3

Synchronous Generators and Motors

3.1 COMMON ASPECTS BETWEEN GENERATORS AND MOTORS

The theoretical operation of synchronous generators and synchronous motors is almost the same. The main differences are the direction of stator current and the flow of power through these machines. The theory of operation of these machines is dealt with in great detail in most standard textbooks on electrical machines, e.g. References 1 to 6.

The construction of generators and motors, of the same kW ratings, used in the oil and gas industry is very similar, as discussed in sub-section 3.9. Variations that are noticeable from the external appearance exist mainly due to the location of the machine and its surrounding environment. It is uncommon for generators to be placed in hazardous areas, whereas it is occasionally necessary to use a synchronous motor in a hazardous area, e.g. driving a large gas compressor. Large induction motors are often used for driving oil pumps and gas compressors that need to operate in hazardous areas.

The rotor of generators may be either ‘cylindrical’ or ‘salient’ in construction. Synchronous motors nearly always have salient pole rotors. Machines with four or more poles are always of the salient pole rotor type. Cylindrical pole rotors are used for two-pole generators, and these generators are usually driven by steam or gas turbines at 3600 rpm for 60 Hz or 3000 rpm for 50 Hz operation and have power output ratings above 30 megawatts.

The methods of cooling and the types of bearings are generally the same.

The remaining discussion in this chapter, up to sub-section 3.9, will concentrate on salient pole machines with an emphasis on generators.

3.2 SIMPLIFIED THEORY OF OPERATION OF A GENERATOR

The stator, also called the armature, carries the three-phase AC winding. The rotor, also called the field, carries the DC excitation or field winding. The field winding therefore rotates at the shaft speed and sets up the main magnetic flux in the machine.

The fundamental magnetic action between the stator and rotor is one of tangential pulling. In a generator, the rotor pole pulls the corresponding stator pole flux around with it. In a motor, the stator pole pulls the rotor pole flux around with it. The action is analogous to stretching a spring, the greater the power developed, the greater the pull and greater the corresponding distance that is created between the rotor and stator flux axes.

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When a machine is not connected to the three-phase supply but is running at rated speed and with rated terminal voltage at the stator, there exists rated flux in the iron circuit and across the air gap. This flux cuts the stator winding and induces rated emf in winding and hence rated voltage at the main terminals. Consider what happens in a generator. Let the generator be connected to a load, or the live switchboard busbars. Stator current is caused to flow. The current in the stator winding causes a stator flux to be created which tends to counteract the air-gap flux that is produced by the excitation. This reduction of air-gap flux causes the terminal voltage to fall. The terminal voltage can be restored by increasing the rotor excitation current and hence the flux. So the demagnetising effect of the stator current can be compensated by increasing the field excitation current. This demagnetising effect of the stator current is called 'armature reaction' and gives rise to what is known as the synchronous reactance, which is also called a 'derived' reactance as described in sub-section 3.4.

The subject of armature reaction in the steady and transient states is explained very well in Reference 7. A brief description is given below.

3.2.1 Steady State Armature Reaction

The rotating field in the air gap of a synchronous machine is generally considered to be free of space harmonics, when the basic operation of the machine is being considered. In an actual machine there are space harmonics present in the air gap, more in salient pole machines than a cylindrical rotor machine, see for example References 4 and 6. It is acceptable to ignore the effects of space harmonics when considering armature reaction and the associated reactances. Therefore the flux wave produced by the rotating field winding can be assumed to be distributed sinusoidally in space around the poles of the rotor and across the air gap.

If the stator winding, which consists of many coils that are basically connected as a series circuit, is not connected to a load then the resulting emf from all the coils is the open circuit emf of the phase winding. Closing the circuit on to a load causes a steady state current to flow in the stator coils. Each coil creates a flux and their total flux opposes the field flux from the rotor. The resulting flux in the air gap is reduced. The emf corresponding to the air-gap flux drives the stator current through the leakage reactance and conductor resistance of the stator coils. The voltage dropped across this winding impedance is small in relation to the air-gap voltage. Deducting this voltage drop from the air-gap voltage gives the terminal voltage of the loaded generator. In the circumstance described thus far the reduction in air-gap flux is called armature reaction and the resulting flux is much smaller than its value when the stator is open circuit. Restoring air gap and terminal voltage requires the field current to be increased, which is the necessary function of the automatic voltage regulator and the exciter.

When the rotor pole axis coincides with the axis of the stator coils the magnetic circuit seen by the stator has minimum reluctance. The reactance corresponding to the armature reaction in this rotor position is called the 'direct axis synchronous reactance X_{sd}'. If the stator winding leakage reactance, X_a, is deducted from X_{sd} the resulting reactance is called the 'direct axis reactance X_d'.

A similar situation occurs when the rotor pole axis is at right angles to the axis of the stator coils. Here the magnetic reluctance is at its maximum value due to the widest part of the air gap facing the stator coils. The complete reactance in this position is called the 'quadrature axis synchronous reactance X_{sq}'. Deducting X_a results in the 'quadrature axis reactance X_q'.

3.2.2 Transient State Armature Reaction

Assume the generator is loaded and operating in a steady state. If the peak-to-peak or rms value of the stator current changes in magnitude then its corresponding change in magneto-motive force (mmf) will try to change the air-gap flux by armature reaction. Relatively slow changes will allow the change in flux to penetrate into the rotor. When this occurs an emf is induced in the field winding. This emf drives a transient current around a circuit consisting of the field winding itself and the exciter that is supplying the winding. The induction of current is by transformer action. An increase in stator current will be matched by an increase in field current during the transient state. A voltage drop will occur in the machine due to the armature reaction and the reduction in air-gap flux. Reactances are associated with this type of armature reaction.

When the rotor poles are coincident with the stator coils axis the armature reaction is a maximum and the reactance is called the 'direct axis transient reactance X'_d'.

The situation is different when the rotor poles are at right angles to the stator coils. There is no induction in the field circuit and the reluctance is high, being almost the same as for the steady state condition. In this situation the corresponding quadrature axis transient reactance X'_q approximately equals the reactance X_q. Cylindrical rotors of two-pole high speed generators have a nearly uniform rotor diameter and almost constant air gap all around the periphery. Hence the reactance X'_q is almost equal to X'_d.

