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Estimation of Plant Electrical Load

One of the earliest tasks for the engineer who is designing a power system is to estimate the normal operating plant load. He is also interested in knowing how much additional margin he should include in the final design. There are no 'hard and fast' rules for estimating loads, and various basic questions need to be answered at the beginning of a project, for example,

- Is the plant a new, 'green field' plant?
- How long will the plant exist e.g. 10, 20, 30 years?
- Is the plant old and being extended?
- Is the power to be generated on site, or drawn from an external utility, or a combination of both?
- Does the owner have a particular philosophy regarding the 'sparing' of equipment?
- Are there any operational or maintenance difficulties to be considered?
- Is the power factor important with regard to importing power from an external source?
- If a generator suddenly shuts down, will this cause a major interruption to the plant production?
- Are there any problems with high fault levels?

1.1 PRELIMINARY SINGLE-LINE DIAGRAMS

In the first few weeks of a new project the engineer will need to roughly draft a key single-line diagram and a set of subsidiary single-line diagrams. The key single-line diagram should show the sources of power e.g. generators, utility intakes, the main switchboard and the interconnections to the subsidiary or secondary switchboards. It should also show important equipment such as power transformers, busbars, busbar section circuit breakers, incoming and interconnecting circuit breakers, large items of equipment such as high voltage induction motors, series reactors for fault current limitation, and connections to old or existing equipment if these are relevant and the main earthing arrangements. The key single-line diagram should show at least, the various voltage levels, system frequency, power or volt-ampere capacity of main items such as generators, motors and transformers, switchboard fault current levels, the vector group for each power transformer and the identification names and unique 'tag' numbers of the main equipment.

The set of single-line diagrams forms the basis of all the electrical work carried out in a particular project. They should be regularly reviewed and updated throughout the project and issued

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Table 1.1. Voltages used in different countries for generation, distribution and transmission

Low voltage generation and three-phase consumers (volts)	High voltage generation and distribution (kilovolts)		High voltage transmission less than 75 kV (kilovolts)	
910	18	7.2*	70	24.5
660	16	6.9	69*	24
600*	14.4	6.6*	66*	23
525	13.8*	6.5	65	22
500	13.2*	6.3	60	20
480	12.6	6.24	50	19
460	12.5	6*	46	15
440*	12.47	5.5	45	
420	12.4	5	44	
415*	12	4.8	38	
400*	11.5	4.16*	36	
380*	11.4	4	35	
346	11*	3.3*	34.5*	
277	10.4	3*	33*	
260	10	2.4	31.5	
254**	9	2.3	30	
240**	8.9		27.6	
230**	8.4		27.5	
220**	8.3		27	
208	8		25	
200	7.3		24.9	
190				

Notes* Commonly used voltages in the oil industry.
Notes** Commonly used as single-phase voltages.

in their final form at the completion of the project. They act as a diary and record the development of the work. Single-line diagrams are also called ‘one-line diagrams’.

At this stage the engineer can begin to prepare a load schedule for each subsidiary switchboard and motor control centre, and a master schedule for the main switchboard. The development of the single-line diagrams during the project is discussed in sub-section 1.7.

The master load schedule will give an early estimate of the total power consumption. From this can be decided the number of generators and utility intakes to install. The kW and kVA ratings of each generator or intake will be used to determine the highest voltage to use in the power system. Table 1.1 shows typical voltages used throughout the world for generation, distribution and transmission of power at oil industry plants, see also sub-section 3.7.

1.2 LOAD SCHEDULES

Each switchboard will supply power to each load connected to it and in many cases it will also supply power to switchboards or distribution boards immediately downstream. Hence the input power to a switchboard will have the possibility of two components, one local and one downstream. Hereinafter the term switchboard will also include the term motor control centre, see sub-section 7.1.

Each local load may be classified into several different categories for example, vital, essential and non-essential. Individual oil companies often use their own terminology and terms such as ‘emergency’ and ‘normal’ are frequently encountered. Some processes in an oil installation may handle fluids that are critical to the loss of power e.g. fluids that rapidly solidify and therefore must be kept hot. Other processes such as general cooling water services, air conditioning, sewage pumping may be able to tolerate a loss of supply for several hours without any long-term serious effects.

In general terms there are three ways of considering a load or group of loads and these may be cast in the form of questions. Firstly will the loss of power jeopardise safety of personnel or cause serious damage within the plant? These loads can be called ‘vital’ loads. Secondly will the loss of power cause a degradation or loss of the manufactured product? These loads can be called the ‘essential’ loads. Thirdly does the loss have no effect on safety or production? These can be called the ‘non-essential’ loads.

