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An Introduction to Diesel-Electric Generating Plants

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CONTENTS

1. DESIGNS FOR DIESEL-ELECTRIC GENERATING PLANTS
2. SYNCHRONOUS GENERATORS, EXCITATION, AND REGULATION
3. ENGINE CONTROLS AND INSTRUMENTS
4. GENERATOR CONTROLS AND PROTECTION

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1. DESIGNS FOR DIESEL-ELECTRIC GENERATING PLANTS. This course discusses the design of diesel-electric generating plants for facilities where utility power is not available.

1.1 DIESEL-ELECTRIC GENERATING PLANTS. Rotational speed and Break Mean Effective Pressure (BMEP) limits are summarized in Table 1 for various unit generator sizes and duties.

Engine Class	output Specified	Maximum Rotational Speed (r/min)	Maximum Break Mean Effective Pressure (lb/in ²)			
			Two-Stroke		Four-Stroke	
			Naturally Aspirated	Turbocharged Aftercooled	Turbocharged Not Aftercooled	Turbocharged Aftercooled
Prime Duty	10 kW to 300 kW	1800	90	105	135	165
	301 kW to 500 kW	1200	--	--	135	170
	501 kW to 1500 kW	900	90	120	--	180
	1501 kW to 2500 kW	720	90	130	--	200
	2501 kW and larger	514	--	--	--	225
Standby/ Emergency Duty	10 kW to 300 kW	1800	90	115	150	185
	301 kW to 1000 kW	1800	90	120	--	200
	1001 kW to 2000 kW	1200	--	130	--	220
	2001 kW to 3000 kW	900	90	140	--	260

Table 1
Recommendations -- Unit Sizes, Maximum Rotational Speeds and Break Mean Effective Pressure

1.1.1 MODIFICATIONS TO DESIGNS. Designs discussed in this course are representative and intended for illustration purposes only. These designs should be considered only as a suggested basis for design from which variations may be made.

Many alterations to meet the specific site requirements or local conditions may be necessary.

1.1.2 MATCHING DESIGNS TO LOAD DEMANDS. Develop design concepts that satisfy electric loads in the most economic manner. Select the design with necessary modifications in accordance with the best design concept. Use economic analysis methodologies as appropriate. Evaluate all plausible deviations from the selected design using the same economic analysis methodology.

1.1.3 DESIGN PLANT CAPACITIES. Suggested designs provide for three initial engine-generator bays for prime duty and two initial bays for standby/emergency duty plants. A future engine-generator bay is indicated for all designs. Most plants will need to be expanded to satisfy future electric loads. The designs provide only for a single operating unit; additional units may be required to meet minimum reliability needs. Provision of a single operating unit is not usually economical. Selection of unit capacities must consider varying electric demands. Plant capacity must be selected to satisfy reliability criteria once the unit capacity has been established.

1.2 CRITERIA FOR UNIT AND PLANT CAPACITIES.

1.2.1 NUMBER OF UNITS. The number of units selected for any plant should provide for the required reliability and flexibility of plant operations. The minimum number of units needed to satisfy these requirements usually results in the most economical and satisfactory installation.

1.2.2 RELIABILITY. Spare units are required to ensure system reliability. Minimum reliability requirements are related to duty types and criticality of loads.

1.2.2.1 PRIME DUTY. Two spare units are required, one for scheduled maintenance and one for standby or spinning reserve.

1.2.2.2 STANDBY DUTY. One spare unit is required for scheduled maintenance. Another unit may be required for spinning reserve when justified.

1.2.2.3 EMERGENCY DUTY. No spare is usually required in the continental United States; one spare unit may be required for plants outside of the continental United States.

1.2.3 FLEXIBILITY. To provide for future growth, the firm capacity (total capacity less spare capacity) shall be no less than 125 percent of the maximum estimated electric demand. For an economical operation, individual generating units should be operated at least 50 percent of their rated capacities to satisfy minimum or average demand. Consider providing a split bus (tie circuit breaker) to permit partial plant operation in the event of a bus failure.

1.3 SELECTION OF UNIT CAPACITY. An example of individual unit capacity sizing based on meeting unit and plant capacity criteria is shown on Table 2. Generally, utilize the National Electrical Manufacturers Association (NEMA) MG 1, *Motors and Generators*, standard sizes. Notice that the largest unit size was selected in the example. Other factors, however, such as the type of the load served may affect optimal unit sizing.

1.3.1 ABILITY TO SERVE LOAD UNDER ABNORMAL CONDITIONS. Prime duty generating units are rated 100 percent of their capacity and are also capable of generating at 110 percent capacity for 2 hours out of any 24-hour period. Standby/emergency duty units are also required to have a continuous rating, but are not provided with any reserve capacity. To prevent the loss of an operating unit in system collapse, even one having reserve capacity, proper load shedding or spinning reserve backup must be provided.

1.3.2 LOAD SHEDDING. Load shedding (electrical load segregation to allow dropping of less critical loads) is preferable to loss of an entire plant.

System Parameters					
Estimated Demands:			Firm Capacity Required:		
Maximum = 2,400 kW			2,400 kW x 1.25 = 3,000 kW		
Average = 1,500 kW					
Minimum = 600 kW					
Unit Rating Size Range					
Maximum engine-generator unit size to supply minimum demand at 50 percent capacity = 600 kW/50 percent = 1,200 kW ²					
Minimum engine-generator unit size to supply minimum demand at 100 percent capacity = 600 kW					
Comparisons of Available Unit Capacities					
Unit Size, kW	600	700 ³	800	900 ³	1,000
Firm Capacity, kW	3,000(5) ⁴	3,500(5)	3,200(4)	3,600(4)	3,000(3)
Operating Unit Loading Comparison					
Maximum Demand	5 at 100%		4 at 93%		3 at 100%
Average Demand	3 at 83%		2 at 94%		2 at 75%
Minimum Demand	1 at 100%		1 at 75%		1 at 60%
Select 1,000 kW unit capacity for fewest number of units.					
For a prime duty plant: Initial Firm Capacity = 3,000 kW (3) ⁴ Total Initial Capacity = 5,000 kW (5)					

¹Using NEMA MG 1 standard ratings.

²Not a NEMA MG 1 standard rating.

³No values shown, since there is no improvement over the next smaller engine generator unit size.

