DIESEL-ELECTRIC POWER STATIONS

Worldwide, interest in today's electricity supplies is focused on centralized systems. Whereas electricity can be supplied almost everywhere in industrialized countries (ICs), thanks to national or international integrated grids, the developing countries (DCs) are far behind. Only 23% of global electricity consumption is generated in DCs, where it supplies about 43% of humanity. A further 35% of the population in DCs has no access to electricity. Although integrated grids are increasing in global importance, they are not feasible in many DCs for technical and economic reasons. Decentralized electricity supply is thus of great interest in such places as well as, for different reasons, in ICs.

Autonomous electric power stations are used wherever we need to have electric energy and there is no power system or when the available grid is not reliable enough (i.e., utility companies cannot provide electric power without any failure or clear and free of disturbances to users); in such cases, to prevent equipment problems, a good solution is for users to provide their own generating units as a supplement to the power supply. A generating set can be installed to have an emergency or standby power source. The emergency system operates in parallel to ensure no loss of continuity in the electric power supply. Standby systems are mainly intended as alternative sources (1).

Large megawatt-range generator sets are frequently combined with other types of power plants both in large isolated grids and in interconnected grids because of their ease of dispatch. Power generating sets for decentralized electricity supply usually consist of several aggregates in the low-to-medium power range. About 37% of the power capacity installed worldwide for local electricity generation is for decentralized use.

Generating units driven by internal combustion engines consist of a synchronous generator mechanically coupled to a power source, both installed on a rigid frame. In some cases the engine and the generator may be connected by a clutch,

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

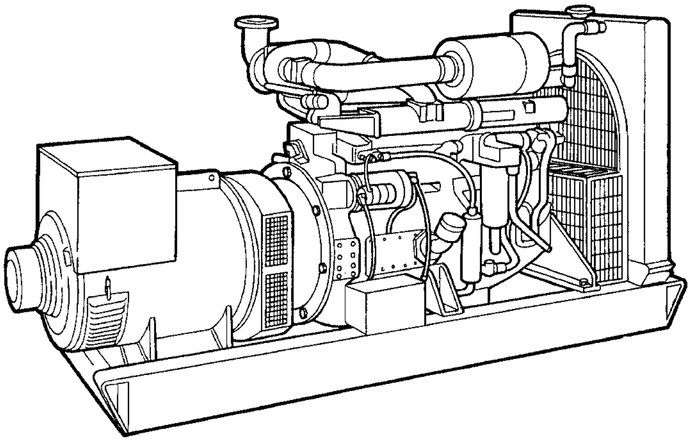

Figure 1. Typical water-cooled diesel generating set in the power range of some tenths of a kilowatt. (Courtesy of Ausonia Generating Set, Marsala, Italy.)

which permits the electric machine to be available as a synchronous motor connected in parallel to the electric grid without the presence of the engine. In this case the electric machine will operate by absorbing a little active power (there are no mechanical loads connected to the synchronous motor) and delivering reactive inductive power to the grid, acting as a so-called synchronous capacitor. The rated powers of generating sets, equipped with internal combustion engines, range between a few kilovolt-amperes to several thousand kilovolt-amperes, which represents the size above which it is convenient to use different prime movers such as steam or gas turbines. Smaller sizes are suitable for small isolated users (home appliances) while larger sizes are used for villages, islands, and industrial and commercial applications. Figure 1 shows a typical diesel engine generating set, illustrating an entire system consisting of a synchronous generator, driven by a diesel engine, with the cooling system at the opposite side of the generator. Figure 2 shows an exploded view of the main components of a diesel generating set: (1) the cooling system of the diesel engine; (2) the built-in small fuel tank; (3) the rigid frame which supports the entire system; (4) the synchronous generator with the electric connection box and automatic voltage regulator (above it); (5) the diesel engine.

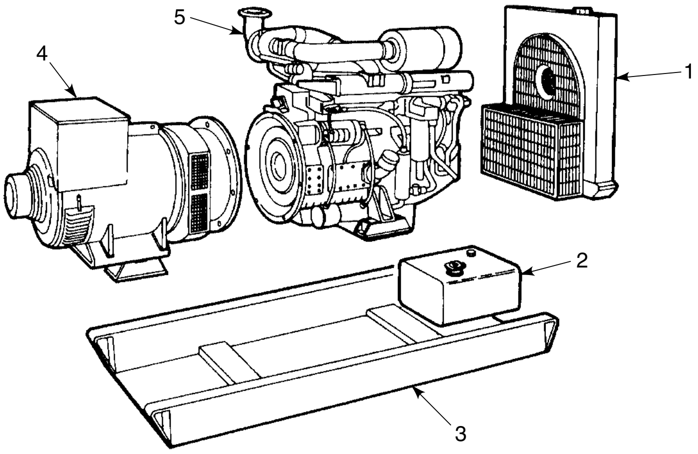

Figure 2. Exploded view of the diesel generating set shown in Fig. 1. (1) Cooling system of the diesel engine. (2) Build-in small fuel tank. (3) Rigid frame supporting the whole system. (4) Brushless synchronous generator. (5) Diesel engine.

The ability to connect in parallel several generating groups permits us to reach installed power up to tenths of a megawatt. Power stations using multiple generators may obtain greater energy conversion efficiency by turning on only those generators which are sufficient to supply the required load, thus allowing each generator to work at a power rate as close as possible to the rated power. Multiple diesel units, working in parallel, may ensure a higher energy availability and a lower probability of transient or steady-state instabilities. A generating set can supply emergency power in a few seconds and when associated with uninterruptible power systems, can ensure long-term operation free of disturbances to a critical load.

INTERNAL COMBUSTION ENGINES

Engines used in generating units burn diesel, gasoline, or natural gas (2,3). Diesel engines, supplied by several companies in different models, are rugged and provide safety against fire and explosions compared with other engines. Smaller sizes use a natural air supply, while larger sizes are turbo-charged. Their rated power ranges between a few kilovolt-amperes to thousands of kilovolt-amperes. Gasoline engine generating units are available with rated power less than 100 kV-A. They offer the advantages of having a quick run-up, having a low cost, and being lightweight. However, the use of gasoline prevents long-term storage of the fuel and increases the hazard of fire and explosion. Moreover, the cost of the energy produced is higher. Gas engine generating units can burn natural gas or a blend of gas, stored as liquid, obtained from crude oil. Gasoline engines can be, by minor adaptation, used as natural gas engines. Major advantages of such an operation are the reduced maintenance due to the limited residue from combustion. On the other hand, a gasoline engine supplied by gas provides reduced output power. Table 1 presents features of commercial generating units available on the market.