Vital loads are normally fed from a switchboard that has one or more dedicated generators and one or more incoming feeders from an upstream switchboard. The generators provide power during the emergency when the main source of power fails. Hence these generators are usually called ‘emergency’ generators and are driven by diesel engines. They are designed to automatically start, run-up and be closed onto the switchboard whenever a loss of voltage at the busbars of the switchboard is detected. An undervoltage relay is often used for this purpose. Testing facilities are usually provided so that the generator can be started and run-up to demonstrate that it is ready to respond when required. Automatic and manual synchronising facilities can also be provided so that the generator can be loaded during the tests.

Low voltage diesel generators are typically rated between 100 and 500 kW, and occasionally as large as 1000 kW. High voltage emergency generator ratings are typically between 1000 and 2500 kW. The total amount of vital load is relatively small compared with the normal load and, in many situations, the essential load. Consequently the vital load is fed from uninterruptible power supplies (UPS), as AC or DC depending upon the functions needed. The vital loads are usually fed from a dedicated part of the emergency switchboard. The UPS units themselves are usually provided with dual incoming feeders, as shown in Figure 17.3.

Some of the vital and essential loads are required when the plant is to be started up, and there is no ‘normal’ power available. In this situation the starting up of the plant is called ‘black starting’. The emergency generator must be started from a source of power, which is usually a high capacity storage battery and a DC starter motor, or a fully charged air receiver and a pneumatic starter motor.

In many plants, especially offshore platforms, the vital and essential loads operate at low voltage e.g. 380, 400, 415 volts. Large plants such as LNG refrigeration and storage facilities require substantial amounts of essential power during their start-up and shut-down sequences and so high voltage e.g. 4160, 6600 volts is used. The vital loads would still operate at low voltage. Tables 1.2 and 1.3 shows typical types of loads that can be divided into vital and essential loads.

All of the vital, essential and non-essential loads can be divided into typically three duty categories:

- Continuous duty.
- Intermittent duty.
- Standby duty (those that are not out of service).

Table 1.2. Vital and essential AC loads

Vital AC loads	Essential AC loads
UPS supplies	Diesel fuel transfer pumps
Emergency lighting	Main generator auxiliaries
Emergency generator auxiliaries	Main compressor auxiliaries
Helicopter pad lighting	Main pump auxiliaries
Control room supplies	Diesel fire pump auxiliaries
Vital LV pumps	Electric fire pumps
	Living quarters
	Air compressor
	General service water pumps
	Fresh water pumps
	Equipment room HVAC supplies
	Life boat davits
	Anti-condensation heaters in panels and switchboards
	Security lighting supplies
	Control room supplies
	UPS supplies
	Radio supplies
	Computer supplies
	Battery chargers for engine starting systems
	Instrumentation supplies

Table 1.3. Vital DC loads

Public address system
Plant alarm systems
System shutdown system
Telemetry systems
Emergency radio supplies
Fire and gas detection system
Navigation aids

Hence each switchboard will usually have an amount of all three of these categories. Call these C for continuous duty, I for intermittent duty and S for the standby duty. Let the total amount of each at a particular switchboard j be $C_{j\text{sum}}$, $I_{j\text{sum}}$ and $S_{j\text{sum}}$. Each of these totals will consist of the active power and the corresponding reactive power.

In order to estimate the total consumption for the particular switchboard it is necessary to assign a diversity factor to each total amount. Let these factors be D_{cj} for $C_{\text{sum}j}$, D_{ij} for $I_{\text{sum}j}$ and D_{sj} for $S_{\text{sum}j}$. Oil companies that use this approach have different values for their diversity factors, largely based upon experience gained over many years of designing plants. Different types of plants may warrant different diversity factors. Table 1.4 shows the range of suitable diversity factors. The factors should be chosen in such a manner that the selection of main generators and main feeders from a power utility company are not excessively rated, thereby leading to a poor choice of equipment in terms of economy and operating efficiency.

Table 1.4. Diversity factors for load estimation

Type of project	D_c for C_{sum}	D_i for I_{sum}	D_s for S_{sum}
Conceptual design of a new plant	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Front-end design of a new plant (FEED)	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Detail design in the first half of the design period	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Detail design in the second half of the design period	0.9 to 1.0	0.3 to 0.5	0.0 to 0.2
Extensions to existing plants	0.9 to 1.0	0.3 to 0.5	0.0 to 0.2

The above method can be used very effectively for estimating power requirements at the beginning of a new project, when the details of equipment are not known until the manufacturers can offer adequate quotations. Later in a project the details of efficiency, power factor, absorbed power, rated current etc. become well known from the purchase order documentation. A more accurate form of load schedule can then be justified. However, the total power to be supplied will be very similar when both methods are compared.

The total load can be considered in two forms, the total plant running load (TPRL) and the total plant peak load (TPPL), hence,

$$\text{TPRL} = \sum_{j=1}^{n}(D_c C_{\text{sum}j} + D_i I_{\text{sum}j}) \quad \text{kW}$$

$$\text{TPPL} = \sum_{j=1}^{n}(D_c C_{\text{sum}j} + D_i I_{\text{sum}j} + D_s S_{\text{sum}j}) \quad \text{kW}$$

Where n is the number of switchboards.

