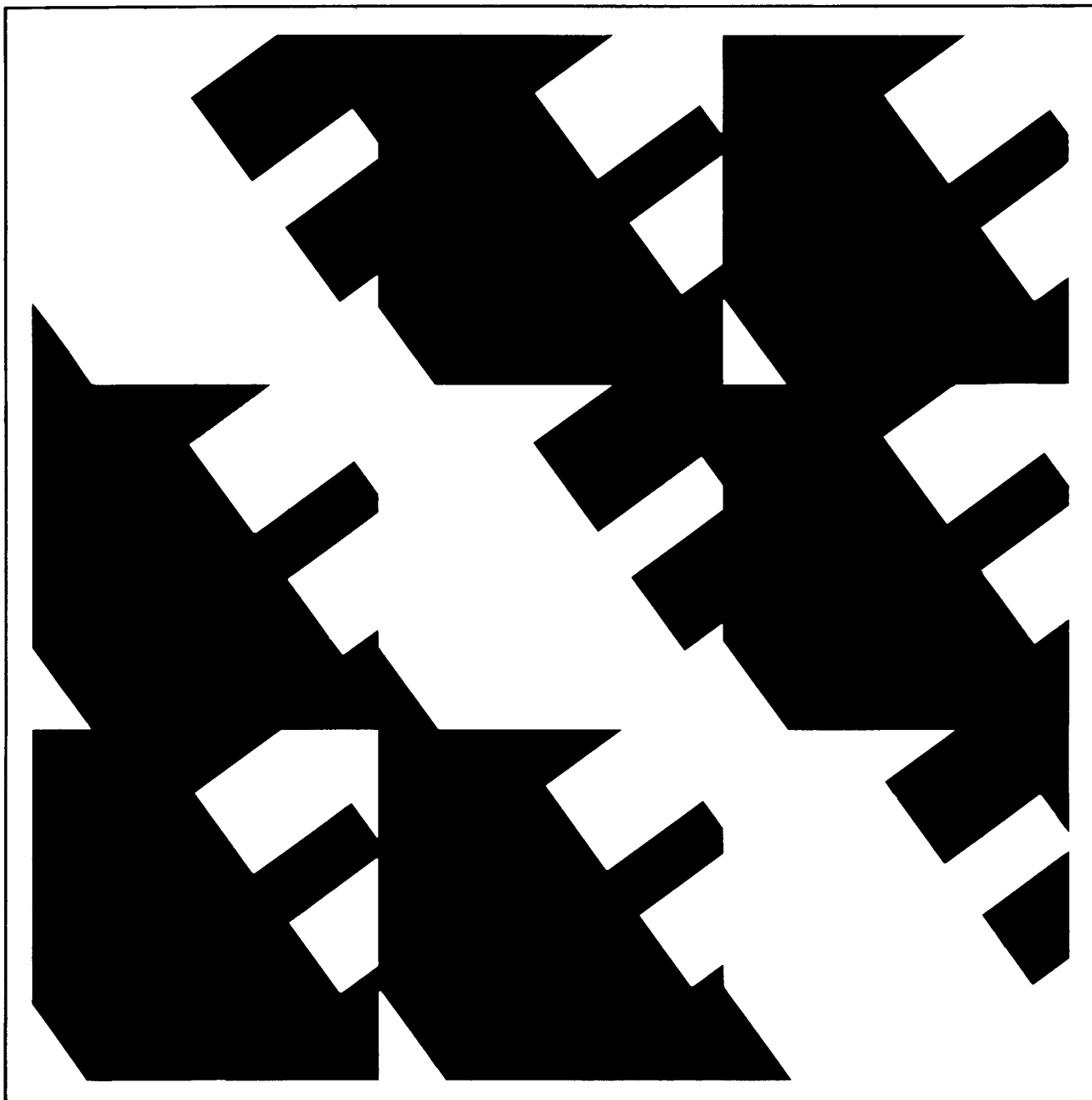


IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems

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Foreword

(This Foreword is not a part of ANSI/IEEE Std 1001-1988, IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems.)

The purpose of this guide is to alert electric utilities, manufacturers of dispersed storage and generation (DSG) equipment, consultants, contractors, present and potential DSG owners and operators, and public regulatory commissions to the engineering concerns inherent in operating dispersed generators in parallel with utility systems; to describe proper interface construction techniques and operating procedures for these generators; to emphasize the safety aspects involved; and to call attention to possible DSG impact on utility customers. It is intended to provide an introduction and general overview of the DSG discipline. Persons requiring technical information on the requirements of constructing and operating a specific type of dispersed generation system should consult manufacturer's instruction books, state public utility regulations, the National Electrical Code (ANSI/NFPA 70-1987), the National Electrical Safety Code (ANSI C2-1987), and appropriate national standards issued by American National Standards Institute, IEEE, ASTM, and other standards-making organizations. Although this document is designed to serve as a guide for interfacing a DSG with its local utility system, the DSG has the sole responsibility of contacting the utility for the purpose of obtaining the requirements necessary to install a dispersed generator. Depending on local conditions, these requirements may be more or less stringent than those outlined in this guide.

This guide was conceived and initiated by Joseph L. Koepfinger, Member Emeritus and former Chairman of the IEEE Standards Board, to which it is respectfully dedicated. The Committee is grateful to Barbara L. Beckwith for her editorial assistance, and to Martha C. Lindsey for typing and retyping and correcting the manuscript over a period of five years.

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An American National Standard

IEEE Guide for Interfacing Dispersed Storage Generation Facilities with Electric Utility Systems

1. Regulatory Requirements

1.1 Introduction. Dispersed storage and generation (DSG) includes electric power produced through cogeneration and through renewable resources, such as biomass, solar, hydro, wind, and municipal waste. A number of federal, state, and local regulations affect the feasibility, design, and operation of a DSG project. These regulations cover such diverse areas as the interchange of electric power, fuel use, financing and ownership, environmental quality, safety, siting, zoning, and local building and electrical codes. While all the regulations in these areas influence the technical and economic feasibility of a DSG project, the intent of this publication is to focus on the engineering aspects of regulations that have an impact on DSG interconnection with a utility system. For a thorough understanding of the legal requirements, the applicable laws and court decisions should be consulted.

1.2 Applicable Regulations. The primary regulatory influence on interconnection is in the area of electric power exchanges. Fuel use and environmental regulations also have a significant technical impact on a DSG project, but do not affect interconnection requirements. While this section lists the more important aspects of federal and state regulations, it primarily focuses on those portions that deal with the exchange of electric power between a DSG project and a utility.

1.3 Public Utility Regulatory Policies Act. The Public Utility Regulatory Policies Act (PURPA) [1]¹ and [2], a part of the 1978 National Energy Act, provides incentives for cogeneration and other forms of alternative energy production from renewable sources. PURPA has fostered changes in the procedures

¹The numbers in brackets correspond to those of the references listed at the end of this section.

in which electricity is generated in the United States and has provided significant opportunities to nonutility generators. Certain provisions of PURPA also have important implications for power exchanges between DSG and utilities.

In the past, a developer of cogeneration or small power production facilities faced three major regulatory and economic obstacles:

- (1) Utilities were not generally required to purchase the electric power generated by these facilities and were not required by law to pay *appropriate* rates for this power.
- (2) Some utilities charged rates for backup power that were considered to be excessive by cogenerators and small power producers.
- (3) A cogenerator or small power producer providing electricity to a utility grid might be subjected to the same state and federal regulations as an electric utility. References [3] and [4] of PURPA were designed to remove these obstacles and encourage cogeneration and small power production.

The Federal Energy Regulatory Commission (FERC) issued proposed regulations implementing [3] and [4] of PURPA in 1979. After a series of public hearings, analysis of the extensive written comments received, and consultation with state public utility regulatory commissions, final rules were issued under [4] on February 19, 1980, and under [3] on March 13, 1980.

The rules to implement [3] of PURPA set forth the criteria and procedures by which DSG facilities can obtain qualifying status to receive the benefits available under [4] of PURPA. The rules implementing [4] require electric utilities to purchase electric power from, and sell electric power to, qualifying

facilities, and exempt qualifying facilities (QF) from certain federal and state regulations. Implementation of these rules is reserved to state regulatory authorities and nonregulated electric utilities.² Specific provisions of the FERC rules are summarized in 1.3.1 and 1.3.2. It should be noted that some DSG projects are viable on their own and do not specifically require the PURPA incentives and related regulatory requirements to succeed. Many utilities have interconnected with successful DSG projects outside of PURPA. Designing a project to meet PURPA requirements can be helpful, but it is not always a prerequisite for project viability.

1.3.1 Rules Under Reference [3] of PURPA. FERC rules under reference [3] of PURPA are as follows:

- (1) Establish the ownership criteria for a QF.
- (2) Establish requirements for sequential energy use, heat utilization, and, for facilities using natural gas or oil, the efficiency that must be achieved by a cogeneration facility to become a qualifying facility.
- (3) Establish an 80 MW limit and fuel use requirements for a small power production qualifying facility.
- (4) Establish the procedures for obtaining qualifying status.

These rules permit cogeneration and small power production facilities to obtain qualifying status (required to receive benefits under [4]) without a need for specific FERC action. They also make available an optional procedure under which, should it prove desirable, a facility can gain FERC certification as a qualifying facility.

1.3.2 Rules Under Reference [4] of PURPA. FERC rules under reference [4] of PURPA include the following requirements:

- (1) Electric utilities must purchase electric energy and capacity made available by qualifying cogenerators and small power producers.
- (2) The rates for utility purchase of energy and capacity must reflect the cost that the purchasing utility can avoid as a result of the purchase, rather than generating

an equivalent amount of energy itself, or purchasing the energy or capacity from other suppliers.

- (3) The rates under private contract with terms not conforming to the rules are not precluded.
- (4) Electric utilities are required to furnish data concerning present and future costs of energy and capacity on their systems.
- (5) Electric utilities must furnish electric energy to qualifying facilities on a nondiscriminatory basis, and at a rate that is just, reasonable, and in the public interest.
- (6) Electric utilities must provide certain types of services that may be needed by qualifying facilities.