CHOICE OF A DIESEL GENERATING SET

The choice of a diesel generating set revolves around several parameters, such as: kind of service to which the generator must be devoted, electrical characteristics of the loads, environmental conditions, the allowed frequency and voltage variations (particularly during transient conditions), and failures which can happen on the main power systems. The precise evaluation of the aforementioned parameters is fundamental to realizing reliable electric power plants, which can produce electric energy at a convenient cost.

Class of Service

A diesel generator set may be used to serve several kinds of applications: (1) main source of energy for isolated users (continuous service), (2) backup systems (service on demand), and (3) emergency systems. Some common failures and distur-

Table 1. Technical Characteristics of Generating Units

50 Hz, 1500 rpm				60 Hz, 1800 rpm				Dimensions			
Emergency Duty		Continuous Duty		Emergency Duty		Continuous Duty					
kW	kVA	kW	kVA	kW	kVA	kW	kVA	Length (mm)	Width (mm)	Height (mm)	Weight (kg)
1.5	1.2	1.5	1.2	1.8	1.44	1.8	1.44	510	340	400	35
10	8	10	8	11	8.8	11	8.8	1,250	500	700	160
100	80	92	73.6	115	92	105	84	2,400	1,050	1,340	1,270
550	400	500	400	640	512	585	468	3,350	1,600	1,850	3,700
1,000	800	910	728	1,250	1,000	1,100	880	4,600	1,900	2,400	8,400
2,000	1,000	1,825	1,460	2,500	2,000	2,250	1,800	5,900	2,200	2,550	13,200

Courtesy of Ausonia Generating Set, Marsala, Italy.

bances regarding electric plants, which can create the need to install generating units, are as follows: (1) interruption (outage, that is, a loss of power that may range from less than a second to several hours and affect all equipment; (2) over- or undervoltage: overvoltage (surge) and undervoltage (dip) are, respectively, increases or decreases in the rated value of the line voltage that range between a few milliseconds and a fraction of a second, which can cause shutdowns (dip) or can damage electrical equipment (surge); (3) voltage spikes, which are short and sharp impulses that appear momentarily from line to line or line to neutral (normal mode) or between neutral and ground (common mode); (4) electrical noise, which is high-frequency interference that ranges between a few kilohertz and tenths of a megahertz; and (5) harmonics, which are frequencies that are multiples of the fundamental frequency.

User needs vary, which affects the type of generator selected. For example, isolated users principally need a system which is as reliable as possible, even if the quality of service may not be the best. Efficiency may be quite important because it is linked to the cost of the energy produced. A backup system permits integration of the power from the main source to meet peak load requirements as needed. An emergency system must be absolutely reliable; efficiency does not have to be considered. The system will probably operate for only a few hours in a year, but for those hours it must be able to start suddenly and operate correctly. To increase reliability, emergency systems may be doubled using two identical generating sets or using two systems based on different sources of energy.

Environmental Conditions

Environmental conditions are often critical to diesel station design. The parameters to be considered are mainly (1) ambient temperature, (2) humidity, and (3) dust. The temperature affects the power of the generator. The humidity also influences the deliverable power due to its effect on combustion, while an excess of dust may require a special air filter for the engine. In some cases, temperature and dust problems may necessitate the use of a special "filter-container" including all the equipment and using particular cooling systems which prevent the external air from entering into the container.

Derating

Rated powers of generating units refer to precise ambient conditions, which are defined by standards for diesel engines and synchronous generators. As an example, typical rated data for ambient conditions of engines are: altitude above the sea level 300 m, relative humidity 60%, pressure 100 kPa, and temperature 29°C. When there are different conditions, some derating must be applied. In fact, pressure, temperature, and humidity influence the air mass introduced to the engine during intake as well as during heat exchange. As a consequence of the reduction of the inlet air, the fuel quantity entering the combustion chamber decreases, which means derating the engine power. Such a derating is different for naturally aspirated and turbo-charged diesel engines. For naturally aspirated engines, a rule of thumb gives a power derating of 2% for each temperature step of 5.5°C over the reference temperature, while for turbo-charged engines, the derating increases to 2.5%. Of course, the ambient temperature in the generator room is normally not allowed to exceed a threshold value since it is controlled to remain in the range 20°C to 50°C. Thus the effective temperature derating is bounded by a small percentage.

A derating factor also needs to be applied as the altitude of the installation increases. Consequently, the rated power should be decreased, as a rule, by 3.5% and 2% for each 300 m increase of altitude, respectively, for naturally aspirated and turbo-charged engines. The humidity derating is considered as a combined action of relative humidity and temperature of the air since the two quantities are strictly tied. In any case, combined effects of high humidity and temperature give a derating of about 5% to 6%. In effect, standards dictate the conditions of derating for the cumulated effect of temperature, humidity, and altitude (atmospheric pressure). Figure 3 shows, for turbo-charged engines, the curves calculated at a relative humidity of 60% of the derating coefficient versus temperature and atmospheric pressure.

Efficiency

The efficiency of the generator in fuel conversion depends on several factors, but mainly on the size of the machine and on the percentage of the load applied to the generator with respect to the rated power (the efficiency is zero at no load and increases almost linearly reaching the highest value at a load close to the rated power). The rated fuel consumption is de-