3.2.3 Sub-Transient State Armature Reaction

Again assume that the generator is loaded and operating in a steady state. In this situation the magnitude of the stator current is allowed to change rapidly, as in the case of a short circuit in the stator circuit. The additional flux produced by the stator winding will try to penetrate the surface of the rotor poles. Most oil industry generators are provided with damper bars to reduce the excursions in rotor speed during major disturbances. The bars are made of copper or copper alloy and placed longitudinally in the face of the rotor poles. They function in a manner similar to a squirrel cage induction motor when there is a transient change in rotor speed relative to the synchronous speed. As soon as the additional flux passes through the pole faces it will induce currents in the damper bars and the solid pole tips, by the process of transformer induction. These induced currents will set up flux in opposition in order to maintain constant flux linkages with the stator.

During this transient condition, or more appropriately called a sub-transient condition, the additional flux is forced to occupy a region consisting of air and the surface of the rotor poles. This is a high reluctance condition which gives rise to reactances of low values.

Some generators have the damper bars connected to a ring at either end of the pole structure, which provides some damping action from the quadrature axis. This provides a set of short-circuited coils in the quadrature axis, which are air cored and able to repel the flux that is attempting to enter their region.

By the same reasoning as for the 'transient' reactances so the 'sub-transient' reactances are derived, and are called the 'direct axis sub-transient reactance X''_d' and the 'quadrature axis sub-transient reactance X''_q'.

3.3 PHASOR DIAGRAM OF VOLTAGES AND CURRENTS

The following points apply to the drawing of phasor diagrams of generators and motors:-

- The terminal voltage V is the reference phasor and is drawn horizontally.
- The emf E lies along the pole axis of the rotor.
- The current in the stator can be resolved into two components, its direct component along the 'direct or d-axis' and its quadrature component along the 'quadrature or q-axis'.

The emf E leads the voltage V in an anti-clockwise direction when the machine is a generator.

Each reactance and resistance in the machine has a volt drop associated with it due to the stator current flowing through it. Consider a generator. The following currents and voltages can be shown in a phasor diagram for both the steady and the dynamic states.

• E	the emf produced by the field current I_f.
• V	the terminal voltage.
• V_d	the component of V along the d-axis.
• V_q	the component of V along the q-axis.
• I	the stator current.
• I_d	the component of I along the d-axis.
• I_q	the component of I along the q-axis.
• IR_a	the volt drop due to the armature or stator current.
• $I_d R_a$	the component of IR_a along the d-axis.
• $I_q R_a$	the component of IR_a along the q-axis.
• $I_d X_d$	the volt drop due to the d-axis synchronous reactance.
• $I_d X'_d$	the volt drop due to the d-axis transient reactance.
• $I_d X''_d$	the volt drop due to the d-axis sub-transient reactance.
• $I_q X_q$	the volt drop due to the q-axis synchronous reactance.
• $I_q X'_q$	the volt drop due to the q-axis transient reactance (normally taken as $I_q X_q$).
• $I_q X''_q$	the volt drop due to the q-axis sub-transient reactance.
• E'	the emf behind the transient impedance.
• E''	the emf behind the sub-transient impedance.

Explanations of the two-axis, or d-q, theory are given in Reference 1, Chapter 17 and in more detail in References 2 and 3.

Figure 3.1 has been drawn for a 15 MW generator operating at full-load and a power factor of 0.8 lagging.

The following per-unit data were used:-

$$E = 2.098$$

$$V = 1.0, \quad V_d = 0.423, \quad V_q = 0.906$$

$$I = 1.0, \quad I_d = 0.882, \quad I_q = 0.472$$

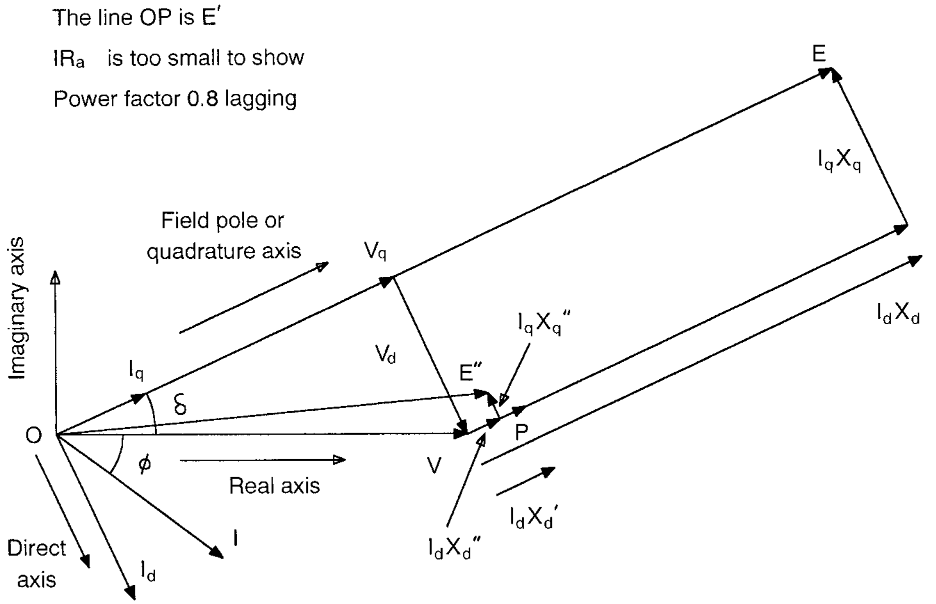

Figure 3.1 Phasor diagram of a two-axis salient pole generator.

$$R_a = 0.002$$

$$X_d = 2.5 \quad X_q = 0.9$$

$$X'_d = 0.18 \quad X'_q = X_q$$

$$X''_d = 0.1 \quad X''_q = 0.15$$

3.4 THE DERIVED REACTANCES

The derived reactances were described in sub-section 3.2 in relation to their effect on armature reaction. They are derived from the actual winding reactances by the standard equations, for example References 8 and 9.