Within the context and scope of this guide, major areas of interest under the PURPA rules include both the basis for obtaining qualifying status and the interconnection rules for DSG projects. These areas are discussed in 1.3.3–1.4. The rates paid by the utility for DSG power are outside the scope of this guide.

1.3.3 Qualifying Status. The key to receiving the benefits offered by PURPA is to obtain qualifying status through either self-qualification or FERC certification. Self-qualification is the easier approach, which requires only a letter to FERC documenting that the proposed facility meets the eligibility requirements described in 1.3.3.1 and 1.3.3.2.

1.3.3.1 Qualifying Cogeneration Facility.

- (1) Produce electric energy and other forms of useful energy (such as heat, steam, and hot gases) for industrial, commercial, heating, or cooling purposes, through the sequential use of energy.
- (2) Owned less than 50% by electric utility.
- (3) Meet certain operating and efficiency standards when oil or natural gas serves as a primary fuel.³

³For a topping-cycle facility, the operating standard requires the annual thermal energy output to be not less than 5% of the total energy output. The operating standard also requires that the useful power output of the facility, plus half the useful thermal energy output, be not less than 42.5% of the total energy input of oil and natural gas. (When the useful thermal energy output is less than 15% of the total energy output, then the standard is 45%.) For a bottoming-cycle facility, there is only an efficiency standard: the useful power output must be not less than 45% of the energy input of oil and natural gas for supplementary firing.

²Nonregulated electric utilities are those not subject to the retail rate-making authority of a state commission. Examples include municipal utilities, public power agencies, and federal power marketing administrations.

1.3.3.2 Qualifying Small Power Production Facility.

- (1) Have a power production capacity of 80 MW or less.
- (2) Produce electric energy using primary energy source of at least 75% biomass, waste, renewable resources, or a combination thereof on an annual basis.
- (3) Be less than 50% owned by an electric utility.

1.3.4 Certification Options. Self-qualification, however, may not always be sufficient. In some cases, either the interconnecting utility or the potential financial backers of the project may challenge the self-qualification. In such instances, FERC has designed an option of applying for certification. The following additional information is required for FERC certification:

- (1) Description of the DSG system, including information required by FERC to determine that applicable operating and efficiency standards are met.
- (2) The installation date of the facility.

Within 90 days of receipt of the application, FERC is required to issue an order granting or denying the application. When any application is denied, FERC will identify specific requirements that were not met. When an order is not issued within 90 days of filing, certification as a QF is automatic. It should be noted that there are special FERC requirements for hydroelectric licenses [5].

1.4 Interconnection. A qualifying facility, upon application to the utility and after meeting certain technical requirements, must be permitted to interconnect with the utility grid. FERC rules cover the obligation of utilities to interconnect with DSG facilities (see [6], (c)) and treatment of interconnection costs (see [7]) as follows:

1.4.1 Obligation to Interconnect

- (1) Subject to [6],(c)(2), any electric utility shall make such interconnections with any qualifying facility as may be necessary to accomplish purchases or sales under this subpart. The obligation to pay for any interconnection costs shall be determined in accordance with [7].
- (2) No electric utility is required to interconnect with any qualifying facility, if

solely by reason of purchases or sales over the interconnection, the electric utility would become subject to regulation as a public utility under Part II of the Federal Power Act.

1.4.2 Interconnection Costs

- (1) *Obligation to pay.* Each qualifying facility shall be obligated to pay any interconnection costs that the state regulatory authority (with respect to any electric utility over which it has ratemaking authority) or nonregulated electric utility may assess against the qualifying facility on a nondiscriminatory basis with respect to other customers with similar load characteristics.
- (2) *Reimbursements of interconnection costs.* Each state regulatory authority (with respect to any electric utility over which it has ratemaking authority) and nonregulated utility shall determine the manner for payments of interconnection costs, which may include reimbursements over a reasonable period of time.

While the FERC rules under PURPA provide some guidance, each state is responsible for developing its own rules for interconnection between a DSG project and a utility. Many states have adopted FERC rules and have done so with varying degrees of specific detail.

Adoption of the FERC interconnection rules in this manner does not provide much guidance to most DSG projects or utilities. The FERC rules identify cost considerations but do not include a basis for computing the cost. Additionally, estimates of costs of interconnecting with a cogenerator or small power producer vary among utilities and for different DSG system sizes, configurations, and locations.

The states have taken different approaches for determining costs of interconnection. Many states that have adopted the FERC rules verbatim require utilities to assess any charges to the qualifying facility on a *nondiscriminatory basis with respect to other customers of similar size and load characteristics* [3] and [4]. Other states have taken an approach that limits the interconnection costs to be borne by a qualifying facility for any

additional expenses incurred by the utility to permit utility purchase of electrical energy.

The types of interconnection equipment which a cogenerator or small power producer may be required to provide depend on specific utility requirements, with state commission review. This would typically include protective isolation devices and metering equipment. The engineering requirements associated with DSG interconnections constitute the primary thrust of this guide and are covered in subsequent sections.

1.5 Understanding the Local Situation. Prior to initiation of any DSG project, it is important to assess the local situation. The following topics should be considered:

- (1) Utility interconnection requirements.
- (2) Previous DSG interconnections with the utility.
- (3) State commission rules for interconnection.
- (4) Utility avoided cost rate, present and future.
- (5) Requirements of ANSI/NFPA 70-1987 [8], Article 705.

Electric utilities have different policies concerning dispersed storage and generation. Some utilities have significant excess capacity, while others have low reserve margins. Some serve areas where small power producers predominate, while others deal primarily with larger cogenerators. An awareness of these issues will help the DSG project developer evaluate the technical requirements and the associated economic impact of interconnection with the utility grid.

1.6 References. The following publications shall be used in conjunction with this section.

[1] 45 CFR, Part 38, (PURPA) Public Utility Regulatory Policies Act.⁴

⁴CFR publications are available from Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

[2] 45 CFR, Part 56, (PURPA) Public Utility Regulatory Policies Act.

[3] 45 CFR, Part 201, (PURPA) Public Utility Regulatory Policies Act.

[4] 45 CFR, Part 210, (PURPA) Public Utility Regulatory Policies Act.

[5] FERC-0100, Application Procedures for Hydro Power Licenses, License Amendments, Exemptions, and Preliminary Permits.⁵

[6] 18 CFR, Part 292, 303(c) and (c)(2), Conservation of Power and Water Resources.

[7] 18 CFR, Part 292, 306, Conservation of Power and Water Resources.

[8] ANSI/NFPA 70-1987, National Electrical Code.⁶

1.7 Bibliography

[B1] Conference Report. Public Utility Regulatory Policies Act, House of Representatives, Report no 95-1750, Oct 10, 1980.

[B2] HARKINS, H. L. PURPA—New Horizons for Electric Utilities and Industry. *IEEE Transactions*, vol PAS-100, no 6, Jun 1981, pp 2783–2789.

[B3] REDDOCH, T. W. PURPA and Associated Technical Issues. *Proceedings of the IEEE 1981 and International Conference on Electric Energy*, Oklahoma City, Oklahoma, Apr 13–15, 1981.

⁵FERC documents are available from the Federal Energy Regulatory Commission, Public Reference Room 1000, 825 North Capitol Street, NE, Washington, DC 20426.

⁶This publication can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from Publication Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

2. Electric Distribution System

2.1 Circuit Description. The majority of electric utility customers in the United States receive service from single-phase transformers connected to three-phase, four-wire solidly grounded distribution circuits. These circuits usually have only one source and are fed by substation transformers connected as shown in Fig 1. The phase-to-phase voltage on these circuits generally ranges from 4160 to 13 800 V, with a large number operating at 12 470 V. Other distribution circuits operate at higher voltages, including particularly 24 900 and 34 500 V. Also, ungrounded delta circuits still exist in certain areas, most often at the 2300 V level, but this type represents a very small percentage of the total.

Most distribution substation transformers are connected so as to block the flow of zero-sequence current between the high-voltage (supply) side and the low-voltage (distribution) side. The delta/gye connection shown in Fig 1 is the most common arrange-

ment, but delta/zig-zag and ungrounded-wye/delta/grounded-wye connections are also employed. With these connections, the substation transformer generally provides the only source of zero-sequence current, except in certain cases noted below. A few utilities serve distribution substations with autotransformers, both with and without delta tertiaries. With this connection, it is usually necessary to coordinate the transmission line ground relays with the ground relays protecting the autotransformer and the distribution circuits.

Most load on four-wire distribution circuits consists of single-phase distribution transformers, connected between one of the phase wires and the neutral conductor (Fig 2). The neutral conductor is connected to earth at the substation and at frequent intervals throughout the length of the circuit. Since it is impossible to exactly balance the load between the three phases, there is usually a continuous flow of residual current in the neutral, but this