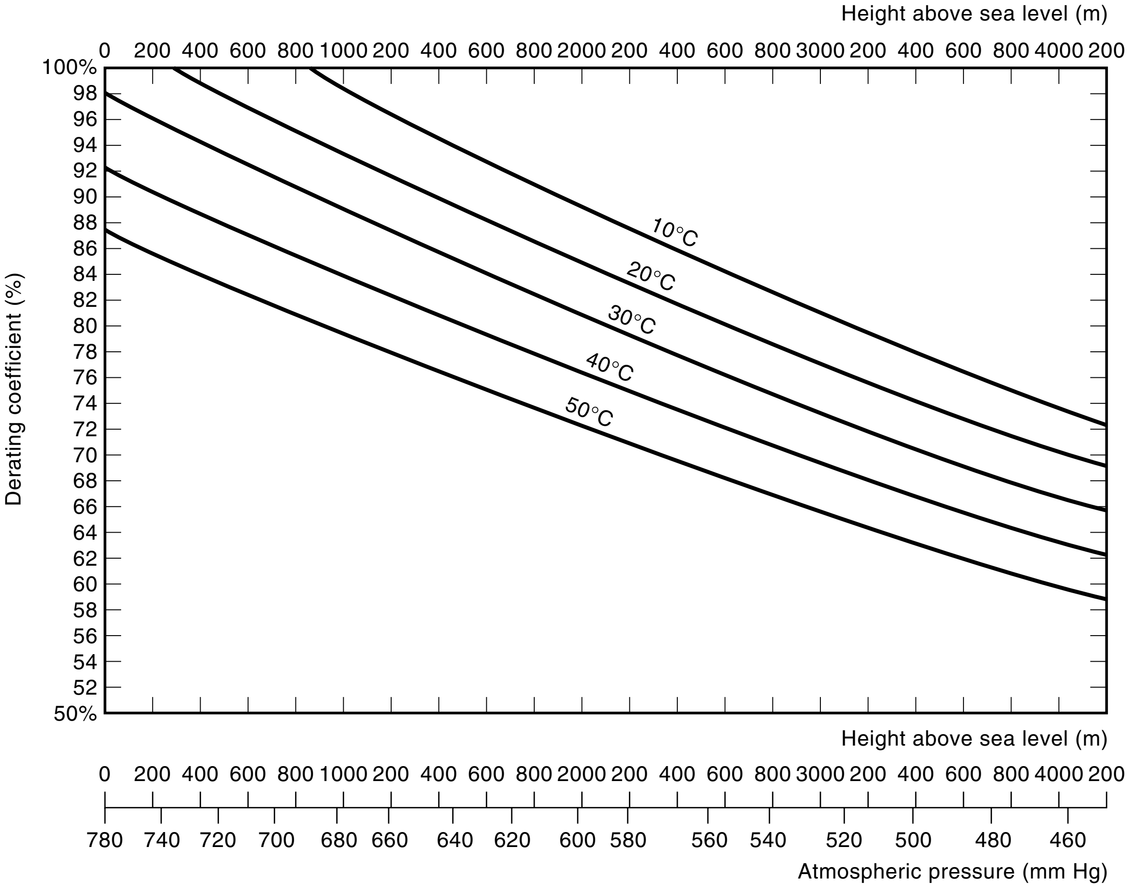

Figure 3. Derating coefficient of turbo-charged engines versus temperature and atmospheric pressure calculated at relative humidity of 60%.

fined per produced kilowatt-hour when the engine runs at rated power. It ranges from 130 g/kW-h to 150 g/kW-h, for big units, to 250 g/kW-h to 300 g/kW-h for small generating sets. The lower fuel consumptions are typical of big turbo-charged diesel units, and the smallest consumption rate (130 g/kW-h) is characteristic of huge diesel units (several MW of rated power) operating with a two-stroke cycle with turbo-charger and low rotational speeds (as low as 100 rpm).

The diesel generator should operate at a level of power as close as possible to the rated power, in order to achieve a higher efficiency. Other operating conditions cause higher specific fuel consumption both for low load and for overload. Figure 4 shows a typical curve of fuel burned even at no load, which represents the worst condition with respect to efficiency. Particular care must be taken not to oversize the diesel set because both diesel engines and synchronous generators are characterized by low efficiencies at low load, thus increasing the specific fuel consumption (g/kW-h) and consequently the cost of the produced kW-h. The specific fuel consumption is not critical when the generating set is used for an emergency service while it is very critical when the plant provides continuous service. Furthermore, at low load, the engine does not reach an optimal temperature condition, and the combustion may not completely consume the fuel injected into the combustion chamber. The fuel not burned may then damage the engine by corrupting the lubricant or, as a result of passing through the exhaust gas, may damage the turbine (for the turbo-charged engines), thereby increasing maintenance costs and lengthening the time that the equipment is out-of-order.

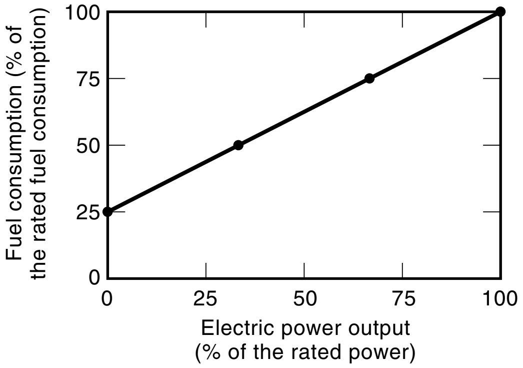

Figure 4. Typical variation of the fuel flow versus output power for a diesel generating set. The fuel consumed without delivering electric power is due to the losses to maintain the system rotating at nominal speed.

PARALLEL OPERATIONS OF MULTIPLE DIESEL GENERATING SETS

A diesel generating set may operate in parallel to have (1) an increase in available power, (2) a backup system, and (3) an increase in reliability. If we consider a generator already running and delivering power to the user as a "grid" and consider another generator to be paralleled to the first one, to obtain a correct parallel connection and operation the following conditions apply: (1) The output voltages must be equal in magnitude both on the grid and on the generator terminals, (2) the frequency of the generator must be as close as possible to the grid frequency, (3) the phase sequence of the two systems must be the same and almost without angle displacement, and (4) each generating unit must be equipped with an automatic power sharing device. The diesel engine can furnish only the "active power" (the mechanical power through its shaft) to the synchronous electric generator, while the generator delivers such an active power subtracted of the total losses plus an amount of reactive power because of the power factor (cos ϕ) of the load which normally ranges between 0.8 and 0.9. Since a low power factor causes inefficient utilization of the diesel-generator (low power request from the diesel and high apparent power request from the generator), in some applications this can be useful to produce a supplemental reactive power by using static devices (stepped back of capacitors).