Direct axis:

$$X_d = X_a + X_{md} \tag{3.1}$$

$$X'_d = X_a + \frac{X_{md}X_f}{X_{md} + X_f} \simeq X_a + X_f \tag{3.2}$$

$$X''_d = X_a + \frac{X_{md}X_f X_{kd}}{X_{md}X_f + X_{md}X_{kd} + X_f X_{kd}} \tag{3.3}$$

$$\simeq X_a + \frac{X_f X_{kd}}{X_f + X_{kd}}$$

Quadrative axis:

$$X_q = X_a + X_{mq} \tag{3.4}$$

$$X''_q = X_a + \frac{X_{mq}X_{kd}}{X_{mq} + X_{kd}} \simeq X_a + X_{kd} \tag{3.5}$$

Where X_{md} and X_{mq} are much larger than any of the other reactances.

These equations can be transposed to find X_f, X_{kd} and X_{kq} in terms of X'_d, X''_d and X''_q in particular. The purchaser may require certain limits to X'_d and X''_d because of constraints on fault currents and volt drop. Consequently the machine designer is faced with finding physical dimensions to satisfy the resulting X_{md}, X_f and X_{kd}. The purchaser is not usually too concerned about the quadrature parameters. Transposing (3.1), (3.2) and (3.3) gives the designer the following:-

$$X_{md} = X_d - X_a \tag{3.6}$$

$$X_f = \frac{X_{md}(X'_d - X_a)}{X_{md} - X'_d + X_a} \tag{3.7}$$

$$X_{kd} = \frac{X_{md}X_f(X''_d - X_a)}{X_{md}(X_f + X_a) + X_aX_f - X''_d(X_{md} + X_f)} \tag{3.8}$$

Where X_a is kept as small as is practically reasonable.

Figures 3.2 and 3.3 show the variations of X'_d and X''_d with X_f for a family of X_{md} and X_{kd} values.

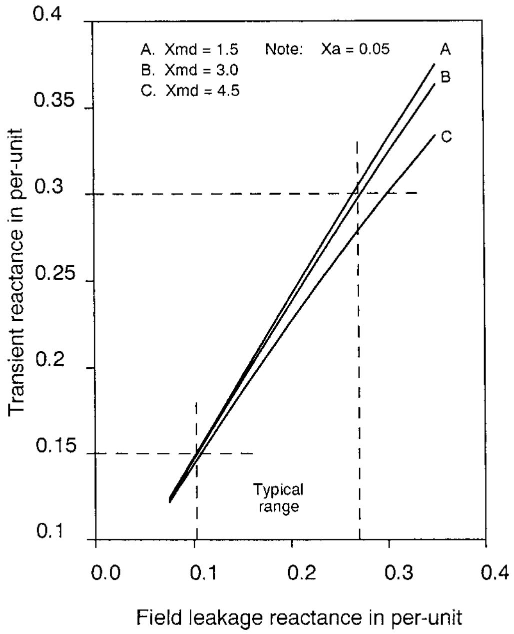

Figure 3.2 D-axis transient reactance versus field leakage reactance.

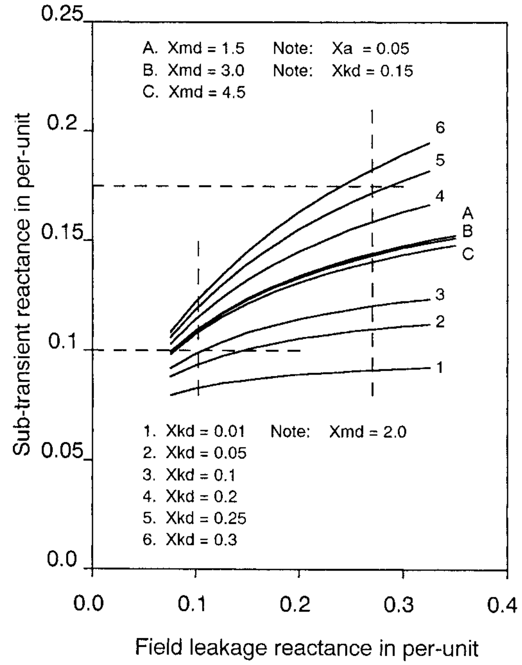

Figure 3.3 *D*-axis sub-transient reactance versus field leakage reactance.

3.4.1 Sensitivity of X_{md}, X_a, X_f and X_{kd} to Changes in Physical Dimensions

Assume a particular machine has a given rotor length and diameter, and radial depth of stator core. Allow other dimensions to vary.

The mutual coupling X_{md} between the rotor and the stator is much influenced by the radial length of the air gap.

A large air gap gives rise to a high reluctance path and a small mutual reactance X_{md}. Large air gaps facilitate the efficient removal of heat from the rotor and stator surfaces. Unfortunately a large air gap also results in more ampere-turns being needed in the rotor to fully excite the machine. This requires more volume in the rotor and for a given air gaps a larger mean diameter of the stator, hence a heavier and more expensive machine. As the kW rating of a machine increases so do its synchronous reactances, see sub-section 3.8.

$$X_{md} \propto \frac{\text{diameter of rotor} \times \text{length of rotor}}{\text{air-gap radial distance}}$$

A low armature leakage reactance X_a requires the number of stator slots per phase to be kept small, and a high utilisation of conductors per slot. Double layer slots are most often used for high voltage machines.

The armature leakage reactance is very much dependent upon the stator slot dimensions. It can be shown that:

$$X_a \propto \frac{\text{axial length of slots} \times \text{depth of slots}}{\text{width of slots}}$$

The field leakage reactance is dependent on the shape of the pole yoke,

$$X_f \propto \frac{\text{circumference of the yoke}}{\text{radial length of the yoke}}$$

Therefore a low value of X_f is obtained by having a radially long yoke of small cross-sectional area. Hence the overall diameter of the rotor tends to increase as the reactance decreases.

The damper bars or winding act in a manner very similar to an induction motor and provide a breaking torque against the transient disturbances in shaft speed. To be effective the damper needs to have a steep torque versus slip characteristic in the region near synchronous speed. The equivalent impedance of the damper requires a low resistance and a high reactance. High conductivity copper bars are embedded into the pole face to provide a low reluctance path for the leakage flux.

The variation in X_{kd} with slot dimensions is similar to the armature leakage,

$$X_{kd} \propto \frac{\text{axial length of slots} \times \text{depth of slots}}{\text{width of slots}}$$

Increasing X_{kd} tends to slightly increase the overall diameter of the rotor.

Reference 10 gives a full description of the physical design of electrical machines.