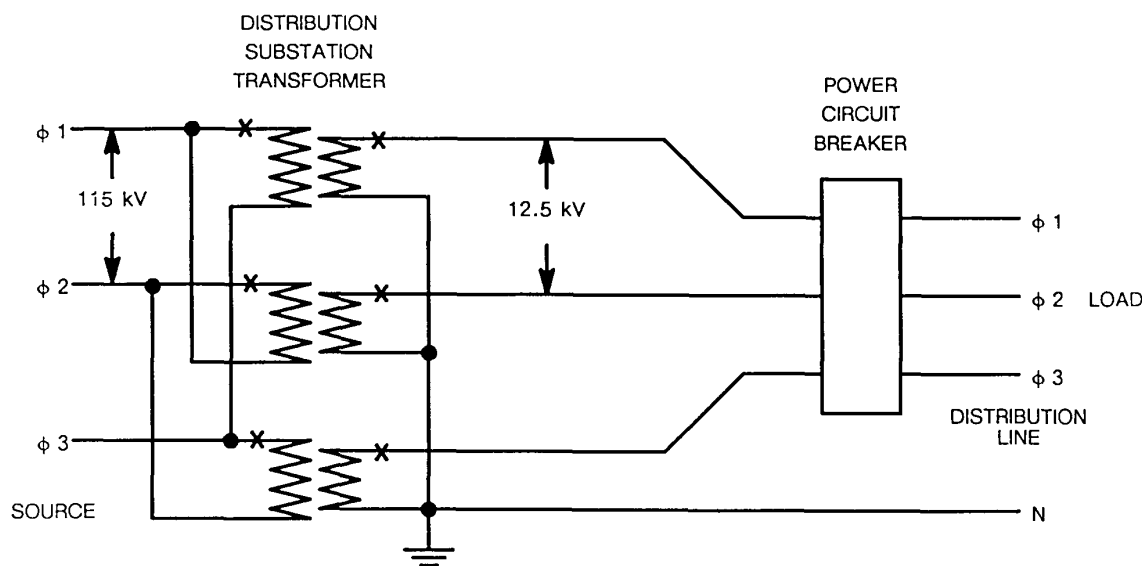


Fig 1
Substation Transformer Connection

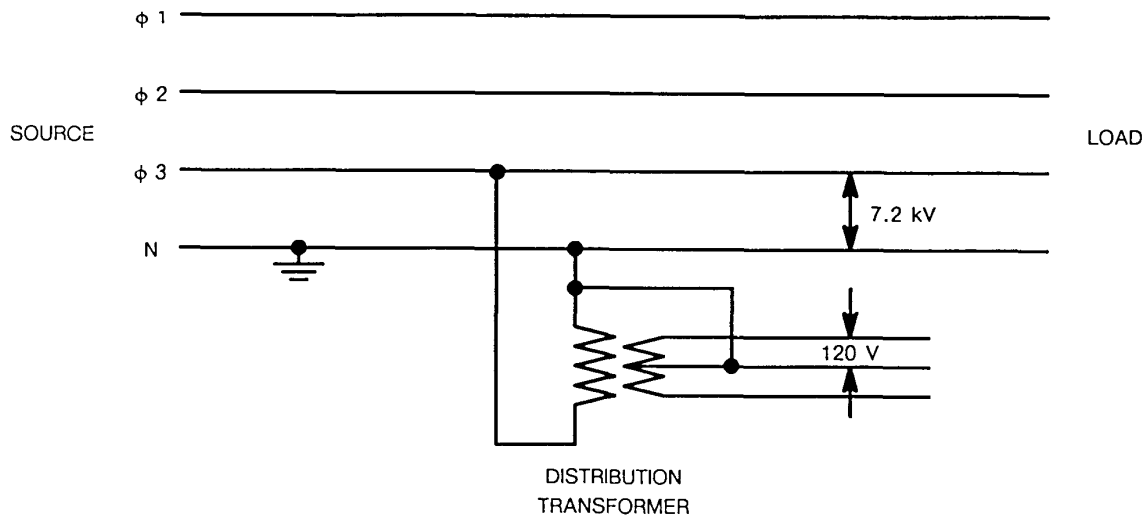


Fig 2
Distribution Transformer Connection

normally presents no hazard since this conductor is maintained at or near ground potential.

Three-phase load is connected to four-wire distribution circuits using a variety of transformer connections. Some of the more common methods are as follows:

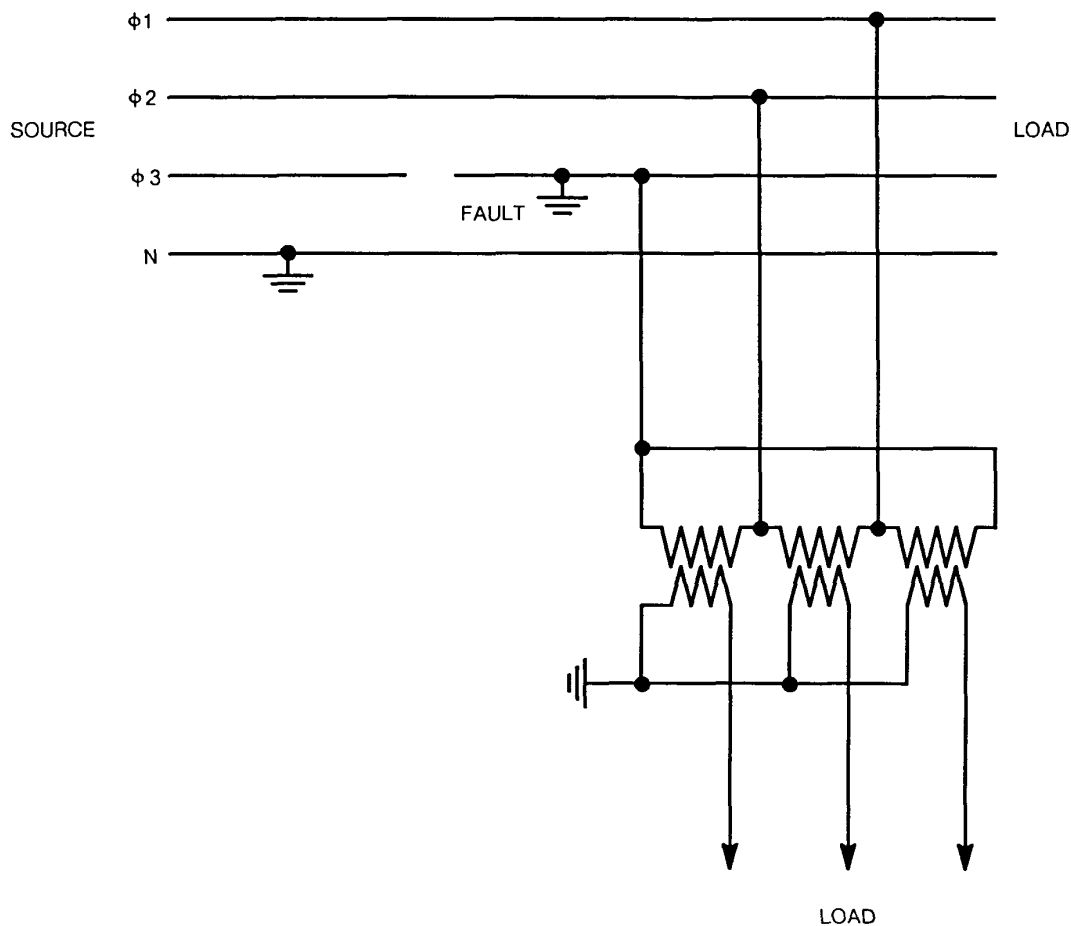
- (1) Primary in ungrounded wye, secondary in delta.
- (2) Primary in grounded wye, secondary in delta.
- (3) Primary and secondary in grounded wye.
- (4) Primary in delta, secondary in grounded wye.
- (5) Primary and secondary in delta.

The method used may have a significant effect on circuit protection. For example, transformers connected as in method (2) will serve as zero-sequence current sources when a ground fault occurs on the primary circuit. For wye-grounded circuits, this will reduce the zero-sequence current available at the source substation and will result in desensitizing the substation ground-fault protective devices. Method (3) is commonly used to connect overhead and underground distribution transformers serving large loads, such as shopping centers, apartments, and small industries.

Transformers connected as in method (3) provide a path for zero-sequence current from the primary to the secondary, so that all line protective devices must be coordinated with the distribution transformer primary fuses. This may tend to force up the settings on some of these devices, and thus reduce their sensitivity. In addition, three-phase transformer banks may energize broken phase wires that are grounded on the load side only if the three-phase bank is located on the same side as the ground (see Fig 3).

A variety of other arrangements for connecting distribution loads also exist. Some utilities connect distribution transformers as shown in Fig 2 but use an insulated neutral, grounded only at the substation. Others do not bring the neutral out of the substation at all but use single-phase transformers connected line-to-line. In general, however, most of the various service methods presently employed in the United States will permit overhead distribution customers to install dispersed storage and generation, if this equipment is properly designed and constructed [1].⁷

⁷The numbers in brackets correspond to those of the references at the end of this section.



3 ϕ bank keeps broken phase energized

Fig 3
Distribution Transformer Connection — 3 ϕ

Feeder and main sections of modern distribution circuits are generally constructed of large conductor, with ampacity ranging from 500–800 A or more. However, a considerable number of circuits are still in service, particularly on branches off the main trunk, that are built with small conductors, such as 1/0 aluminum or no 6 copper. These lines have limited load capability and tend to anneal and

melt quickly when faulted; for this reason they are normally protected by small line fuses that must be coordinated with the distribution transformer cutouts. Circuit lengths vary considerably, from 1 or 2 mi in dense urban areas to as much as 20 mi or more in sparsely populated rural locations.

A large percentage of distribution consumers in the United States are served from

single-phase lines, and some are many miles from the nearest three-phase supply. Dispersed storage and generation (DSG) facilities connected to these circuits will be limited to relatively small capacity. This might mean, for example, that someone wishing to install a small hydroelectric unit in the 500–1000 kW range would be faced with the expense of paying the nearest utility to extend three-phase service over a considerable distance.

Some utility customers are connected to radial underground distribution circuits. Those connected to underground residential distribution (URD) lines can probably install DSG equipment on the same basis and with the same limitations as customers connected to overhead lines. DSG connected to underground secondary networks, or *spot* networks, may have difficulty maintaining continuous parallel operation with the utility. This is because the network transformer secondary circuit breakers are usually equipped with sensitive network protector relays, and these devices will not permit any reverse power flow. This could mean that even a very slight excess of generation over load would cause operation of the network protectors and result in total disconnection of all customers, even under normal, steady-state (no fault) conditions.

Most customers connected to distribution circuits are metered by one single-phase watthour meter. If a customer decides to install a generator for parallel operation, additional meters may be required, according to what tariffs are adopted for a particular area. For example, one state utility commission requires four meters:

- (1) A meter registering the energy consumed by the customer.
- (2) A meter registering the energy produced by the customer's generator.
- (3) A detented meter registering total kWh flowing from the utility to the customer.
- (4) A detented meter registering total kWh flowing from the customer to the utility.

These additional meters obviously involve additional costs, most of which would probably have to be borne by the DSG owner [1]. On the other hand, in some states no additional metering is required for small DSG facilities.

2.2 Short Circuits. Short circuit currents on distribution circuits in the United States range from over 20 000 A to values less than 1 A

for high-impedance single-phase-to-ground faults. The maximum fault can be controlled by system design, and most utilities set an upper limit of approximately 10 000 A, so as not to exceed the rating of certain types of distribution line equipment. Maximum faults are limited by restricting substation transformer size and impedance, or both, by installing bus or circuit reactors, or by inserting reactance or resistance in the transformer neutral. On most circuits, the maximum fault is a bolted single phase-to-ground fault at the substation; but since the zero-sequence impedance of a distribution circuit is about three times the positive-sequence value, a three-phase short circuit becomes the higher magnitude fault after moving down the circuit a few thousand feet. Minimum fault magnitude cannot be controlled, as this value is largely dependent on fault resistance; and these faults are the most dangerous and difficult to detect.