The installed generators or the main feeders to the plant must be sufficient to supply the TPPL on a continuous basis with a high load factor. This may be required when the production at the plant is near or at its maximum level, as is often the case with a seasonal demand.

Where a plant load is predominantly induction motors it is reasonable to assume the overall power factor of a switchboard to be 0.87 lagging for low voltage and 0.89 lagging for high voltage situations. If the overall power factor is important with regard to payment for imported power, and where a penalty may be imposed on a low power factor, then a detailed calculation of active and reactive powers should be made separately, and the total kVA determined from these two totals. Any necessary power factor improvement can then be calculated from this information.

1.2.1 Worked Example

An offshore production and drilling platform is proposed as a future project, but before the detail design commences it is considered necessary to prepare an estimate of the power consumption. The results of the estimate will be used to determine how many gas-turbine driven generators to install.

Table 1.5. Subsidiary load schedule for the low voltage process switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Production area lighting	2	75	150	0	0
Glycol pumps	4	2	4	0	4
Glycol reboilers	2	75	75	0	75
Glycol transfer pump	1	15	15	0	0
Refrigeration compressor	3	160	320	0	160
Deareator vacuum pumps	2	30	30	0	30
Water injection booster pumps	4	90	270	0	90
Deareator chem. injection pumps	4	2	4	0	4
Sea drain sump pumps	1	10	10	0	0
Water inj. chem. injection pumps	6	2	8	0	4
Reclaim oil pumps	2	37	37	37	0
Treated water pumps	2	132	132	132	0
Oil transfer pumps	4	10	30	10	0
Electric gas heating	2	300	300	0	300
HP gas comp. pre-lube pumps	2	5	5	0	5
2 × HP gas comp. auxiliaries	2	—	35	35	100
LP gas comp. pre-lube pumps	2	5	5	0	5
2 × LP gas comp. auxiliaries	2	—	35	35	100
4 × water inj. pump auxiliaries	4	—	70	70	200
Corrosion inhibitor pumps	1	37	37	0	0
Trace heating	2	40	80	0	0
Sub-totals for the switchboard			1652	319	1077

Normal running load for the switchboard = $(1.0 \times 1652) + (0.5 \times 319) + (0.1 \times 1077) = 1920$ kW

Table 1.6. Subsidiary load schedule for the low voltage utilities switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Utilities area lighting	2	75	150	0	0
Potable water pumps	2	5	5	5	0
Living quarters feeder-A(on)	1	500	300	200	0
Living quarters hot water pumps	2	15	15	15	0
Control room supplies	1	15	15	0	0
Computer supplies	2	15	15	0	15
Radio supplies	2	30	30	0	30
Instrument air compressor	2	90	90	0	90
Instrument air driers	2	10	10	0	10
Plant air compressors	2	90	90	0	90
HVAC fans	16	11	88	0	88
HVAC main air handling unit	1	30	30	0	0
HVAC standby air handling unit	1	10	0	0	10
HVAC refrigeration unit	1	15	15	0	0
Gas turbo-generator auxiliaries	4	—	100	100	300
Trace heating	2	30	60	0	0
Sub-totals for the switchboard			1013	320	600

Normal running load for the switchboard = $(1.0 \times 1013) + (0.5 \times 320) + (0.1 \times 633) = 1236$ kW

This in turn will enable an initial layout of all the facilities and equipment to be proposed. Since this is a new plant and the preliminary data is estimated from process calculations, mechanical calculations and comparisons with similar plants, it is acceptable to use the following diversity factors, $D_c = 1.0$, $D_i = 0.5$ and $D_s = 0.1$.

Tables 1.5, 1.6, 1.7 and 1.8 show the individual loads that are known at the beginning of the project.

The total power is found to be 12,029 kW. At this stage it is not known whether the plant is capable of future expansion. The oil and gas geological reservoir may not have a long life expectation, and the number of wells that can be accommodated on the platform may be limited. The 4000 kW of power consumed by the drilling operations may only be required for a short period of time e.g. one year, and thereafter the demand may be much lower.