Active Load Sharing in Local Grid

The active load sharing between different generators in local grid connections is controlled by varying the fuel actuator of the diesel engines. If several generators are delivering power on the same load, each generator takes a load angle which depends on the amount of load it is supplying. An efficient load sharing will cause each generator to deliver power proportional to its rated power. On an autonomous grid, powered by multiple diesel generators, to perform load sharing the generators must be able to change their output frequency by realizing a frequency drop between the full load (lower frequency) and no load (higher frequency). If one of the generators delivering power on the load has a different frequency drop characteristic, it can be easily overloaded or underloaded. Consequently, the diesel engines of the units in parallel must have the same frequency drop characteristic (identical speed variation for each load condition from no load to rated load), which normally is approximately 4%. For lower values of frequency drop, imbalance and instability of load sharing may occur.

Reactive Load Sharing

The reactive load sharing depends on the excitation systems of the synchronous generators. The voltage regulator of the synchronous generators must allow the same voltage drop (identical voltage variation for each load condition from no load to rated load). If the regulator does not have the same voltage drop, current circulation may occur between the generators.

Neutral Links and Grounding

For multiple diesel stations with two or more generating sets in parallel having generators with different electric characteristics, we must be careful when connecting the neutral conductors. These connections can produce third harmonic current circulation which may be greater than the first harmonic rated current, causing the parallel operations to fail. The neutral of the generator may be connected to the earth in one of the following ways: (1) solidly by direct wiring to a grounding electrode, (2) by a grounding resistor inserted between the terminals of the system and the grounding electrode, (3) ungrounded by leaving the winding potential floating. Detailed alternatives to grounding systems can be found in Ref. 1.

SIZING OF THE GENERATING GROUPS

Sizing of the generating groups to cover the needs of a power plant requires a careful analysis of the nature of the loads (induction machine, lamps, electric oven, etc.) in order to comply with the transient currents, the effective power due to nonsimultaneous presence of loads, and the power factor which changes depending on the operating conditions. Moreover, we must be careful during transient stability, when a step application of load may cause a severe transient on the generator. In fact, in such a case, a momentary decrease of both frequency and voltage occurs. Some limitation may be required on the maximum applicable load step for it to remain within a tolerable percentage of voltage and frequency drops. There are standards that set limits and also give some constraints depending on the mean effective pressure of the engine driving the generator. We must use care during induction motor starting. In fact, induction motors are designed for line starting capability with a stiff source, and in such a case the inrushing current can be five to eight times the rated current at full load. The torque developed by induction motors is proportional to the square of the terminal voltage. Depending on the characteristic of the load torque and the robustness of the power source, the startup may fail. We must calculate the maximum tolerable decrease of the line voltage, which must comply with the motor starting needs. The line starting of motors also requires particular attention to the evaluation of the power required at low power factor. An induction motor with a full load power factor of 0.8 can have a 0.2 power factor at no load. Assuming the case of a motor of 100 kW, which has an efficiency of 0.90, the active power at full load absorbed from the line will be $100/0.90 = 111$ kW, and the apparent power will be $111/0.8 = 138$ kV-A. At startup with no load, the line current can reach up to eight times the rated value and the same applies to the apparent power, which will be $138 \times 8 = 1104$ kV-A with an active power equal to $1104 \times 0.2 = 220$ kW. The active power absorbed for a few seconds, during the startup transient, can be two times the rated power.

Rated Power of Synchronous Generators

Rated power is calculated according to standards at the following ambient conditions: ambient temperature 40°C; altitude less than 1000 m; power factor equal to 0.8. For different altitudes, temperatures, or power factors a derating must be calculated. A suitable method to evaluate the power derating

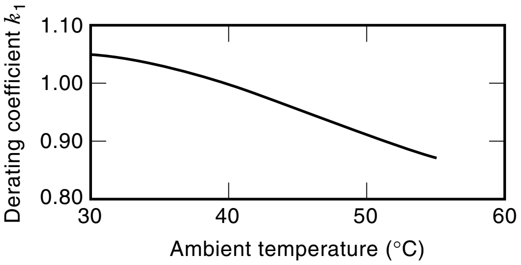

Figure 5. Derating coefficient for temperature variation of a synchronous generator at temperature above 40°C.

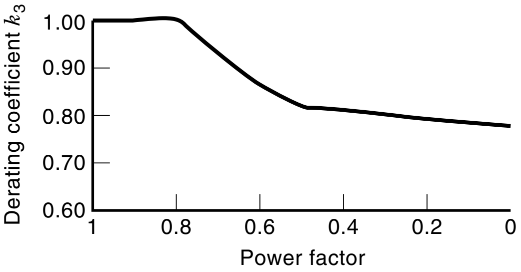

Figure 7. Derating coefficient for a synchronous generator loaded with a power factor different from 0.8.

based on k coefficients can be applied. Figures 5, 6, and 7, give the k_1, k_2, and k_3 derating coefficients, respectively, referring to variations of temperature, altitude, and power factor. The total derated power can be calculated as the product of the rated power for reference conditions times the coefficients k_1, k_2, and k_3.

ELECTRIC PERFORMANCE AND CONSTRAINTS

Regulating the fuel flow to the diesel engine, which generates electric power at constant speed, implements the power control. The control also regulates the current of the excitation field of the synchronous generator in order to maintain a constant output voltage at both variable load and power factor. The terminal voltage of synchronous generators can be controlled by altering the current in the field winding. An automatic voltage regulator (AVR) compares the terminal voltage of the generator with a voltage reference, and the error is processed to drive a rotating or static exciter. A need for accurate modeling arises from the fact that the excitation system forms a feedback loop around the generator and we must be careful not to introduce instability in the generator system. An IEEE Committee has developed models to represent excitation systems (4,5).

Excitation Systems

Very old types of excitation systems contain auxiliary direct-current (dc) machines with lower power than the generator; these machines feed the dc power to the rotor windings of the synchronous machine by two copper rings fitted on the shaft. The current flows through a system of brushes. Almost all the modern generators for diesel sets have a static or brushless excitation system. In brushless alternators the excitation power is fed by an auxiliary alternator, coaxial with the main generator, which has stationery fields and a rotating armature. The rotating armature supplies the rotor winding through a three-phase rotating bridge rectifier as shown in Fig. 8. The excitation power of the field winding of the auxiliary machine is fed by the main generator. The auxiliary stationary field is fed by a power supply controlled by an automatic voltage regulator.