3.5 ACTIVE AND REACTIVE POWER DELIVERED FROM A GENERATOR

3.5.1 A General Case

If the steady state, transient and sub-transient phasors in Figure 3.1 are considered separately, then there is seen to be a similar structure. The terminal voltage V is resolved into its two-axis components V_d and V_q. The emfs E, E' and E'' can also be resolved into their components; E_d, E_q, E'_d, E'_q, E''_d and E''_q. In practical machines E_d does not exist (except for an interesting prototype built for the CEGB in approximately 1970, called the Divided Winding Rotor generator, see References 12 and 13). E_d would require a second exciter to produce it.

The variables can be regarded as ‘sending-end’ and ‘receiving-end’ variables. The sending-end variables are the emfs E, E_d and E_q, whilst the receiving-end ones are V, V_d and V_q. The current I, resolved into I_d and I_q, is common to both ends. The emfs, voltages and volt drops along each axis can be equated as,

For the d-axis

$$E_d = V_d + I_d R_d - I_q X_q \tag{3.9}$$

For the q-axis

$$E_q = V_q + I_q R_q + I_d X_d \tag{3.10}$$

Where R_d and R_q are the resistances present in their respective axis, usually both are equal to R_a the armature resistance.

To distinguish between the sending-end and the receiving-end the subscripts 's' and 'r' are introduced for the δ angles between E and E_q, and V and V_q respectively. Hence their components are:-

$$
\begin{aligned}
V_d &= V \sin \delta_r \\
V_q &= V \cos \delta_r \\
E_d &= E \sin \delta_s \\
E_q &= E \cos \delta_s \\
I_d &= -I \sin(\emptyset + \delta_r) \\
I_q &= I \cos(\emptyset + \delta_r)
\end{aligned}
$$

Equations (3.9) and (3.10) can be transposed to find I_d and I_q,

$$I_d = \frac{(E_q - V_q)X_q + (E_d - V_d)R_q}{X_d X_q + R_d R_q}$$

And

$$I_q = \frac{(E_q - V_q)R_d - (E_d - V_d)X_d}{X_d X_q + R_d R_q}$$

Active and reactive power leaving the terminals of the 'receiving-end' and received by the load are,

$$P_r = \frac{P_{r1} + P_{r2}}{\text{DEN}}$$

$$Q_r = \frac{Q_{r1} + Q_{r2}}{\text{DEN}}$$

Where,

$$
\begin{aligned}
P_{r1} &= V \sin \delta_r (E_q X_q + E_d R_q) + \frac{V^2}{2} \sin 2\delta_r (X_d - X_q) \\
P_{r2} &= V \cos \delta_r (E_q R_d - E_d X_d) - V^2 (R_q \sin \delta_r + R_d \cos^2 \delta_r) \\
Q_{r1} &= V \cos \delta_r (E_q X_q + E_d R_q) + \frac{V^2}{2} \sin 2\delta_r (R_d - R_q) \\
Q_{r2} &= V \sin \delta_r (E_d X_d - E_q R_d) - V^2 (X_d \sin^2 \delta_r + X_q \cos^2 \delta_r) \\
\text{DEN} &= X_d X_q + R_d R_q
\end{aligned}
$$

Also the active and reactive power leaving the shaft and the exciter are,

$$
\begin{aligned}
P_s &= \text{Real part of } (\text{EI}^*) \\
&= I \left(E_q \cos(\delta_r + \emptyset) + E_d \sin(\delta_r + \emptyset) \right)
\end{aligned}
$$

Where I* denotes the conjugate of the phasor I.

$$\begin{aligned} Q_s &= \text{Imaginary part of (EI}^*) \\ &= I\left(E_q \sin(\delta_r + \emptyset) - E_d \cos(\delta_r + \emptyset)\right) \end{aligned}$$

The active and reactive power losses are,

$$\begin{aligned} P_{\text{loss}} &= I_d{}^2 R_d + I_q{}^2 R_q \\ Q_{\text{loss}} &= I_d{}^2 X_d + I_q{}^2 X_q \end{aligned}$$

From which the summations of powers are,

$$\begin{aligned} P_S &= P_r + P_{\text{loss}} \\ Q_S &= Q_r + Q_{\text{loss}} \end{aligned}$$

The equations above are shown for the steady state. However they apply equally well for the transient and sub-transient states provided the substitutions for E'_d, E'_q, E''_d, E''_q, X'_d, X'_q, X''_d and X''_q are made systematically. Such substitutions are necessary in the digital computation of transient disturbances in power systems, those that are often called 'transient stability studies'.

3.5.2 The Particular Case of a Salient Pole Generator

The first simplification is to assume $R_d = R_q = R_a$ which is very practical. In addition the steady state variables E_d and δ_r can be assumed to be zero. Hence the equations in sub-section 3.5.1 become.

$$\begin{aligned} V_d &= V \sin\delta \\ V_q &= V \cos\delta \\ E_d &= 0 \\ E_q &= E \\ I_d &= -I \sin(\phi + \delta) \\ I_q &= I \cos(\phi + \delta) \\ I_d &= \frac{(E_q - V_q)X_q - V_d R_a}{X_d X_q + R_a{}^2} \\ I_q &= \frac{(E_q - V_q)R_a - V_d X_d}{X_d X_q + R_a{}^2} \\ P_r &= \frac{P_{r1} + P_{r2}}{\text{DEN}} \\ Q_r &= \frac{Q_{r1} + Q_{r2}}{\text{DEN}} \end{aligned}$$

Where,

$$
\begin{aligned}
P_{r1} &= V\sin\delta(E_q X_q) + \frac{V^2}{2}\sin 2\delta(X_d - X_q)\\
P_{r2} &= V\cos\delta(E_q R_a) - V^2 R_a\\
Q_{r1} &= V\cos\delta(E_q X_q)\\
Q_{r2} &= V\sin\delta(-E_q R_a) - V^2(X_d\sin^2\delta + X_q\cos^2\delta)\\
\mathrm{DEN} &= X_d X_q + {R_a}^2
\end{aligned}
$$

The sending-end variables become,

$$
\begin{aligned}
P_S &= I\ E_q\cos(\delta+\phi)\\
Q_S &= I\ E_q\sin(\delta+\phi)
\end{aligned}
$$