Clearing times for short circuits on distribution circuits vary widely, depending on fault magnitude and the type of protective equipment installed. In general, on most circuits, faults above about 3000 A will be cleared in 0.1 s or faster. Low current faults frequently require clearing times of 5–10 s or longer; and some very low level but potentially dangerous ground faults may not be cleared at all, except by manual disconnection of the circuit.

Consumers considering DSG installations will generally not have to concern themselves with how high or how low the short circuit current values are on the distribution supply line, since the impedance of distribution transformers effectively isolates the secondary service from damage due to primary faults. However, generators connected directly to the distribution line would definitely be affected by the fault level, if such a connection was permitted by the utility.

2.3 Circuit Protection. A one-line diagram of a typical distribution circuit, showing some of the protective devices commonly employed, is shown in Fig 4. The circuit is normally supplied through a single power circuit breaker located at the supply substation and is divided into various zones by automatic sectionalizing devices. These devices are all carefully coordinated, so that a fault in any section can be quickly isolated with minimum or no

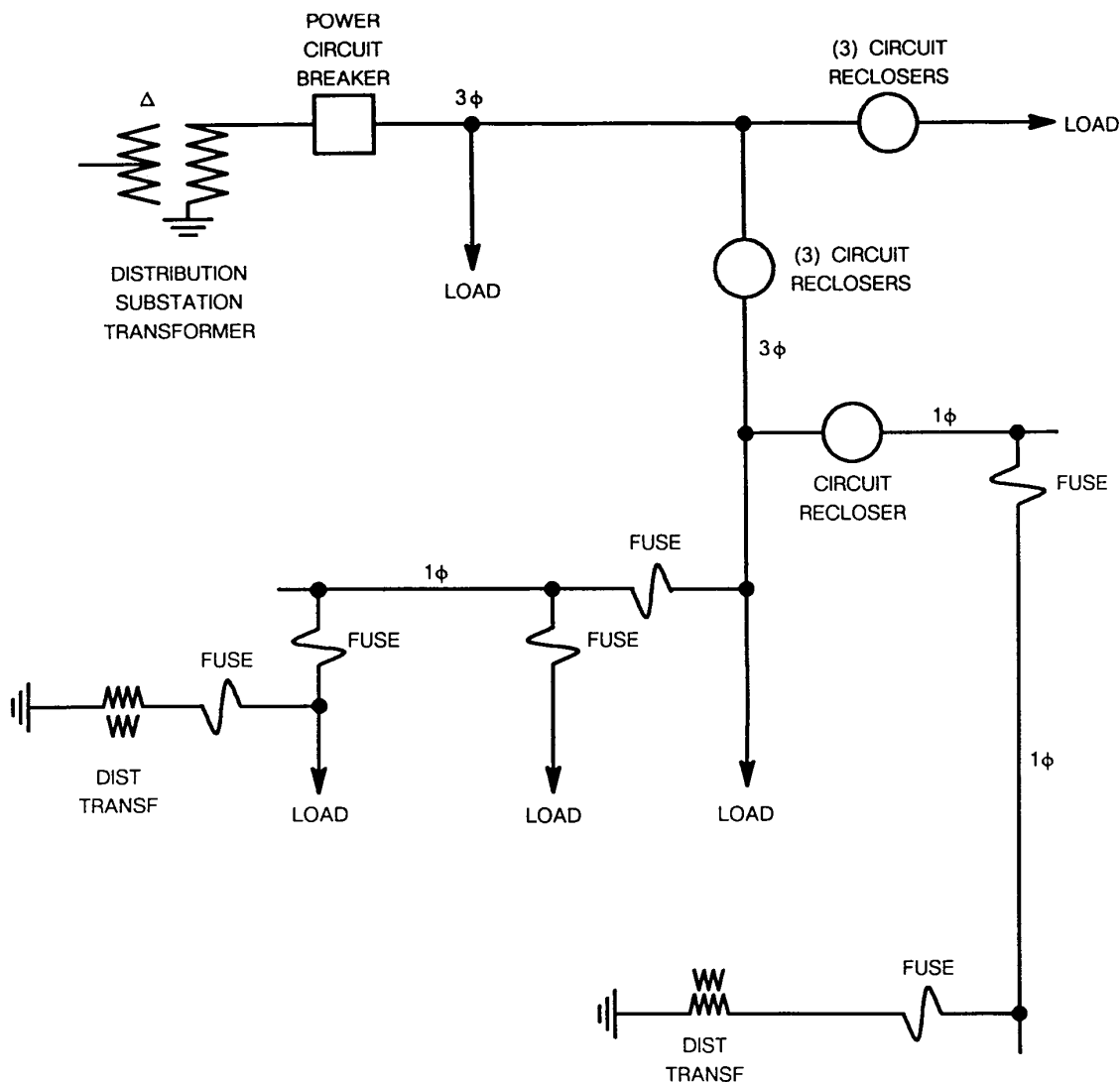


Fig 4
Distribution Circuit Diagram

interruption to other portions of the circuit. Of course, a fault in the main trunk section near the source breaker will require that the entire circuit be interrupted. However, if automatic reclosing is employed, the duration of outages due to transient faults in this zone will be limited to a brief interval, often considerably less than 1 s.

Most electric utilities depend upon phase overcurrent relays and a residually connected overcurrent relay, usually referred to as a *ground relay*, to detect faults on the main trunk portion of distribution circuits. These relays may be installed in the control cabinet of the substation power circuit breaker protecting the circuit, and are connected as

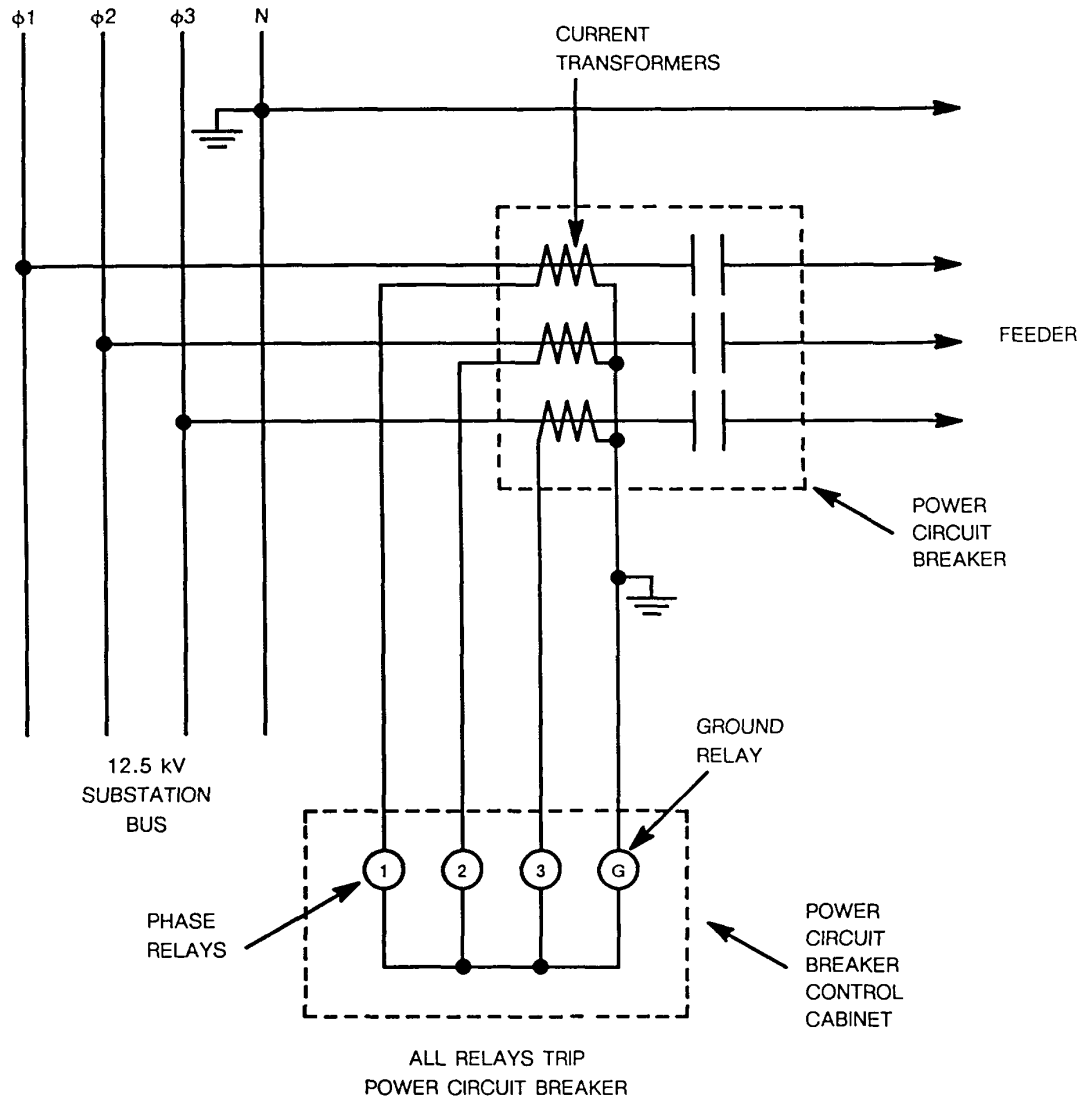


Fig 5
Overcurrent Relay Connection Diagram

shown in Fig 5. The phase relays are relatively insensitive to single phase-to-ground faults, because they must be set to operate above the maximum expected load current under emergency conditions. As a result, phase relay settings of 600–1200 A are not uncommon, particularly in urban areas. The circuit ground relay receives the phasor

sum of the currents in the three phase relays, and both types of relays must be coordinated with all protective devices on the circuit.