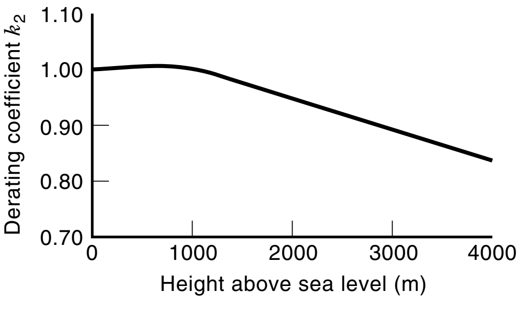

Figure 6. Derating coefficient for a synchronous generator installed at altitude higher than 1000 m above sea level.

Frequency

The voltage frequency of the electric power delivered by the diesel-generator is usually 50 or 60 Hz depending on the local standard. Such a frequency is determined by the rotational speed and by the number of pole pairs of the diesel generator; its value is maintained fixed by means of a speed regulator when the generator works alone. The frequency in this case does not depend on the amount of power (torque on the main axis) delivered to the load. If more than one generator is paralleled on a common bus to carry a load, it is necessary to allow each generator to vary its frequency in order to share correctly the power between all generators.

Frequency and Voltage Regulations

The speed regulator of the diesel engines can be mechanical or electronic. Regulators can work in droop mode or isochronous mode. Droop mode regulators allow a frequency regulation of about ±2% between no-load to full load in steady-state conditions. Isochronous regulators guarantee a narrower regulation bounded by ±0.5% for the same load variation. Voltage regulation in steady-state conditions allows a variation of ±1.5% for loads ranging from 0% to 100% and power factor between 0.8 and 1. In transient conditions the voltage drop is prevented from exceeding 15% in the least favorable case of sudden application of a full load. In this case, the time needed to return to within ±3% of the steady-state voltage ranges from a fraction of a second to several seconds.

Power Factor

Rated powers (kilovolt-amperes) of generating units correspond to a power factor of 0.8. At this power factor the active rated power of the synchronous generator corresponds to the rated power (kilowatts) of the diesel engine. The limit of power of the diesel engine is the active power delivered to the load while the limit of the synchronous generator is the apparent power, as the limit is imposed by the current circu-

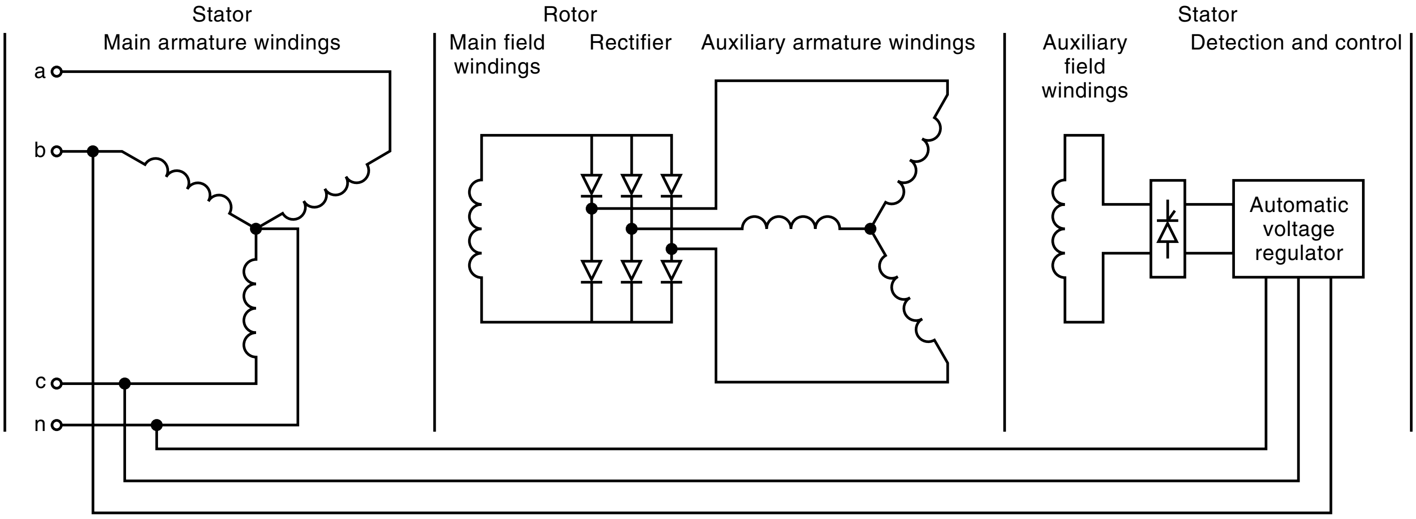

Figure 8. Simplified electric schematic of a three-phase "brushless"-type generator, showing the rotating bridge rectifier used to realize the excitation of the synchronous machine, the automatic voltage regulator, and the auxiliary excitation generator delivering the excitation power.

lating in the stator winding. In case of variation between 0.8 and 1 the engine can always deliver the same rated power (which corresponds to the active power delivered by the generator). If the power factor is lower than 0.8, the apparent power must be the same but the diesel will be underloaded with reduction of the diesel efficiency. Consequently, as the power factor decreases, the active power delivered by the synchronous generator must also decrease, with only the apparent power remaining constant. Conversely, if the power factor is greater than 0.8, as the power delivered by the diesel engine must not remain higher than its rated power, the apparent power (volt-amperes) which may be delivered to the load, must decrease. At a power factor equal to 1 the apparent power of the generator will equal the active power delivered at a power factor equal to 0.8. At low power factor values with respect to the rated value, the active power delivered is reduced, while the excitation system is overcharged, which sets a limit owing to the thermal conditions of the field winding. If the diesel engine is undercharged (the active power is less than the rated value), this yields too low a temperature in the combustion chamber where poor combustion may cause the formation of liquid particles. These phenomena are particularly dangerous in turbo-charged units, because the particles mixed with the exhaust gas may damage the turbine. So it is preferable to provide an automatic power factor regulator in order to avoid low-power-factor operating conditions.

Single-Phase Loads

Single-phase loads can be fed by the generating set if the phase current does not exceed the rated value. However, such an imbalance will increase the voltage drop, which can exceed the value guaranteed by the three-phase load regulator.