⁴Number in parenthesis is the number of engine generator units required.

Table 2

Example of Individual Generating Unit Capacity Sizing 1

1.3.3 SPINNING RESERVE. Where critical loads cannot be shed, spinning reserve is required for backup in the event that a unit is lost from the system. Spinning reserve must provide for shutdown of one unit when operating at maximum demand and with generators running at their maximum 2-hour capacity.

1.3.4 TYPE OF LOAD SERVED. Motor loads may affect unit sizes, either because of other voltage-sensitive loads or because of the size of the motor in relation to unit size.

1.3.4.1 VOLTAGE-SENSITIVE LOADS. Communication, data processing, and other voltage-sensitive loads should be segregated from all motor and other types of utility loads by providing a split-bus system.

1.3.4.2 SIZE OF MOTORS. Starting large motors will have an effect on generators because the starting kilovoltamperes (kVA) of a motor is about three to eight times its running kVA. Design motor starting loads to prevent voltage dips which are significant enough to cause the system to shut down. Reduced-voltage starters and sequential starting of motors are usually provided to prevent unacceptable voltage dips. A unit supplying a single motor may have to be evaluated to determine the cost-effectiveness of special generator starting modifications, use of shunt capacitors, or oversizing of generators.

1.4 FUEL SELECTION.

1.4.1 FUEL TYPES. The fuel for diesel engines may be any of the following types, depending on availability and economics:

- Grade Navy Distillate DF-2 Diesel Fuel Oil of Federal Specification VV-F-800, Fuel Oil, Diesel.
- Marine Diesel of Military Specification MIL-F-16884, Fuel Oil, Diesel Marine.
- Jet Fuel Grades JP-4 and JP-5 of Military Specification MIL-J-5624, Jet Fuel Grade JP-5. Diesel engines may require special metallurgy to accommodate the use of JP-4 or JP-5 on a continuous basis.
- Arctic Grade DBF-800 of Federal Specification VV-F-8001.
- Jet (commercial) fuel.

1.4.2 NONDIESEL FUELS. The use of a nonstandard fuel such as natural gas, liquid petroleum gas, residual oils and gasoline may be allowed if economic advantages are proven through a detailed life-cycle cost economic analysis.

1.4.3 FUEL STORAGE AND HANDLING

1.4.3.1 FUEL PREPARATION. Diesel engine fuel injection systems can be seriously damaged by water and dirt in the fuel. It is important to provide fuel oil centrifuging of all fuels delivered by water transport as fuels can be easily contaminated with water or solids. Provide heating for heavy fuel oils, and in cold climates for all fuels. Filtration shall be provided for all types of fuel. Comply with applicable state and local regulations concerning storage and treatment of fuels.

1.4.3.2 CONVERSION FUEL. On some prime duty plants, provide additional space for installing future additions to the fuel handling equipment, for example, fuel storage for residual fuel and pilot diesel fuel if required, plus residual fuel heaters and centrifuges, dirty fuel tanks and similar items.

1.4.3 FUEL STORAGE AND DAY TANK VOLUMES. Use above-ground storage tanks within diked areas. Provide 30-day storage capacity for prime duty plants and 7-day storage for standby/emergency duty plants unless local conditions will allow less or require greater volume. Storage tank volume shall be based on the rate of fuel consumption of all engines including spares, at 100 percent load, multiplied by a 0.75 operating factor. Tanks should be selected in standard manufactured sizes and should be vertical or horizontal, as best suits the site conditions. The use of underground storage tanks may be considered for small plants if leak detection and double containment provisions are provided. Day tank volumes shall be determined based on the following:

1.4.3.1 PRIME DUTY PLANTS. Provide a day tank for each engine with storage for not less than 2 hours full load operation and with automatic transfer pumps and level controls.

1.4.3.2 STANDBY/EMERGENCY DUTY PLANTS IN STANDBY SERVICE. Provide manually-filled day tanks, each of a capacity able to satisfy 8 hours of full load operations.

1.4.3.3 STANDBY/EMERGENCY DUTY PLANTS IN EMERGENCY SERVICE.

Provide a day tank and transfer pump unit for each engine, as recommended by the engine manufacturer. Interior tank capacities shall not exceed the requirements given in the National Fire Protection Association (NFPA) No. 37, Stationary Combustion Engines and Gas Turbines.

1.4.4 AIR INTAKE SYSTEMS. Use an outdoor air intake for all prime and standby/emergency duty plant designs, except for very small units in warm climates. Intake velocities and pressure drops should be selected in keeping with engine limitations. In frigid temperature zones, air preheating, or a bypass of outside air sources should be provided to facilitate engine starting. Four-stroke engines require approximately 3 to 3.5 cfm of free air per brake horsepower (bhp) (1.8 to 2.2 liters per second per kW). Two-stroke engines require approximately 4 to 5 cfm per bhp (2.5 to 3.1 liters per second per kW).

1.4.5 PRECOOLING AND AFTERCOOLING. Precooling of intake air is not allowed. Aftercooling, sometimes referred to as "intercooling" of intake air after turbocharging is desirable. Sufficient coolant should be made available at the required temperature. Standby/emergency duty and prime duty generator units may utilize separate electric motor driven pumps; however, engine-driven pumps are preferred, with standby motor-driven pumps available.

1.4.6 ENGINE EXHAUST SYSTEMS.

1.4.6.1 EXHAUST SILENCERS. Heat recovery silencers should be considered for all prime duty installations. Recovered heat can be used for space heating.

1.4.6.2 EXHAUST GAS QUANTITIES. Exhaust velocities and pressure drops should be selected to match engine requirements as provided by the engine manufacturer. Whenever manufacturer's data is not available, base system and piping component sizing on approximately 8.4 cfm of exhaust per bhp (5.3 liters per second per kW) for four-stroke engines and on 13 cfm per bhp (82 liters per second per kW) for two-stroke engines.

1.4.6.3 EXHAUST CONNECTIONS. The use of flexible connections at connections to the engine exhaust outlets or turbocharger exhaust outlets should be included to eliminate excessive structural stresses on those units. Exhaust system structural supports, expansion joints and anchors for exhaust system movement, and expansion and contraction due to heat, must be considered and provided in the plant design. Silencers should be mounted outside the building unless the manufacturer's standard unit is provided with an attached silencer or other special design considerations dictate otherwise at a specific site.

