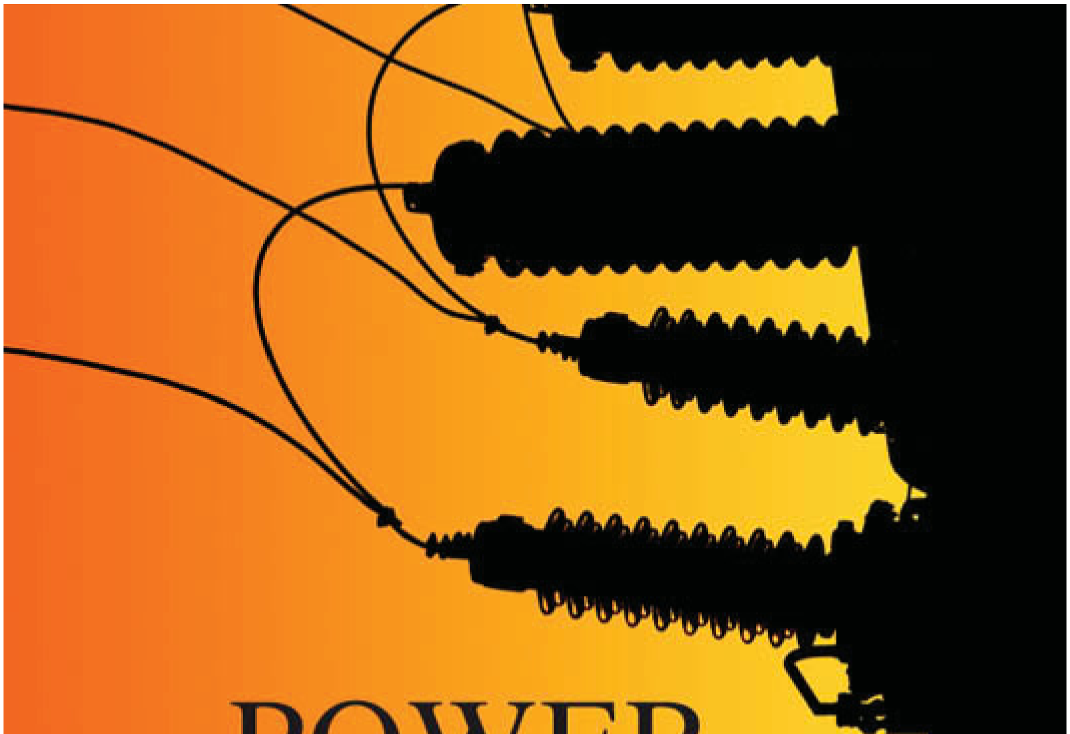

POWER QUALITY in ELECTRICAL SYSTEMS

ALEXANDER KUSKO
and MARC T. THOMPSON

Power Quality in Electrical Systems

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Chapter

9

Uninterruptible Power Supplies

The term Uninterruptible Power Supplies (UPS) has been applied both to an uninterruptible power system and to the specific battery-inverter equipment incorporated into the system. In this chapter, we will use the term UPS for the specific equipment.

The UPS was developed in parallel with digital computers and other IT equipment to provide a reliable uninterruptible electric power source to create a standard the electric-utility industry could not provide. The computer industry would not have developed without some type of UPS, which either used engine-generator sets or static inverters employing power electronic devices. If the concept of an independent UPS had not been developed, then all electronic equipment sensitive to disturbances in source voltage would have had to incorporate energy storage means—for example, batteries to counteract such disturbances in the source voltage.

Introduction

The concept of a double-conversion UPS is shown in Figure 9.1a [9.1]. The essential parts are

- The **inverter**, for converting power from DC to AC
- The **battery**, to supply power to the inverter when AC power is interrupted
- The **converter-battery charger**, to supply DC power to the inverter, as well as to charge the battery
- The **by-pass circuit**, to supply AC power directly to the load when the inverter fails. A second by-pass circuit external to the UPS—the

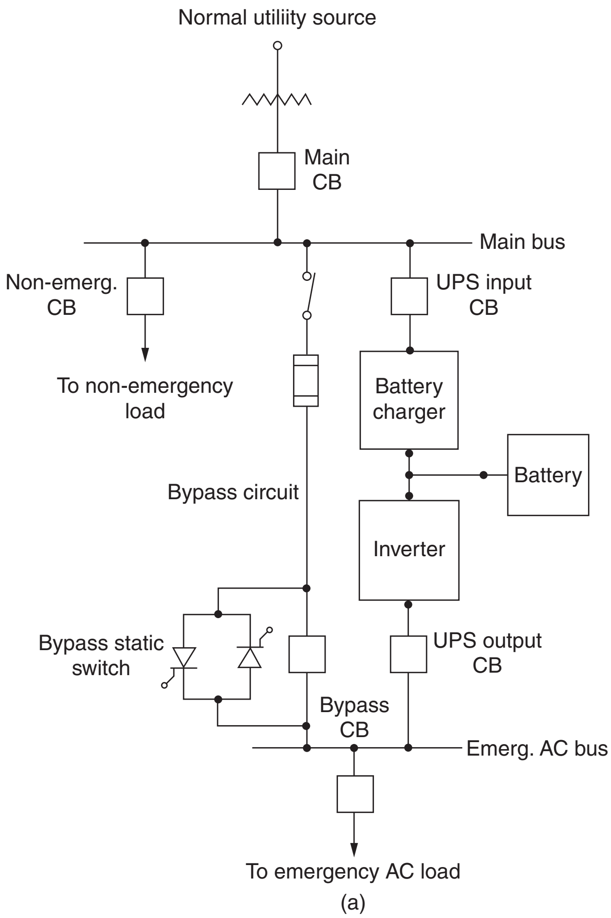


Figure 9.1a Double conversion UPS: inverter; battery; converter-battery charger; by-pass circuit [9.1].

maintenance by-pass—is usually provided when the UPS is taken out of service.

Both the battery charger (rectifier) and the inverter utilize power semiconductor devices, which are switched to convert power from AC to DC, or DC to AC. The theory of operation is described in Chapter 5. The devices are usually pulse-width modulated to shape the line-current waveform of the rectifier, as well as the output voltage of the inverter to sine waveforms. Additional elimination of input and output harmonics is done with filters.

The concept of the "Delta UPS" is shown in Figure 9.1b. The battery-inverter circuit only supplies the "delta" or difference between the line

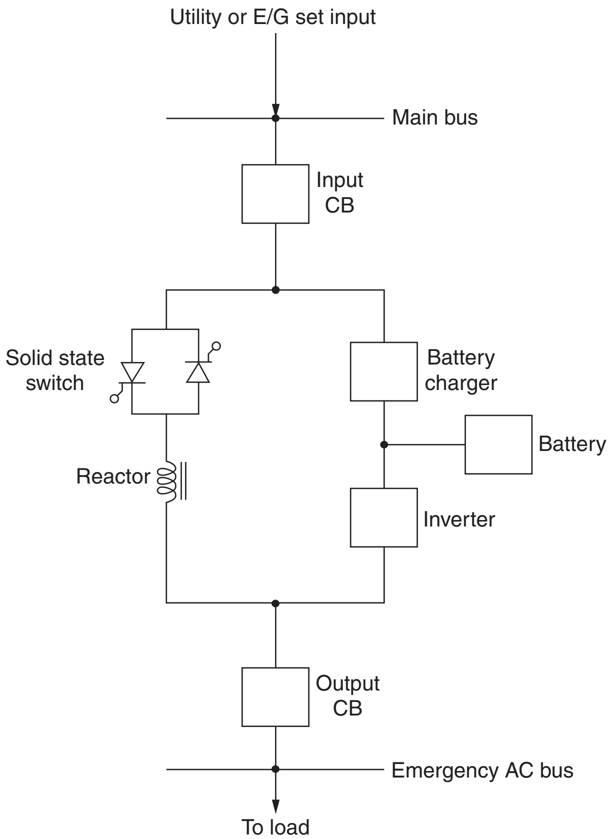


Figure 9.1b Delta UPS: solid-state switch; reactor; battery charger; inverter; battery.

voltage and the required load voltage. The Delta UPS is more efficient than the double-conversion UPS because the load power is supplied directly from the line nearly all of the time. The inverter and battery still have to be sized for the longest utility outage time.

History

The silicon-controlled rectifier (SCR) was introduced in 1957. The development of inverters using SCRs for UPS was expedited by the book, *Principles of Inverter Circuits*, by Bedford and Hoft, published in 1964 [9.2]. An early publication by Fink, Johnston, and Krings in 1963 described three-phase static inverters for essential loads up to 800 kVA [9.3]. Kusko and Gilmore described in 1967 a four-module redundant UPS for

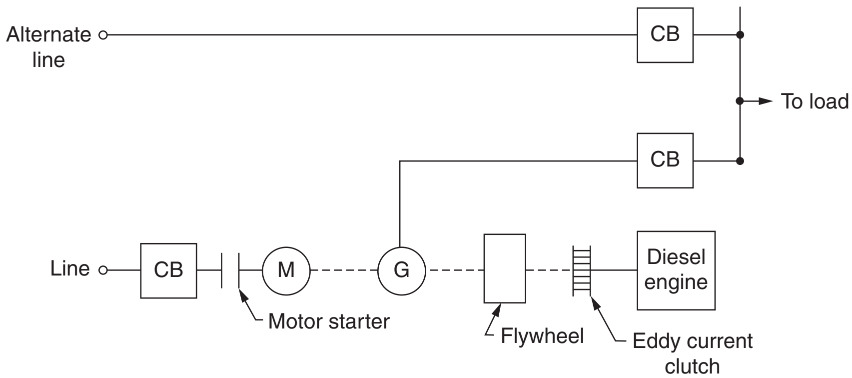


Figure 9.2a MG UPS with flywheel, clutch, and diesel engine [9.1].

500 kVA for the FAA Air Route Air Traffic Control Centers. The overall MTBF requirement was 100,000 h and the MTTR was 1h [9.4].[1] The individual modules were assumed to have an MTBF of 1100 h. Modern UPS modules are considerably more reliable. The concept of uninterruptible system availability is described in Chapter 8.

The major change in the design of inverters since their inception for UPSs is the replacement of the silicon controlled rectifiers (SCRs) as the switch devices by IGBTs. The SCRs require forced commutation to turn off the current—that is, to open the switch. The IGBTs are controlled by the gate voltage. The forced commutation for SCRs required additional circuits and operations that increased the failure rates and reduced the reliability of the inverters. Furthermore, the IGBTs can be switched much faster than SCRs, which enabled pulse-width modulation (PWM)—in other words, the voltage and current waveform shaping to be used.

An early concept of UPS that preceded the SCR is shown in Figure 9.2a. It was a rotary machine set consisting of a diesel engine, clutch, electric motor, flywheel, and generator [9.1]. When utility power was available, the motor drove the generator. When utility power failed, the engine would be started while the flywheel and the generator slowed. At a certain speed, the clutch was engaged so the engine could drive the generator to restore and maintain its synchronous speed. A motor-generator which is a UPS, but employs batteries to provide energy when utility power fails, is shown in Figure 9.2b.

[1] MTBF = Mean time between failures. MTTR = Mean time to repair.