GENERAL CHARACTERISTICS FOR INSTALLATION

Successful installation of a generating set requires careful consideration of the following: (1) building characteristics, (2) foundation block design, (3) air supply and generating set cooling, (4) exhaust pipeline, (5) noise reduction, (6) fuel supply systems, (7) electric wiring.

Building Characteristics

A direct connection by a large door of the generator room to the outside will facilitate the installation of the diesel set, while two opposite walls should be used for intake of fresh air and to exhaust hot air coming from the cooling system. Care must be taken to ensure good air circulation inside the generator room. The sizing of the generator room will consider also the needs for the fuel tank, control switch-gear, and aisles for maintenance service.

Foundation Block and Noise Reduction

Internal combustion engines, because they are reciprocating machinery, are a typical source of vibrations. Thus we must isolate the generating sets by noise-reducing mufflers. High levels of noise insulation are normally expensive, and a trade-off is generally accepted between cost and acceptable level of noise, depending on the specific application and according to the noise reduction standards. In case of ground installation, a heavy block of concrete having two to three times the weight of the generating set will ensure a reliable foundation. The maximal horizontal dimensions of the generating set may be used to establish the horizontal dimensions of the foundation block, and consequently the block height can be easily calculated because the block weight is known.

Air Supply and Generating Set Cooling

Fresh air supply must be ensured in the generator room to maintain a comfortable temperature and to provide a fresh charge of air for engine combustion. Good rules of practice are as follows: (1) Intake of fresh air should be far from heat sources; (2) possibly provide a direct connection of the engine radiator to the outside by a duct, (3) fresh air should flow through a path with surfaces at increasing temperatures, (4) air flow should be at speeds less than or equal to 1.5 m/s.

Exhaust Pipeline

The exhaust pipeline must ensure low resistance to gas expulsion in order to avoid high back pressure on the engine exhaust system, which can cause (1) loss of engine power, and (2) increase of both the combustion temperature and specific fuel consumption, which yields smoky exhaust and accelerated wear. We must isolate the pipeline in order to avoid the presence of very hot surfaces and exhaust leakage in the generator room. Rules of good practice for the design of exhaust pipelines are as follows: (1) Avoid small diameter pipes; (2) reduce as much as possible changes in pipe diameter; (3) avoid pipe elbows with radius less than two times the pipe diameter; (4) minimize the whole length of the pipeline; (5) include some flexible pipes which absorb noise and vibration and which also compensate for length increase due to thermal variation and mechanical inaccuracies.

Noise Reduction

Diesel generating sets are strong sources of noise, and standards give mandatory admissible acoustic levels to protect the health of operators. Several methods of noise reduction can be applied, depending on the goal, as a single means or as associated means: (1) shielding by placing physical barriers between the sources and operators; (2) absorption by porous materials, which avoid reflection and reverberation close to the source of the noise; (3) damping by flexible panels which cover the source of the noise; (4) isolation of the source of noise by elastic supports between the noise source and the frame rigidly connected to the ground; (5) suitable separation of the noise sources aiming to reduce the whole noise. The main sources of noise are (1) the diesel engine, (2) the cooling fans, (3) inlet and outlet air windows, (4) synchronous generator, and (5) pumps, compressor, and other auxiliary machinery.

Fuel Supply System

A small tank (50 to 100 L) is normally installed on the frame, while an auxiliary tank should be located as close as possible to the generating group to ensure the daily stock of the fuel. The main tank should have a capacity adequate to power the whole diesel station. Position and accessibility, as well as distance from heat sources, should be carefully evaluated. The daily filling of the tank is performed by a level switch controlling an electric pump. Correct operation of diesel engines requires unspoiled fuel. The stored fuel may release solid particles while allowed to fit undisturbed inside the tank, or it may be filtered. The water content of the fuel must be separated by a water separator device. It is necessary to ensure the following in the fuel supply system: (1) A valve to stop fuel flow must be placed outside the generator room; (2) include adequate pipeline junctions to prevent fuel leakage; (3) the fuel pipeline must be separated from electrical cable ducts; (4) fabricate the fuel tanks with steel-based materials and shape them to allow easy removal of the bottom residuals (water, solid particles, etc.).

SYNCHRONOUS GENERATOR MODELING

Prediction of electromechanical behavior of synchronous generators can be performed by a system of equations describing the synchronous machine (6,7). The rotors of synchronous generators used in a diesel set are fabricated as salient pole structures, with magnetic anisotropy, carrying a field winding F and a damper winding k. The voltage frequency of the generating groups is 50 Hz or 60 Hz and is given by $f = (NP/120)$, with N the rotational speed per minute and P the number of poles of the machine. Diesel groups have at least four pole machines, and for large power groups a higher number of poles are more suitable in order to lower the rotational speed of the diesel engines. A suitable methodology used to represent the electromagnetic phenomena in such machines is to transform the three-phase stationary winding, located on the stator, into a reference frame rotating at synchronous speed with two winding axes aligned with the direct axis and quadrature axis in the rotor. A simplified electric equivalent circuit of a two-pole three-phase synchronous generator is shown in Fig. 9. The stator windings in the actual machine are uniformly distributed in slots and have a mechanical displacement of 120°. The rotor has a field winding and a damper winding (squirrel-cage type). The angle θ represents the displacement between the stator axis a (fixed) and the rotor axis q (rotating), and thus it is a function of speed $\omega = d\theta/dt$. The voltage equations of the machine expressed in stator quantities are much too complicated. In fact, the explicit time derivatives of the flux linkages contain many terms that are functions of the angle θ, which is a function of time. The voltage equations result in a system with time-varying coefficients. Transformation in a rotating reference frame simplifies the voltage equations and also results in equations which have constant coefficients in time. The algebraic complexity, without applying such a transformation, can be seen by writing, for the electric circuit depicted in Fig. 9, the voltage equation relative to phase a:

$$v_a = -r_s i_a + p\lambda_a \tag{1}$$

$$\lambda_a = -(\mathcal{L}_{aa} i_a + \mathcal{L}_{ab} i_b + \mathcal{L}_{ac} i_c) + \mathcal{L}_{af} i_f + \mathcal{L}_{akd} i_{kd} + \mathcal{L}_{akq} i_{kq} \tag{2}$$