The sensitivity of phase and ground overcurrent relays is generally limited by the fact that they must be set high enough to coordinate with all downstream protective devices, and high enough to prevent incorrect

tripping due to the large inrush currents that may occur during cold-load pickup. Ground relays must also be set high enough to prevent accidental tripping due to unbalanced load conditions, and it should be noted that this imbalance may be greatly increased when a fuse or oil circuit recloser serving a single-phase tap operates. It should also be noted that the sensitivity of any overcurrent protective device will always be limited by the need to survive the high inrush currents that will occur when the circuit is reenergized after a long outage. These currents have increased markedly in recent years, particularly with the advent of large numbers of home and commercial electric heating and cooling units now installed in most areas.

The detection of ground faults on single-phase taps may be greatly improved if a fuse or recloser is installed at the point where the tap is connected to the main line. These devices will usually operate at a considerably lower fault current level than the relays in the station breaker; however, their sensitivity is still limited by the amount of load current that must be carried on the tap and the fact that they must coordinate with the fuse protecting the largest transformer connected to the tap.

The ability of substation protective devices to detect line faults may be degraded by the addition of DSG to a distribution circuit. This problem will be particularly acute in those instances where the DSG is connected to the system through a grounded wye/delta transformer bank, with the wye connected to the utility line. In this case, some line-to-ground fault current will be shunted out of the utility source breaker by the DSG bank, thus desensitizing the circuit protection. Circuit protection will also be impaired if it becomes necessary to remove line reclosers or fuses in order to permit DSG operation; and overall circuit coordination may be adversely affected, particularly if the DSG is capable of contributing a significant amount of fault current [2].

A DSG connected to a wye-grounded circuit may cause dangerous overvoltages when a fault occurs between an energized phase conductor and ground, particularly if the substation transformer is the only zero-sequence current source on the circuit. Once the fault is detected and *cleared* by opening the station breaker, the circuit is no longer

effectively grounded. If there is a three-phase DSG that feeds into the utility system through transformers that are delta-connected on the utility side, all phase-to-ground connected equipment on the unfaulted phases will be subjected to full line voltage. Since damage may result if this condition is allowed to persist, a zero-sequence voltage relay that will promptly disconnect the dispersed generator and prevent isolated operation is generally installed (see Section 7).

2.4 Automatic Reclosing. Operation of dispersed storage and generation in the United States may be affected by the automatic reclosing schedule adopted by individual utilities for their distribution circuits. Some companies do not reclose the substation power circuit breaker after a protective relay operation under any circumstances, but prefer to rely on supervisory control or manual restoration of service. Other companies prefer one-shot, ultra-high-speed reclosing on all overhead circuits. Most utilities, however, utilize multiple-shot reclosing for their distribution station breakers. The initial reclosure can be high-speed (0.2–0.5 s), or delayed for 3–5 s. Then, one or two additional time-delayed reclosures are programmed on the reclosing relay. Typical schedules might be *instantaneous*, followed by 15 s, followed by 60 s; or *instantaneous*, followed by 30 s; or 3 s, followed by 15 s. In general, automatic reclosing is not used on underground network cables.

Three-phase and single-phase oil or vacuum circuit reclosers are widely used on overhead distribution lines. Most of these devices are set to provide *three shots to lockout*. That is, after a fault is detected by the overcurrent sensing element, the recloser will open to deenergize the circuit and reclose after about 1.5 s. This sequence will be repeated two more times, unless the fault has been cleared. If the fault is *permanent*, the recloser locks open after the fourth trip operation.

The possible effects of automatic reclosing on dispersed storage and generation are discussed in later sections. However, it is probable that some of these effects are not clearly understood at present, due to lack of experience in the industry.

2.5 References. The following references shall be used in conjunction with this section.

[1] STAFFORD, R. W. and SODERHOLM, L. H. Analysis of Problems of Interfacing Wind Systems to Rural Power Distribution Systems, *US Dept of Agriculture Report DOE/ARS-3408-20691/83/1*, Iowa State University, Mar 1983.

[2] Protection of Electric Distribution Systems with Dispersed Storage and Generation (DSG) Devices, *Oak Ridge National Laboratory Report ORNL/CON-123*, Sep 1983.

2.6 Bibliography

[B1] Distribution System Protection Manual. McGraw-Edison Co, Canonsburg, PA, Bulletin no 71022.

[B2] Distribution Systems. Westinghouse Electric Corp, East Pittsburgh, PA, 1965.

[B3] EASLEY, J. H. Dispersed Storage and Generation—How it will Affect the Distribution System. *Electric Forum*, General Electric Co, vol 8, no 1, 1982, pp 26–31.

[B4] RIZY, D. T., JEWEL, W. T., and STOVAL, J. P. Operational and Design Considerations for Electric Distribution Systems with Dispersed Storage and Generation (DSG). *Oak Ridge National Laboratory Report ORNL/CON-134*, Sep 1984.

3. Dispersed Storage and Generation Technologies

3.1 Dispersed Storage and Generation Systems. A dispersed storage and generation (DSG) system consists of both a source of energy for conversion to electricity and a means to interconnect this power to the electric utility system. This section provides an overview of the generation technologies and power conversion equipment used in DSG installations. The emphasis is on *small power producers* using renewable forms of energy, rather than on large cogeneration equipment used in industrial applications. In general, small dispersed generators are less than 5 MW and are normally connected to the utility distribution system. Installations of this size constitute the majority of DSG interconnections in the United States. Larger systems are typically connected to utility transmission and subtransmission circuits and may have capacities up to several hundred megawatts.

Electric energy generated by cogenerators and small power producers may be directly connected to a utility system, or indirectly connected through a device called a static power converter (SPC). Directly connected synchronous generators must run at a synchronous shaft speed so that the power output is electrically in synchronism with the utility system. Directly connected induction generators are asynchronous (not in synchronism). They operate at a rotational speed that varies with the prime mover and is slightly higher than that required by a synchronous generator. Indirect connection through a static power converter allows the electric energy source to operate independently of the utility voltage and frequency. The method chosen to interconnect any of these energy sources to the utility is dependent on the type of generation, its characteristics, its capacity, and the type of utility service available at the site. It is important to note that *qualified personnel* are required for the proper design, construction, operation, and maintenance of DSG installations.

3.2 Mechanical and Electrical Power Conversion Devices

3.2.1 Rotating Synchronous Generators.

Most generators in service today are synchronous generators. A synchronous generator is an ac machine in which the rotational speed of normal operation is constant and in synchronism with the frequency of the electric utility system to which it is connected. Synchronous generators that have their field excitation supplied either by a separate motor-generator set, a directly coupled self-excited dc generator, or a brushless exciter do not require an outside electrical source; therefore, this type of generator can run either *stand alone* or interconnected with the utility. When interconnected, the generator output is exactly in step with the utility voltage and frequency. Note that separately excited synchronous generators can supply sustained fault current under nearly all operating conditions.

A synchronous generator requires more complex control than an induction generator, both to synchronize it with the utility system, and to control its field excitation. It also requires special protective equipment to isolate it from the utility under fault conditions. Significant advantages include the fact that this type of machine can provide power during utility outages and it also permits the DSG owner to control the power factor at his facility by adjusting the dc field current.

3.2.2 Induction Generators [1].⁸ An induction generator is an asynchronous machine that requires an external source to provide the magnetizing current necessary to establish the magnetic field across the air gap between the generator rotor and stator. Without such a source, an induction generator cannot supply electric power but must always operate in parallel with a utility, a synchronous machine, or

⁸The numbers in brackets correspond to those of the references listed at the end of this section.

a capacitor that can supply the reactive requirements of the induction generator.

In certain instances, an induction generator may continue to generate electric power after the utility source is removed. This phenomenon, known as self-excitation, can occur whenever there is sufficient capacitance in parallel with the induction generator to provide the necessary excitation and when the connected load has certain resistive characteristics. This external capacitance may be part of the DSG system or may consist of power factor correction capacitors located on the utility circuit to which the DSG is directly connected.

Induction generators operate at a rotational speed that is determined by the prime mover and is slightly higher than that required for exact synchronism. Below synchronous speed, these machines operate as induction motors and thus become a load on the electric utility.

Some advantages of the induction generator are as follows:

- (1) It needs only a very basic control system, since its operation is relatively simple.
- (2) It does not require special procedures to synchronize with the electric utility, since this occurs essentially automatically.
- (3) It will normally cease to operate when a utility outage occurs.

However, it should be noted that, although no special synchronizing controls are required, potentially damaging inrush currents and associated torques can result when connecting some types of induction generators to the utility at speeds significantly below synchronous speed. An induction generator, regardless of load, draws reactive power from the utility system and may adversely affect the voltage regulation on the circuit to which it is connected.

3.2.3 Electric Power Converters. Some DSG installations produce electric power having voltages not in synchronism with those of the electric utility network to which they are connected. The purpose of an electric power converter is to provide an interface between the nonsynchronous DSG output and the utility. Two categories of nonsynchronous DSG output voltages are as follows:

- (1) Direct current voltages generated by dc generators, by fuel cells, by photovoltaic

devices, by storage batteries, or by an ac generator through a rectifier.

- (2) Alternating current voltages generated by a synchronous generator running at nonsynchronous speed, or by an asynchronous generator.

As a consequence of these two broad categories of nonsynchronous DSG output voltages, two broad categories of electric power converters can be used to connect the DSG to the utility network:

- (1) dc-to-ac electric power converter: In this case, the input voltage to the device is generally a nonregulated dc voltage. The output of the device is at the appropriate frequency and voltage magnitude as specified by the local utility.
- (2) ac-to-ac electric power converter: In this case, the input frequency and voltage magnitude to the device, or both, is not that required by the local utility. The output of the device is at the appropriate frequency and voltage magnitude as specified by the local utility.

Two types of converters are available to achieve dc-to-ac or ac-to-ac conversion:

- (1) *Rotating machinery converters:* Rotating power converters are highly reliable and provide a *clean* output to the utility network, with voltage and current harmonic content typical of asynchronous and synchronous generators. Their principal disadvantage is their high initial cost as compared to static power converters.
- (2) *Static power converters (SPC)* are built using diodes, transistors, and thyristors, with ratings compatible with DSG applications. These solid-state devices are configured into rectifiers (to convert an ac voltage into a dc voltage), or into inverters (to convert a dc voltage into an ac voltage), or into cyclo-converters (to convert ac voltage at one frequency into ac voltage at another frequency). Some types require the utility source to operate while others may continue to function normally after a utility failure. The major advantages of solid-state converters are their higher efficiency and their potentially higher reliability as compared with rotating machinery

converters. The disadvantages can be the relatively high harmonic content of their output and their high reactive demand on the utility system. Appropriate techniques are available to limit both the harmonics and the var requirements; but if power factor correction capacitors are installed, they must be applied with care in order to prevent resonance.