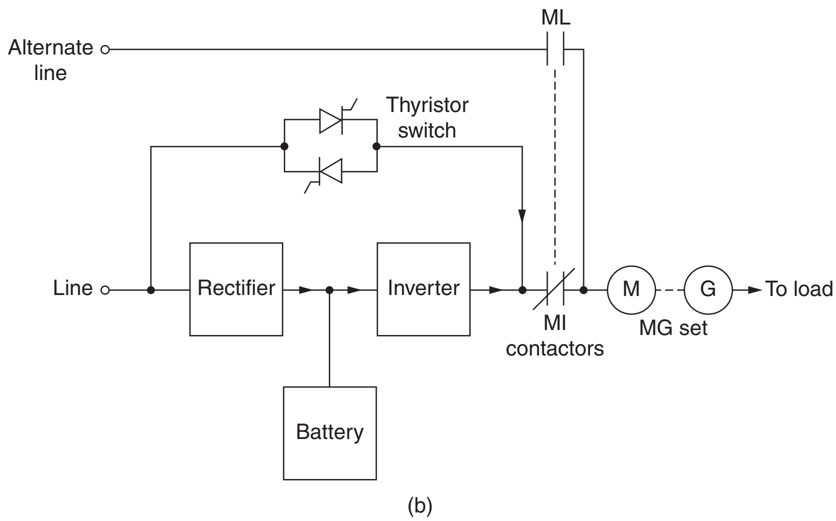


Figure 9.2b MG UPS with load-commutated inverter and battery [9.1].

Types of UPS Equipment

Commercially available UPS equipment can be categorized into the following types, depending upon the manufacturer and the application.

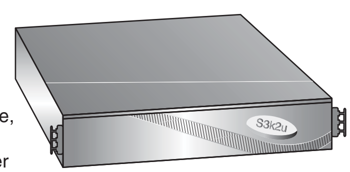
- **Output Ratings**
  - Power: 1 kVA single-phase to 1000 kVA three-phase per module
  - Voltage: 120 V single-phase to 208 V/120 V or 480 V three-phase
- **Design**
  - Double: Conversion or Delta
  - Inverter: Power transistors, IGBTs. Pulse-width modulated with output filter
  - Battery Charger: Input rectifier or separate charger
  - By-pass Circuit: Thyristors or IGBTs
  - Maintenance By-pass: Circuit breaker
- **Energy Storage**
  - Batteries: Flooded, VLRA (value regulated lead acid)
  - Flywheels
  - Fuel cells
- **Typical Run Time**
  - Batteries: 5 to 20 minutes at full load
  - Flywheels: 15 seconds, enough time to start E/G set
  - Fuel cells: 8 hours

Commercial equipment

The following are examples of commercial UPS equipment in order of power ratings:

- **Rating, 1000 to 2200 VA (Figure 9.3)**
  - Delta battery-inverter
  - 120- and 240-V single-phase models
  - AVR, automatic voltage regulator, topology, voltage compensation (See Chapter 10)
  - Hot swappable batteries
- **Rating, 3 to 10 kVA (Figure 9.4) [9.5]**
  - Battery-inverter
  - Double-conversion (online rectifier-inverter)
  - Various input and output voltages, three-phase
  - Monitor and control via the Web browser
- **Rating, 120 kVA (Figure 9.5) [9.6]**
  - Battery-inverter
  - 480 V, three-phase
  - Run-time: full load, 8 minutes; half load, 22 minutes
  - Interphase port, DB-25, RS-232
- **Rating, 1000 kVA, (Figure 9.6) [9.6]**
  - Battery inverter
  - 480 V, three-phase
  - Configurable for N+1 internal redundancy

The slim 2U shape and advanced networking and remote control options make this UPS the perfect choice for networking or process control racks. The S3K2U series UPS's protect against most severe power disturbances including over/under voltages through state of art sinewave, line-interactive technology. Utility power is continually protected by the S3K2U series while internal battery power is maintained for deep sag conditions.



The built-in protection for under and over voltage conditions of the S3K2U units includes low-energy lightning surge protection on the input power source. They are provided with an input circuit protector and a pair of surge protected data line connectors (RJ-45).

The S3K2U series include an automatic bi-weekly test function to ensure the capability of the battery to supply power in deep sag situations. Should the battery fail this test, the UPS will display a warning to indicate that the battery needs to be replaced.

Figure 9.3 Delta line-interactive UPS, 1000VA to 2200 VA. [Courtesy Sola/Hevi-Duty]

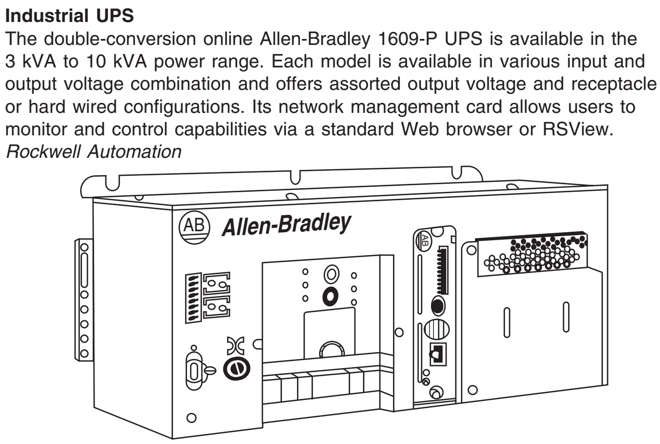


Figure 9.4 Double-conversion UPS, 3 to 10 kVA [9.5].

- Modular design for fast service and reduced maintenance requirements

- **Rating, for 225 kVA UPS, (Figure 9.7) [9.7]**
  - Flywheel power system support for UPS
  - Run time, 13 seconds at UPS full load, 28 seconds at UPS 50 percent load
  - Recharge time, 20 seconds
  - N+1 configurable

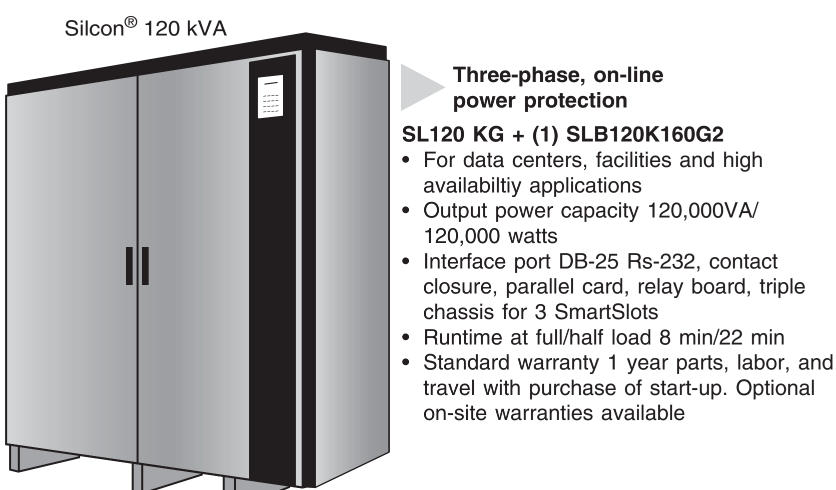


Figure 9.5 Double-conversion UPS, 8 min run time, 120 kVA [9.6]. [Courtesy APC]

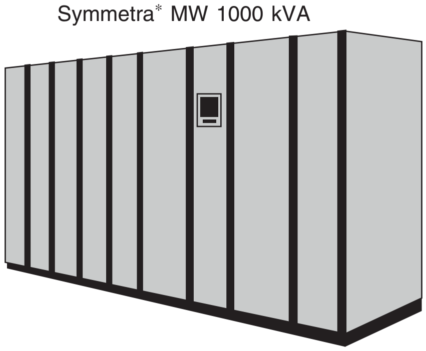


Figure 9.6 Double-conversion UPS, 1000 kVA [9.6]. [Courtesy APC]

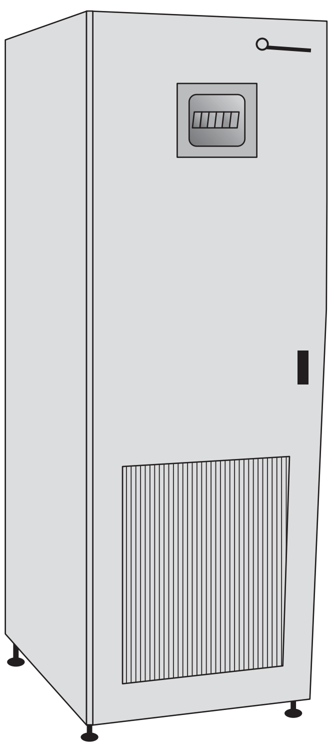


Figure 9.7 Flywheel UPS, 130 kVA, 25 s [9.7]. [Courtesy Pentadyne Power Corporation]

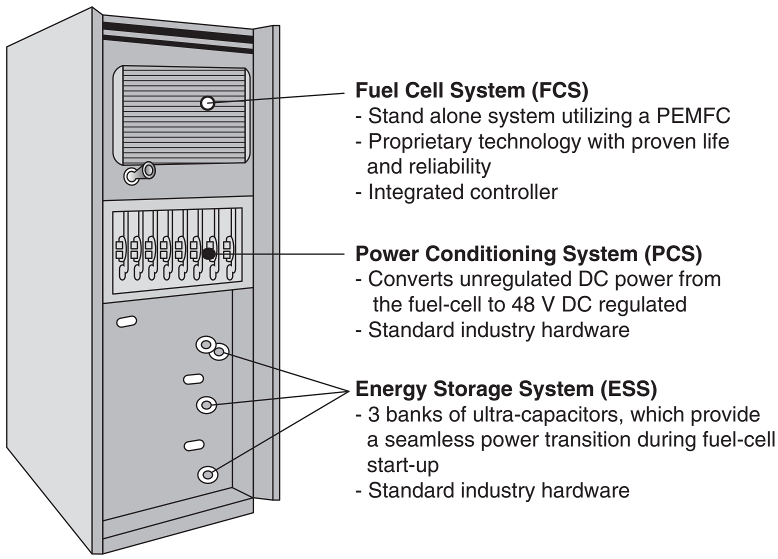


Figure 9.8 Fuel-cell UPS, 48 V DC power, 4.5 kW [9.8].
[Courtesy UTC Power]

- **Rating, 4.5 kW, (Figure 9.8) [9.8]**
  - Fuel cell–powered UPS
  - Ultra capacitors for fuel cell startup
  - Output, 28 V DC

Energy storage

The requirement for stored energy in an uninterruptible (standby) power system is predicated on at least two parameters: (1) the time duration of power delivery (term), and (2) the power level (energy). The requirements further defined by the time duration can be categorized as follows [9.8]:

- **Short Term:** Standby systems without available transfer means to engine-generator sets or alternate utility feeders. These stand-alone systems range from 100 W to 1000 kW and include 5 to 30 minutes of stored energy capability, based on estimates of utility outage time.
- **Medium Term:** Standby systems with available transfer means to engine-generator sets, alternate utility feeders, or other sources. These systems range up to 10,000 kW and include up to 5 minutes of stored energy capability, based on the time to start engine-generator sets and make the transfer.
- **Long Term:** Standby systems that operate as part of a utility system, which provide, in addition to standby function, other functions such

as peak shaving, voltage and frequency stabilization, and reactive power supply. These systems can be rated up to 20 MW and can deliver energy for up to 8 hours.

Requirements for uninterruptible power for specific loads can be met by short- and medium-term systems described earlier.

