for EMI Shielding

Analog Signal Conditioning using Ferrite Beads

DC side High Power Wiring for EMI shielding

White Paper

SOLECTRIA RENEWABLES

4. Harmonics Generated by Firmware Control

Conventional PV inverters firmware runs at least two nested control loops. One is the AC current control loop to control the inverter output current, purely sinusoidal and in phase with the grid voltage, generating active power. The other is the DC voltage control loop in conjunction with a Maximum Power Point Tracking (MPPT) algorithm to most efficiently harvest the DC power generated by the solar panels.

When grid conditions change due to power grid transients, power line faults or load based voltage fluctuations in the distribution line, the inverter output current is controlled to balance the power transfer from the PV array to the grid. If the current control loop gains are tuned properly, the dynamic response due to the transients can be controlled at the bandwidth usually less than 1kHz. The DC voltage control loop is around the current control loop and is usually controlled at a lower sampling rate. If the DC voltage fluctuates due to sudden changes in weather conditions, the DC voltage control loop has a certain bandwidth to react and stabilize the system output. During sunlight transients, the system might generate even slower oscillations in the DC bus voltage and output AC currents control. Since the DC voltage control loop bandwidth is low, it does not cause any harmonics or EMI issues. However, if the voltage control loop were not tuned properly, the generation efficiency would decrease due to failure to track the maximum power point of the PV panels.

Solectria Renewables' inverters have been fully tested at different load conditions to have excellent dynamic characteristics for both the AC current and DC voltage control loops. The AC current control bandwidth is about 2kHz and the DC voltage control bandwidth is more than 100Hz.

5. Conclusion

This article described how the current harmonics and EMI are controlled in PV inverters. IEEE 1547, UL 1741 and FCC Part 15B standards impose strong guidelines for grid-tied PV inverters to reduce current harmonics and eliminate electromagnetic noise. Extra attention is given by the PV inverter manufacturer to design inverters that are immune to EMI problems and guarantee reliable operation of the inverter in all worst case operating conditions.

Different types of practical harmonics and noise reduction strategies for a commercial three-phase PV inverter were introduced in this article. The filtering of harmonics and EMI needs to be carefully designed to maintain the control bandwidth of the inverter and to provide clean and reliable control signals in both analog and digital electronic circuits. The PVI 82kW inverter system is equipped with several levels of harmonics and EMI filtering and its effectiveness and reliability have been proven in the harshest commercial and utility scale applications.

Controlled Workmanship

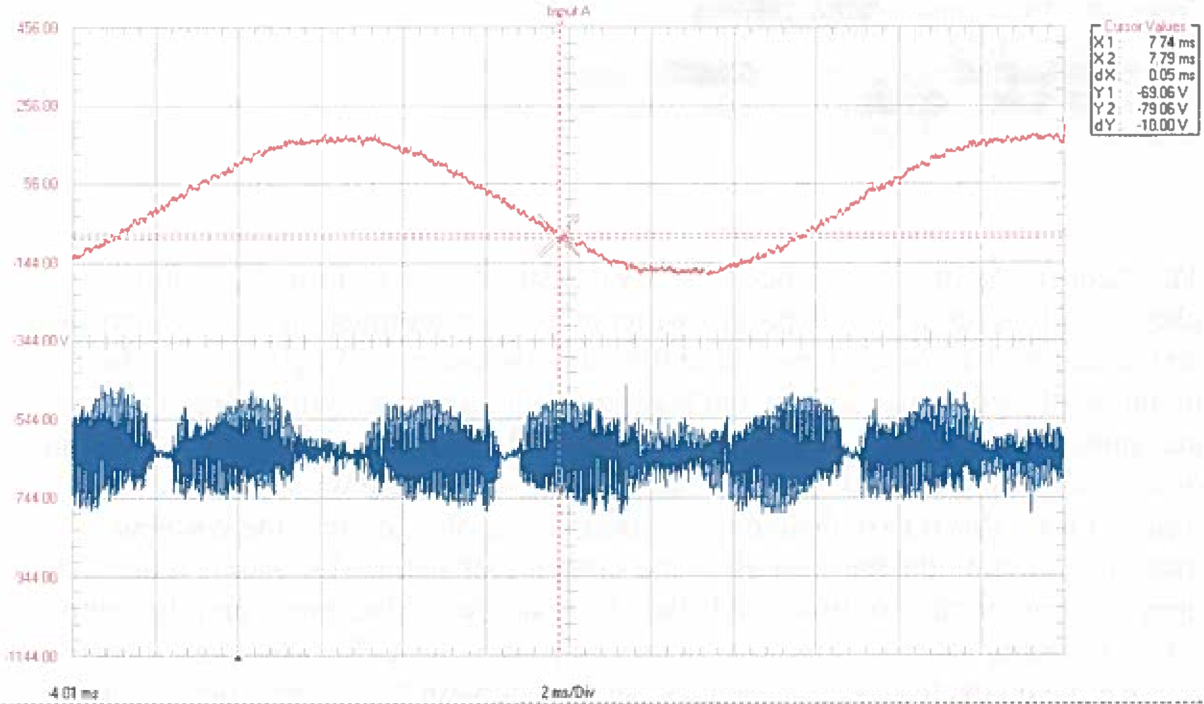
8 Hour HASS Burn-in Test and Final Verification