1.4.7 COOLING SYSTEMS. Decide by economic analysis and site conditions whether radiator, cooling tower, or a natural circulating water system should be used. Where cooling systems are subject to freezing temperatures, cooling systems must be protected during operation and when shut down. Freeze preventing solutions (such as glycol or Dowtherm) should be considered for circuits exposed to freezing outdoor ambient temperatures. In severe freezing conditions, it is desirable to separate the interior and exterior circuits by means of heat exchangers in addition to the use of antifreeze solutions. When these solutions are used, equipment and piping will require care in design and selection due to the lower specific gravity (and specific heat) of the antifreeze solutions as compared to water. Higher pumping rates will require larger piping systems and more heat exchange surface areas. Refer to the engine manufacturer for their specific recommendations relative to jacket coolant and lubricant cooler temperature control and fluid requirements.

1.4.7.1 EBULLIENT COOLING. Ebullient cooling may be used if an economic advantage can be demonstrated. The use of steam must be continuous and cannot replace heat recovery from jacket coolant or heat recovery silencers.

1.4.7.2 SELECTION GUIDANCE. Outside cooling units shall be carefully sited and oriented so as to minimize the effect of prevailing winds and adjacent structures on the equipment cooling capacity. Vertically discharging radiators and cooling towers should be given preference over other types and configurations. Where ambient air temperatures are favorable, the use of radiator (dry) type cooling will reduce maintenance costs and water treatment requirements. Engine radiant heat and

generator heat must be removed by the building ventilation system. Sufficient ventilation shall be provided to limit temperature rise to 15 deg. F (9 deg. C) above ambient wherever possible.

1.4.7.3 DESIGN TEMPERATURE. Outside ambient temperatures given in design guides are usually not peak temperatures. Their use in the selection of cooling equipment such as radiators for engines may not be adequate as peak electrical loads can occur at the same times as those of maximum temperature. It is recommended that summer design dry bulb temperatures be increased by 10 deg. F to 15 deg. F (6 deg. C to 9 deg. C) over the design temperature listed. In no case should the design temperature be less than 110 deg. F (61deg. C). Incalculable factors such as wind direction and eddies, unusual weather conditions, and other causes of air recirculation through a radiator or cooling tower, can only be incorporated into plant design by such means.

1.4.8 LUBRICATING OIL SYSTEMS. The lubricating oil system should include clean and dirty oil storage tanks, transfer pumps, piping for transfer and unloading, filters and operating control systems. Storage tank size needs vary for unit and plant sizes. Sufficient supplies of lubricating oil shall be provided so that a delay in delivery will not impair plant operation. Oil storage tank volumes shall be based on the engine manufacturer's oil consumption data for the specific engines involved with all engines in the plant including spares, operating at 100 percent load multiplied by a 0.75 operating factor. Containerized storage is allowed for both clean and dirty oil storage on smaller sized standby/emergency duty generating plants.

1.4.8.1 LUBRICATING OIL FILTERS. Engines are normally supplied with lubricant filters, pumps, and coolers by the engine manufacturer. If they are to be supplied separately, they should conform to the engine manufacturer's specifications. Each engine should be fitted with a duplex full-flow filter. Bypass filtering may not be economically justified for the smaller plants. Strainer mesh size shall conform to the engine manufacturer's standard practice.

1.4.8.2 WARM-UP SYSTEMS. All engines should be fitted with jacket coolant, and in some cases lubricant oil warm-up systems, as recommended by the engine

manufacturer when operating temperatures warrant. The lubricant warm-up system is usually required on standby/emergency units.

1.4.8.3 LUBRICANT PUMPS. Normally, main lubricant pumps are mechanically driven from the engine. Warm-up and bypass filter pumps may be driven separately with electric motors.

1.4.8.4 WASTE OIL. Provisions must be made for removing and holding waste oil from the generating plant.

1.4.8.5 SPECIAL LUBRICANT TREATMENT. For prime duty plants, lubricating oil should be reclaimed by removing dilutants and insoluble contaminants. Acidity should be controlled by means of a combination absorption and vaporizing process, and possibly centrifugal purifiers and clarifiers in either a batch or continuous operation. Packaged reclaiming systems designed specifically for this purpose are available. The heat source for these systems can be from direct fired equipment, reclaimed heat, or electric power. Provisions must be made for the removal of waste solids from these systems. All diesel-electric plants using heavy fuel oil or blends of heavy and light oils should be provided with lubricating oil reclaiming systems. Lubricating oil treatment systems shall be of the type approved by the engine manufacturer and suitable for the type of lubricating oil recommended by the engine manufacturer. Some types of treatment remove desirable additives required by the engine manufacturers, and removal of these additives may nullify engine manufacturer's guarantees.

1.4.9 STARTING SYSTEMS.

1.4.9.1 AIR STARTING. The method used for starting shall be the standard design of the engine manufacturer. Direct injection of compressed air into cylinders is the preferred method of starting large diesel engines in prime duty and standby/emergency duty plants. Air motors are optional for smaller units. Where engine size requires the use of more than one starting air motor as indicated by the manufacturer's standard instruction, the extra motors, controls and assembly shall be provided as part of the engine package.

1.4.9.2 COMPRESSORS FOR AIR STARTING. Where compressed air is used for starting, two starting-air compressor units should be provided. One unit should have an

electric-motor drive, and one unit should have a dual electric-motor/diesel-engine drive with battery start for the engine drive.

1.4.9.3 STARTING AIR RECEIVERS. Where air starting is to be used, air receivers shall be sized to provide multiple starts based on the following:

- For prime and standby duty plants with 2 engines, a minimum of 3 starts shall be provided for each engine. This requires a minimum of 6 starts. For each additional engine air receiver capacity shall be added to provide 3 starts for each engine added up to a total of 12 starts. One receiver should be sized to provide a minimum of 3 starts for the largest unit installed.
- Receivers shall be manifolded in parallel, each with safety valves, isolating and flow check valves, and automatic condensate drain trap assemblies. For normal operating each engine has its own starting air tank so that unsuccessful start of a specific engine does not deplete the available compressed air. However under emergency conditions, the manifold
- Starting air pressure shall be as recommended by the engine manufacturer. Normal starting air pressure is 250 lb/in² with a 300 lb/in² design pressure.
- Receiver construction shall conform to American Society of Mechanical Engineers (ASME) SEC 8D, Pressure Vessels, for the system pressures involved.

