

IEEE Recommended Practice for the Electrical Design and Operation of Windfarm Generating Stations

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1. Introduction

1.1 Scope. This recommended practice contains design information and procedures for the interconnection of multiple wind turbines (a windfarm generating station) with an electric utility. This document addresses issues relating to the interface and the electrical system between the utility and the individual wind turbines (an intraplant electrical system). It also provides recommended practices for monitoring systems, protection systems, and safe operations for personnel and equipment.

1.2 Scope Limitations. This document does not discuss protection of the windfarm-utility interface, which is covered by IEEE Std 1001-1988 [35]¹, or protection of the utility system. It also does not address the control or protection functions of individual wind turbines. Information on these functions is provided in AWEA Standard 3.1-1988 [6]² and IEEE Std 1021-1988 [36]. The unique aspects of wind-turbine generators using power electronics are not discussed in this document since they are not currently in widespread use in windfarms. However, this document does not preclude their use.

1.3 Significance and Use. This document is intended to facilitate sound, economic engineering design and safe operations of a windfarm generating station. It should be utilized in conjunction with other standards, local

utility requirements, and sound engineering practices.

1.4 References. This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

[1] ANSI C2-1990, National Electrical Safety Code.³

[2] ANSI C84.1-1989, American National Standard Electric Power Systems and Equipment Voltage Ratings (60 Hz).

[3] ANSI C93.1-1981, Requirements for Power Line Carrier Coupling Capacitors.

[4] ANSI C93.2-1976, Requirements for Power Line Coupling Capacitor Voltage Transformers.⁴

[5] ANSI/NFPA 70-1990, National Electrical Code.⁵

[6] AWEA Standard 3.1-1988, Design Criteria Recommended Practices Wind Energy Conversion Systems.⁶

¹The numbers in brackets correspond to those of the references in 1.4.

²AWEA is the acronym for the American Wind Energy Association.

³ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁴ANSI C93.2-1976 has been withdrawn; however, copies can be obtained from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁵NFPA publications are available from Publications Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA.

⁶AWEA publications are available from the American Wind Energy Association, Standards Program, 777 North Capital Street NE, #805, Washington, D.C. 20002, USA.

- [7] AWEA Standard 5.1-1985, Wind Energy Conversion Systems Terminology.
- [8] IEEE C37.1-1987, IEEE Standard Definition, Specification, and Analysis of Systems Used for Supervisory Control, Data Acquisition, and Automatic Control.⁷
- [9] IEEE C37.90-1989, IEEE Standard for Relays and Relay Systems Associated With Electric Power Apparatus (ANSI).
- [10] IEEE C37.91-1985, IEEE Guide for Protective Relay Applications to Power Transformers (ANSI).
- [11] IEEE C37.95-1989, IEEE Guide for Protective Relaying of Utilities-Consumer Interconnections (ANSI).
- [12] IEEE C37.97-1979 (Reaff. 1984), IEEE Guide for Protective Relay Applications to Power System Buses (ANSI).
- [13] IEEE C37.99-1990, IEEE Guide for Protection of Shunt Capacitor Banks.
- [14] IEEE C37.101-1985, IEEE Guide for Generator Ground Protection (ANSI).
- [15] IEEE C37.102-1987, IEEE Guide for AC Generator Protection.
- [16] IEEE C37.010-1979 (Reaff. 1988), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).
- [17] IEEE C37.012-1979 (Reaff. 1988), IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).
- [18] IEEE C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers (ANSI).
- [19] IEEE C57.12.01-1989, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.
- [20] IEEE C57.13-1978 (Reaff. 1986), IEEE Standard Requirements for Instrument Transformers (ANSI).
- [21] IEEE C62.2-1987, IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems (ANSI).
- [22] IEEE C62.41-1980, IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits (ANSI).
- [23] IEEE C62.45-1987, IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits (ANSI).
- [24] IEEE C62.92-1989, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II—Grounding of Synchronous Generator Systems (ANSI).
- [25] IEEE Std 18-1980, IEEE Standard for Shunt Power Capacitors (ANSI).
- [26] IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding (ANSI).
- [27] IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.
- [28] IEEE Std 100-1988, IEEE Dictionary of Electrical and Electronics Terms.
- [29] IEEE Std 141-1986 (Red Book), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (ANSI).
- [30] IEEE Std 142-1982 (Green Book), IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (ANSI).
- [31] IEEE Std 242-1986 (Buff Book), IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (ANSI).