where $p = d/dt$ is the derivative operator, and the self-inductance $\mathcal{L}_{aa}$ and the mutual inductances ($\mathcal{L}_{ab}$, $\mathcal{L}_{ac}$, $\mathcal{L}_{af}$, $\mathcal{L}_{akd}$, and $\mathcal{L}_{akq}$) are periodic functions of θ; thus when the rotor is moving, $\mathcal{L}_{aa}$ are functions of time, expressed by

$$\mathcal{L}_{aa} = L_\ell + L_A - L_B \cos 2\theta \tag{3}$$

$$\mathcal{L}_{ab} = -\frac{1}{2} L_A - L_B \cos\left(2\theta - \frac{2\pi}{3}\right) \tag{4}$$

$$\mathcal{L}_{ac} = -\frac{1}{2} L_A - L_B \cos\left(2\theta + \frac{2\pi}{3}\right) \tag{5}$$

$$\mathcal{L}_{af} = L_{af} \sin\theta \tag{6}$$

$$\mathcal{L}_{akd} = L_{akd} \sin\theta \tag{7}$$

$$\mathcal{L}_{akq} = L_{akq} \cos\theta \tag{8}$$

with both the leakage inductance L_ℓ of the windings and other inductances (L_A, L_B, etc.), depending on the specific machine.

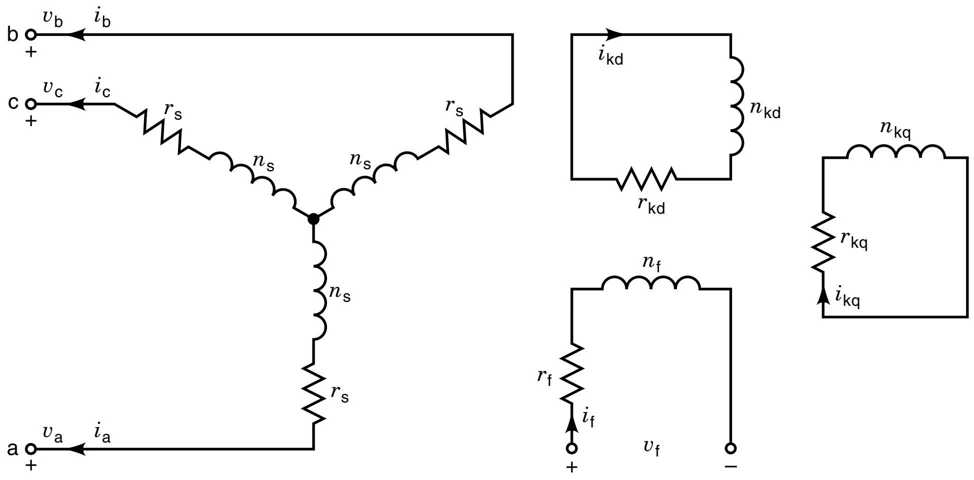

Figure 9. Simplified electric equivalent circuit of a two-pole three-phase synchronous generator. The layout represents the stator windings, the rotor field excitation, and the rotor damper winding.

From inspection of Eqs. (1) to (8), it is clear that the expression of the phase *a* voltage is complicated. In contrast, by transforming the stator variables to the rotor reference frame, all the time-varying inductances reduce to constant terms and the voltage equations (Park's equations) simplify noticeably, resulting in $dq0$ quantities:

$$v_q = -r_s i_q + \omega\lambda_d + p\lambda_q \tag{9}$$

$$v_d = -r_s i_d - \omega\lambda_q + p\lambda_d \tag{10}$$

$$v_0 = -r_s i_0 + p\lambda_0 \tag{11}$$

$$v'_f = r'_f i'_f + p\lambda'_f \tag{12}$$

$$0 = r'_{kq} i'_{kq} + p\lambda'_{kq} \tag{13}$$

$$0 = r'_{kd} i'_{kd} + pf\lambda'_{kd} \tag{14}$$

where the prime on the variables and parameters of rotor quantities means that they have been referred to the stator by properly multiplying by the turns ratio of the windings. The flux linkages are expressed by

$$\lambda_q = -L_\ell i_q + L_{mq}(-i_q + i'_{kg}) \tag{15}$$

$$\lambda_d = -L_\ell i_d + L_{md}(-i_d + i'_{kd} + i'_f) \tag{16}$$

$$\lambda_0 = -L_\ell\, i_0 \tag{17}$$

$$\lambda'_{kq} = L'_{\ell kq} i'_{kq} + L_{mq}(+i'_{kq} - i_q) \tag{18}$$

$$\lambda'_{kd} = L'_{\ell kd} i'_{kd} + L_{md}(-i_d + i'_f + i'_{kd}) \tag{19}$$

$$\lambda'_f = L'_{\ell f} i'_f + L_{md}(-i_d + i'_f + i'_{kd}) \tag{20}$$

where $L_{mq} = -\frac{3}{2}(L_A - L_B)$, and L_{md} $-\frac{3}{2}(L_A + L_B)$ are the q- and d-axis magnetizing inductances, and $L'_{\ell kq}$, $L'_{\ell kd}$, L_ℓ, and $L'_{\ell f}$ are leakage inductances.

The electromagnetic torque can be calculated by

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d) \tag{21}$$

The mechanical equation is

$$T_e = -J\frac{2}{P}p\omega + T_D \tag{22}$$

with $\omega = p\theta$.

By considering a steady-state sinusoidal behavior with a terminal voltage V_t, equations that have been written for a generic behavior reduce to

$$V_d = V_t \sin\delta = r_s I_d + X_q I_q \tag{23}$$

$$V_q = V_r \cos\delta = -r_s I_q - X_d I_d + E_f \tag{24}$$

The torque equation, expressed in terms of the terminal voltage, is

$$T_e = \frac{3}{2}\frac{P}{2}\frac{E_f V_t}{X_d}\sin\delta + \frac{1}{2}\left(\frac{1}{X_d} - \frac{1}{X_q}\right)V_t^2 \sin 2\delta \tag{25}$$

where δ is the rotor angle defined as the electric angular displacement of the rotor with respect to the peak value of the terminal voltage; E_f is the internal electromotive force; and X_d and X_q are, respectively, the direct and quadrature reactances.