1.4.9.4 ELECTRIC STARTING. In standby/emergency duty plants serving emergency loads and where compressed air will normally not be provided, electric starting using batteries may be employed if standard with the engine manufacturer. Electric starting batteries shall be furnished to provide the same starting capacity as is required for air starting receiver capacity. Batteries shall be heavy duty type complete with battery racks, cabling, chargers, meters, hydrometers and controls as recommended by the engine starter and battery manufacturers.

1.4.9.5 PREHEAT SYSTEM FOR TESTING STANDBY/EMERGENCY DUTY UNITS. Consider providing engine coolant and lubricating oil preheating systems to facilitate scheduled tests of generator sets.

1.4.10 FOUNDATIONS. Diesel engine-generator unit foundation design must take into account the dynamic characteristics of the soil and machinery characteristics to avoid resonance of the foundation with the operating equipment. Investigation of these characteristics often results in inexact data and thus requires field adjustments to the design. The design guidelines given herein should be considered minimums to be adjusted to meet actual requirements.

1.4.10.1 INVESTIGATION. The following investigations are necessary for units larger than 750 kW, and elsewhere, where special conditions indicate such a need:

- **SOIL CHARACTERISTICS.** Dynamic properties vary widely and can be defined only roughly within rather wide limits. Each type of soil, sand, gravel, clay, rock, and the degree of moisture saturation of the soil provides a different and widely varying response to dynamic loads. Size of bearing area and its dimensions may also influence dynamic properties of the soil.
- **MACHINERY CHARACTERISTICS.** The equipment manufacturer usually provides estimated values based on equipment dimensions, weights, and operating speeds which may not furnish precise values. Beyond the usual static data, it is necessary to have such data as the unbalanced forces and couples with their location, magnitude, and direction (both primary and secondary); plus starting torque and stopping torque, without load and with full load on the generator.

1.4.10.2 DESIGN. As a design basis, a designer uses data regarding soil and machine characteristics which may be considered as approximate rather than precise. In many engineering problems which defy an exact analysis, a safe design may be assured by the use of a greater factor of safety. In the field of machinery foundation design, this approach may ensure structural adequacy but not necessarily dynamic stability. Normal differences between the predicted and actual characteristics of the soil and machinery may have adverse effect upon the characteristics which might destroy or wipe out

expected design margins. The foundation characteristics may be further affected by deviations in actual construction from the details specified by the foundation designer. The designer should include provisions for field testing and adjustment of foundation mass in cases where design studies indicate a possible deficiency in design margins. This may be accomplished by making the bottom base slab extend outside the main foundation block. The dynamic stability may then be checked experimentally by placing bagged sand at various points around the unit upon the base slab extension while the engine-generator is operating. When optimum dynamic equilibrium is thus determined, sand may be replaced with equivalent mass concrete anchored to the main foundation block and base slab extension.

1.4.10.3 MINIMUM REQUIREMENTS. Soil borings should extend no less than 50 ft (15 m) below the bottom of unit foundations, unless rock will be encountered at shallower depth. From these borings, allowable soil bearing pressures and the need for piles can be determined. Foundation design should be governed by the following:

- The entire foundation bearing surface should be at the same elevation. Steps or cascades at support level should be avoided.
- The unit foundation support level should be carried at least 30 in (762 mm) below any trenches or basement floor levels which are adjacent to the unit. This may be reduced to 18 inches (457.2 mm) for 750 kW or smaller units.
- Minimum static load design reinforcement is 2/10 of one percent of the cross-sectional area vertically and horizontally for all foundations. Minimum reinforcement for dynamic loads shall be at least 3 to 5 times this requirement. Usually, the entire foundation block is considered to be affected by dynamic loads. For larger or not well balanced units, reinforcing should be designed substantially heavier.
- If bearing level is solid rock, such that there is a minimum depth of 5 ft (1.5 m) of rock, cover the bearing surface with a 12-inch (304.8 mm) layer of sand for a cushion.
- Great care should be taken to avoid excessive or unequal settlements.
Generally, the soil at elevations upon which unit foundations will bear directly

should be capable of supporting a minimum uniform load of 3,000 psf (14,646 kg/m²) without excessive settlement. The soil, at elevations lower than the bearing level for depths at least equal to unit block lengths, should be of uniform quality without layers or pockets of weak soils. If the quality of soil remains in doubt, even after a comprehensive soil investigation, then consider the use of piles, piers, or caissons.

- Where piles are necessary, lateral forces may be resisted by battering a portion of the piles. Concrete piles, if used, should be reinforced for at least the upper one-third of their length. Drive so top of pile will project into diesel foundation block or base slab a minimum of 6 in (152.4 mm).
- For small units, isolated foundations may not be necessary, instead vibration isolators might be employed. Vibration isolators are required when recommended by the engine manufacturer, such as for units which come "skid-mounted", that is mounted on structural steel subbases.
- Seismic restraints are needed for each unit located in an International Conference of Building Officials, (ICBO), Uniform Building Code (UBC); risk zone 3 or 4 (or subsequent publication).

1.4.11 CRANES FOR ENGINE SERVICING.

1.4.11.1 SIZING. Hoists should be sized for the servicing of engine and generator components. Cranes should not be sized to extend over the entire engine operating area, but only over engine-generator units and their associated laydown space area. Follow the engine-generator unit manufacturer's recommendations for crane and hoist capacities. Hoist capacities of 1 to 2 tons (900 to 1,800 kg) are usually adequate for smaller-sized generating units and capacities of 3 to 5 tons (2,700 to 4,500 kg) are normally adequate for larger-sized engine-generating units.

1.4.11.2 ELECTRIC OPERATION. Hoists should be electrically powered for 2,000 kW units and larger. Plants with 500 kW to 1,000 kW units should have manually operated cranes and hoists. Plants with smaller units should be provided with monorails and manually operated hoists.

1.4.11.3 OPENINGS. Where hoists are provided to service equipment in basement or lower floor areas, openings should be provided in ground level floor slabs to allow penetration to the equipment in the lower areas. Fit openings with removable gratings. Hoist lengths should be adequate to serve the upper and lower plant levels.