Table 1.7. Subsidiary load schedule for the low voltage emergency switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Emergency lighting	1	75	75	0	0
Chlorine generator	1*	30	30	0	0
Desalination unit	1*	75	75	0	0
Potable water pumps	1	5	5	0	0
Instrument air compressors	1	90	90	0	0
Instrument air driers	1	10	10	0	0
Living quarters feeder-B(off)	1*	500	0	0	0
Living quarters emergency feeder	1	100	50	50	0
Living quarters hot water pumps	1	15	15	0	0
Diesel fuel transfer pump	1	5	5	0	0
Emergency diesel eng. sump heater	1	3	3	0	0
Emergency diesel gen. auxiliaries	1	2	0	0	2
Emergency diesel eng. bat. charger	1	1	0	1	0
Emergency diesel eng. room fans	2	11	11	0	0
Control room fans	2	22	22	0	0
Computer UPS supply	1	5	5	0	0
Emergency radio supplies	1	10	0	0	10
Navigation aids UPS supply	1	10	10	0	0
Life boat davit supplies	2	37	0	50	24
Life boat diesel heater supplies	2	4	4	4	0
Fire pump engine battery chargers	2	22	22	22	0
Seawater washdown pump	1*	37	0	37	0
Anti-condensation swbd heaters	—	25	25	0	0
Anti-condensation motor heaters	—	25	10	15	0
Portable lighting supplies	1	1	1	0	0
Sub-totals for the switchboard			468	179	58

Normal running load for the switchboard = $(1.0 \times 468) + (0.5 \times 179) + (0.1 \times 58) = 563$ kW

For black start delete loads marked (*)

Black start sub-totals for the switchboard = $(1.0 \times 363) + (0.5 \times 142) + (0.1 \times 0) = 434$ kW

Table 1.8. Master load schedule for the high voltage main switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
HV motor loads					
Main oil expert pumps	3	650	1300	0	650
Gas compressor	4	500	1500	0	500
Seawater lift pumps	4	450	1350	0	450
LV motor loads					
Feeder to drilling	1	0	2700	2400	1000
Feeder to LV process MCC	2	0	1652	319	1077
Feeder to LV utilities MCC	1	0	1013	320	633
Feeder to LV emergency MCC	1	0	168	179	58
Sub-totals			9983	3218	4368

Totals for the main generator to supply $= (1.0 \times 9983) + (0.5 \times 3218) + (0.1 \times 4368) = 12{,}029$ kW

During the detail design phase of the project the load schedules will be modified and additional loads will inevitably be added. At least 10% extra load should be added to the first estimate i.e. 1203 kW. The total when rounded-up to the nearest 100 kW would be 13,300 kW.

Sufficient generators should be installed such that those that are necessary to run should be loaded to about 80 to 85% of their continuous ratings, at the declared ambient temperature. This subject is discussed in more detail in sub-section 1.3. If four generators are installed on the basis that one is a non-running standby unit, then three must share the load. Hence a reasonable power rating for each generator is between 5216 kW and 5542 kW.

1.3 DETERMINATION OF POWER SUPPLY CAPACITY

After the load has been carefully estimated it is necessary to select the ratings and numbers of generators, or main incoming feeders from a power utility company. Occasionally a plant may require a combination of generators and incoming feeders e.g. refinery, which may operate in isolation or in synchronism with the utility company.

Usually a plant has scope for expansion in the future. This scope may be easy to determine or it may have a high degree of uncertainty. The owner may have strong reasons to economise initially and therefore be only willing to install enough capacity to meet the plant requirements in the first few years of operation. If this is the case then it is prudent to ensure that the switchgear in particular has adequate busbar normal current rating and fault current rating for all future expansion. The main circuit breakers should be rated in a similar manner. If the switchgear is rated properly at the beginning of a project, then all future additions should be relatively easy to achieve in a practical and economical manner. Such an approach also leads to a power system that is easy to start up, operate and shut down.

The supply capacity normally consists of two parts. One part to match the known or initial consumption and a second part to account for keeping a spare generator or feeder ready for service.

Any allowance required for future load growth should be included in the power consumption calculations. This two-part approach is often referred to as the '$N - 1$ philosophy', where N is the number of installed generators or feeders. The philosophy is that under normal operating conditions in a fully load plant $N - 1$ generators or feeders should be sufficient to supply the load at a reasonably high load factor.

Let P_l = power consumption required at the site ambient conditions
P_g = rated power of each generator or feeder at the site ambient conditions
F_o = overload power in % when one generator or feeder is suddenly switched out of service
F_i = load factor in % of each generator or feeder before one is switched out of service
N = number of installed generators or feeders. N is usually between 4 and 6 for an economical design of a generating plant and 2 or 3 for feeders.

P_l and P_g are usually the known variables, with F_i and F_o being the unknown variables. Several feasible ratings of P_g may be available and the value of N may be open to choice. A good choice of P_g and N will ensure that the normally running load factor is high i.e. between 70% and 85%, whilst the post-disturbance overload on the remaining generators or feeders will not be so high that they trip soon after the disturbance, i.e. less than 125%.