3.5.3 A Simpler Case of a Salient Pole Generator

Most practical generators have an armature resistance R_a that is much less in value than the synchronous reactances X_d and X_q. Consequently the equations in sub-section 3.5.2 can be further simplified without incurring a noticeable error. They become,

$$
\begin{aligned}
V_d &= V\sin\delta\\
V_q &= V\cos\delta\\
E_q &= E\\
I_d &= -I\sin(\phi+\delta)\\
I_q &= I\cos(\phi+\delta)\\
I_d &= \frac{E_q - V_q}{X_d}\\
I_q &= \frac{V_d}{X_q}\\
P_r &= \frac{P_{r1}+P_{r2}}{\mathrm{DEN}}\\
Q_r &= \frac{Q_{r1}+Q_{r2}}{\mathrm{DEN}}
\end{aligned}
$$

Where,

$$
\begin{aligned}
P_{r1} &= V\sin\delta(E_q X_q) + \frac{V^2}{2}\sin^2\delta(X_d - X_q)\\
P_{r2} &= 0\\
Q_{r1} &= V\cos\delta(E_q X_q)
\end{aligned}
$$

$$Q_{r2} = -V^2(X_d \sin^2 \delta + X_q \cos^2 \delta)$$

$$\mathrm{DEN} = X_d X_q$$

The sending-end variables remain the same. These equations are of the same form as those found in most textbooks that cover this subject.

3.6 THE POWER VERSUS ANGLE CHART OF A SALIENT POLE GENERATOR

Manufacturers of synchronous generators will usually provide a power-angle chart of the form shown in Figure 3.4, which was drawn using typical data. Let the volt drop $I_q X_q$ in Figure 3.1 be extended at its intersection with E to a value $I_q X_d$, and then divide all the variables by X_d. Figure 3.4 is the resulting power angle diagram, derived in the manner recommended in Reference 11, which incidentally has not changed since then. The line AB represents the kVA of the generator and OB the excitation emf.

Power-angle charts are normally used where a generator feeds into a utility grid rather than a local captive load as with 'island mode' operation. When a generator feeds into a grid its operating condition is not only determined by the overall load on the grid but also by the reactive power requirements of the overhead lines at and near to the generator. For example at night-time the active power demand tends to be lower than in the day-time but since the transmission system is still connected it requires compensation to counteract the excessive capacitance charging current that is

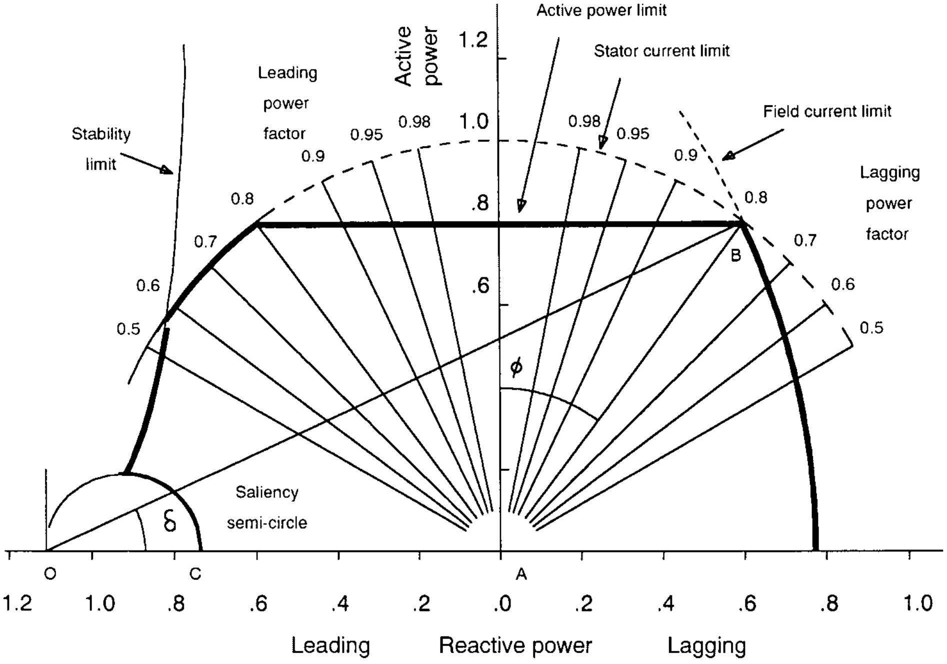

Figure 3.4 Operating chart of a two-axis salient pole generator.

Table 3.1. Preferred rated voltages of generators

Generator rating (kVA)	Approximate voltage rating (volts)	
	Min.	Max.
100	200	450
200	200	800
500	300	3,000
1,000	400	7,500
2,000	600	15,000
5,000	2,000	15,000
10,000	5,000	15,000
20,000	10,000	15,000
30,000	15,000	15,000

present. This can only be achieved by under-exciting the generator, thereby causing it to operate near or in its leading power factor region.

The above situation cannot normally occur with a self-contained power plant such as those on marine installations, unless they are interconnected by submarine cables to other installations that also have running generators. Even with interconnections of typically 20 km the amount of capacitance charging current is not sufficient to cause generators to operate in their leading power factor regions. It is possible under abnormal operating conditions, but these are too rare to consider. Oil industry power plants operate with a lagging power factor at or near to 0.9.

In conclusion it can be seen that the use and benefit of power-angle charts are minimal for most oil industry power plants.

3.7 CHOICE OF VOLTAGES FOR GENERATORS

The rated voltage of generators tends to increase in steps as the power rating increases. The most preferred voltages are given as a guide in Table 3.1. See also IEC60038.