2. SYNCHRONOUS GENERATORS, EXCITATION, AND REGULATION

2.1 GENERAL. Diesel engine generating units commonly are rated for from 10 kW to over 2,500 kW continuous output. Figure 1 indicates the major components that comprise a synchronous generator.

2.2 SYNCHRONOUS GENERATORS. Synchronous generators are built to the requirements of the National Electrical Manufacturers Association (NEMA) MG 1, Motor and Generators.

2.2.1 RATING. Regardless of the duty rating (i.e. for prime, standby, or emergency use) the usual specifications require that generators be capable of carrying the gross kW of the diesel engine without exceeding the temperature limits of NEMA MG 1 for continuous duty.

2.2.2 NEMA TEMPERATURE LIMITATION. Limitations are based on a 40 degree C ambient and altitudes not exceeding 3,300 ft (1,000 m) utilizing the specified insulation classes (B and F). Where these values are exceeded, NEMA MG 1 stipulates a decrease in the allowable temperature rise.

2.2.3 NEMA TEMPERATURE CLASSIFICATIONS. NEMA MG 1 has two temperature rise classifications, continuous and standby. The NEMA MG 1 standby temperature rise shall not be used as a basis for generator ratings used in standby or emergency duty plants.

2.2.4 GENERATED (TERMINAL) VOLTAGE. The generator voltage should be the highest standard voltage commensurate with the load served and the electric distribution or utilization system characteristics. NEMA standard voltage ratings shall be

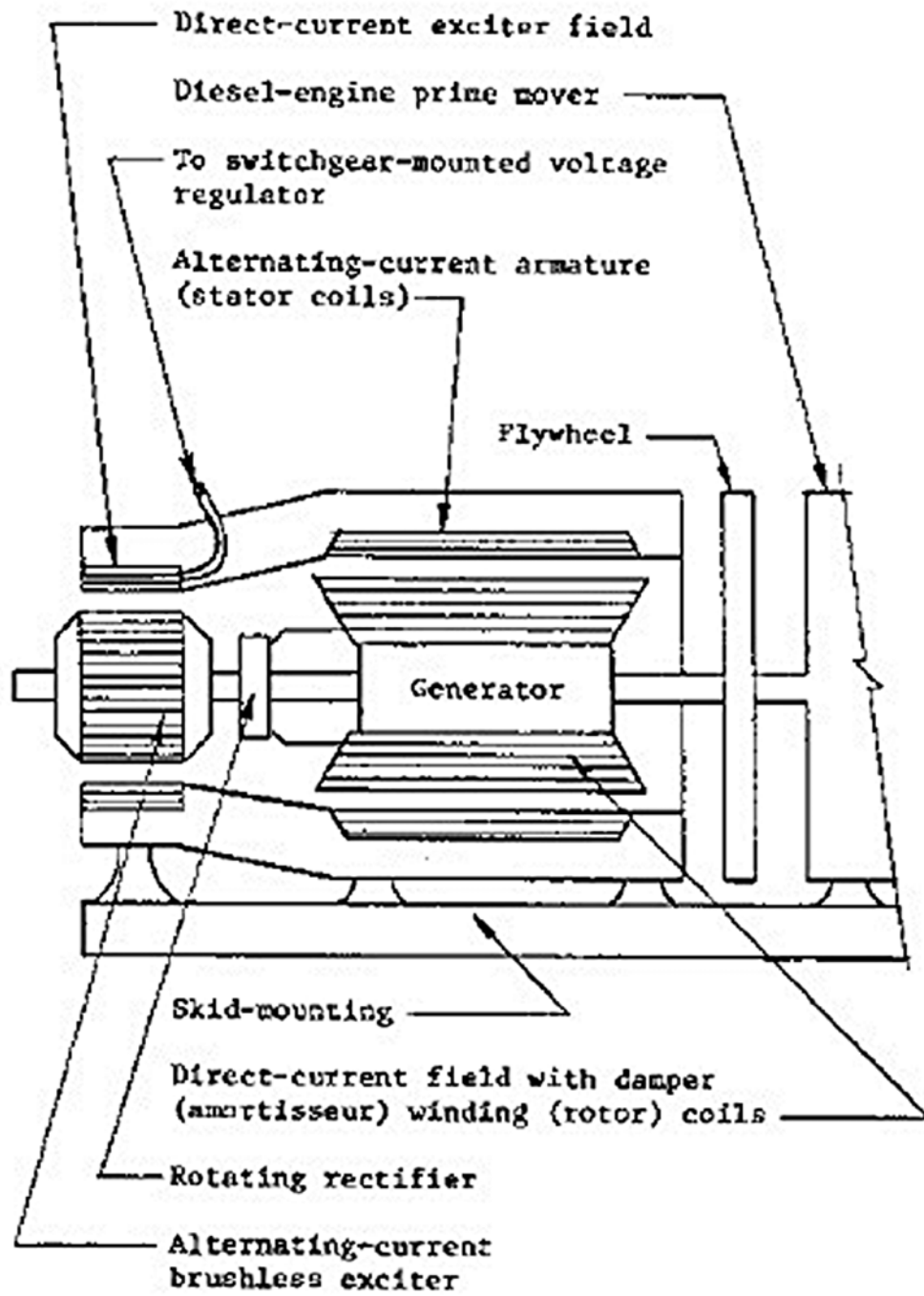


Figure 1
Synchronous Generator Configuration

used, except where special conditions prevail. The use of stepup or stepdown transformers should be considered only under extending circumstances. Standard generator voltages to be used are as follows:

- 208Y/120 V
- 480Y/277 V
- 4,160 V
- 13,800 V

2.3 EXCITATION AND VOLTAGE REGULATION. The brushless exciter and static voltage regulator combination is considered to provide the best performance available as it provides all the features available from brush-type rotating dc generators or brush-type static exciters while eliminating the maintenance and radio-noise features of the brush type.

2.4 PARALLELING AND SYNCHRONIZING. All generators in a plant shall be capable of operating in parallel with each other and shall be connected so that any or all units can furnish power to the main bus at the same time. Where plants may operate in parallel with commercial power, coordination with the serving utility must be maintained. The plant shall be designed with the capability for paralleling with an infinite bus.