The initial load factor can be found as,

$$F_i = \frac{100P_l}{P_g(N-1)}\%$$

The post-disturbance overload can be found as,

$$F_o = \frac{100P_l}{P_g(N-2)}\%$$

If it is required that F_i is chosen for the design such that $F = 100\%$ and no overload occurs then let F be called F_{i100} and so,

$$F_{i100} = \frac{(N-2)100}{N-1} \quad \text{for no overloading.}$$

Table 1.9 shows the values of F_i against N for the no overloading requirement.

Table 1.9. Selecting N and F_{i100} on the basis of $N - 1$ capacity with overloading not tolerated

No. of installed generator or feeders N	Value of F_{i100} to ensure no overloading $F_{i100}\%$
2	Not practical
3	50.0
4	66.67
5	75.00
6	80.00
7	83.33
8	86.71

Table 1.10 shows the values of the load factor F_i and the overload factor F_o for a range of typical power consumptions P_l. The values of P_g are the site requirements and relate approximately to the ratings of gas-turbine generators that are available and used in the oil industry i.e. 2.5 to 40.0 MW.

The table was compiled by constraining F_i and F_o to be within good practical limits,

$$66.7\% \leqslant F_i \leqslant 90.0\%$$

and

$$80 \leqslant F_o \leqslant 125\%$$

Table 1.10. Selecting generator ratings on the basis of $N - 1$ capacity with tolerance of overloading

Power consumption (MW) P_l	Initial load factor (%) F_i	Number of installed generators N	Generator rating at site conditions (MW) P_g	Turbine ISO ratings for a site amb. temp of 40°C (MW) P_{iso40}	Final load factor (%) F_o
10	66.7	4	5.0	5.9	100.0
10	74.1	4	4.5	5.3	111.1
10	83.3	4	4.0	4.7	125.0
10	71.4	5	3.5	4.1	95.2
10	83.3	5	3.0	3.5	111.1
10	66.7	6	3.0	3.5	83.3
10	80.0	6	2.5	2.9	100.0
15	66.7	4	7.5	8.8	100.0
15	75.0	5	5.0	5.9	100.0
15	83.3	5	4.5	5.3	111.1
15	66.7	6	4.5	5.3	83.3
15	75.0	6	4.0	4.7	93.8
15	85.7	6	3.5	4.1	107.1
20	66.7	4	10.0	11.8	100.0
20	66.7	5	7.5	8.8	89.9
20	80.0	6	5.0	5.9	100.0
20	88.9	6	4.5	5.3	111.1
25	69.4	4	12.0	14.1	104.2
25	83.3	4	10.5	11.8	125.0
25	83.3	5	7.5	8.8	111.1
25	66.7	6	7.5	8.8	83.3
30	71.4	4	14.0	16.5	107.1
30	83.3	4	12.0	14.1	125.0
30	75.0	5	10.0	11.8	100.0
30	80.0	6	7.5	8.8	100.0
40	66.7	4	20.0	23.5	100.0
40	74.1	4	18.0	21.2	111.1
40	83.3	4	16.0	18.8	125.0
40	71.4	5	14.0	16.5	95.2
40	83.3	5	12.0	14.1	111.1
40	66.7	6	12.0	14.1	83.3

Table 1.10. (*continued*)

Power consumption (MW) P_l	Initial load factor (%) F_i	Number of installed generators N	Generator rating at site conditions (MW) P_g	Turbine ISO ratings for a site amb. temp of 40°C (MW) P_{iso40}	Final load factor (%) F_o
40	80.0	6	10.0	11.8	100.0
60	66.7	4	30.0	35.3	100.0
60	72.7	4	27.5	32.4	109.1
60	80.0	4	25.0	29.4	120.0
60	66.7	5	22.5	26.5	88.9
60	75.0	5	20.0	23.5	100.0
60	83.3	5	18.0	21.2	111.1
60	66.7	6	18.0	21.2	83.3
60	75.0	6	16.0	18.8	93.8
60	85.7	6	14.0	16.5	107.1
80	66.7	4	40.0	47.1	100.0
80	76.2	4	35.0	41.2	114.3
80	66.7	5	30.0	35.3	88.9
80	72.7	5	27.5	32.4	97.0
80	80.0	5	25.0	29.4	106.7
80	88.9	5	22.5	26.5	118.5
80	71.1	6	22.5	26.5	88.9
80	80.0	6	20.0	23.5	100.0
80	88.9	6	18.0	21.2	111.1
100	83.3	4	40.0	47.1	125.0
100	71.4	5	35.0	41.2	95.2
100	83.3	5	30.0	35.3	111.1
100	66.7	6	30.0	35.3	83.3
100	72.7	6	27.5	32.4	91.9
100	80.0	6	25.0	29.4	100.0
100	88.9	6	22.5	26.5	111.1

In practice if F_i is too high the operator of the plant will become nervous and will often switch into service the spare generator. If F_i is too low then there will be too many generators in service and it should be possible to withdraw one. Gas turbines have poor fuel economy when they are lightly loaded.