⁷IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[32] IEEE Std 367-1987, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault (ANSI).

[33] IEEE Std 399-1980 (Brown Book), IEEE Recommended Practice for Industrial and Commercial Power System Analysis (ANSI).

[34] IEEE Std 493-1990 (Gold Book), IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.

[35] IEEE Std 1001-1988, IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems (ANSI).

[36] IEEE Std 1021-1988, IEEE Recommended Practice for Utility Interconnection of Small Wind Energy Conversion Systems (ANSI).

[37] Bassett, E. D. and Potter, F. M. "Capacitive Excitation for Induction Generators." *AIEE Transactions*. vol. 54, May 1935, pp. 540-545.

[38] *Electrical Transmission and Distribution Reference Book*. East Pittsburgh, PA: Westinghouse Electric Corp., 1950.

[39] Feero, W. E. and Gish, W. B. "Overvoltages Caused by DSG Operation: Synchronous and Induction Generators." *IEEE Transactions on Power Delivery*. vol. 1, January 1986, pp. 258-264.

[40] Gish, W. B., Feero, W. E., and Gruel, S. "Ferroresonance and Loading Relationships for DSG Installations." *IEEE Transactions on Power Delivery*. vol. 2, July 1987, pp. 953-959.

[41] "Intertie Protection of Consumer-Owned Sources of Generation, 3 MVA or Less." IEEE Power Engineering Society Special Publication 88 TH0224-6-PWR.

[42] Smith, D., Swanson, S., and Borst, J. "Overvoltages with Remotely-Switched Cable-Fed Grounded Wye-Wye Transformers." *IEEE Transactions*. vol. PAS-94, 1975, pp. 1843-1853.

[43] Wagner, C. F. "Self-Excitation of Induction Motors." *AIEE Transactions*. vol. 58, February 1938, pp. 47-51.

[44] Working Group on Fast Transfer of Motors, IAS-PSPC. "Source Transfer and Reclosing Transients in Motors: A Preliminary Working Group Report." *IEEE 1982 Industrial and Commercial Power Systems Technical Conference*. pp. 43-50.

1.5 Bibliography

ASME PTC42-1988, Wind Turbines.⁸

UL 347-1985, The Standard for High-Voltage Industrial Control Equipment.⁹

UL 493-1988, The Standard for Thermoplastic Insulated Underground Feeder and Branch Circuit Cables.

UL 508-1989, The Standard for Industrial Control Equipment.

UL 810-1981, The Standard for Capacitors.

UL 891-1984, The Standard for Dead-Front Switchboards.

UL 1062-1983, The Standard for Unit Substations.

UL 1072-1986, The Standard for Medium-Voltage Power Cables.

UL 1558-1988, The Standard for Metal Enclosed, Low-Voltage Power Circuit Breaker Switchgear.

UL 1561-1986, The Standard for Dry-Type General Purpose and Power Transformers.

1.6 Definitions. Terms other than those defined below have standard definitions as listed in IEEE Std 100-1988 [28] or AWEA Standard 5.1-1985 [7].

islanding. Operation of non-utility electric generation equipment, with or without a portion of an electric utility system, isolated from the remainder of the utility system.

⁸ASME publications are available from the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017, USA.

⁹UL publications are available from Underwriters Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, USA.

micrositing. Of, or related to, the characteristics of a particular wind-turbine site, as contrasted to those characteristics that prevail over the entire windfarm.

self-excitation. A condition in which an induction generator, operating in an isolated power system, derives its excitation from shunt capacitors or the natural capacitance of the power lines. Applies only to induction machines.

2. Intraplant Electrical System

2.1 Collection System Design. An electrical system must be provided to collect the generator outputs and transmit the aggregate net electrical output to the electric utility interconnection point, described in Section 3. This system is referred to as the “collection system.” The collection system is also the source of start-up/auxiliary power to each individual generator or site electrical load. Fig 1 shows a typical windfarm interconnection with collection system.

Disconnecting means should be provided for each collection system element in accordance with the requirements in ANSI/NFPA 70-1990 [5] (the National Electrical Code). In addition, overload and short-circuit protection should be provided to protect conductors and equipment by mitigating the consequences of electrical faults and to minimize the disruption to the remaining system.

2.1.1 Voltage Levels. The collection system usually consists of distinct low-voltage and medium-voltage systems. The low-voltage system connects one or more individual wind generators to low-voltage/medium-voltage step-up transformers. The medium-voltage system connects the step-up transformer outputs to the utility interconnection substation, which may further step up the voltage to a transmission voltage level.