2.4.1 SYNCHRONIZATION. Synchronizing operation can be performed manually or automatically. For both methods, control of incoming voltage and speed is required to match the system before closing the generator circuit breaker. The use of a permissive synchronism-check relay series with the synchronizing switch is suggested. Manual synchronizing is provided on most attended electric generating plants. Automatic start up, synchronization, and shutdown is normally only provided for unattended plants.

2.4.2 LOAD DIVISION. When generators are operated in parallel, proportional division of the electric load (kW) depends on the power supplied by the engine which is controlled by the speed. However, reactive Kilovoltampere Reactive Power (KVAR)

division is shared according to generator excitation. Provisions to adjust excitation for kvar sharing in the generator control is called crosscurrent compensation. Crosscurrent compensation is provided by each current transformer supplying each voltage regulator and acts to limit each generator's share of the total kvar required. The load is proportionally shared to each generator's rating.

3. ENGINE CONTROLS AND INSTRUMENTS

3.1 GENERAL. Controls and instruments assist in economical operation, supervision, and maintenance of a generating plant. Instruments sense changes in operating conditions and provide data to measure operating economy. An operator can control the changes in operating conditions to some extent by remote equipment. Continuous duty electric generating plants, provided with 24-hour manned operation are usually arranged for manual starting, synchronizing, and stopping and with only automatic protective controls. Standby/emergency generating plants are usually completely automated and controls are unattended. Remote monitoring devices and controls may be limited to system status indication and start/stop controls.

3.2 SPEED GOVERNING SYSTEM. Speed governing systems maintain the same operating speed (frequency) after load increase or decrease by adjusting the fuel delivered to the engine in proportion to the load regulated. As long as the specified performance characteristics are met, the type of the speed governing system provided (i.e. mechanical-hydraulic, electric hydraulic, electric, etc.) should be left to the engine manufacturer's discretion.

3.2.1 SPEED REGULATION. Speed regulators can be either speed droop or isochronous type. Droop operation permits engine speed to increase as load is removed. Isochronous operation maintains the same speed at any load. Some governors can be operated in either mode.

3.2.2 GOVERNOR OPERATION. Governors consist of hydraulic or servo systems used for fuel control in conjunction with speed sensing elements. Hydraulic governors utilize the centrifugal force produced by rotating fly-weights to actuate the hydraulic servo system. The electric-hydraulic type uses electric signals for actuation of hydraulic servo mechanisms. There are also completely electronic governing systems. Electric signals can also be initiated by changes in frequency (speed) or respond even faster, if initiated by load changes.

3.2.3 PERFORMANCE REQUIREMENTS. Industry-recognized performance requirements are given in Table 3. These requirements provide uniform concepts for the appropriate application classification without introducing unwarranted technical refinements and augmented costs. The referenced guide specifications and the industry specification from the Institute of Electrical and Electronics Engineers (IEEE) 126, Speed Governing of Internal Combustion Engine-Generator Units provide systems for independent or parallel operation.

3.2.4 MODIFICATIONS. Generally the use of the appropriate specification is all that is necessary. However, when paralleling with the local utility company is a requirement, special review and approval of the performance characteristics and the type of load sharing control specified may be appropriate. Special applications such as another incoming service or more precise frequency and voltage requirements must be evaluated on a case-by-case basis. Values given in Table 9 may not be available for all engine sizes, duties, or manufacturers and may either be excessive or not exacting enough for a specific requirement. It may be more economical to provide some type of power conditioning for many precise voltage and frequency applications.

3.3 CONTROLS. Monitoring and shutdown controls are necessary for unit protection. Also needed are devices to start and stop the unit and to select the operational mode when more than one method of operation is provided.

3.3.1 ENGINE FAULT MONITORING AND SHUTDOWN CONTROLS. The minimum

Performance Requirement	Electric Service Application		
	Industrial/Commercial	Public Utility	Precise Power
Basis for Specification	IEEE, Section II	IEEE, Section III, as upgraded	None
Steady-State Governing Speed Band	+/- 0.5%	+/- 0.25%	+/- 0.10%
Recovery Time	4 seconds	3 seconds	1.5 seconds

Table 3
Speed Governing Performance Requirements

requirements for protection of any diesel generator set incorporate the following shutdown devices monitoring the engine:

- low lube-oil pressure with pre-alarm before shutdown,
- high water temperature with pre-alarm before shutdown, and
- overspeed.

Depending on the size of unit and the type of duty, additional monitoring and shutdown controls, such as: monitoring cooling water pressure, lube oil pressure of engine and turbocharger, high lube oil temperature to engine and day tank level may be provided. The designer should specify at least the devices recommended by the manufacturer of the engine.

3.3.2 ENGINE START/STOP CRANKING CONTROL. Engine start/stop control logic circuitry may be mounted on the unit or in the generator switchgear. The start cycle is initiated by a signal to the cranking motor which starts the engine. The stop sequence can be initiated manually by a stop button, automatically by engine shutdown devices, or by protective relays. In the automatic mode, when the cranking cycle is initiated, it will

operate for a preset period usually of one-minute duration with alternate crank and rest periods of about 10 seconds. If the engine does not start during this cycle, the cranking circuitry is shut down. Emergency stops may be initiated by the engine and generator protective devices and, when activated, shut down the engine and disconnect the generator from the load.

3.3.3 OPERATION MODE SWITCH. A selector switch is located on the engine gage board to select automatic or manual starting and stopping modes when both types of operation are required.

3.4 INSTRUMENTATION. Instrumentation is provided to monitor the engine and generator operation and is mounted on the engine gage board and at the generator control panel. In small plants all instrumentation may be located at the diesel generator. The number of instruments may vary depending on the size and complexity of the plant. The use of solid-state control devices and instrumentation is recommended.

4. GENERATOR CONTROLS AND PROTECTION

4.1 CONTROL CAPABILITIES. Generator devices provide the following control features:

- The generator circuit breaker provides a switching device to connect or disconnect a generator from the system.
- The operating control point permits generator switching, voltage and frequency changing, synchronization of generators and commercial sources, and a central point for monitoring of system operation.
- The generator protective devices provide for safe operation. Refer to the American National Standards Institute (ANSI), C37.2, Electrical Power System Device Function Numbers, for ANSI device numbering system assignments.