Batteries

Batteries consist of one or more cells electrically interconnected to achieve the required voltage, stored energy, and other characteristics. Two types of operation are important: float and cycling. Float operation describes batteries in telephone central offices where the batteries maintain a relatively constant voltage—for example, 48 V DC. Cycling operation describes batteries in standby systems—for example, UPS, where the battery charge is drawn down to supply the inverter and the AC load when the utility power fails. These batteries for UPS rated 100 kVA and higher, are typically rated 460 V DC. The batteries are recharged when utility power returns, or engine generators are started and run [9.8].

The specific energy and energy density of the batteries used for standby service are shown in Figure 9.9 [9.9]. The application of these batteries depends on additional factors besides those in the figure. The batteries employed for standby service are described in the following [9.8]:

- **Flooded, lead acid batteries:** These have been used for UPSs since the 1960s [9.4], and as the backup for communications power supplies before 1983 [9.10]. This type of battery requires periodic additions of water to comply with its specific gravity measurements. It discharges inflammable gas, and thus requires special facilities for safety. To facilitate venting, the gas space in flooded cells is open to outside air but

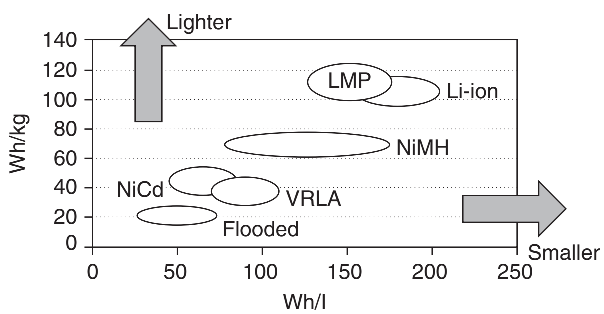


Figure 9.9 Specific energy and energy density comparison of batteries: Wh/kg and Wh/l [9.9].
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separated from it through a vent that incorporates a flash arresting device. Note in Figure 9.9 that the flooded lead acid battery has the lowest specific energy and lowest energy density compared to other batteries.

- **Valve-regulated lead-acid (VRLA) batteries:** These have seen tremendous growth in standby usage in the last two decades [9.11]. Note their approximately two-to-one advantage over flooded batteries in Figure 9.9 in specific energy and energy density. In the VRLA cell, the vent for the gas space incorporates a pressure relief valve to minimize the gas loss and prevent direct contact of the headspace with the outside air.

Standard VRLA battery warranties range from 5 to 20 years depending upon their construction, manufacturer-based requirements concerning proper charging and maintenance, and whether the battery is kept in a 25°C (77°F) environment compared to a −40 to +65°C outdoor environment. When placed in an outdoor environment, the batteries must be heated to prevent freezing, or loss of capacity. At −6°C (20°F), battery capacity is reduced by 30 percent. At −16°C (4°F), battery capacity is reduced by 55 percent. [9.12]

Flywheels

Flywheels were the original means for energy storage in early designs of "no-break" engine-generator sets. (See Figure 9.2a.) They are returning to serve for short-time supply in standby systems as an alternative to batteries, and in other applications.

The energy stored in a flywheel is given by the classical equation:

$$W = (1/2)I\omega^2$$

where W = energy, joules or watt seconds ($m^2 \times kg/s^2$)
I = moment of inertia ($N \times m \times s^2$)
ω = rotational velocity (rad/s)

Note that the energy W stored in the flywheel is always known by the speed ω.

Sample ratings are given by Weissback [9.13] of low speed systems (less than 10,000 rpm) capable of delivering power over 1 MVA, with energy storage below 10 kWh. Reiner [9.14] describes a flywheel plant concept that can supply power peaks of 50 MW for about 13 s, equivalent to energy storage of 181 kWh.

For perspective, consider a UPS that requires 1000 kW at its DC bus for 10 s to insure time for start up and transfer to back-up engine generators. The calculated energy is 2.78 kWh. Assume that the flywheel speed slows to 70 percent and that the flywheel generator and converter efficiency is 0.90, the calculated flywheel stored energy must be 6.3 kWh at full speed.

Applications. Applications of flywheels include the following:

- No-break engine-generator set with flywheel and clutch [9.15]. The flywheel provides energy to the generator when the utility source fails, until the engine starts and reaches operating speed.
- AC UPS, which delivers AC power to the load when the utility source fails, as shown by Lawrence in Figure 9.10 [9.15].
- Battery substitute in UPS, as shown by Takashi in Figure 9.11 [9.16].
- Support medium voltage distribution network, as described by Richard against voltage sags and interruptions [9.17].

Profactors primarily comparing flywheels to batteries include the following:

- Maintenance-free, bearings might need service in three to five years [9.18]. Bearing-free flywheels utilizing magnetic levitation have been built.
- Long life—for example, three times that of batteries [9.16].
- Can provide typically 15 s of power for engine, or turbine-generator start [9.18].
- Short recharge time; depends on power available—for example, for one-tenth the discharge power, approximately 20 times the discharge time [9.19].
- Smaller footprint than batteries [9.19].

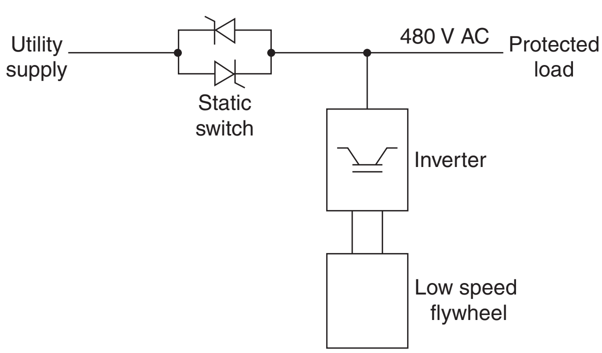

Figure 9.10 Block diagram of flywheel UPS with static switch, inverter [9.15].
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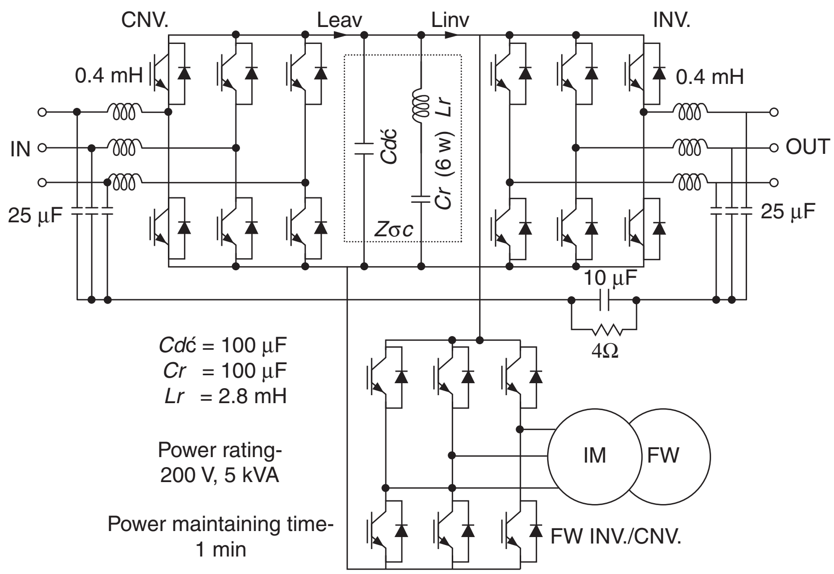

Figure 9.11 Electrical diagram of double-conversion UPS with flywheel energy storage, rating 5 kVA, 1 min [9.16].

- Minimum end-of-life disposal problem [9.16 and 9.19].
- Ambient temperature (0 to 40°C) compared to batteries (20 to 25°C) [9.19].
- Measure available energy accurately by calculating speed and energy.
- Can provide AC generator or DC converter output.

Con factors include the following:

- Installed cost 1 to 1.4 times that of batteries [9.19]
- Storage expansion not easy, requires adding units of comparable size

Other pro and con factors include availability and operator's experience with flywheels.

Fuel cells

Fuel cells, using hydrogen as a fuel, have become a possibility to replace lead-acid batteries in standby applications [9.20]. Figure 9.12 shows a comparison of the acquisition cost of lead-acid batteries and fuel cells for a 10-year period in a standby power application. The rising cost of batteries is based upon an assumption of replacement at 36- to 60-month intervals [9.21].

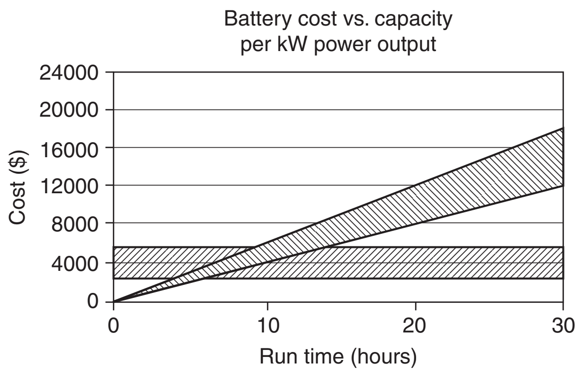

Figure 9.12 Battery cost versus capacity per kW power output. Acquisitions cost comparison for fuel cells and lead-acid batteries in standby power applications. Battery cost-diagonal shading. Fuel cell cost [9.21].
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Table 9.1 shows the major types of fuel cells considered for standby and alternative electric power use. For applications that require frequent and rapid start-ups, and where hydrogen and air are the available reactants, a polymer-electrolyte membrane fuel cell (PEMFC) is the obvious

TABLE 9.1 Major Types of Fuel Cells. (Advantages vs. Disadvantages) [9.22]

Electrolyte	Operating temp. (°C)	Advantages	Disadvantages
Polymer-electrolyte membrane fuel cell (PEMFC)	60–100	■ Highest power density ■ Reduced corrosion and electrolyte-management problems ■ Rapid start-up time	■ Relatively expensive catalysts required ■ High sensitivity to fuel impurities
Alkaline fuel cell (AFC)	90–100	■ High power density ■ Demonstrated in space applications	■ High sensitivity to fuel impurities ■ Intolerant to CO_2
Phosphoric acid fuel cell (PAFC)	175–200	■ High quality waste heat (for cogeneration applications) ■ Demonstrated long life	■ Relatively expensive catalysts required ■ Relatively low power density
Molten carbonate fuel cell (MCFC)	600–1000	■ High quality waste heat ■ Inexpensive catalysts ■ Tolerant to fuel impurities	■ High temperature enhances corrosion and breakdown of all cell components ■ Relatively low power density
Solid oxide fuel cell (SOFC)	600–1000	■ High quality waste heat ■ Inexpensive catalysts ■ Tolerant to fuel impurities ■ Solid electrolyte	■ High temperature enhances corrosion and breakdown of all cell components ■ Sealing of stacks

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choice. PEMFC fuel cells also have the highest power density of all of the types in Table 9.1 [9.22]. Fuel cells utilizing hydrogen as fuel can operate for relatively long periods of time—for example, hours—or for short periods, in standby service, in the nature of engine-generator sets or batteries.

Applications. Specific applications include the following:

- Space (used on Gemini, Apollo, and space shuttle missions)
- As a UPS, which requires instant availability of power when utility service fails. The fuel cell by itself requires heating to start up. UTC Fuel Cells show a 5-kW UPS to supply 48 V dc for telecom applications, which uses ultracapacitors to supply the energy during the start up of the fuel cell system.
- The telecom industry is considering fuel cells as an alternative to VRLA batteries for sites requiring 1 to 3 kW for up to eight hours [9.20–22].
- Nakamoto, et al. show a 4.5-kW fuel cell system to produce 300 V ac power, Figures 9-13 and 9-14 [9.23].
- Utility industry applications include a study by Sedghisigarchi and Feliachi of 1.5-MW fuel cell systems and gas-turbine generators operating on a common bus in a 9-MW system [9.24].