High values of F_o should be avoided because of the risk of cascade tripping by the gas turbines. The margin of overload that a gas turbine can tolerate is relatively small and varies with the turbine design. The higher the normal combustion temperature within the turbine, the lower the tolerance is usually found to be available. A high overload will also be accompanied by a significant fall in electrical system frequency, caused by the slowing down of the power turbine and the relatively long time taken by the speed governing system to respond. Many power systems that use gas-turbine generators are provided with underfrequency and overfrequency protective relays, and these may be set to trip the generator when a high overload occurs. The initial rate of decline in frequency is determined by the moment of inertia of the power turbine, plus the generator rotor, and the magnitude of the power change seen at the terminals of the generator. See Reference 1. This subject is discussed and illustrated in sub-section 12.2.10 and Appendix D.

If F_o is designed to be less than approximately 105% then the generators will be able to absorb the overload until some corrective action by an operator is taken e.g. puts the spare generator into service.

However, it is also possible to introduce a high-speed load shedding scheme into the power system when F_o is found to be above 105%. Such a scheme will compute in an anticipatory manner how much consumption should be deleted in the event of a loss of one generator. The designer will be able to predetermine enough low priority consumers to achieve the necessary corrective action. See Chapter 16.

The application of the $N - 1$ philosophy is less complicated with incoming feeders e.g. underground cables, overhead lines. N is usually chosen as 2 because it is not usually economical to use three or more feeders for one switchboard. Both feeders are usually in service and so the 'spare' does not usually exist. However, each feeder is rated to carry the full demand of the switchboard. Therefore with both in service each one carries half of the demand, and can rapidly take the full demand if one is switched out of service. This approach also enables a feeder to be taken out service for periodic maintenance, without disturbing the consumers.

1.4 STANDBY CAPACITY OF PLAIN CABLE FEEDERS AND TRANSFORMER FEEDERS

In sub-section 1.2 the three ways of considering consumers were discussed, and the terms, vital, essential and non-essential were introduced. Because of the sensitive nature of the vital and essential consumers with regard to personnel safety and production continuity, it is established practice to supply their associated switchboards with dual, or occasionally triple, feeders. For non-essential switchboards it may be practical to use only one feeder.

For switchboards other than those for the generator or intake feeders it is established practice to add some margin in power capacity of their feeders so that some future growth can be accommodated. The margin is often chosen to be 25% above the TPPL.

If the feeders are plain cables or overhead lines then it is a simple matter to choose their cross-sectional areas to match the current at the 125% duty.

For transformer feeders there are two choices that are normally available. Most power transformers can be fitted with external cooling fans, provided the attachments for these fans are included in the original purchase order. It is common practice to order transformers initially without fans and operate them as ONAN until the demand increases to justify the fan cooling. Thereafter the transformer is operated as ONAF, see sub-section 6.5. Adding fans can increase the capacity of the transformer by 25% to 35%, depending upon the particular design and ambient conditions. The alternative choice is simply to rate the ONAN transformer for the 125% duty, and initially operate it at a lower level. The decision is often a matter of economics and an uncertainty about the future growth.

When standby or future capacity is required for transformers it is necessary to rate the secondary cables or busbars correctly at the design stage of the project. Likewise the secondary circuit breakers and switchgear busbars need to be appropriately rated for the future demand. The decision to over-rate the primary cables or lines may be made at the beginning of the project or later when demand increases. Again this is a matter of economics and forecasting demand.

1.5 RATING OF GENERATORS IN RELATION TO THEIR PRIME MOVERS

1.5.1 Operation at Low Ambient Temperatures

In some countries the ambient temperature can vary significantly over a 24-hour period, and its average daily value can also vary widely over a 12-month period. The power plant designer should therefore ascertain the minimum and maximum ambient temperatures that apply to the plant. The maximum value will be used frequently in the sizing and specification of equipment. The minimum value will seldom be used, but it is very important when the sizing of generators and their prime movers are being examined.

Prime movers will produce more output power at their shafts when the ambient temperature is low. The combustion air in the prime mover is taken in at the ambient temperature. Gas turbines are more sensitive to the ambient air temperature than are piston engines.

If the ambient temperature is low for long periods of time then the power plant can generate its highest output, which can be beneficial to the plant especially if a seasonal peak demand occurs during this period of low temperature. In some situations a generator may be able to be taken out of service, and hence save on wear and tear, and fuel.

With this in mind the generator rating should exceed that of the prime mover when power is required at the low ambient temperature. A margin of between 5% and 10% should be added to the prime mover output to obtain a suitable rating for the generator. It should be noted that when the output of a prime mover is being considered, it should be the output from the main gearbox if one is used. Gearbox losses can amount to 1% to 2% of rated output power.