4.2 CONTROL LOCATIONS. The generator circuit breaker and protective devices are located as appropriate to the installation. The operating control point may be installed either with or separately from its associated circuit breaker.

4.2.1 COMMON PRACTICE. Common practice is to utilize a separate control switchboard to provide the operating control point. No controls are provided on the generator and feeder switchgear except for operating the bus tie unit. For plants having a capacity of less than 2,000 kW, consider a need for a control console on the basis of providing the following features:

- Economy, including manpower requirements and operating costs; or,
- More reliable control, the system requires large and varied load changes which cause frequent stopping and starting of generating units.

4.2.2 ALTERNATE DESIGN CONTROL. In some cases it may be desirable to also provide control at the switchgear. Such a case might one in which the design configuration requires a significant separation between the Control Room and the Switchgear Room or if simplicity of operation is paramount. Safety considerations for maintenance at the switchgear can be provided as long as the circuit breaker is of the drawout type having a test position, otherwise some other method of preventing simultaneous local and remote control is necessary.

4.2.3 SMALL LOW-VOLTAGE PLANTS. Low-voltage generators quite often have the generator controls and circuit breaker provided as a part of the skid-mounted engine-generator used.

4.2.3.1 AUTOMATIC TRANSFER SWITCH (SINGLE UNITS ONLY). Generally, an automatic transfer switch is used for single low-voltage diesel generator operation to transfer loads from a normal source to the generator. Circuitry is included to sense normal source failure, initiate starting of the engine generator, and transfer the load to the generator. When the normal source is restored, the switch will automatically transfer

the load back to the normal source and shutdown the engine after a predetermined time.

4.2.3.2 MULTIPLE GROUND POINTS. Emergency or standby power supplies in conjunction with the normal incoming utility service for low-voltage systems can introduce objectionable stray currents because of the multiplicity of neutral grounds. A properly designed ground system is necessary to eliminate stray neutral current paths and undesirable ground-fault current sensing path. Grounding arrangements for emergency and standby power systems are discussed in the Institute of Electrical and Electronics Engineers (IEEE) 446, Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications.

4.3 OPERATING CONTROL REQUIREMENTS. Requirements depend upon the size, complexity, and voltage level of the plant. Requirement covered herein apply to medium-voltage, multiple-unit plants and should be adjusted as appropriate for low-voltage plants which are often single-unit plants. Devices should be arranged on control switchboards or switchgear in a simple and distinctive number of circuit breakers to be operated provides a complex electric configuration, consider providing a mimic bus. Organize devices by unit control, synchronizing control, and system monitoring.

4.3.1 UNIT CONTROL. Minimum unit control should provide the following devices:

- Circuit breakers.
 - Control switch.
 - Ammeter and transfer switch.
- Power sources such as generators or commercial input require synchronizing switches.
- Generators.
 - Voltage regulator adjusting rheostat.
 - Voltage regulator manual-off-automatic switch.
 - Governor switch.
 - Wattmeter.

- 5) Varmeter
- 6) Watthour (Wh) demand meter.
- 7) Elapsed operating time meter.

4.3.2 SYNCHRONIZING CONTROL. The synchronizing control is energized through the synchronizing control switch at the selected source and consists of the following devices:

- Synchroscope.
- Bus frequency meter.
- Bus voltmeter.
- Incoming voltmeter.

4.3.3 PERMISSIVE CONTROL. Local policy synchronization may dictate the use of a permissive type synchronism check relay (ANSI Device 25) which is provided in series with the synchronizing switch to prevent closure when the two sources are too far out of synchronization. This device checks voltage on both sides of a circuit breaker, this providing protection against operating errors.

4.3.4 SYSTEM MONITORING. System monitoring is provided to aid the operator in avoiding system abnormalities. The amount of reporting, alarming, and control can vary from alarms reporting there is a problem at a certain location, or reporting only of electrical quantities and control as previously discussed, to complex microprocessor-based Supervisory, Control, and Data Acquisition Systems (SCADA).

4.3.4.1 TYPE OF SYSTEM. The operating duties of the plant should be considered in system selection. Large prime duty plants in remote locations or cogeneration plants may require SCADA. Where plants are continuously manned, requiring only the minimum monitoring is usually adequate.

4.3.4.2 SCADA. This system provides a master station which utilizes input from equipment-mounted, field interface panels normally in conjunction with a record-keeping printer. The selected reporting, alarm, and control functions should consider those

required for Energy Management Control systems (EMCS) either by utilizing an existing EMCS or providing a new system.

4.4 GENERATOR PROTECTION. Surge protection, neutral grounding, and protective relays are used to protect the system from electric power system disturbances whose abnormality could damage equipment or harm personnel.

4.4.1 SURGE PROTECTION. Some form of surge protection is usually necessary within a generator plant. Surge arresters in parallel with surge protective capacitors may need to be installed at the terminals of each generator. Surge protective capacitors reduce steep wave fronts, which if imposed on rotating machinery could result in stresses exceeding insulation impulse strength of a machine. Small units supplying emergency loads within a building which are not subject to lightning or switching surges usually do not require surge protection.

4.4.2 GENERATOR NEUTRAL GROUNDING. Generator neutrals are grounded to provide service reliability and reduce fault stresses in equipment. For low-voltage systems, the neutral supplies phase-to-neutral loads as well. The method of connecting the neutral to the station ground system is selected as required to limit the available ground fault current.

4.4.2.1 SOLID GROUNDING. For generators having a ground return path which limits the ground current to safe values and where harmonic currents are small, a solid ground connection is acceptable. Low-voltage generators are usually provided with additional phase-to-neutral bracing so that the less expensive solid grounding can be provided, but this feature should be specified.

4.4.2.2 IMPEDANCE GROUNDING. For medium-voltage systems, impedance grounding is normally provided to limit ground fault current to a value equal to or below the three-phase fault current. Reactance grounding is used where ground fault currents of 25 to 100 percent of three-phase currents allows for satisfactory ground fault relaying. Resistance grounding is used when even lower values of ground fault current are necessary for system protection or coordination.

4.4.3 PROTECTIVE RELAYING. Protective relays constantly monitor the power system to assure maximum continuity of the generation and distribution system and to minimize the damage to life and property.