3.3 DSG Energy Sources. Generation of electric power by DSG installations can be obtained from a variety of renewable energy sources, such as hydro, solar, and wind, as well as from conventional fossil fuels. The characteristics and capabilities of the major dispersed generation sources are briefly described in 3.3.1 through 3.3.5.

3.3.1 Hydroelectric Power [2]. DSG hydroelectric generators may range in size from a few kilowatts to 80 MW (by PURPA definition, see Sec 1, reference [1]). Many of the low-head, low-flow hydro units now being marketed are in the 100 to 1000 kW range. A one-line electric diagram of a typical small hydroelectric installation is shown in Fig 6.

The potential energy and peak capacity available from a DSG hydroelectric site depend on several factors. One is the average stream flow at the site, which depends on annual precipitation and on watershed characteristics, including drainage area, type of cover, slope, etc. Other important factors are the head available to the water turbine and the degree of hydraulic, mechanical, and electrical losses involved.

A rough approximation of the peak capacity (in kW) available from a site can be made by multiplying the head in feet by the maximum flow rate in cubic feet per second and dividing by 15. Energy available in kWh may be approximated by multiplying the head in feet by the average flow rate in ft³/s, dividing by 15, and multiplying by the number of hours in the time period being analyzed.

If the flow rate is not known, it can be estimated by multiplying precipitation for a given period (month or year) by the drainage area, and dividing by the time period to obtain rainfall in ft³/s. Flow actually reaching the site (runoff), however, is less than this amount because of hydrologic losses. This runoff may be approximated by multiplying the rainfall

by a runoff coefficient of 50% or less.

DSG hydroelectric facilities utilize both synchronous and induction generators, with the induction machines generally limited to the smaller sizes. Most will be three-phase units, but single-phase types may be found in ratings below about 100 kW. The cost and complexity of voltage and frequency regulation, as well as automatic control and protection, increases with the size of installations.

Whenever a consumer-owned generating facility becomes isolated on a portion of an electric utility, the possibility exists that the machine may be capable of sustaining power or fault current, or both, on the utility system. This is particularly true in the case of wind farms and large hydroelectric synchronous generators. In most instances the utility will prohibit DSG installations from furnishing service to isolated utility customers due to legal constraints and the concern for the safety of utility personnel and the general public. If, however, the utility permits a DSG to continue to operate under isolated nonfault conditions, complex control equipment will have to be installed by the DSG owner and the utility, and appropriate joint operating procedures should be established.

3.3.2 Photovoltaic Generators [3], [4]. Photovoltaic (PV) generation systems are solid-state dc current sources that generate electricity from solar irradiance. This is accomplished by the *photovoltaic effect* that produces a voltage when a semiconductor junction is illuminated. PV generators, which produce dc electric power, can only be connected to the utility through an SPC. A block diagram of a dispersed photovoltaic system is shown in Fig 7.

PV systems are generally rated according to the number of kilowatts that they produce during periods of peak sunlight. Typically, PV panels are able to convert between 5% and 15% of incident radiation into dc electric power. Over the period of a year, PV systems located in latitudes and climates of the United States will produce between 1000 and 2600 kWh for each kilowatt of installed capacity. The lower extreme is representative of a cloudy northern site and the higher is typical of tracking PV system performance in the southwest desert. PV systems perform with high availability and with annual capacity factors in the 11% to 40% range, depending on location.

Legend

13-Speed switch
27-Undervoltage
32-Reverse power
38-Bearing temperature
47-Phase Sequence Voltage
49G-Overtemperature generator
49T-Overtemperature transformer
50-Instantaneous overcurrent
51V-Time overcurrent with voltage restraint
52-Power circuit breaker

59-Overvoltage
64-Ground detection
64C-Capacitor ground detection
81/O/U-Over/Under frequency
A-Ammeter
L.A.-Lightning arrestor
V-Voltmeter
VAR-Varmeter
W-Wattmeter
WH-Watthour meter

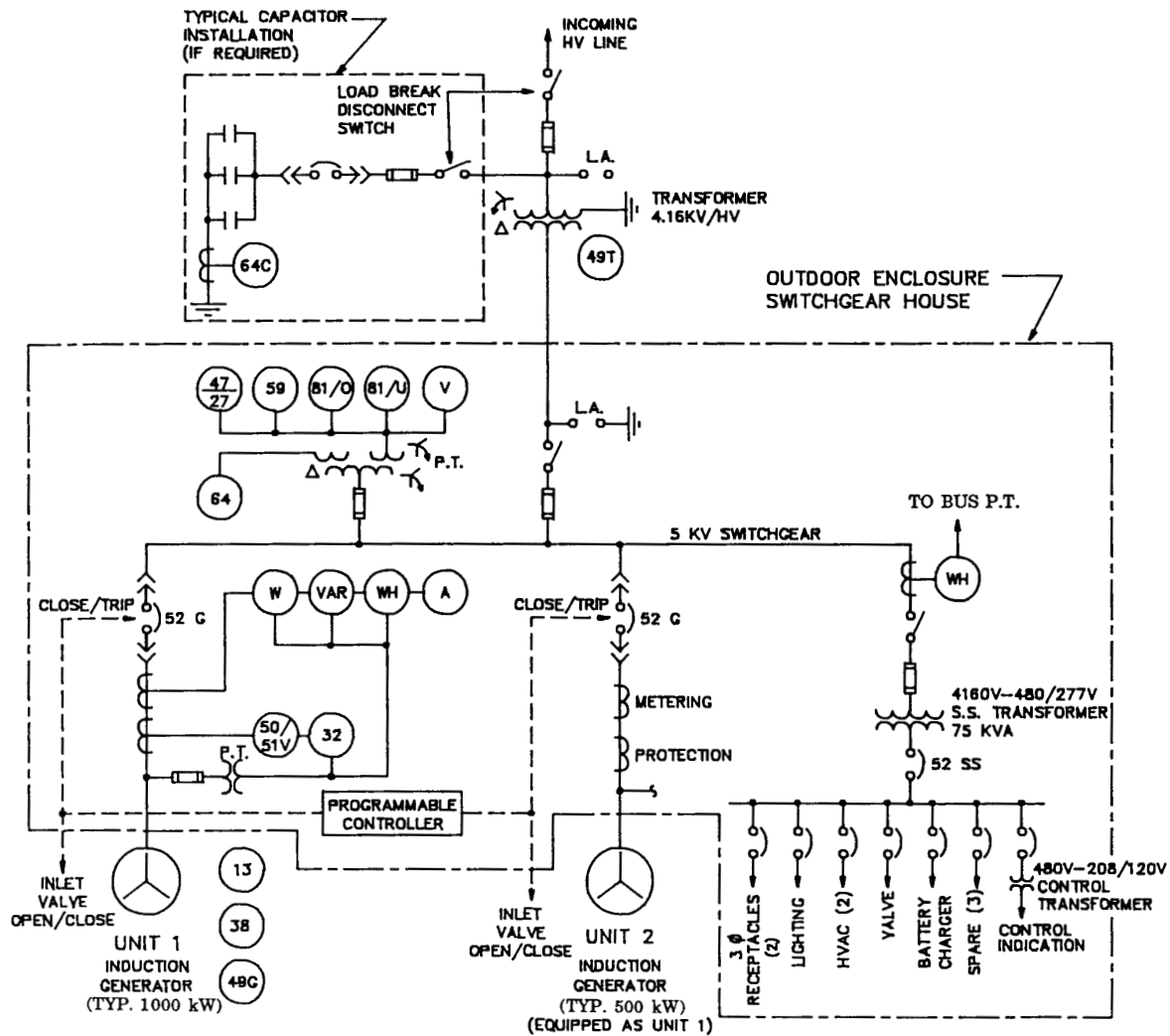


Fig 6

Typical Single-Line Diagram of a Small Hydroelectric Generating Facility

(Source: Copyright © 1984 Electric Power Research Institute, EPRI EM-3534, vol 2, *Cost and Design Study of Modular Small Hydro Plants*. Reprinted with permission.)