From: Sam Milham [mailto:[redacted]om]
Sent: Wednesday, April 17, 2013 7:09 PM
To: '[redacted]@yahoo.com'; 'm[redacted]@sbcglobal.net'
Cc: 'D[redacted]T[redacted]'; 'p[redacted]@citizensenergy.com'; dave stetzer
Subject: Solar house , El centro

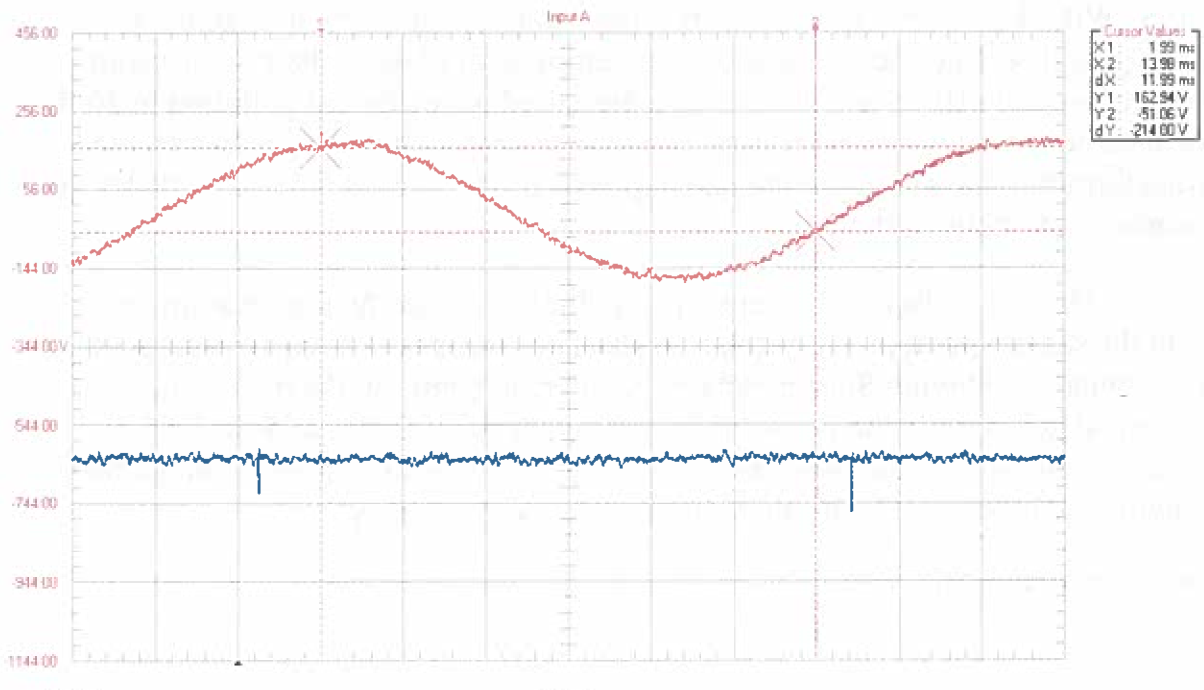
The Azucena Romero residence at 838 Vine Street in El Centro has rooftop photovoltaic solar cells (see photo) with the inverter mounted next to a smart meter on the rear of the house. I measured the dirty electricity at 5 outlets in the house including the computer station and bedroom, with a Stetzer Microsurge meter. This measures rate of change of voltage with time (dV/dT), and gives a digital readout of dirty electricity DE (electrical pollution) levels in house wiring. At the same time, a Fluke 199 B two channel oscilloscope was plugged into the washing machine outlet on the back porch in the same outlet as the Microsurge meter. The upper tracing on the oscilloscope is the utility 60 cycle sine wave, and the bottom line is a tracing after the sine wave has been passed through a high pass filter to remove the 60 cycle signal. Readings were made with the inverter on and off. With the inverter off, the outlets were normal with dirty electricity levels between 30 and 70 units. With the inverter on, the outlets read between 1,430 and 2,200 units. With the inverter off, the oscilloscope tracing was normal, with it on, the high pass filter line shows a tracing characteristic of photo voltaic solar invert pollution at 20 kHz (See below). I also measured the electrical pollution in 40 feet of wire between the ground rod attached to the center tap of the pole- mounted transformer in the house picture and a ground probe. This is labeled as PNEV or primary neutral to earth voltage.