The voltage levels of the collection system should be chosen by an economic analysis to minimize the total cost of equipment and losses over the expected lifetime of the facility. Voltage levels should normally be chosen from those listed as “preferred” in ANSI C84.1-1989 [2]. Equipment with the preferred ratings will generally cost less and be more readily available than nonstandard equip-

ment. Use of a nonstandard voltage may be justified, however, if that voltage is supplied by the interfacing utility.

When carrying power, the actual voltage level of the collection system will deviate from the nominal voltage (see 2.5.1). The changing voltage may affect the efficiency of the wind-turbine generators. The transformer ratios and generator voltage ratings should be chosen to maximize the total energy production of the windfarm for the expected wind regime. Conversely, equipment ratings should not be exceeded under any expected wind conditions.

2.1.2 Conductors. Underground cable is typically used for the low-voltage collection system. Medium-voltage systems typically are a combination of underground and overhead conductors. When overhead conductors are used, special consideration should be given to safe working distances for cranes and other equipment.

Underground cable systems can be either direct-buried, installed in conduit, or installed in concrete-encased duct banks. A concentric-neutral cable or dedicated-neutral return cable should be installed with each collector system feeder cable. This neutral-return conductor(s) provides a fault return path and can assist in alleviating certain ferroresonance conditions (see 2.6.2).

2.2 Power Flow and Equipment Loading

2.2.1 Power Flow. When the turbines are operational, real power will flow from the generators to the utility when the electrical output exceeds the turbine and site service loads. When turbines are not operating, or are in start-up mode, utility power will be used for electronics, motors, transformer losses, and site support. Some types of turbines “motor” to start, i.e., they draw power from the collection system to accelerate the turbine to operating speed. This can cause an inrush of power from the utility or from other operating turbines. Other types of wind turbines are driven to operating speed by the wind. Reactive power flow will be determined by the type of generator (synchronous or induction), any capacitors in the system, and the excitation level of synchronous generators. Generally, most wind turbines use induction generators with a moderate quantity of local capacitance. The var demand of an induction generator changes with its power output, whereas the var supply of