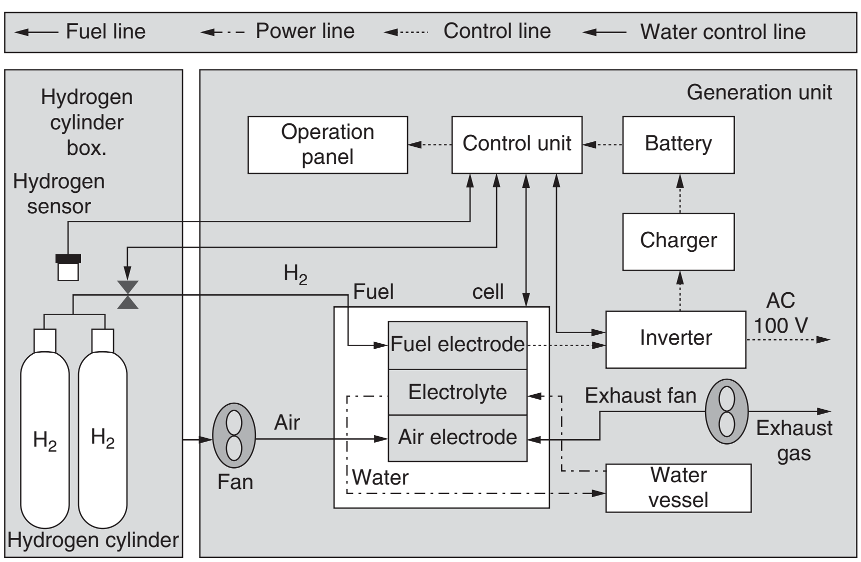

Figure 9.13 Block diagram of 4.5-kW fuel cell UPS [9.23].
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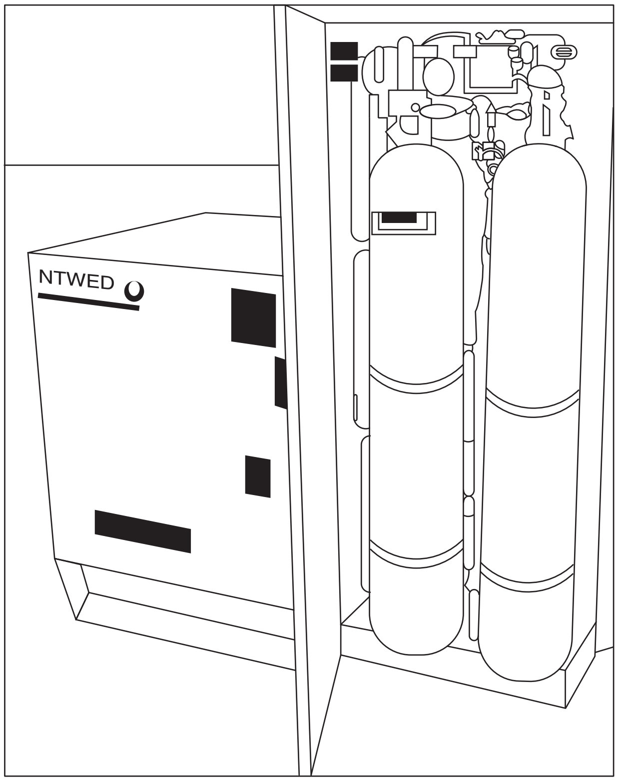

Figure 9.14 External appearance of 4.5-kW fuel cell UPS [9.23].
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Ultracapacitors

Ultracapacitors can substitute for batteries in low-power UPS. Their features include

- **Construction:** These capacitors utilize electrodes of highly porous carbon to achieve large values of capacitance per unit weight. Zorpetta quotes surface area of 1500 m^2/g; a typical electrode of 250 g would have an area of 375,000 m^2 [9.25].
- **Ratings:** Maxwell Technologies offers ultracapacitors ranging from 5 to 10 F to cylindrical 2700 F, rated 2.5 V DC per cell [9.26]. Storage amounts to 3 or 4 Wh/kg [9.25].
- **Applications:** One manufacturer offers UPS modules rated 1.6 and 2.3 kW, replacing batteries, employing 2300 F of ultracapacitors [9.27]. M. L. Perry describes a 5-kW fuel cell standby power unit in which three banks of ultracapacitors provide the energy while the fuel cells

are coming on line [9.22]. Usage of ultracapacitors to supply peak power loads over average power is described by Maher [9.26].

- **Problems:** Because of the low voltage rating of ultracapacitor cells—for example, 2.5 V DC—the cells must be connected in series for a typical 48 V DC application, with the usual problems of cell current and voltage division during charging [9.26]. Cost of $9500/kWh is five times that of lead-acid batteries [9.26].

Summary

The uninterruptible power system is necessary to provide reliable power to critical loads that cannot tolerate interruption. The most widely used equipment is the battery inverter UPS module that is available in power ratings from 100 W to 1000 kW (and higher) at all commercial input and output voltage and phase configurations. Energy storage is usually provided by flooded or VLRA-type batteries for full-load operating times in the range of minutes. Recently developed energy-storage alternatives include flywheels and fuel cells.

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Chapter

13

Standby Power Systems

The term standby power systems describes the equipment interposed between the utility power source and the electrical load to improve the reliability of the electric power supply to the load. In previous chapters, we have described the deficiencies in the electric power supply, such as voltage sags and interruptions, and their effect on individual types of loads. The loads that require standby power can range from a single personal computer supplied by a battery-powered UPS to a large data processing center. In this chapter, we will describe the principal components used in standby power systems—namely, UPSs, transfer switches, and engine-generator (E/G) sets.

Principles: Standby Power System Design

The design of a standby power system for a specific electric-power load requires consideration of the following factors:

- **Reliability:** The questions are
  - What is the power quality of the utility source?
  - What is the cost of a power-quality event?
  - Will the system be required to operate continuously (24/7)?
  - What reliability of the electric power supply is required in terms of MTBF, minutes per year unavailability, Tiers, or other measures?
- **Maintenance:** The questions are
  - Can the load be shut down to perform maintenance or equipment replacement on the standby power system?
  - Can the standby power system be designed as online, or standby-redundant, for reliability or maintenance?

- **Expansion:** The questions are
  - Is expansion or modification of the load planned with or without shutdown?
  - Is expansion of the standby power system planned in terms of increased UPS-kVA rating, energy-storage capacity (batteries) or engine-generator kVA?
- **Personnel:** The questions are
  - What type of monitoring system is planned? Onsite, contract-type, alarm equipment?
  - What level of training will be given to personnel? Instruction regarding the complexity of the system? Will the training be done by vendors?
- **Cost:** The questions are
  - How much are measures worth for a standby power system over the basic unprotected supply of power to the load?

Components to Assemble Standby Power Systems

Components have been described in the previous chapters to correct for utility and internal-plant power deficiencies. These components can be assembled into standby power systems for critical loads and systems. They include the following [13.1]:

- **Transformers:**
  - Constant-voltage (CV) transformers for voltage regulation
  - Phase-shifting transformers for harmonic cancellation
  - Power distribution unit (PDU) transformers to supply individual loads
- **Dynamic Voltage Compensators:**
  - Compensation for short-time voltage sag and interruption
  - Extended time operation
  - Single-phase, three-phase loads
- **Uninterruptible Power Supplies (UPSs):**
  - Single-phase, battery support
  - Three-phase, battery support
  - Flywheel energy storage
  - Fuel-cell energy storage
- **Support Equipment:**
  - Engine-generator set
  - Gas-turbine generator set
  - Transfer switch, E/G set
  - Transfer switch, utility feeders

Sample Standby Power Systems

The design of practically every standby power system using the preceding list of components is unique. Each design is based upon the total electrical load (kVA), the reliability and number of utility feeders, the space available, the reliability requirements for the load power, the selection of the UPS modules, PDUs, transfer switches and E/G sets, the dollars available, and other factors. Sample basic systems in order of cost and complexity include the following:

1. **Dynamic Voltage Compensator plus a PC:** The simplest combination of a standby power system and a PC is shown in Figure 13.1. The compensator only protects the PC from short-time utility voltage interruptions up to three cycles (50 ms) and sags to 50 percent for up to 2 s.
2. **UPS plus a PC:** This configuration (as shown in Figure 13.2) of a single-phase battery-powered UPS supplying a single personal computer, is the most common arrangement for preventing voltage distortion, sags, surges, and interruptions from affecting the PC. Typical UPSs of 300-W rating, 5-min battery run time, and 120-V terminals in and out are commercially available. The UPSs are line-interactive (Delta) or double-conversion (online). The PC plus UPS can be used in an office, home, factory, or as part of an industrial control or monitoring system.
3. **UPS plus a server and PCs:** The battery-powered UPS can supply multiple PCs from the load terminals of a three-phase UPS, as shown in Figure 13.3, or a local area network (LAN), as shown in Figure 13.4. The UPS would be rated in the 2-to 10-kVA range, typically 208/120-V output, and 10-min battery run time. The UPS must have a sufficient power rating to provide the start-up inrush current to the inputs of the PCs, servers, and printers. The UPS will shut down for utility power interruptions exceeding the battery ampere-hour run time. For maintenance work on the UPS, such as battery replacement or repair, either the UPS is shut down, or the load is transferred to the utility source with a synchronized by-pass switch. Some UPSs utilize "hot swappable batteries."

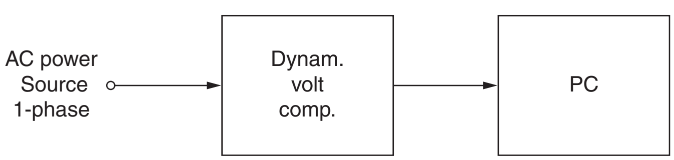

Figure 13.1 Block diagram of a dynamic voltage compensator supplying a PC.

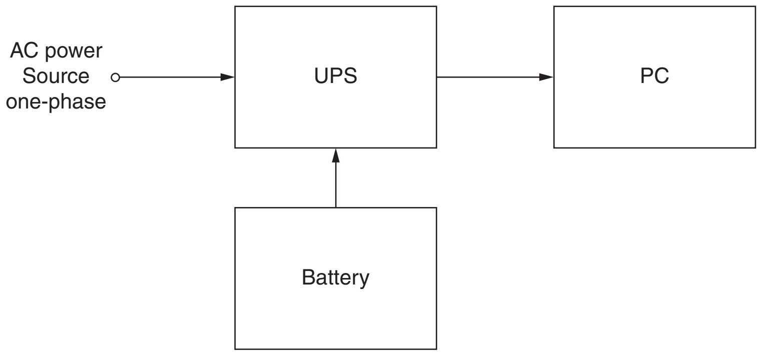

Figure 13.2 Block diagram of a single-phase battery-powered UPS supplying a PC.