3.8 TYPICAL PARAMETERS OF GENERATORS

Often at the beginning of a design project it is necessary to carry out some basic calculations and studies. For example, estimating the maximum fault current at the main generator switchboard and a preliminary stability assessment. At this stage equipment will not have been fully specified and so definitive data are not available from the chosen manufacturers. Typical data need to be used. Figures 3.5 through 3.12 show typical reactances and time constants for generators in the range 1.0 to 40 MVA drawn from a modest sample of generators. In each figure it can be seen that there is a spread of points about the average line. This is partly due to the data being taken from some generators that have had constraints placed on them for minimum fault currents and volt drops. Other generators were closer to the standard or preferred design of the manufacturer. For preliminary studies and calculations the data taken from the average (or trend) lines would give reasonable results. If worst-case situations are to be considered then a value either side of the trend line within the range

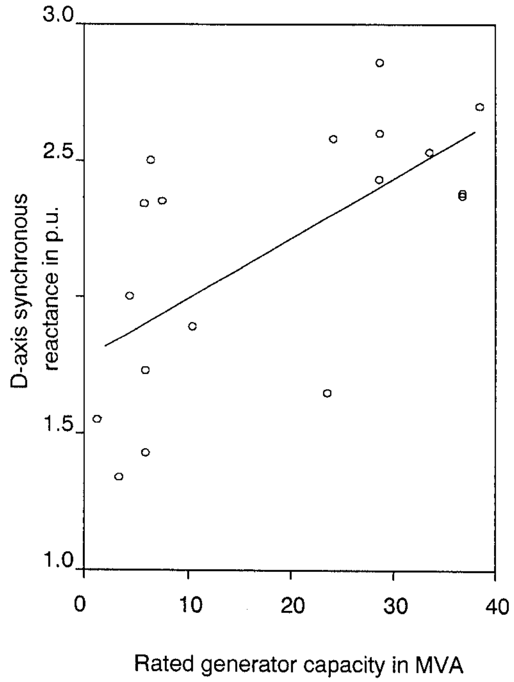

Figure 3.5 *D*-axis synchronous reactance versus generator MVA rating.

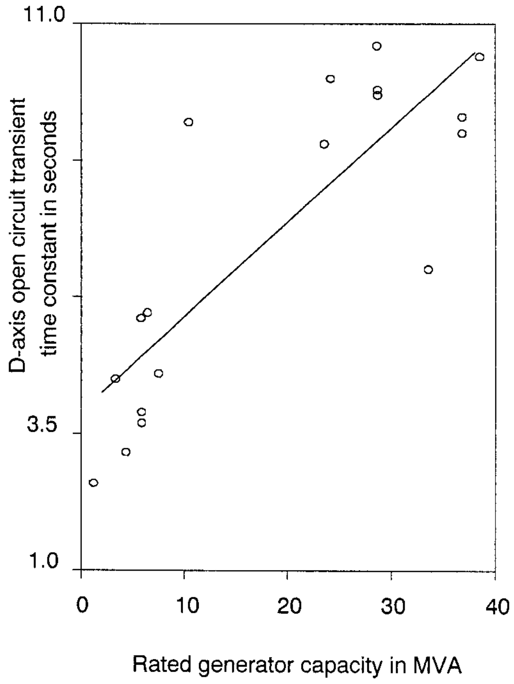

Figure 3.6 *D*-axis open circuit time constant versus generator MVA rating.

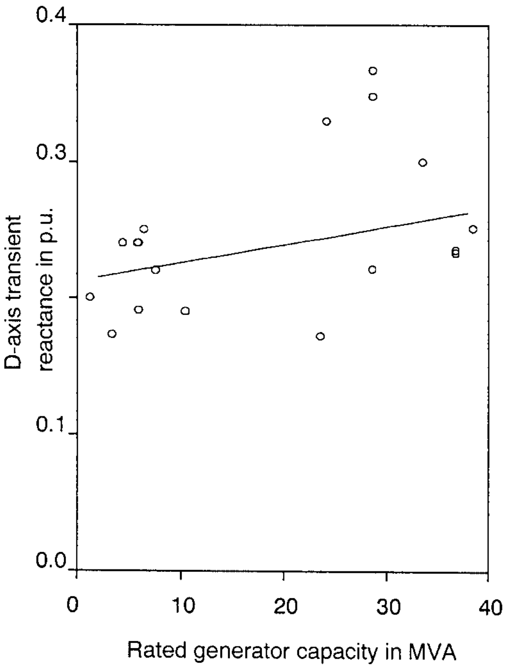

Figure 3.7 *D*-axis transient reactance versus generator MVA rating.

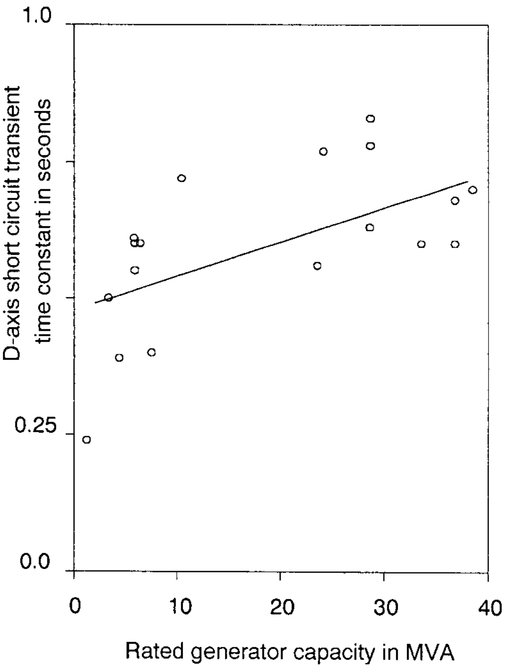

Figure 3.8 *D*-axis short circuit transient time constant versus generator MVA rating.

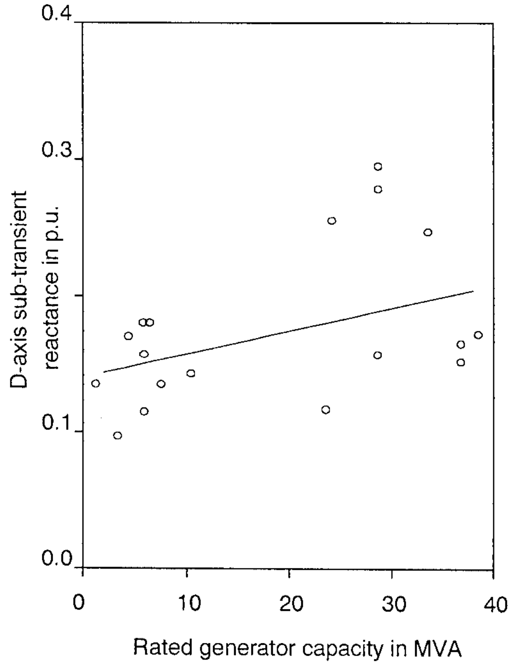

Figure 3.9 *D*-axis sub-transient reactance versus generator MVA rating.