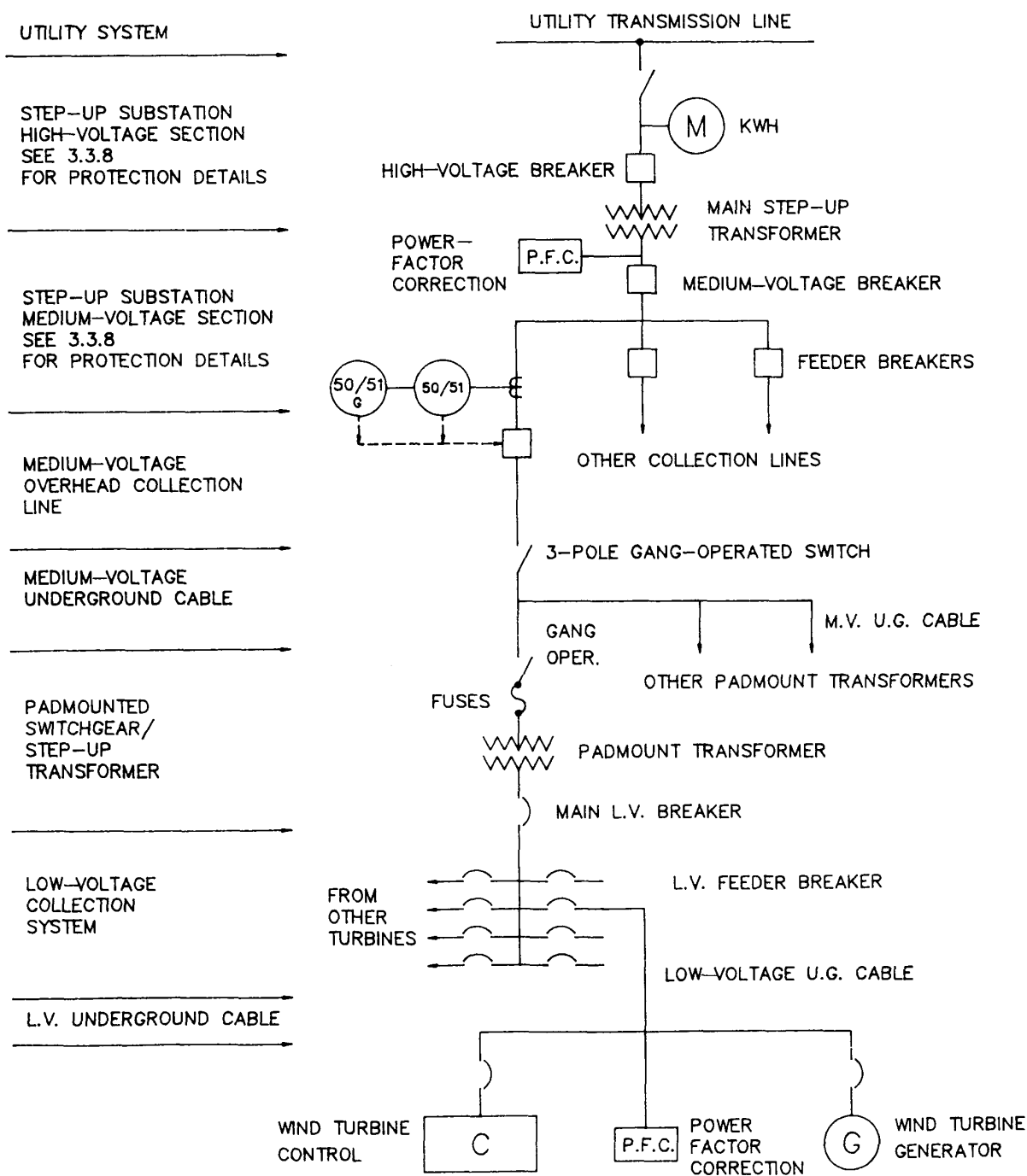


Fig 1
Typical Single-Line Diagram

a capacitor is constant, assuming constant voltage. Their combination may result in reactive power (var) flow from the utility to the windfarm at high generator output levels and flow from the windfarm to the utility during periods of low power output. Capacitors are often switched off and on with various schemes (see 2.5.4).

2.2.2 Equipment Loading Considerations. Several important factors should be considered in the specification of equipment loading capability. First, the maximum simultaneous output of all wind turbines should be estimated from the wind-turbine ratings (or actual output, if higher) to provide a basis for determining electrical equipment loading. Secondly, ambient temperatures and prevailing winds should be taken into consideration for the loading, placement, and orientation of equipment. This may allow increased loading due to wind cooling of transformers, generators, and overhead conductors. Likewise, de-rating due to high ambient temperature and solar radiation may be required. Transformers should be oriented to allow prevailing winds to pass freely through the cooling radiators. Cooling fans should be directed so as not to compete with prevailing wind patterns. Project capital costs and loss economics should also be considered in the loading and selection of equipment. For recommended practices for system design and analysis, see IEEE Std 141-1986 [29], IEEE Std 399-1980 [33], and ANSI/NFPA 70-1990 [5].

2.3 System Protection. The protection of the intraplant power collection system and the wind-turbine generator connection is similar in protection concepts to those of utility and industrial systems involving the same voltages. The IEEE color book series [29–31, 33–34], the National Electrical Safety Code (ANSI C2-1990 [1]), ANSI/NFPA 70-1990 [5], and the IEEE Protection Guides [9–15] can be applied in most cases. However, the windfarm application of these documents does require some special consideration. Fig 1 shows typical protection for the windfarm collection lines and transformers.

2.3.1 Fault Current Flow. Sources of fault current include both the utility system and the wind-turbine generators themselves. In most cases, the utility network will supply the majority of the fault current. This is particularly

true in the case of induction generators. Even when equipped with power-factor correction capacitors, the fault contribution from induction generators will be moderate in magnitude and short in duration. Fault current contribution will be similar to motor contribution values used in standard short-circuit calculations. Most induction generators operate ungrounded and, as a result, have no zero-sequence contribution to the fault current.

Synchronous generators will normally be wye-connected and, if grounded, are capable of supplying positive, negative, and zero-sequence currents. Like any other synchronous generator, they will be able to maintain these fault currents based on the particular characteristics of the generator and the excitation system. Recommended techniques for fault current analysis will be found in IEEE Std 399-1980 [33].

2.3.2 Fault Interruption and Momentary Ratings. A system fault study should be performed early in the project. All electrical equipment should be rated to withstand and, if required, interrupt calculated system fault currents. Applicable guides and standards are IEEE C37.010-1979 (Reaff. 1988) [16], IEEE Std 141-1986 [29], and IEEE Std 242-1986 [31].