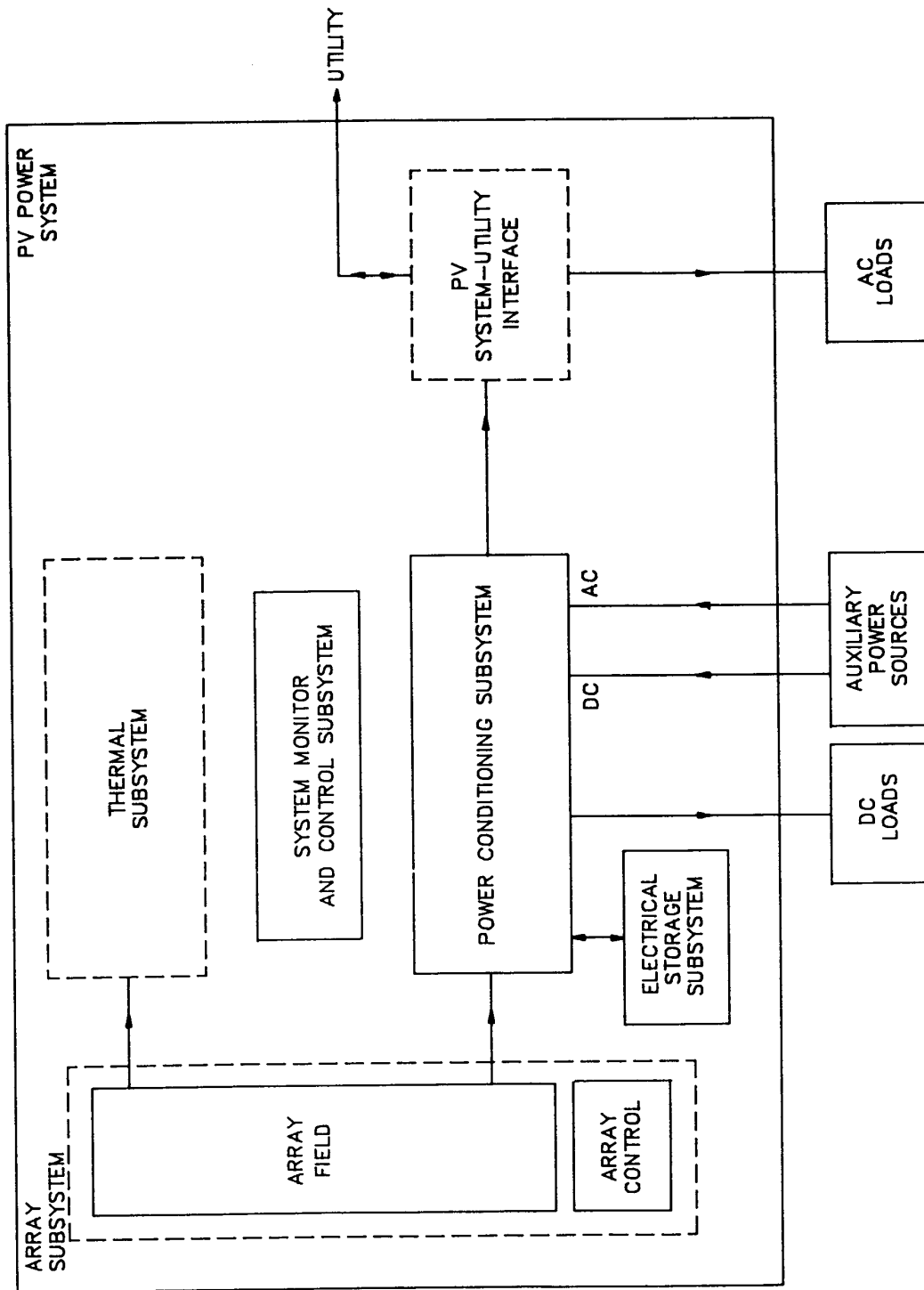


Fig 7
Block and Interface Diagram of a Photovoltaic/Thermal Power System
(Source: ANSI/IEEE Std 928-1986, IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems)

PV systems inherently require relatively large areas to obtain significant amounts of power. In residential-sized systems (2–8 kW), approximately 115 ft² of array area is required to obtain 1 kW peak generation. For intermediate-sized arrays, 100 kW will require approximately 2/3 acre. In the central station-sized arrays, approximately 1 mi² is required for 50 MW. These values reflect varying *packing factors* required for personnel and vehicular access.

PV arrays have a current/voltage characteristic (I–V curve) as shown in Fig 8. Voltage and current operating points of the array can be any point on these curves. To maximize the energy obtained from the PV array, the system should operate at the point that provides maximum power (the *max power point*). It can be seen that the max power point is in the region of the *knee* of the I–V curve. The I–V curve and the resulting max power point change with solar irradiance and with PV cell temperature. Figure 8 shows that the array current is proportional to irradiance, measured in W/m², and that the array voltage decreases with increasing temperature. Power conditioning units (PCU) are available that have the capability of following the max power point.

Another aspect of PV systems that is demonstrated by the I–V curve is short circuit current capability. Under short circuit conditions, system voltage goes very low, sometimes to zero (the so-called *bolted fault*). Inspection of the I–V curve shows that, under zero voltage conditions, the current output of PV arrays is about 25% higher than the current available at the max power point. This is in contrast to more traditional rotating generators, which can provide fault current many times higher than normal output current. Also, the impact of the PV short circuit characteristic is different on the ac side of the SPC than on the dc side. As noted, a fault on the ac side will be limited, since both the PV array and its associated SPC are current-limited devices. This may make it impossible to utilize standard current-sensing devices to clear faults on circuits supplied by PV generators, since the difference between normal current and fault current is small. For this reason, static power converters for PV systems generally monitor ac voltage and frequency and utilize any aberrations in either of these quantities to detect abnormal conditions and disconnect the

PV generator. The PV system on the dc side of the SPC is energized whenever the array is exposed to light. It should therefore be designed to operate safely under fault conditions, since only limited isolation of the faulted segment of the array is possible.

3.3.3 Wind Energy Conversion Systems [5].

A wind energy conversion system (WECS) is a machine that converts kinetic energy in the wind into usable mechanical or electrical energy. An electrical output WECS usually consists of a mechanical device (rotor) of one or more rotating aerodynamic elements (blades) attached to a single shaft that is connected to an electric generator. The WECS rotor axis may be mounted either horizontally or vertically. The horizontal WECS has a rotor mounted either upwind or downwind of the support tower. The vertical WECS is typically a two- or three-bladed machine, with either straight (giromill or cycloturbine) or curved (Darrieus) blades. The WECS blades may be either fixed in pitch (as in the Darrieus and some horizontal machines) or articulated (as in the giromill, cycloturbines, and some horizontal machines). The rotor control system is generally a mechanical or aerodynamic device. Mechanical devices include mechanical, hydraulic, or electromechanical brakes on the rotor shaft, while aerodynamic devices include blade pitching, tip-brake, rotor orientation (either yaw or pitch), and control surface (ailerons, tip-vanes, etc) systems. A single-line electric diagram of a typical wind system is shown in Fig 9.

The WECS electric generator is usually one of four types: induction, synchronous, variable frequency, or dc. In the case of the latter two types, the WECS requires an SPC to convert and regulate the electric power into a form acceptable for interconnection to an electric distribution system.

The power available in the wind is proportional to half the product of the air density, the area swept by the rotor, and the windspeed cubed (that is, $(\rho A V^3)/2$). Due to fundamental physical constraints, the conversion of wind power to mechanical shaft power by the WECS is limited to a theoretical maximum of approximately 60%. Depending on the efficiency of the rotor, the electric generator, and the drive train, the net power output may be reduced to 30% to 45%. Note, however, that generation is available only

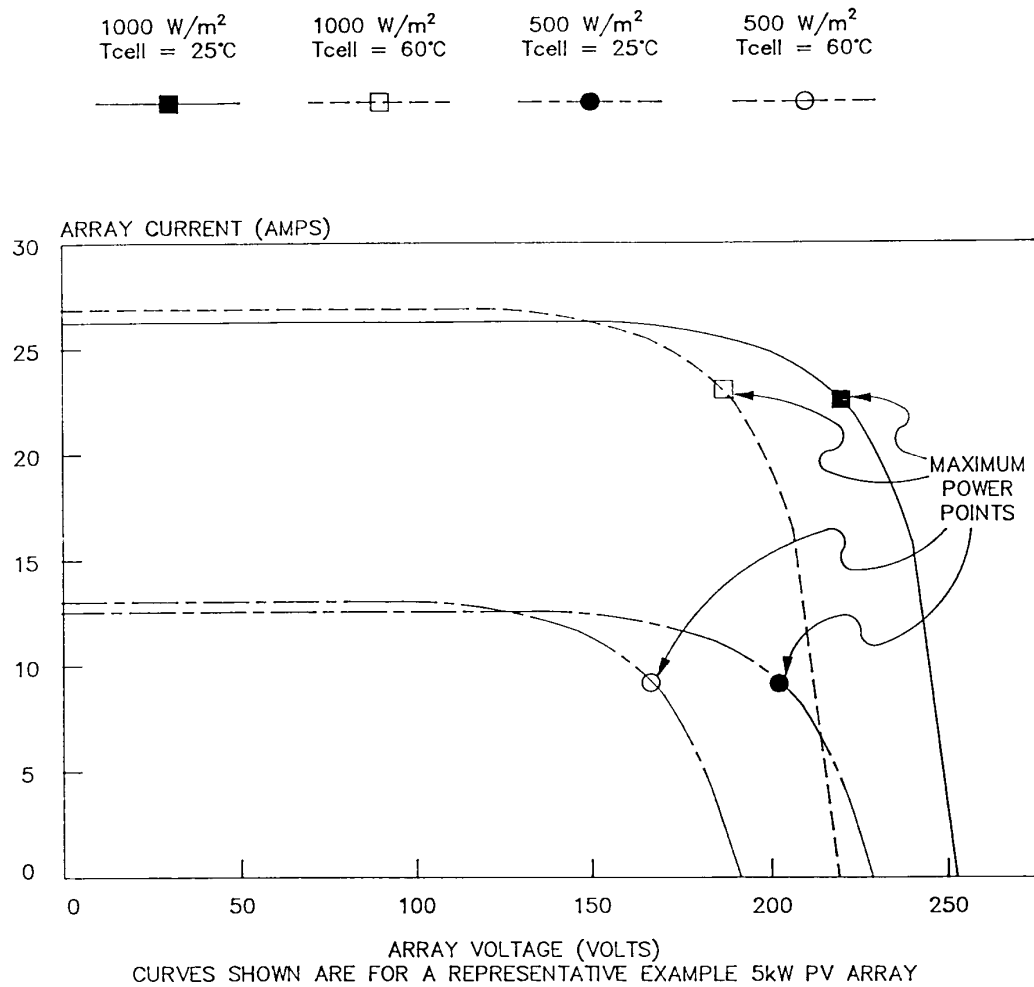


Fig 8
Typical Current-Voltage Characteristic Curve for Very Small (Residential Scale)
Photovoltaic Array

(Source: RUSSELL, M.C. *Residential PV Design Handbook*. MIT Energy Laboratory, Cambridge MA 1984.)