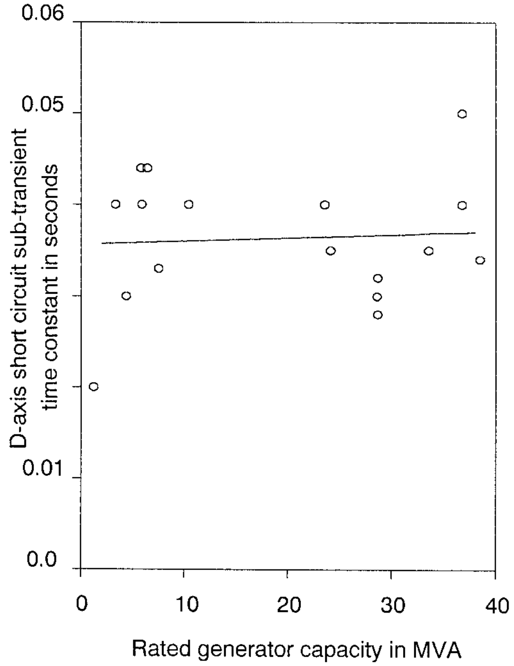

Figure 3.10 *D*-axis short circuit sub-transient time constant versus generator MVA rating.

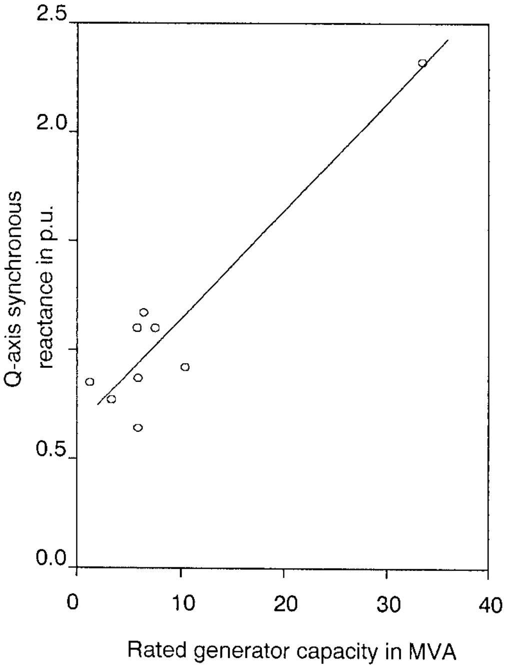

Figure 3.11 Q-axis synchronous reactance versus generator MVA rating.

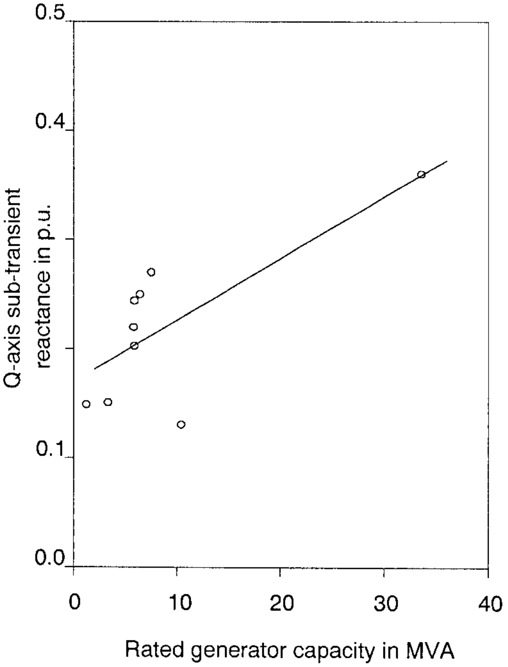

Figure 3.12 Q-axis sub-transient reactance generator MVA rating.

of the spread would also give realistic results. It should be remembered that manufacturers normally quote data with a tolerance of plus and minus 15%.

The inertia constant H for four pole machines varies from about 1.2 MW seconds/MVA for a 1 MVA generator to about 2.5 for a 40 MVA generator.

3.9 CONSTRUCTION FEATURES OF HIGH VOLTAGE GENERATORS AND INDUCTION MOTORS

From outward appearances a high voltage generator will look very similar to a high voltage motor. The first noticeable difference will be the presence of the exciter at the non-drive end of the generator. Less noticeable is the rotor. Synchronous machines will have wound rotors fed with DC current from an exciter. Induction motors will invariably have caged rotor bars and no external excitation to the rotor. (There are special designs of induction motors that have external connections to the rotor, but these are outside the scope of this book.)

3.9.1 Enclosure

The enclosure or casing of the machine needs to withstand the ingress of liquids and dust that become present at oil industry sites. For outdoor locations the environment can range from cold and stormy marine conditions to hot and dry desert conditions. In offshore locations the machines are usually, but not always, placed indoors in a room or module. This protects them from heavy rain and saltwater spray. Even inside the room or module they need to withstand firewater spray, if used, and hosing down with water. The environment in land-based plants can also be hostile and the machine needs protection against ingress from, for example, coastal weather, desert sand storms, smoke pollution.

The IEC60529 standard describes in detail the ingress protection to be achieved, see also section 10.6 herein. For indoor locations machines of megawatt ratings may be specified for IP44 or, for extra protection, IP54. Machines with ratings below approximately 2000 kW, and which are of standard 'off-the-shelf' designs, the protection may be IP54, IP55 or IP56. The cost differences may not be significant for standard machines.

Outdoor locations require a more rigorous protection and IP54 would be the minimum for the larger machines. For 'off-the-shelf' designs again IP55 or IP56 would be acceptable.

In all outdoor and indoor situations it is common practice to specify IP55 for the main and auxiliary terminal boxes.

Generators should not be located in classified hazardous areas. Whereas it is often unavoidable to locate a high voltage motor in a Zone 2 or Zone 1 hazardous area. The lower ratings of motors are generally available in at least Ex 'd' certification for use in Zone 2 and Zone 1 locations. Large motors are difficult and expensive to manufacture with Ex 'd' enclosures. It is therefore common practice to require an Ex 'n' enclosure design and purge the interior with air or nitrogen from a safe source. This design of motor would then be certified as an Ex 'p' machine. The terminal boxes for such a motor would be specified as Ex 'de' with ingress protection IP55 as a minimum. This subject is covered in more detail in Chapter 10.