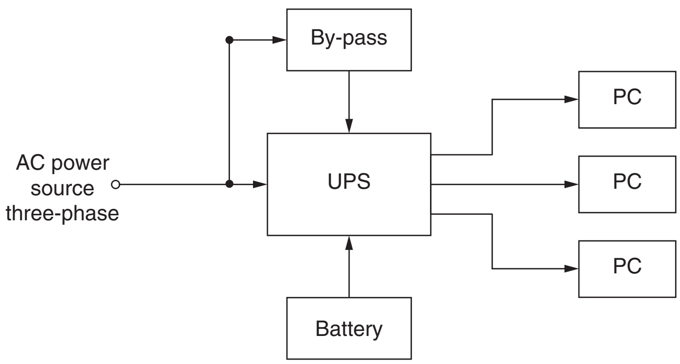

Figure 13.3 Block diagram of a three-phase battery-powered UPS supplying multiple PCs.

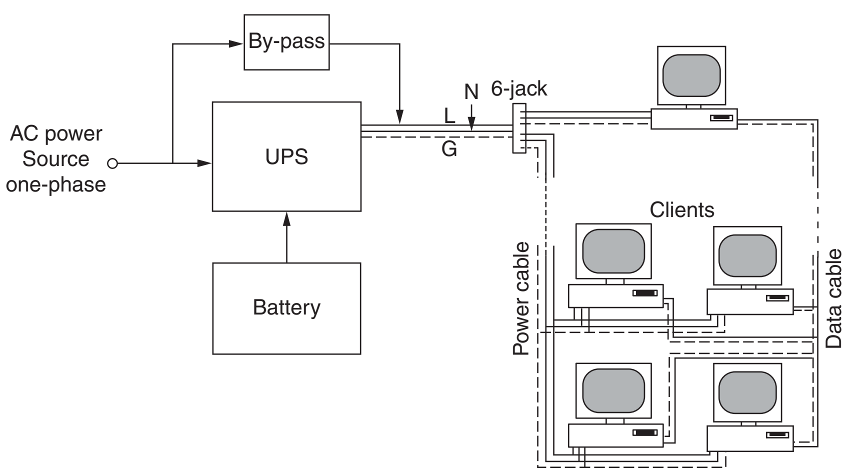

Figure 13.4 Battery-powered UPS supplying a PC local area network (LAN).

4. **UPS plus a Transfer Switch and an E/G Set:** An elementary standby power system to withstand long utility power interruptions and long UPS maintenance periods is shown in Figure 13.5. The system operates in the following ways:
   - Normal-utility service. The UPS receives power from the UPS bus and delivers power to the load. The battery has been charged by utility power.
   - Utility service is interrupted. The UPS receives power from its battery and continues to deliver power to the load. The E/G set starts. The transfer switch operates to supply generator power to the UPS. The UPS bus is transferred to the E/G set. The battery recharges. When utility service is restored, the process is reversed.
   - UPS must be taken out of service. The E/G set is started. When it is up to speed, voltage, and frequency, the transfer switch operates. The UPS by-pass switch is closed to supply the load from the E/G set. The UPS is taken out of service. When the UPS is to be returned to service, the process is reversed.

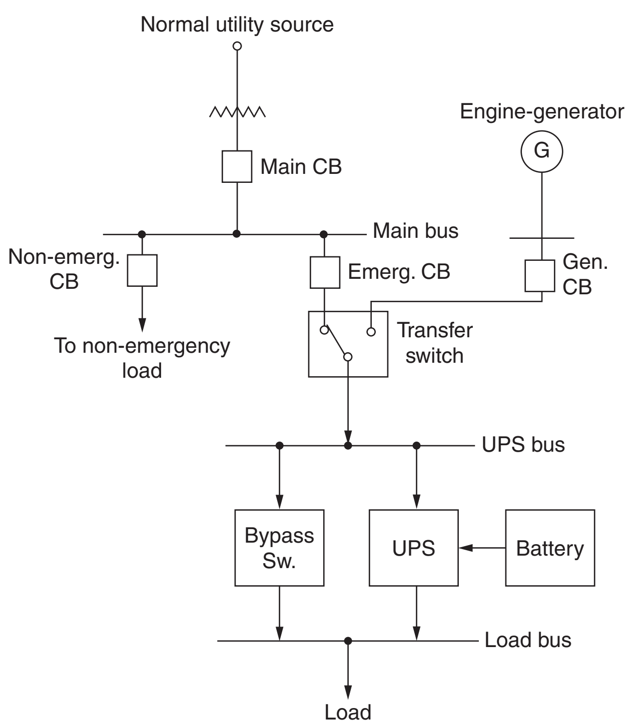

Figure 13.5 A battery-powered UPS system: utility source, engine-generator set, transfer switch, and by-pass switch.

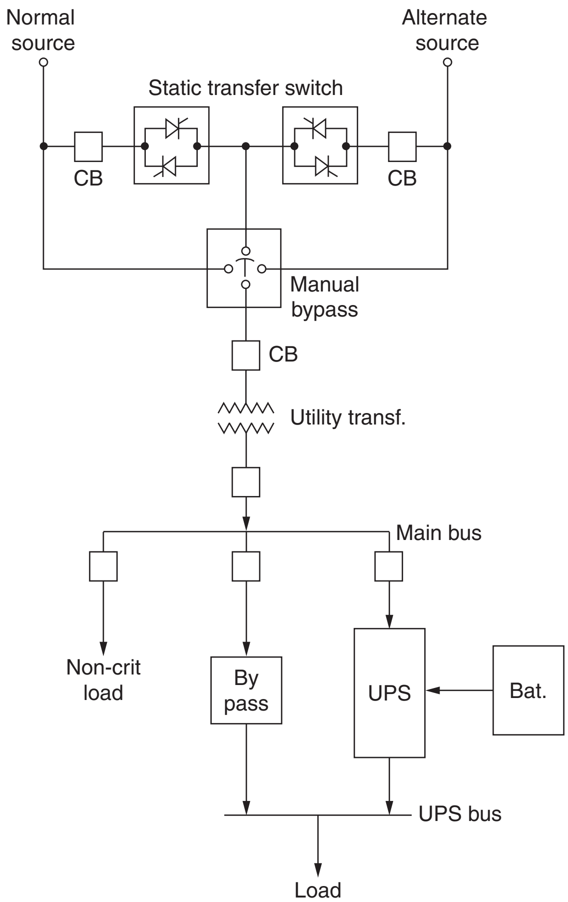

Figure 13.6 Two primary-voltage utility feeders with static transfer switch.

5. **UPS plus Two Feeders and a Utility Transfer Switch:** An elementary standby power system utilizing two utility feeders from two substations is shown in Figure 13.6. In case of a feeder fault or failure, the utility transfer switch transfers the service to the alternate feeder. The UPS operates from its battery during the transition. Other loads, such as air conditioning, heating, and lighting, either continue to operate or must be restarted.

Engine-Generator Sets

Engine-generator sets (E/G sets) are used in standby power systems to extend the operation time of the UPS beyond the available discharge time of the batteries. For large UPSs (for example, larger than 100 kVA), the battery time is usually only several minutes. The transfer from utility line to E/G set, including starting and stabilizing the generator for frequency and voltage, can be accomplished in about 10 s. Sometimes a short time delay is introduced in starting to avoid too frequent E/G starts for short-time voltage sags and interruptions that can be handled by the batteries of the UPS.

Engine-generator sets are available from 50 to 2500 kVA. A 218-kVA diesel-engine generator set is shown in Figure 13.7 [13.1]. For larger loads, it is common to employ multiple E/G sets operating in parallel to obtain reliability through redundancy and to have a set available for maintenance. In addition, electric power is required for non-UPS load—that is, air conditioning, lighting, and water pumps. Combustion turbines are also employed to drive generators in standby applications.

Standards

The major problem for the installation of E/G sets is environmental. The sets produce noise, exhaust, and vibration; they require coolant air or water, fuel, and fuel systems; they are heavy and require adequate foundations. A list of codes and standards governing E/G sets as an alternative to utility power includes the following:

- ANSI/IEEE 446-1995, "Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications" [13.2]

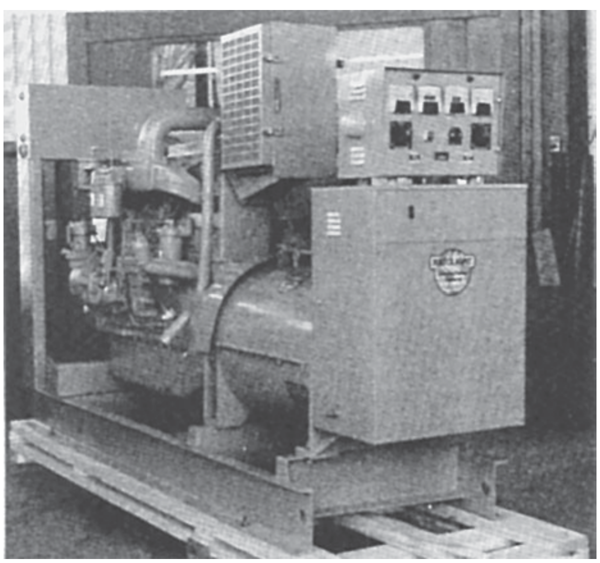

Figure 13.7 Diesel engine-generator set. Rating: 175 kW, 0.8 PF, 480 Y / 277 V, 60Hz [13.1].

- NFPA 110-2002, "Standards for Emergency and Standby Power Systems" [13.3]
- NFPA 70-2005, " National Electrical Code" specifically [13.4]
  - Art. 700, "Emergency Systems"
  - Art. 701, "Legally Required Standby Power Systems"
  - Art. 702, "Optional Standby Power Systems"

Component parts of an E/G set installation

The component parts or subsystems of an E/G set are shown in Figure 13.8. Detailed information is given in *On-Site Power Generation: A Reference Book*, fourth edition [13.5]. The parts are described as follows:

- **Engine:** Gasoline, diesel, internal combustion engine, or a combustion gas turbine. Turbine requires minutes to start and acquire load, compared to seconds for an internal combustion engine.
- **Generator:** Three-phase salient-pole (1800 r/min or 3600 r/min) exciter for field current and damper windings for parallel operation.
- **Fuel:** Gasoline, diesel oil, natural gas, or another. Requires day tank and offsite tank, pumps, piping, vents, and filters.
- **Coolant:** Radiator and fan mounted on the engine, or external to the engine, with ducts to the engine.
- **Exhaust:** Muffler and exhaust piping to discharge gases and control noise.
- **Starter:** Electric motor, battery, and charger, or pneumatic means and high-pressure air storage. Start initiated by signal from manual switch or transfer switch.

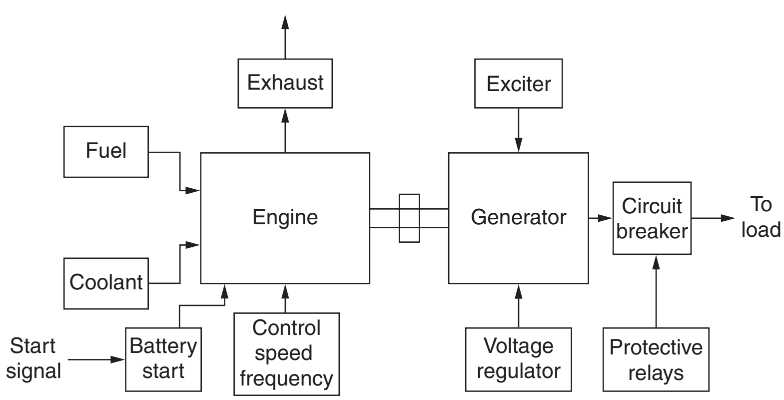

Figure 13.8 Block diagrams. Functions of E/G set.