The detailed model of synchronous generators, described by Eqs. (9) to (22), contains two state variables relative to the mechanical part (position and speed of the rotor) and six state variables relative to the electromagnetic part. This model is used when there are large variations of the variables. In certain circumstances it would be unnecessary to adopt this model, and some approximations can be applied. One of the common assumptions is that the rate of change in the stator flux linkages is negligible, thus reducing the voltage equations to algebraic relations. The same can be applied to the flux linkages of the damper windings. As a further approximation the rate of change in the field flux linkage can be ignored. Reduced models (8) can be used for electric transients and electromechanical transients. Electric transients are defined as behaviors which have fast constant times and do not involve speed variations of the generators. In the worst case, these can be used as a fourth-order model by neglecting the time derivatives of the flux linkages and the mechanical equation. Electromechanical transients are defined as behaviors which neglect only the time derivatives of fluxes in the voltage equations. In such cases the model can be reduced to sixth order or lower. A complication in modeling of electrical machines is caused by saturation in the magnetic paths of the machine. Modeling of transient (effect of the field winding) or subtransient (effect of the damper winding) behavior can be performed neglecting saturation. It is, however, essential to include the saturation issue in the steady-state model to obtain accurate initial conditions. Various methods for dealing with saturation exist, and the final choice is often governed by the availability of reliable machine data.

DIESEL ENGINE MODELING

Diesel engine modeling is very complex due to the difficulties in describing the engine internal processes by equations (2,3). Two basic types of models are used to predict performance and emissions of engines. Models based on equations derived by the energy conservation principle are known as thermodynamic-based models, while models based on equations describing the fluid motion are named fluid-dynamic models. Basic assumptions of the former models are knowledge of the mass transfer into (intake) and out (exhaust) of the cylinders, the energy release from the fuel, and the heat transfer between the gases inside the cylinders and the inner surfaces of the chamber. The calculated quantities are the work transfer and the pressure on the piston surface. To use the thermodynamic-based model, the data of the pressure p of the gas inside the cylinder and the volume V of the cylinder during a cycle can be plotted as a p–V diagram, in order to calculate the area enclosed within the cycle trajectory. Such an area is the work transfer W_c per cylinder:

$$W_c = \oint p\,dV \tag{26}$$

From knowledge of the work, the masses of fuel and air inducted, and the engine speed, the performance parameters can be derived. The power P developed per cylinder by a four-stroke diesel engine is expressed by

$$P = \frac{W_c n}{2} \tag{27}$$

where n is the rotational speed (rev/s) of the crankshaft.

The above is gross power, which differs from the brake power by the power required for friction, for engine accessories, and to expel exhaust gases and induct fresh charge. The mechanical efficiency can be defined as

$$\eta_m = \frac{P_b}{P} = 1 - \frac{P_f}{P} \tag{28}$$

where P_b is the power measured at the brake, and P_f is the power equivalent to all losses. The mean effective pressure (mep) is defined as the ratio of the work per cycle divided by the volume displaced for cycle:

$$\text{mep} = \frac{W_c}{V_d} \tag{29}$$

The capacity of an engine to convert the energy contained in fuels into mechanical energy can be evaluated by the fuel conversion efficiency, given by the ratio of the work per cycle divided by the energy of the fuel mass:

$$\eta_f = \frac{W_c}{m_f Q_{HV}} = \frac{P}{pm_f Q_{HV}} \tag{30}$$

where Q_{HV} is the heating value of the fuel, m_f is the mass of fuel, and pm_f is the rate of mass per unit time. The intake system efficiency can be evaluated by the volumetric efficiency η_V, defined as the ratio of the volume of the mass of air inducted in the cylinder per cycle divided by the volume displaced by the piston:

$$\eta_v = \frac{m_a}{\rho_{a,i} V_d} \tag{31}$$

where $\rho_{a,i}$ is the inlet air density.

Substituting Eqs. (30) and (31) into Eq. (27), we get

$$P = \frac{\eta_f \eta_v n V_d Q_{HV} \rho_{a,i} \dfrac{m_f}{m_a}}{2} \tag{32}$$

and the torque

$$T_D = \frac{P}{2\pi n} = \frac{\eta_f \eta_v V_d Q_{HV} \rho_{a,i} \dfrac{m_f}{m_a}}{4\pi} \tag{33}$$

Finally, substituting Eqs. Eqs. (30) and (31) into Eq. (29), we get

$$\text{mep} = \eta_f \eta_v Q_{HV} \rho_{a,i} \frac{m_f}{m_a} \tag{34}$$

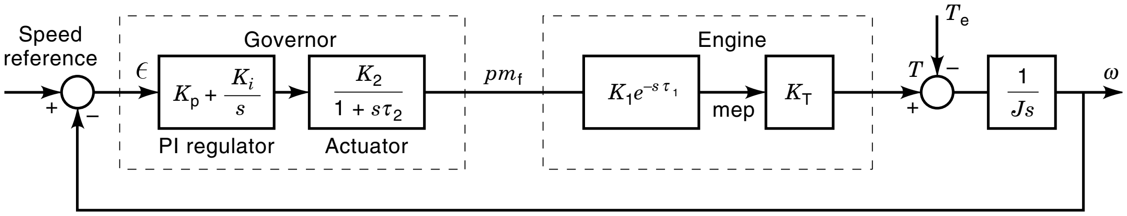

Figure 10. Block diagram of the diesel engine and of its governor. The generator electric torque (T_e) is represented as a disturbance.

The fuel actuator is commonly represented as a first-order system characterized by a gain K_2 and a time constant τ_2. The command to the actuator yields a flow of fuel mass m_f, which is linked to the mep by a time delay τ_1.

Diesel Engine Governor

A governor controls the intake fuel flow in the engine, which regulates the speed. The regulator is normally realized by a PI controller which yields a proportional action to correct the speed according to the operating conditions and an integral action to nullify the steady-state error (9–11). In recent years, some proposals have been presented to utilize adaptive regulators instead of PI regulators in order to obtain faster responses, in case of load variation or disturbances (9). When called into service, diesel prime movers are requested to operate at almost constant speed to obtain a constant frequency, even in the case of transients caused by load insertions or faults. The diesel model described above can be represented by the block diagram shown in Fig. 10, which gives a simple representation of engine behavior.

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DIFFERENCE SETS, THEORY. See THEORY OF DIFFERENCE SETS.