1.5.2 Upgrading of Prime Movers

Some prime movers, especially new designs, are conservatively rated by their manufacturer. As the years pass some designs are upgraded to produce more power. As much as 10% to 15% can be increased in this manner. If the power system designer is aware of this potential increase in rating then the generator rating should be chosen initially to allow for this benefit. At the same time the cables and switchgear should be rated accordingly.

Situations occur, especially with offshore platforms, where no physical space is available to install an extra generator and its associated equipment. Sometimes the main switchrooms cannot accept any more switchgear, not even one more generator circuit breaker. Therefore the potential for upgrading a prime mover without having to make major changes to the electrical system is an option that should be considered seriously at the beginning of a project.

1.6 RATING OF MOTORS IN RELATION TO THEIR DRIVEN MACHINES

The rating of a motor should exceed that of its driven machine by a suitable margin. The selection of this margin is often made by the manufacturer of the driven machine, unless advised otherwise. The actual choice depends on various factors e.g.

Table 1.11. Ratio of motor rating to the driven machine rating

Approximate rating of the motor or machine (kW)	Margin of the motor rating above the machine rating (%)
Up to 15	125
16.0 to 55	115
Above 55	110

- The absolute rating of either the motor or the driven machine i.e. small or large machines.
- The function of the driven machine e.g. pump, compressor, fan, crane, conveyor.
- Expected operating level e.g. often near to maximum performance, short-term overloading permitted.
- Shape of the operating characteristic of the machine e.g. pressure (head) versus liquid flow rate in a pump.
- Change in energy conversion efficiency of the machine over its working range.
- Machine is driven at nearly constant speed.
- Machine is driven by a variable speed motor.
- Harmonic currents will be present in the motor.
- The nearest standard kW rating available of the motor.
- Ambient temperature.

Some rule-of-thumb methods are often stated in the purchasing specifications of the motor–machine unit, see for example Table 1.11, which applies to low voltage three-phase induction motors.

Where the driven machine is a centrifugal type i.e. pump or compressor, the shaft power may be taken as that which occurs at the ‘end of curve’ operating point. This rule-of-thumb point is defined as being 125% of the power required at the maximum operating efficiency point on the designed curve of pressure (head) versus fluid flow rate, at the rated shaft speed.

These rule-of-thumb methods can be used to check the declared performance and ratings from a machine manufacturer.

1.7 DEVELOPMENT OF SINGLE-LINE DIAGRAMS

Single-line diagrams are the most essential documents that are developed during the detail design phase of a project. They identify almost all the main items of power equipment and their associated ancillaries. Initially they define the starting point of a project. Finally they are a concise record of the design, from which all the design and purchasing work evolved.

The final single-line diagrams should contain at least the following information. Complicated power systems may require the single-line diagrams to be sub-divided into several companion diagrams, in which aspects such as protection, interlocking and earthing are treated separately. This ensures that the diagrams are not overly congested with information. The end results should be unambiguous and be easily read and understood by the recipient.

1.7.1 The Key Single Line Diagram

Switchboards and motor control centres:

- All switchboards and motor control centre names, bus-section numbers, line voltages, number of phases, number of wires, frequency, busbar continuous current rating.
- Identification of main incoming, bus-section, outgoing and interconnecting circuit breakers, including spare and unequipped cubicles.
- Some diagrams show the cable tag number of the principal cables.

Generators:

- Names and tag numbers.
- Nominal ratings in MVA or kVA and power factor.
- D-axis synchronous reactance in per-unit.
- D-axis transient reactance in per-unit.
- D-axis sub-transient reactance in per-unit.
- Neutral earthing arrangements, e.g. solid, with a neutral earthing resistance (NER), with a common busbar, switches or circuit breakers for isolation.
- Current and time rating of the NER if used, and the voltage ratio of the earthing transformer if used.

Transformer feeders:

- Names and tag numbers.
- Nominal ratings in MVA or kVA.
- Leakage impedance in per-unit.
- Symbolic winding arrangement of the primary and secondary.
- Line voltage ratio.

High voltage and large low voltage motors:

- Names and tag numbers.
- Nominal ratings in kW.

General notes column or box:

Usually several notes are added to the diagram to explain unusual or particular features, such as interlocking, limitations on impedance values for fault currents or voltdrop.

1.7.2 Individual Switchboards and Motor Control Centres

- Switchboards and motor control centre name and tag number.
- Bus-section numbers or letters.
- Cubicle numbers or letters.