- **Control:** Electronic isochronous governor for independent operation and when synchronized to other generators and/or to the utility line. Active power load division.
- **Generator Protection:** Relays to monitor load current, terminal voltage, reverse power, frequency, over temperature, to operate alarms and trip the circuit breaker.
- **Voltage Regulator:** Electronic regulator for the exciter or main field current to regulate terminal voltage. Reactive power load division.
- **Synchronizer:** Controls engine speed and circuit breaker closing when the E/G set is to operate in synchronism with the utility line and/or other E/G sets.
- **Circuit Breaker:** Electrically operated. Rated for generator overload current and for maximum three-phase short-circuit current.

Operation. The E/G set is a universal, useful, piece of equipment at a site whose output supplements utility service. Its operation includes the following functions:

- **Loads:** Include UPS, lighting, air conditioning, heating, fans, pumps, electronic equipment, and appliances. To a degree, loads can draw non-sinusoidal current (harmonics) and be unbalanced. The generator must have low subtransient reactance (damper windings) and/or be oversized for harmonic load current.
- **Emergency Operation:** The controls of the transfer switch order the E/G set to start when an interruption in utility voltage is detected (or a manual test signal is entered). When the generator voltage has stabilized at the correct amplitude and frequency, the transfer switch transfers the load to the E/G set. Starting and transfer usually takes about 10 s. When utility power is restored, the controls allow the E/G set to run for about 30 min before the transfer switch transfers the load back to the utility power. Multiple engine-generator sets start in sequence.
- **Testing:** E/G sets for emergency service should be tested about once a week, and allowed to run at least 30 min. The generator can be loaded with one of the following: (1) a dummy load, (2) a facility load, or (3) it can be synchronized to the utility line. The test can be initiated manually or automatically from a programmable controller.
- **Non-emergency Standby:** The E/G can be used to provide power to equipment or facilities when the normal power source is not available—for example, when they are under construction or maintenance work is being done. The UPS can be placed on by-pass. Adequate fuel must be available.

- **Parallel Operation:** Two or more E/G sets can be operated in parallel for redundancy, to secure more than one set's power, and to handle large motor starting. The governors and voltage regulators must insure parallel operation at the required voltage and frequency, as well as active and reactive power division.

Transfer switches

The purpose for a transfer switch is shown in Figure 13-5. The switch connects the load, in this case a UPS, to either the utility source or to an E/G set. The operation is usually conducted when power from the utility line is interrupted and the output of the E/G set must supplement the capacity of the batteries of the UPS. The transfer switch has other functions, such as transferring between two feeders or transformers, and transferring power to a motor from a failed feeder to an alternate feeder. The subject is covered extensively in reference [13.5].

Standards. Pertinent standards on transfer switches include the following:

- NEMA, "AC Automatic Transfer Switches," ICS 2-44 [13.6]
- NFPA, "National Electrical Code," NFPA 70-2005 [13.4]
- UL, *Standard for Automatic Transfer Switches*, fourth edition, UL 1008 [13.7]
- NFPA, "Emergency and Standby Power Systems," NFPA 110-2005 [13.3]

Types of transfer switches. Several types of transfer switches are available and include the following:

- **Manual:** The transfer switch can consist of a double-throw multipole switch, or two mechanically interlocked circuit breakers or contactors.
- **Automatic Electromechanical**
  - Three-pole or four-pole to switch three phases with or without neutral.
  - Open or closed transition, which usually requires utility permission when switching E/G sets with respect to a utility line.
  - Controls, including voltage sensing, engine starting and shutdowns.
- **By-pass:** Incorporates a by pass switch section that can connect the preferred line to the load while the transfer switch is removed for maintenance, as shown in Figure 13.9 [13.5].

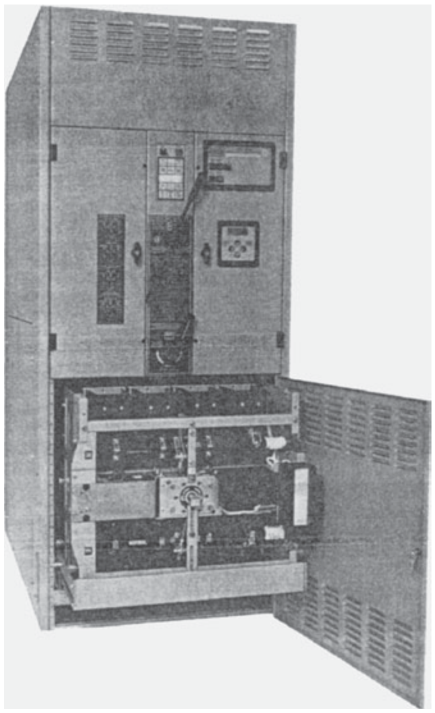

Figure 13.9 Automatic transfer switch with optional bypass- isolation switch [13.5].

- **Solid State:** Utilizes thyristor or GTO AC switches in each leg, as shown in Figure 13-6. Transfer switches have been built for switching utility feeders rated up to 34 kV.

Applications. Applications for transfer switches include nearly every area of electrical application, particularly those devoted to high reliability and safety. These include the following:

- **Utility to E/G Set:** A generic diagram is shown in Figure 13.10. The shape of the movable contact is typical to obtain a short travel distance and no ambiguity of contact positions.
- **UPS Supply:** Transfer from a utility line to an E/G set to supplement the UPS battery. Data centers employ up to 10,000 kVA of E/G sets and suitable transfer switches.
- **Electric-Motor Transfers:** For large induction motor–driven fans and pumps, as in power plants, transfer switches are employed where two alternate transformers or feeders are provided.
- **Lighting:** Alternate and emergency lighting systems supplied by transfer switches from batteries, inverters, and alternate feeders.

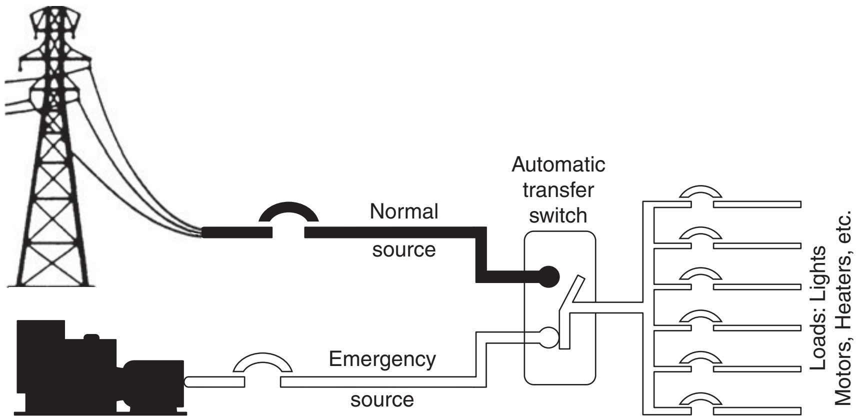

Figure 13.10 Normal/emergency sources. Automatic transfer switch [13.5].

Summary

Standby power equipment provides the means to improve the reliability of the utility electric power supply to critical load equipment. Alternate feeders and E/G sets utilizing transfer switches are the principal means of providing both power and standby power to UPSs, health care facilities, and telecommunications systems. The design requires consideration of all aspects of the existing utility supply and the desired objectives of the high-reliability system.

References

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Chapter

14

Power Quality Measurements

In this chapter, we shall discuss practical issues related to making power-quality measurements. Any measurement job requires the proper tools to do that job. The monitoring of power quality at the supply end, at distribution and transmission, and at the load end has become of major interest in recent years. In the following, we will discuss various types of equipment used in power-quality measurements, and the proper use and limitations of such equipment.

Multimeters

Multimeters are used to measure voltages, currents, and resistances. Typical applications of multimeter measurements are line-voltage measurements and imbalance measurements. In making voltage and current measurements, generally we're interested in measuring the rms value of the waveforms. Some subtleties are associated with this measurement.

In one type of multimeter, the input waveform is rectified and averaged, as shown in Figure 14.1a. This method works well for pure sine waves (where the rms value is the peak value divided by the square root of two), but for waveforms with harmonics, this method is prone to errors. Error is especially high for waveforms with a high crest factor.

Several types of multimeters produce "true-rms" readings—that is, they accurately report the rms value of waveforms with harmonic distortion. One type of true-rms multimeter employs an rms-to-DC converter (Figure 14.1b). Several IC manufacturers produce rms-to-DC converter integrated circuits.[1] Another method of producing true-rms readings involves a thermal measurement method (Figure 14.1c) [14.1].

[1] See, for example, Analog Devices and Linear Technology.

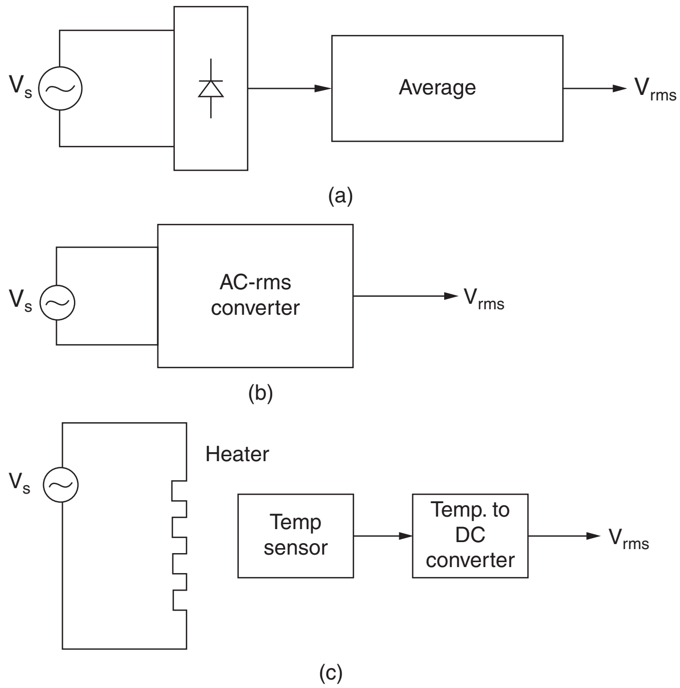

Figure 14.1 Multimeter types for making AC voltage measurements. (a) Rectify and average. (b) Analog computation. (c) Thermal.

True-rms multimeters are more accurate in the measurement of the rms value of periodic waveforms.

Oscilloscopes

Today's oscilloscopes have more than enough bandwidth to display the harmonics present in all power-quality events. For instance, the 20th harmonic of the line frequency in the U.S. is 1200 Hz, which is much lower than the bandwidth of even an inexpensive oscilloscope. Impulsive transients (like that caused by lightning strikes or power switching) typically last a few microseconds. It is well within the capability of oscilloscopes to measure and display these waveforms with good accuracy.

Scopes are often used in conjunction with current probes[2] to measure AC line currents. Often, differential voltage probe[3] modules are used to

[2] See, for example, the Tektronix P6042 current probe, which has a response from DC to 50MHz.

[3] The differential probe overcomes the practical problem of using a single-ended scope probe, which has a signal input and a ground clip.