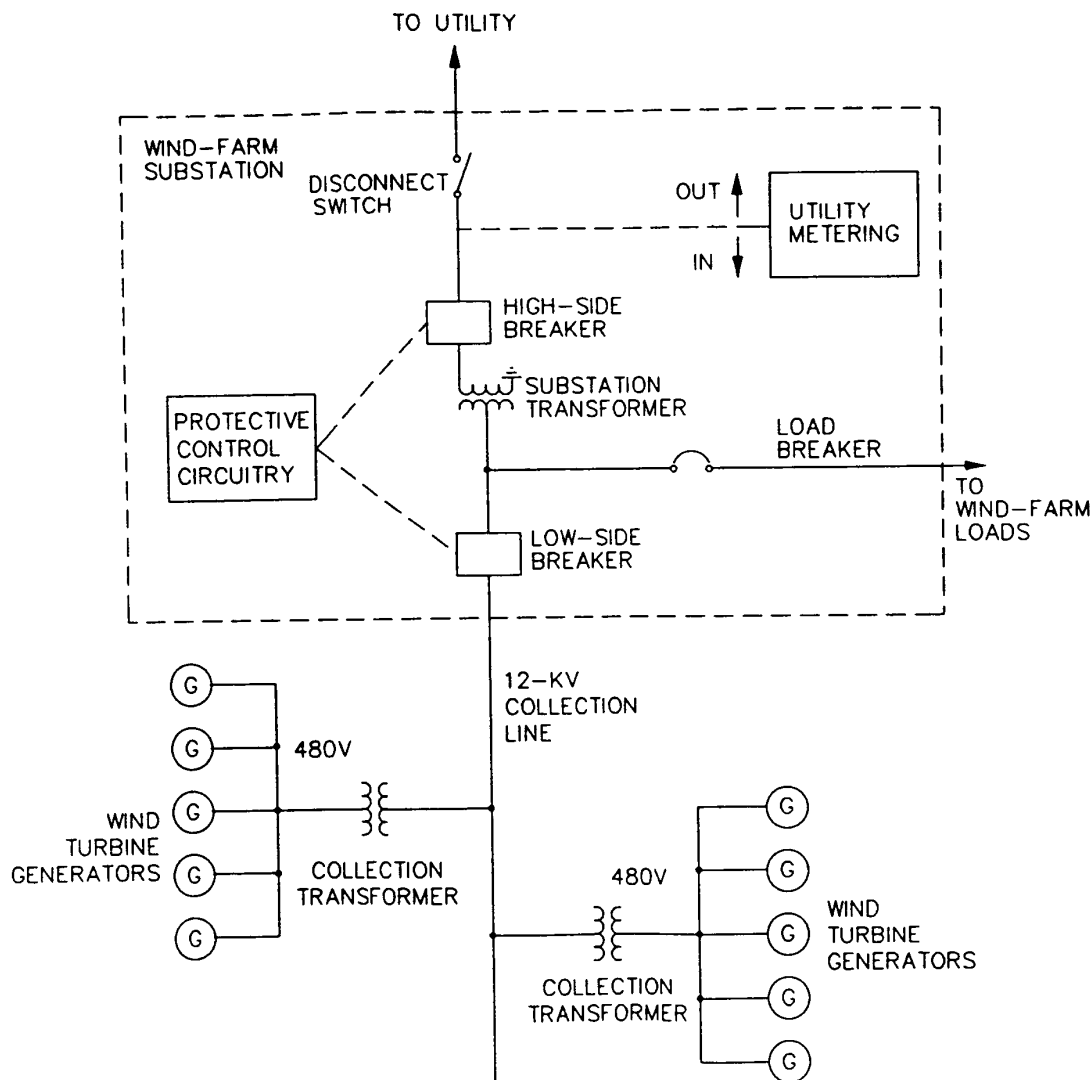


Fig 9
Typical Single-Line Diagram for a Wind Farm Interconnection with a
Utility Transmission System

(Source: Transmission and Distribution, Jul 1984.)

when the wind is blowing between a lower cut-in speed, below which useful energy cannot be extracted, and a higher cut-out speed, above which the system is normally shut down to prevent mechanical damage.

WECS are usually classified by size in terms of electrical real power output as:

- (1) Small—up to 100 kW.
- (2) Intermediate—>100 kW, <1 MW.
- (3) Large—equal to or greater than 1 MW.

3.3.3.1 WECS Utilizing Induction Generators. Induction generators are commonly used in small to intermediate capacity WECS. Their advantages are:

- (1) Simplicity of operation and interconnection.
- (2) Low cost, since most are squirrel cage induction motors with minor modifications.

Their disadvantages are:

- (1) The narrow operating range of shaft angular velocity, which limits the wind speed range of efficient operation.
- (2) Current surges as the generator is switched in and out in gusting winds.
- (3) A relatively high reactive power demand.
- (4) The need for a speed-up drive train between the rotor and generator.

Single-phase generators are used in capacities of 1 kW to 20 kW, while three-phase units range from 10 kW upward.

3.3.3.2 WECS Utilizing Synchronous Generators. Synchronous generators are used primarily in sizes from 50 kW upward. The favorable characteristics of synchronous generators include:

- (1) Low harmonic distortion in the generated voltage waveform.
- (2) Ability to control generated voltage and reactive power.

The disadvantages are:

- (1) Higher cost and complexity of the generator and its protection and control equipment.
- (2) Constant shaft speed, which means constant rotor speed and consequent need for blade pitch control.
- (3) Likely need for speed-up drive train between rotor and generator shaft.

3.3.3.3 WECS Utilizing SPC-Coupled Generators. Direct current generators and variable-frequency ac generators are con-

nected to the utility through static power converters. SPC-coupled WECS generally operate at variable speed, which allows the rotor to operate at its maximum efficiency (that is, maximum power coefficient) over a range of wind speeds. In contrast, the constant-speed machine, such as a WECS with an induction generator, will operate at its maximum power coefficient at only one windspeed.

The increase in energy capture and other benefits afforded by variable speed operation must be balanced against the increased cost and complexity of variable speed generator systems. Other benefits of coupling a WECS to a utility through a PCU include reduced structural loads in the wind system and damping of power transients that may be imposed on the utility network.

3.3.3.4 WECS Utilizing Multiple-Speed Generators. Discrete multiple-speed concepts have demonstrated a capacity to increase energy capture by permitting the wind system to operate at more favorable tip speed ratios. Multiple-speed systems are of two major designs: dual generator and dual winding.

The dual generator design uses two induction generators coupled to a common output shaft. Control circuitry alternately connects one generator or the other to the utility supply, depending on wind speed. The difference in the generator operating speeds is obtained through different gear-pulley ratios or by employing generators with different numbers of poles. For example, one manufacturer uses a gearbelt to obtain rotor speeds of 33 rpm when connected to a 13 kW generator and 48 rpm when connected to a 60 kW generator. Both generators are six-pole machines (1200 rpm).

The dual winding design incorporates two separate stator windings in a single induction machine frame. For example, two-speed operation is obtained by having the machine wound for four-pole (1800 rpm) and six-pole (1200 rpm) operation. Control circuitry switches from one winding to the other, depending upon wind speed.

3.3.3.5 WECS Utilizing Variable Speed Constant Frequency (VSCF) Generators. VSCF concepts have demonstrated the potential to reduce mechanical system loads as well as increase energy capture. One example of a VSCF system incorporates a wound rotor induction generator (WRIG) and an SPC. The

stator of the WRIG is connected directly to the utility service through appropriate switchgear. The rotor of the WRIG is also connected to the utility service, but through an SPC, so that its output (or input) can vary in voltage and frequency. Depending on the particular SPC technology used, power from the utility is fed into the rotor or power is extracted from the rotor and fed into the utility; this permits generation in both subsynchronous and supersynchronous modes. A representative system is shown in Fig 10.

3.3.4 Steam Turbines Powered by Wood Waste. A rapidly growing DSG technology is the generation of electricity by steam turbines powered by wood waste. The waste may be burned by cogenerators or by small power producers, such as saw mills, where the sawdust has previously been destroyed by open burning. An electrical diagram of a typical wood waste generating plant is shown in Fig 11.

3.3.5 Non-Renewable DSG Energy Sources

3.3.5.1 Battery Energy Storage Plants [6]. Battery energy storage plants utilize reversible electrochemical reactions of suitable chemical substances to convert electric energy to chemical energy for storage and subsequent reconversion to electric energy. When the primary source of energy is an ac system, bidirectional power conversion is required for the charge and discharge of the battery; in dc systems, dc-to-dc converters are usually employed. A block diagram of a generic battery energy storage system is shown in Fig 12.

Battery energy storage plants are of modular design and can be configured in sizes ranging from a few kWh to several hundred MWh. Typical applications of battery energy storage are load leveling and peak shaving by electric utilities and their customers.

Battery charging energy may be supplied by either the electric utility or by the DSG owner's dc source (such as a PV array). Discharge energy may be used entirely by the DSG owner or returned to the utility. The overall efficiency of a battery energy storage system is primarily determined by the dc-to-dc energy storage efficiency of the particular battery. A *roundtrip* (ac-to-ac) conversion efficiency of between 50% and 85% is possible with modern batteries and converters. Depending on the depth of discharge, battery cycle lifetimes ranging from a few hundred to several thousand cycles are achievable.

Measurement and control of ac parameters is identical to other DSG equipment; dc control, measurements, and protection are specific to the type of battery, and may in some instances require development of new techniques and equipment.

In normal operation, battery energy storage plants have no noticeable effects on the environment. Protection against accidental emissions and provisions for chemical waste disposal are specific to different battery types and must be addressed in accordance with applicable federal, state, and municipal regulations.

3.3.5.2 Fuel Cells [7]. Fuel cells convert the energy of a fuel to electricity and heat via an electrochemical process that is similar to the operation of a battery. A fuel cell power plant consists of three integrated subsystems: a reformer, a fuel cell power section, and a static power converter (SPC).

The reformer processes the fuel supply to a hydrogen-rich gas and can be designed to accept many different fuels, including coal gas, coal-derived or petroleum distillates, pipeline gases, methanol, or almost any other fuel with a boiling point below 650 °F and a sulphur content of less than 2500 parts per million.

The fuel cell power section converts the hydrogen-rich gas and oxygen from the air to dc electric power and usable heat (hot water and steam). The combined output of electricity and heat translates to an overall efficiency of about 80%. Further development should increase the electrical conversion portion to well over 50%. Since the only emissions or by-products are carbon dioxide, water, and heat, fuel cell power plants can be readily sited in populated areas. The SPC converts the dc electrical output of the power section to ac power. (See 3.2.3.) Figure 13 shows how a fuel cell power plant may be connected to a customer's electric service while operating in parallel with the utility.

3.3.5.3 Diesel Generators [8]. Diesel generator sets range from small, high-speed to large, low-speed, two- and four-cycle engines. They may be used for peak shaving, emergency and standby power, cogeneration, or for base load generation on small systems. Sizes range from about 100 kW to over 5000 kW for very large units. Larger units are more efficient and have a longer operating period