- Line voltage, number of phases, number of wires, frequency, busbar continuous current rating.
- Busbar nominal fault breaking capacity in kA at 1 or 3 seconds.
- Identification of all circuit breakers, fuse-contactor units, and their nominal current ratings.
- Neutral earthing arrangements, e.g. connections to the incomers.
- Protective devices of all incomers, bus-section circuit breakers, busbars, and outgoing circuits.
- Interlocking systems in schematic form.
- Local and remote indication facilities.
- Details of special devices such as transducers, automatic voltage regulators, synchronising schemes, fault limiting reactors, reduced voltage motor starters, busbar trunking.
- Rating, ratio and accuracy class of current and voltage transformers.
- Identification of spare and unequipped cubicles.
- References to other drawing numbers, e.g. continuation of a switchboard, associated switchgear, drawing in the same series, legend drawing, cables schedule and protective relay schedule.
- Column or box for detailed notes.
- Column or box for legend of symbols.

1.8 COORDINATION WITH OTHER DISCIPLINES

At the earliest practical time in a project the engineers will need to identify areas of engineering and design where interfaces are necessary. An efficient system of communication and exchange of information should be established and implemented at regular intervals. Meetings should be arranged to discuss problem areas and short-falls in information. The following generally summarises what is needed, particularly during the feasibility and conceptual stage of a project.

In order to be able to engineer an economical and efficient power system it is desirable for the electrical engineer to have:

- A basic understanding of the hydrocarbon and chemical processes and their supporting utilities e.g. compression, pumping, control and operation, cooling arrangements.
- A procedure for regular communication with engineers of other disciplines, e.g. instrument, process, mechanical, safety, telecommunications, facilities, operations and maintenance.
- An appreciation of the technical and economical benefits and shortcomings of the various electrical engineering options that may be available for a particular project.
- The technical flexibility to enable the final design to be kept simple, easy to operate and easy to maintain.

1.8.1 Process Engineers

The process engineers should be able to inform the electrical engineers on matters relating to the production processes and supporting utilities e.g.:

- Oil, gas, condensate and product compositions and rates, and their method of delivery to and from a plant.
- Variation of production rates with time over the anticipated lifetime of the plant.

- Fuel availability, rates and calorific values, pollution components e.g. sulphur, carbon dioxide, alkali contaminants, particle size and filtration.
- Electrical heating and refrigeration loads, trace heating of vessels and piping.
- Make available process flow diagrams, process and instrumentation diagrams, utilities and instrumentation diagrams.

1.8.2 Mechanical Engineers

The mechanical engineers will normally need to advise on power consumption data for rotating machines, e.g. pumps, compressors, fans, conveyors, and cranes. They will also advise the power output options available for the different types and models of prime movers for generators, e.g. gas turbines, diesel engines, gas engines.

In all cases the electrical engineer needs to know the shaft power at the coupling of the electrical machine. He is then able to calculate or check that the electrical power consumption is appropriate for the rating of the motor, or the power output is adequate for the generator.

The mechanical engineer will also advise on the necessary duplication of machinery, e.g. continuous duty, maximum short-time duty, standby duty and out-of-service spare machines. He will also give some advice on the proposed method of operation and control of rotating machines, and this may influence the choice of cooling media, construction materials, types of bearings, ducting systems, sources of fresh air, hazardous area suitability, etc.

The electrical engineer should keep in close ‘contact’ with the progress of machinery selection during the early stages of a project up to the procurement stage in particular, so that he is sure the electrical machines and their associated equipment are correctly specified. Likewise after the purchase orders are placed he should ensure that he receives all the latest manufacturers’ data relating to the electrical aspects, e.g. data sheets, drawings, changes, hazardous area information. See also Chapter 19 and Appendix E.

1.8.3 Instrument Engineers

The process and instrument engineers will generally develop the operation and control philosophies for individual equipments and overall schemes. The electrical engineer should then interface to enable the following to be understood:

- Interlocking and controls that affect motor control centres and switchboards, generator controls, control panels, local and remote stations, mimic panels, SCADA, computer networking, displays in the CCR and other locations.
- Cabling specifications and requirements, e.g. screening, numbers of cores, materials, earthing, routing, segregation and racking of cables.
- Power supplies for control systems, AC and DC, UPS requirements, battery systems.
- Symbolic notation, e.g. tag numbers, equipment names and labels, cable and core numbering systems.

1.8.4 Communication and Safety Engineers

The communication and safety engineers will be able to advise on power supply requirements for:

- Radar, radio, telecommunications and public address.
- Aids to navigation, e.g. lamps, beacons, foghorns, sirens; also alarms, lifeboat davits, etc.
- Emergency routing and exit lighting systems.
- Supplies for emergency shut-down systems.

1.8.5 Facilities and Operations Engineers

These engineers do not normally contribute any power consumption data, but their input to the work of the electrical engineer is to advise on subjects such as equipment layout, access to equipment, maintainability, maintenance lay-down space, emergency exit routing, operational philosophies of plant and systems, hazardous area classification.

REFERENCE

1. J. L. Blackburn, *Applied protective relaying*. Westinghouse Electric Corporation (1976). Newark, NJ 07101, USA. Library of Congress Card No. 76-8060.