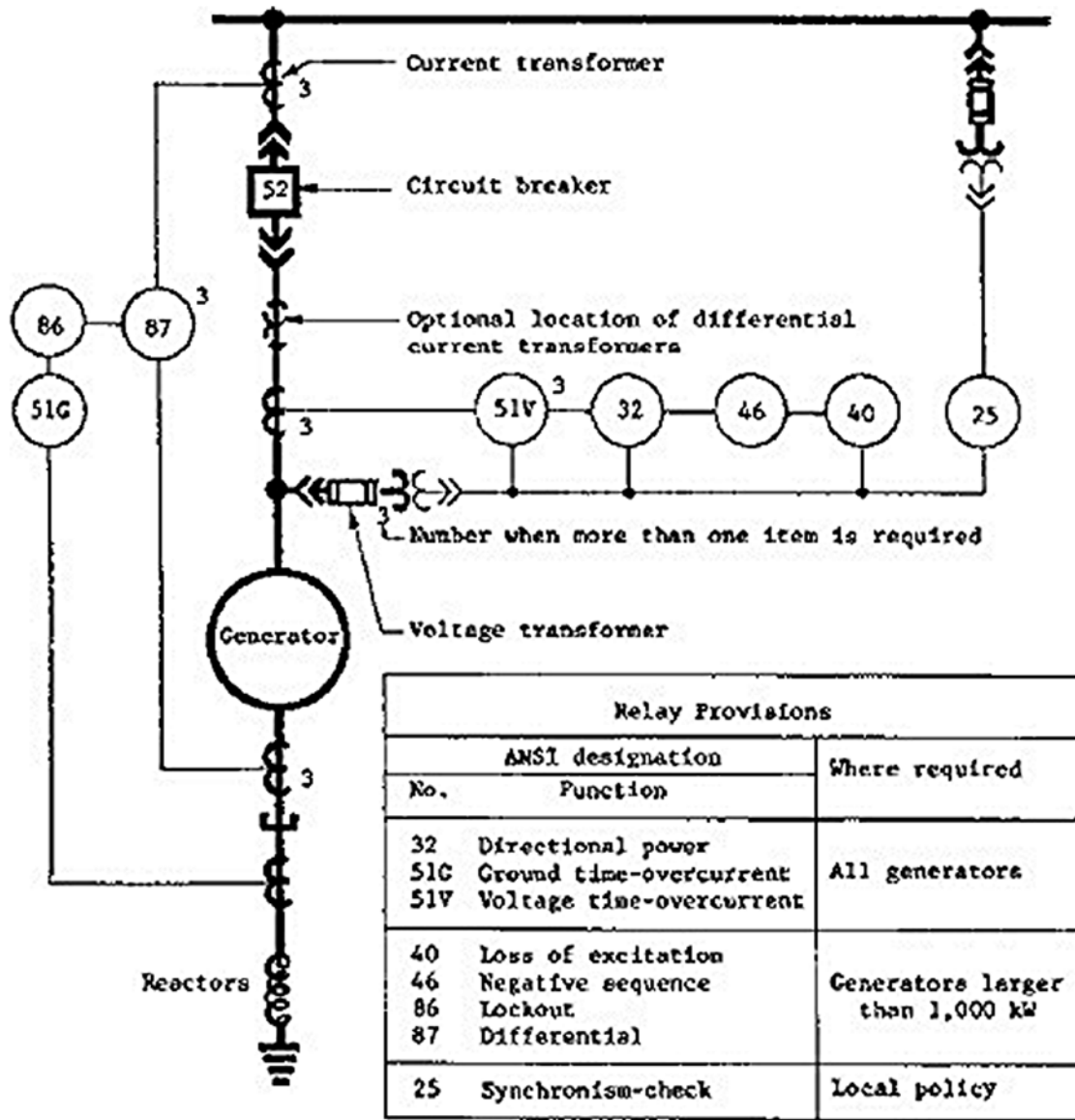


Figure 2
Minimum Relay Protection

4.4.3.1 GENERATOR PROTECTION. The normal protection required for medium-voltage generators is shown on Figure 2. Control power is supplied from the station battery system.

- Differential Relaying (ANSI Device 87): Since differential relaying utilizes a current difference between two points to indicate a fault, differential current transformers should not be used to supply other devices. The current transformer location points are shown on Figure 2. The generator current transformers can be located on either side of the generator circuit breaker in accordance with the manufacturer's standard practice. The lockout feature (ANSI Device 86) is standard for differential relaying.
- Ground Relaying (ANSI Device 51G): The lockout feature is desirable for ground relaying, but it is not necessary in plants having adequately trained personnel.

4.4.3.2 INCOMING LINE AND FEEDER PROTECTION. The minimum relaying requirements shall consist of overcurrent protection. Although time-overcurrent relaying (ANSI Device 51) may be sufficient for protection, it normally also provides the instantaneous element, (ANSI Device 50), an accessory feature in the same enclosure with the time-overcurrent relay. This unit can be blocked, if not needed, but is available for changing system conditions.

4.4.3.3 LOAD SHEDDING CAPABILITY. A load shedding system capability can be provided based on sensing underfrequency or a rate of frequency decline on the system caused by sudden load changes. System balance can be established by temporarily dropping selected feeder loads. Underfrequency schemes are usually arranged in steps to continue dropping load until the system is stabilized. The use of undervoltage sensing is inadvisable since the generator voltage regulators will tend to compensate for voltage decay.

4.4.3.4 ANALYSIS. To determine actual protective relaying requirements, an analysis should be performed concerning requirements for new systems and coordination with existing systems. Fault calculations may indicate the need for protection in addition to the minimum requirements covered previously. Additional protection may be indicated

because of either the size of the new distribution system or to match the existing distribution system.

4.4.3.5 CONTROL POWER. Direct-current closing and tripping for medium-voltage circuit breakers should usually be provided by a 125 V station battery system. For low-voltage generating plants, 24 V or 48 V systems should normally be supplied, except where very small systems utilize automatic transfer switches for commercial to generating system transfer. Lead calcium cells should be utilized except when maintenance requirements justify the use of the more costly nickel-cadmium cells. Batteries are highly reliable devices when properly maintained. Provision of a second battery system will usually not provide any more reliability, since such its system maintenance will be on the same level as the system it backs up. However, for very large plants consider supplying one-half of the plant loads from separate battery systems which can interlocked so either or both systems can supply the load but systems cannot be paralleled.