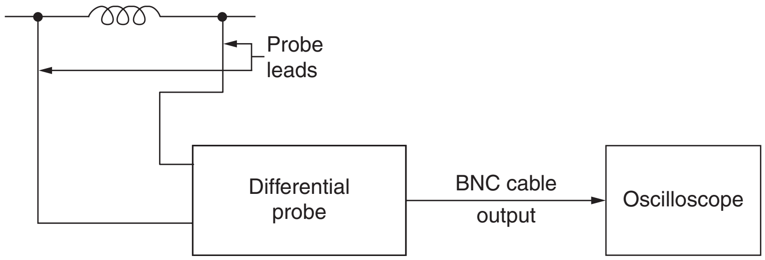

Figure 14.2 Measurement system for making high voltage differential measurements.

measure the voltage difference between two points in a system. Many manufacturers make high voltage differential probes that are compatible with oscilloscope inputs. Typical specifications for differential probes[4] are

- Bandwidth: 100 MHz
- Differential voltage: 5000 V
- Common-mode voltage: 2000 V

A typical system for making high voltage differential measurements is shown in Figure 14.2. We see that the output of the differential probe is a 50-Ω BNC cable[5] that interfaces with an oscilloscope. The differential probe has a conversion ratio (millivolts per volt) that brings down the signal levels to the oscilloscope to a manageable level.

Current Probes

Current probes come in several different types. Hall-effect current probes (like that used in the Tektronix P6042) detect all the way down to DC by utilizing the "Hall effect." Hall devices are semiconductors that generate an output voltage in response to a magnetic field created by a current. Hall probes have the advantage that they provide output at DC. Unfortunately, they are prone to drift and should be calibrated prior to use.

Other types of current probes use current transformers (CTs). CT current probes do not give an output at DC since they are based on transformer action. A typical test setup using a CT and an oscilloscope is shown in Figure 14.3. CT current probes give a conversion ratio (volts per amp) when terminated in the proper resistance—in most cases 50 Ω.

[4] See, for example, the Tektronix P5200 high-voltage differential probe.

[5] BNC cables are coaxial cables used in instrumentation and video. A BNC cable is characterised by its transmission line characteristic impedance, which is typically 50 or 75 Ω

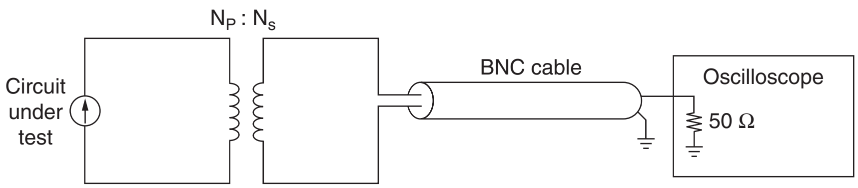

Figure 14.3 A measurement system for making high current measurements using a CT and an oscilloscope.

Search Coils

The magnetic field produced by a current can be detected by a "search coil" as shown in Figure 14.4. The voltage output of the search coil is found using

$$v_o = \mathrm{NA}\frac{dB}{dt}$$

where N is the number of turns in the search coil, A is the area of the coil, and dB/dt is the time rate of change of the magnetic flux density perpendicular to the plane of the search coil. In the setup of Figure 14.4, the magnetic field H and the magnetic flux density B are found using

$$H = \frac{i}{2\pi r}$$

$$B = \mu_o H$$

where r is the mean radius from the current-carrying wire to the search coil, and μ_o is the magnetic permeability of free space. Note that this measurement can be affected by stray time-varying fields from sources other than the current-carrying wire being measured.

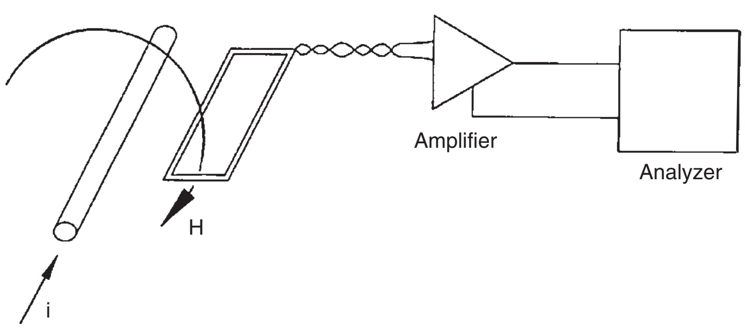

Figure 14.4 A search coil setup [14.2].
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Power-Quality Meters and Analyzers

A number of manufacturers make "power-quality meters" and "power-quality analyzers," which are instruments similar to oscilloscopes,[6] but that have a number of functions particularly suited to making power-quality measurements. In measuring power quality, we must be able to trigger on events that are not continuous (such as a voltage sag) or transient (like that caused by lightning strikes or utility faults). For instance, typical power-quality meters/analyzers and analyzers have the following functionalities:

- Datalogging—capturing waveforms in real-time for later display
- The ability to trigger on power-quality events such as sags, swells, or transients
- Calculation of power-quality metrics such as total harmonic distortion in real-time
- Spectrum analysis
- Inputs for high-voltage probes and high-current probes

Numerous factors [14.3] should be considered when selecting a power-quality measurement meter/analyzer, including:

- The number of channels (for instance, single-phase or three-phase)
- The input voltage range
- The current measurement range
- Isolation
- Communication capabilities (For example, can the instrument be networked or tied to a stand-alone computer?)

The block diagram of a typical system with a power-quality analyzer is shown in Figure 14.5. The power-quality analyzer A/D converts system voltages and currents. Power indices such as THD, harmonic content, and the like are calculated in real-time. In addition, the analyzer has on-board memory so data may be saved for future analysis.

The output of a typical power-quality analyzer is shown in Figure 14.6, where we see the time waveform of the line current in a copy machine (top trace) and the harmonics (bottom trace).

Current Transformer Analysis in Detail

A typical setup for high-current sensing is shown in Figure 14.7. The primary side current we are trying to measure is I_p, and is supplied by a bus bar. The CT steps the current down with the ratio $1{:}N_s$. We resistively

[6] See, for example, Fluke and Dranetz BMI, among others.

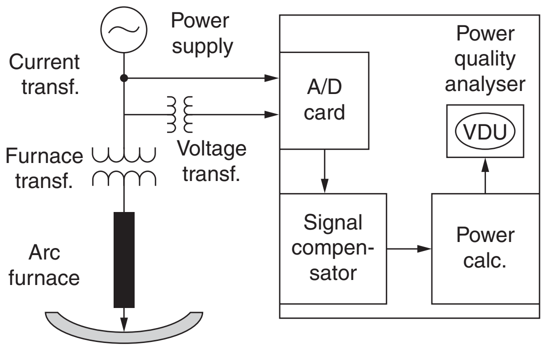

Figure 14.5 A block diagram of a power-quality analyzer [14.4].
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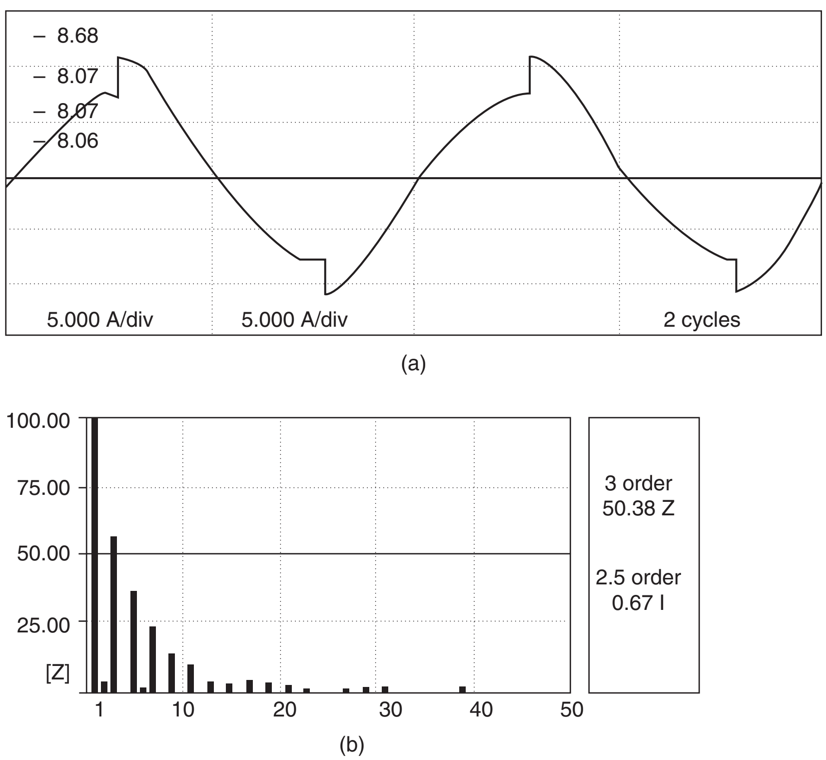

Figure 14.6 Power-quality analyzer measurements on a Xerox machine [14.5]. (a) Line current (b) Spectrum.
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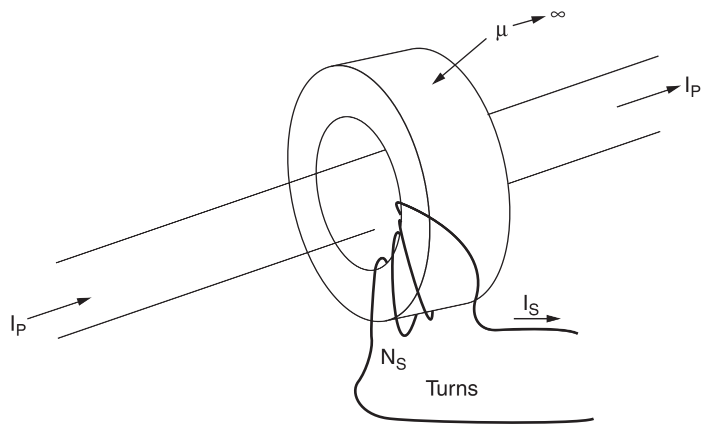


Figure 14.7 A typical current transformer for a high-current application. The primary of the transformer has one turn (due to the bus bar) and the secondary has Ns turns. The CT provides a current step-down.

load the secondary in order to convert the secondary current I_s to a voltage that we measure.

In order to sense the primary-side current, the CT secondary is loaded with a resistive load R_B (called the "burden"), as shown in Figure 14.8. This burden converts the secondary current I_S to a voltage V_{sense}, which is detected by electronics further downstream. The ideal input-output transfer function between the input current I_p and the sensed voltage V_{sense}, assuming no transformer parasitics, is

$$V_{\text{sense}} = \frac{I_p R_B}{N_s}$$

Of course, this transfer function assumes the transformer is ideal. A more realistic model of a current transformer is shown in Figure 14.9a. Elements of this model include

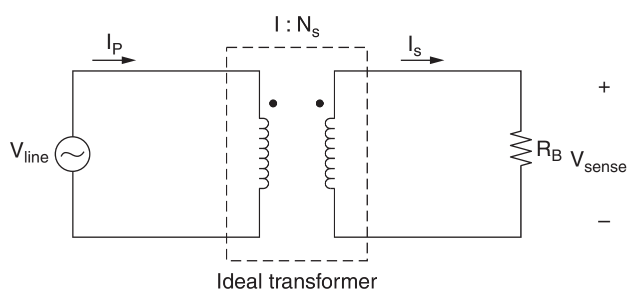
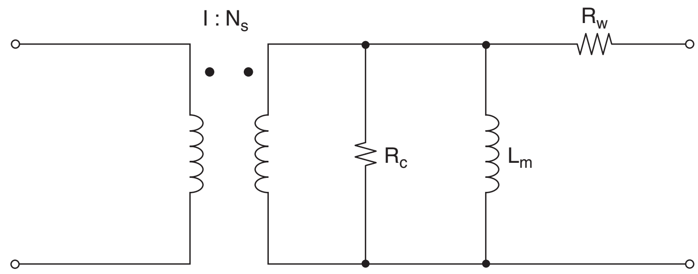


Figure 14.8 The ideal CT loaded with the "burden" resistor R_B.