2.3.3 Protective Device Coordination. A protective device coordination study should be performed on the entire intraplant electrical system, including the utility interface. Relay settings should be coordinated with the local utility for proper operation. Settings must be calculated and relays set and tested to specified values. Relays should be retested and their calibration and tripping verified on a two- to three-year schedule. The utility may have other requirements for relays at the interconnection station.

2.3.4 Phase Sequence and Single Phasing. Particular care should be taken to connect and check the phase sequence at each wind turbine. Some wind turbines may sustain damage if the phase sequence is incorrect. For some applications a phase-sequence relay may be advisable.

Single phasing can result in damage to three-phase generators. Each wind turbine should employ a protective device capable of detecting loss of one phase. It may be necessary to use a detection scheme that monitors current or both voltage and current. Single-pole switching should be avoided to minimize

the possibility of single-phase operation of a three-phase system.

2.3.5 Wind Turbine Shutdown. Shutdown is typically required for maintenance, overspeed, mechanical failure, and electrical fault conditions. Wind turbines should be able to shut down safely without utility power. It is also recommended that the site communication system not be required for safe shutdown.

2.3.6 Reclosing and Torque Transients. As a result of very short duration power outages or islanding, very high mechanical torque transients can be experienced by the rotating equipment. When an outage occurs and the electrical interconnection is opened, the rotating equipment accelerates and becomes out-of-phase with the utility system. Upon reconnection, the electrical transients can be very high, up to twice the locked rotor current, and the mechanical drive train torques can reach up to 20 times rated values. For more information, see [44]. This transient can be caused by site collection-line reclosing or by high-speed reclosing on the utility system.

2.4 Insulation, Grounding, and Surge Protection

2.4.1 Insulation Ratings. Standard insulation guidelines may be applied in most cases (see the *Electrical Transmission and Distribution Reference Book* [38]). Local utility practice may also be used as a guide. Special considerations may, however, need to be given to overhead lines, outdoor substations, and metal-clad switchgear due to blowing dust, sand, salt spray, agricultural chemicals, and other contamination in some windfarm areas.

2.4.2 Grounding. Generally, effectively grounded collection systems are preferred for their simplicity and freedom from transient overvoltage and simultaneous fault problems. Effectively grounded systems are usually obtained by a wye-connected, low-voltage winding on the interface station transformer. The high-voltage windings of that transformer may be wye or delta, depending upon the voltage level and utility requirements. Wye-wye connected transformers may require a delta tertiary winding to provide a path for zero-sequence and triplen harmonic current flow.

If the collection system is tied directly to utility lines without an intervening transformer, the collection system grounding must

be coordinated with the utility. The utility should be consulted as to the types of transformers permitted to be connected to such a system. Recommended practice for grounding is given in IEEE Std 142-1982 [30]. For additional information on system neutral grounding, refer to IEEE C62.92-1989 [24].

Regardless of the method of system grounding, it is recommended that the entire windfarm installation have a continuous metallic ground system connecting all equipment. See Fig 2 for a typical arrangement. This should include, but not be limited to, the substation, transformers, towers, wind turbine, generators, and electronic equipment. This system will consist of ground conductors, rods, mats, and connectors. This system will serve to

- (1) Minimize shock hazards to personnel
- (2) Establish a preferred path of return current for fault currents to prevent damage to on-site electrical systems
- (3) Provide a multigrounded neutral to assist in ferroresonance suppression in the site collection system
- (4) Improve reliability and consistency in sensing faults and operation of overcurrent relays
- (5) Improve protection from lightning

2.4.3 Surge Protection. Surge protection for lightning and, particularly, switching surges should be part of the system. Guidelines for surge protection of medium-voltage collection systems can be found in IEEE C62.2-1987 [21]. Information on typical surge environments for low-voltage systems is provided in IEEE C62.41-1980 [22] and IEEE C62.45-1987 [23].

2.5 Voltage Control and Reactive Power Supply

2.5.1 Voltage Considerations. Careful management of the system voltage is very important for several reasons.

- (1) Changes in voltage have an effect on the slip, torque, and power output characteristics of an induction generator.
- (2) Induction generator installations may reduce the line voltage when loaded because of their reactive power (var) demand.
- (3) On-site electronic equipment may be sensitive to variations in voltage.