3.9.2 Reactances

Where possible it is most economical to accept the design values of reactances offered by manufacturers. However, in the design of the power system as a whole certain constraints may arise. For example the plant load may be predominantly induction motors, of which a large proportion may be at high voltage. This situation will impose two main constraints:

i) A high contribution of sub-transient fault current at the inception of a major fault.

ii) Potentially high volt drop at the main switchboard if the high voltage motors are to be started 'direct-on-line'.

Constraint i) will need the sub-transient reactances of the generators to be higher than for a standard design. It may also require the starting impedance of the motors to be higher than normal in order to reduce their sub-transient currents.

Constraint ii) requires the transient reactances of the generator to be kept as small as practically possible. At the same time the starting current of the motors should be kept as low as possible, without unduly increasing their run-up time.

These two constraints counteract in the design of the generator, because the physical dimensions of items such as rotor and stator conductor slots affect the sub-transient and transient reactances differently. In general fixing one of these reactances will limit the choice available for the other.

3.9.3 Stator Windings

Modern switchgear is fast acting in the interruption of current, which happens near to a current zero. The sharp cut-off of a current which is not at zero gives rise to a high induced emf in the windings of motors. In addition to the high magnitude of the emf, its rate of rise is also high which imposes stress on the winding insulation. Earlier designs of motors that were switched by vacuum contactors suffered damage to their insulation and it became an established practice to install surge diverters on the feeder cables, either at the switchboard or in the motor terminal box. Modern motors do not suffer from this problem as much as their older designs. Improvements have been made to insulating materials and to the reduction of voltage stressing within the windings, for example as the winding coils emerge from their slots.

Modern machines are connected to power systems that often have relatively high prospective fault levels and so the generators and motors need to have their windings and terminations robustly braced to avoid movement during a major fault. General-purpose industrial machines may not be robust enough for such high fault level service.

The winding insulation temperature rise criteria are often specified to be Class F design but the performance limited to Class B. This results in a conservative design and potentially longer mean time before failure of the insulation. The class of insulation is common to several international standards e.g. IEC60085. The choice of Class B operating temperature rise will tend to slightly increase the volume of material used to build the machine. The insulating materials are often vacuum impregnated to render them resistant to the absorption of moisture, which is necessary for coastal, marine and tropical installations.

3.9.4 Terminal Boxes

Motors and generators should be provided with properly designed terminal boxes. They should be capable of withstanding a full three-phase fault without destruction and with the minimum of subsequent repair work and materials being needed. The duration of the fault would be typical of the relay or fuse protection provided in the switchboard. With a generator the limitation of damage by the corrective action of the switchgear protective devices is not as effective as for a motor. The switchgear in feed to the terminal box fault can be isolated by the relays in the circuit breaker. However, unless the exciter can be shut down or the machine brought to rest there is a possibility that the generator will feed its own fault. These events are rare but possible, and when they do occur they are very disruptive to the production from the plant.

Large high voltage machines are usually protected by differential stator current (87) relays and earth fault (51G) and (64) relays. These systems require current transformers to be fitted close to the winding terminals. It is very desirable to mount these transformers inside the main terminal box. Frequently it is necessary to have two main terminal boxes, one for the high-tension transformers and cable connections, and one for the star point transformers and NER cable connection. It is also preferable to fit the transformers in the star point ends of the windings because these are at almost zero potential for the majority of the life-time of the machine. This minimizes the problems in designing adequate space at the high-tension ends of the windings to locate these items. The usual alternative is to fit them at the switchgear end of the feeder cable or bus-ducting which also has the advantage of including these in the zone of protection.

3.9.5 Cooling Methods

The majority of motors are cooled by a simple shaft mounted fan which is attached to the non-drive end and blows air across ribs or channels in the outer surface of the enclosure. This method is satisfactory with machines rated up to about 1000 kW, thereafter a more elaborate system of air-to-air (CACA) or air-to-water (CACW) heat exchangers is necessary. In all cases the main enclosure should be totally enclosed and sealed from the surrounding atmosphere by machined faces and shaft seals. This concept is also called ‘totally enclosed fan cooled or TEFC’, where the fan referred to is generally the internal fan which circulates the enclosed air along the air gap and amongst the windings. IEC60034 Part 6 and the NEMA standard MG1 give details of motor and generator enclosures.

Externally mounted fans on the shaft or in the heat exchangers should be made of a material that cannot produce a spark if the blades happen to touch their surrounding metalwork. See also sub-section 5.1.8 for further comments on the construction of induction motors.

3.9.6 Bearings

Machines rated up to about 150 kW generally use rolling element bearings, one of which usually acts as the centralising and thrust-carrying element for the shaft. The lubricating medium is grease. Some driven machines impart a longitudinal thrust on to the shaft of motors (150 kW is also near the limit for the use of low voltage machines when direct-on-line starting is to be used). The above limit may be extended to 500 kW for high voltage machines. Above 500 kW the practice is to use sleeve bearings with or without forced lubrication. As the ratings increase the use of forced lubrication becomes necessary, and with it the need for a cooling system for the lubricant.

The rotating metal components such as the shaft itself, the rotor poles and the laminations move in space relative to the magnetic fields that are present in the air gap and in the vicinity of the stator end windings. These magnetic fields contain small levels of harmonic components due to slotting and the sharp corners of the iron circuits near the end windings. As the metal components pass through these complex field patterns they induce small levels of harmonic emfs. This subject is discussed in Reference 7 in relation to induction motors. The induced emfs are capable of driving currents around a conductive metal circuit, which can be the rotor body, the shaft, the bearing surfaces, the stator frame and enclosure. If the stationary parts of the bearings are not insulated from their housings then a low conductivity circuit is available for the induced currents, which are called 'circulating currents'. Motors and generators are usually specified to have their non-drive and bearing housing or pedestal insulated so that the presence of circulating currents is minimised. If these currents are allowed to pass across the shaft-bearing interface, then there is always a risk that some sparking will occur that will rapidly lead to serious damage to the bearing surfaces.

The insulation should not be applied only to the drive end because the driven machine will act as a short circuit across the insulation, and thereby put the bearing surfaces of the driven machine also at risk. Some purchasers specify that both bearings are insulated.

The level of induced voltage that is typically deemed acceptable is between 200 and 500 mV, measurable as the root-mean-square value when the insulation is present. Rolling element bearings cannot tolerate the higher voltage that can be accepted for sleeve bearings.

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