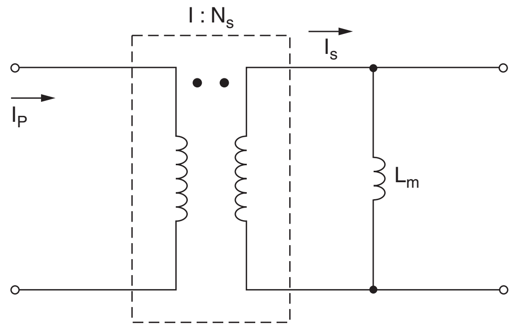


Figure 14.9 Models of a current transformer. (a) Includes parasitic elements such as core loss resistance R_c, magnetizing inductance L_m (referred to the secondary), and secondary winding resistance R_w. (b) Model resulting from the assumption that the core loss and secondary winding resistance have negligible effects.

- $\boldsymbol{R_c}$: The core loss resistance, which models power dissipation due to eddy currents and hysteresis in the core
- $\boldsymbol{L_m}$: The magnetizing inductance. This is the inductance you would measure if you connected up an impedance analyzer to the secondary side of the transformer, with the primary open-circuited.
- $\boldsymbol{R_w}$: The copper winding resistance of the secondary winding.

In some cases, the core loss and secondary winding loss are negligible, and we can model the transformer as shown in Figure 14.9b.

A model[7] of the secondary circuit is shown in Figure 14.10. In this circuit, we've referred the primary current to the secondary side of the

[7] Of course, this more realistic view still ignores many important parasitic effects, including secondary winding resistance, core loss, and primary to secondary leakage inductance.

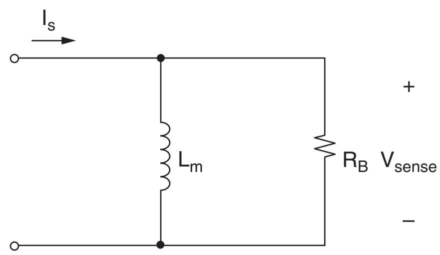


Figure 14.10 A secondary circuit. The current I_s is the primary current referred to the secondary through the turns ratio N_s.

transformer, and termed it I_s. The value of I_s is stepped-down from the primary and is

$$I_p' = \frac{I_p}{N_s}$$

We see that the sensed voltage V_{sense} depends not only on the value of the burden resistor R_b, but also on the value of the "magnetizing inductance"[8] L_m as measured on the secondary side. The transfer function relating the reflected primary current I_p' to the sensed voltage V_{sense} in the Laplace domain is

$$\frac{V_{\text{sense}}(s)}{I_p'(s)} = \frac{L_m s}{\dfrac{L_m}{R_B}s + 1}$$

The magnitude and phase[9] of this transfer function are

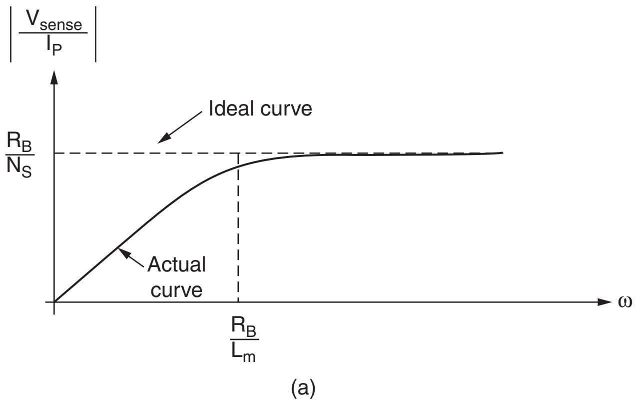
$$\left|\frac{V_{\text{sense}}(\omega^2)}{I_p'(\omega^2)}\right| = \frac{L_m\omega}{\sqrt{\left(\dfrac{L_m}{R_B}\omega\right)^2 + 1}}$$

$$\angle\frac{V_{\text{sense}}(\omega)}{I_p'(\omega)} = \frac{\pi}{2} - tan^{-1}\left(\frac{\omega L_m}{R_B}\right)$$

Note that at very low frequencies (well below R_B/L_m), the transfer function magnitude approaches zero. This is as expected, because a transformer does not pass currents at DC. At very high frequencies, the magnetizing inductance L_m essentially becomes an open circuit and all the current passes through the R_B burden resistor.

[8] The magnetizing inductance is the inductance you would measure if you put the secondary winding on an impedance analyzer.

[9] Note that the phase is expressed in radians. The conversion to degrees is degrees = radians × (360/2π).



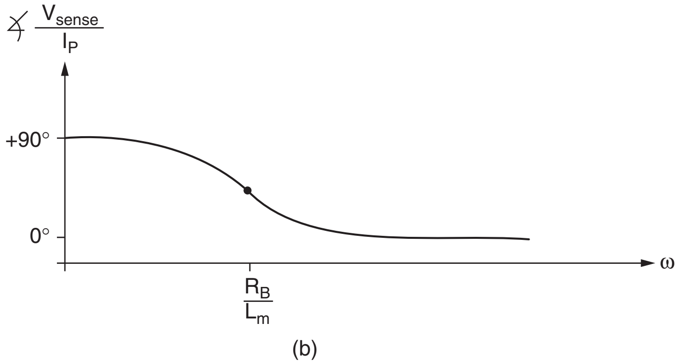


Figure 14.11 The transfer function relating sensed voltage V_{sense} to input primary current I_p. Note that the ideal input-output transfer function has a flat gain over all frequencies, and zero phase shift.

The magnitude and angle of this transfer function are shown in the Bode plots of Figure 14.11. Note that the transfer function of the current transformer approaches the ideal only for frequencies where $\omega \gg R_B/L_m$. Also note that there can be significant phase shift through the CT even if the magnitude of the transfer function is very close to the ideal. Let's examine the transfer function gain and angle in the case of $\omega \gg R_B/L_m$.

$$\left|\frac{V_{\text{sense}}(\omega)}{I_p^{'}(s)}\right|_{\omega \gg \frac{R_B}{L_m}} \approx R_B$$

$$\angle \frac{V_{\text{sense}}(\omega)}{I_p^{'}(\omega)} = \frac{\pi}{2} - \tan^{-1}\left(\frac{\omega L_m}{R_B}\right) \approx \frac{R_B}{\omega L_m}$$

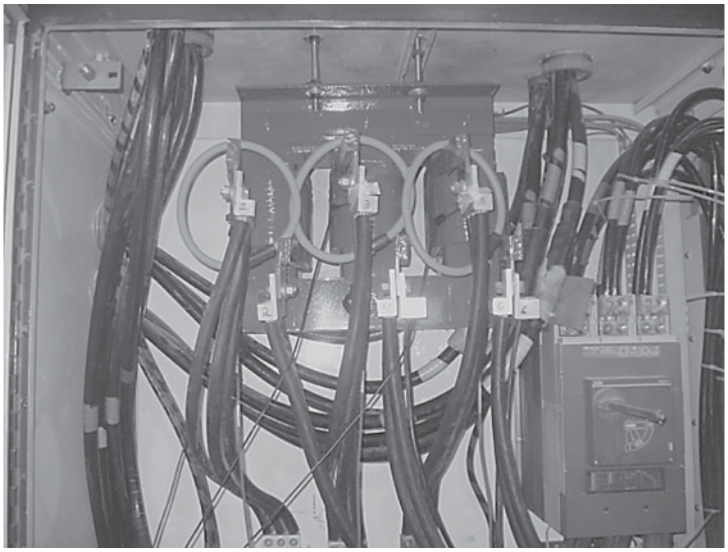


Figure 14.12 Current probe measurements on a adjustable-speed drive.

Note that the angle is expressed in radians. This result shows that there can be significant phase shift through the transformer even if the magnitude is very close to the ideal.[10]

Figure 14.12 shows three current probes for making real-time measurements on a 600-V adjustable speed drive, used by one of the authors in a factory measurement in 2005. Instrument transformers are discussed in much detail in references [14.6] and [14.7].

Example 14.1: Current transformer. A 60 Hz current transformer has a primary current of 500 A and a turns ratio of 1000:1. The CT has a burden resistor of 1 ohm and a magnetizing inductance of 100 millihenries. We'll find the 60 Hz gain and phase error for a current transformer with magnetizing inductance $L_m = 1$ millihenry and burden resistor $R_B = 1\ \Omega$. We'll also find the ideal output voltage level V_{sense}, assuming a transformer turns ratio of 1000:1, and the power dissipated in the burden resistor.

The ideal output voltage level is

$$V_{\text{sense}} = \frac{I_p R_{\text{sense}}}{N_s} = \frac{(500)(1)}{1000} = 0.5\,\text{V}$$

[10] This result is characteristic of first-order systems.

The magnitude of the sensed voltage is

$$|V_{\text{sense}}| = \left(\frac{I_p R_B}{N_s}\right)\frac{1}{\sqrt{\left(\frac{L_m \omega}{R_B}\right)^2 + 1}} = (0.5\text{ V})(0.999648) = 0.4998\text{ V}$$

Therefore, the magnitude error is only 0.04 percent. We find the angle[11] as follows:

$$\angle V_{\text{sense}} = 90° - \tan^{-1}\left(\frac{\omega L_m}{R_B}\right) = 90° - 88.5° = +1.5°$$

Therefore, the sensed voltage has a +1.5° phase shift in relation to the primary current. The power dissipated in the burden resistor is due to the secondary current of 0.5A, and is

$$P_{\text{diss}} = I_s^2 R_B = 0.25\text{ W}.$$

Example 14.2: CT error. A CT is utilized in a data acquisition system and is used in the calculation of real power, reactive power, and the power factor in a single-phase system with sinusoidal voltages and currents. CT has an ideal magnitude response, but a positive phase shift of 5 degrees. Using data from this CT and other instrumentation, the data acquisition system calculates values of:

- Apparent power $S = 10$ kVA
- Real power $P = 9$ kW
- Reactive power $Q = 4.36$ kVAr
- Power factor PF = 0.9 lagging

We shall determine the error in the four measurements due to the phase shift through the CT.

The calculation of apparent power is correct, since calculation of S does not depend on the phasing of the measured voltage and current. So, we find

$$S = 10\text{ kVA}$$

[11] The +90° is due to the inductor at low frequencies. For a purely inductive circuit, the voltage leads the current by 90 degrees.

Next, we'll look at the power factor. The data acquisition system calculated a power factor of 0.9, which means the angle between voltage and current is

$$\theta = \cos^{-1}(0.9) = -25.8°$$

However, we know that the actual angle is 5 degrees more (due to the error in phase shift from the CT). Therefore, the actual power factor is

$$\text{PF} = \cos(-30.8) = 0.86$$

We now find the real power:

$$P = (\text{PF})(\text{S}) = (0.86)(10\ \text{kVA}) = 8.6\ \text{kW}$$

Next, we find the reactive power:

$$Q = \sqrt{S^2 - P^2} = 5.1\ \text{kVAr}$$

The result is that a relatively small phase shift can result in large calculation errors.

Summary

In this chapter, we have discussed some of the subtleties of power-quality measurement, including selection of the proper measurement equipment. A successful power-quality measurement involves choosing the proper measurement tool, and using it correctly.

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