This house has serious electrical pollution caused by the solar inverter. I find the same pattern in every solar residence or business I have measured. I recommend deploying Stetzer capacitive filters to short out the high frequency electrical pollution in the house wiring. Also get rid of CFLs, and the DECT cordless telephone, other sources of electrical pollution. I'd strongly recommend leaving the inverter off until the pollution can be cleaned up.

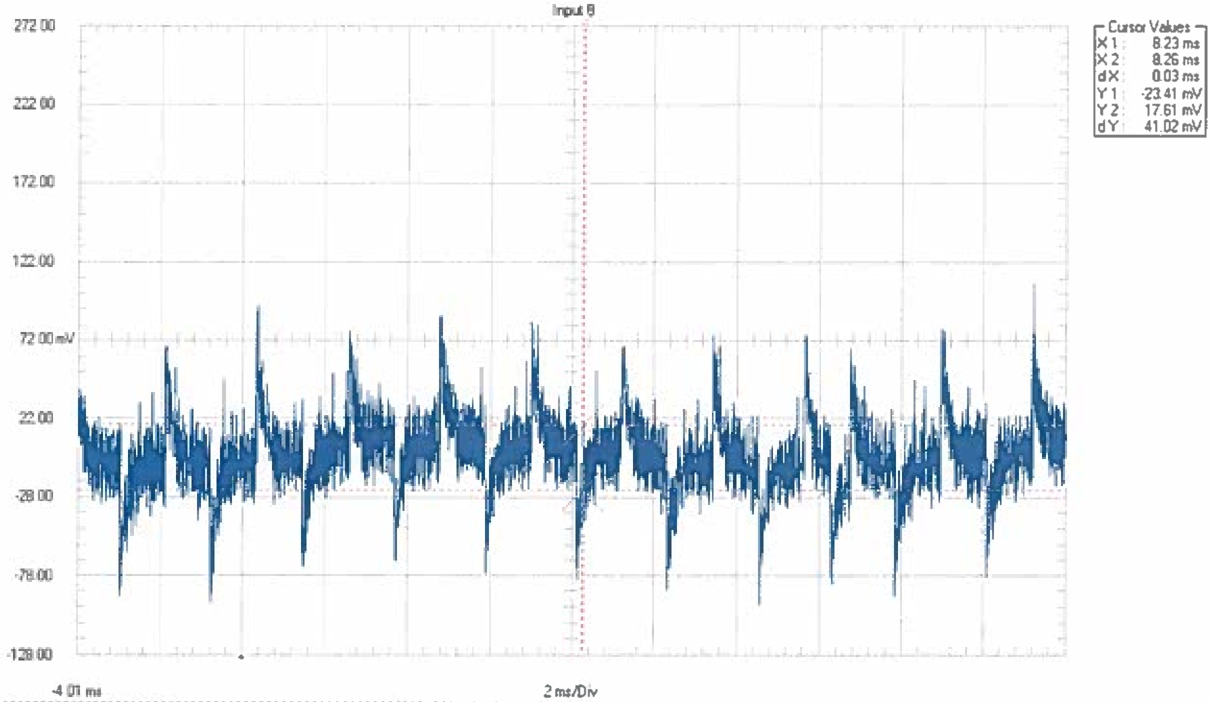
Best, Sam Milham MD. MPH



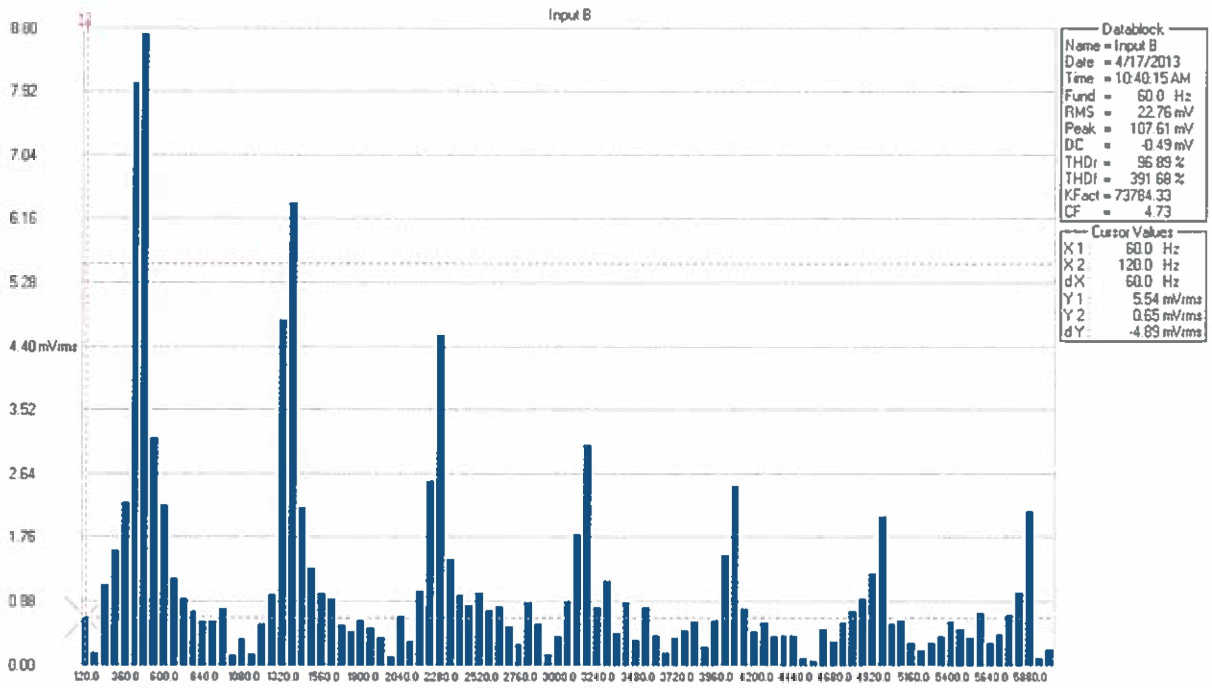
838 Vine st El Centro CA Solar inverter on. DE 1,400 to 2,200 in house outlets 20 kHz



838 Vine st El Centro CA Solar inverter off DE 30 to 70 in house outlets



El Centro solar house PNEV at back yard power pole 50 kHz



El centro solar house PNEV spectrum