Abstract: The design and the performance of synchronous generators and induction motors are discussed. Two Victorian generators, a 500 MW turbo generator unit for Loy Yang A, a 150 MW hydro-generator for Dartmouth and a 1312 kW squirrel cage induction motor are used as examples. Related issues such as machine ratings, peak load duty and superconductivity are also discussed.

1. INTRODUCTION

The rotating magnetic field generated by a three phase winding fed by balanced three phase currents was an invention by Tesla in 1886 (Ref 6) of huge significance. The rotating field is the seminal principle behind the synchronous generator and the induction motor which are both vital to civilisation. The synchronous machine as a motor is also essential for large loads and, along with the induction motor, also useful for variable speed drive applications.

Some features of synchronous machines and induction machines are identical. Both machines require the same three phase winding. For both machines the number of stator slots is always a multiple of 3 and often a multiple of the pole number p. Generator conductors however are usually larger and require a Roebel conductor design and provision for water cooling. Both machines have similar magnetic cores.

But there are significant differences between the two machines. The generator rotor has a direct current field system fed by one of a variety of excitation methods whereas the induction motor has an isolated rotor circuit and the squirrel cage circuit is not even insulated.

The behaviour of an induction motor is controlled by leakage reactances whereas the behaviour of a synchronous machine is controlled by armature reaction. The synchronous machine airgap length controls armature reaction and usually the airgap length is considerable (eg. 10 cms). In an induction motor the airgap length is short (eg. 2 mm) to reduce magnetising current and improve the operating power factor.

Both machines exhibit special transient behaviour and for a synchronous generator there are a series of constants which define this behaviour, for example following a short circuit. Induction machine transient behaviour, for example, their contribution to a short circuit, is not often explored.

For a given mean flux density B and current density J the four features of a machine: output, losses, cooling and efficiency can be broadly related to airgap dimensions, diameter D and core length L. The output increases in proportion to $D^3L$ whereas the losses increase with the volume $D^2L$. Larger machines are therefore more efficient. However, cooling processes depend on heat transfer from cooling surfaces proportional to DL. Thus larger machines are more difficult to cool.
2. SYNCHRONOUS GENERATORS

The three phase synchronous machine is still the principle means to convert mechanical energy into electrical energy and throughout the world almost all electricity is generated by these machines. Turbo-generators, usually 2-pole designs running at 3000 rpm for 50 Hz systems, are the most common generators although some nuclear power station generators (abroad) run at 1500 rpm (4-pole, 50 Hz).

High speed generators have a cylindrical rotor design (Appendix A). Hydro power station generators run at a lower speed down to 100 rpm and have a characteristic salient pole rotor field system (Appendix B).

Over the past twenty years the reliability of generating plant has received prominence especially for generators rated at 500 MW and above. Typically a large European manufacturer announced to prospective customers that:

"Our greatest possible emphasis is on reliability, with a reasonable balance between the demands of minimum cost, maximum efficiency, maximum reliability and maximum availability".

Generators have a set of three phase armature windings on the stator, a field winding on the rotor and possibly a set of damper windings on the rotor as well. The field rotates at the synchronous speed corresponding to the number of pole pairs. The selected armature winding design usually gives a rated line voltage of around 20-30 kV.

For a given kVA rating the armature currents generate their own rotating magnetic field in a process called armature reaction (AR). The AR magnetic field combines with the field winding magnetic field to produce a combined synchronously rotating field. The strength of this field depends on the armature and field current magnitudes and the angle between the fields is set by the load power factor. The effect of armature reaction can be represented by an equivalent circuit series reactance $X_d$ (direct axis synchronous reactance). For a salient pole design there are two reactances $X_d$ and $X_q$ (direct and quadrature axis synchronous reactances).

3. DESIGN OF SYNCHRONOUS MACHINES

A generator is designed on the basis that voltage developed in a coil system is equal to the rate-of-change of flux linkages ($\psi$) and that including circuit losses:

$$\text{phase winding voltage} = ri + \frac{d\psi}{dt} \quad (1)$$

The current required and the cooling system used (internal or external) determines the size of the winding conductor and the temperature class of insulation also influences the current density decision.

For sinusoidal conditions the above voltage equation becomes the emf equation:

$$V = 4.44 fN\Phi_p k_w \quad (2)$$

The design variables N and $\Phi_p$ control the size of the slots and the pole area and these design decisions control the performance and design dimensions of the generator. The magnitude of the core flux density depends on slow advances in materials technology.
Winding theory is used to design the 3-phase winding for the given specification and Figure 1 shows the part slot layout in a 6-pole 3-phase generator with 60 stator slots and a fractional slot-pole-phase double layer winding.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>4</th>
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<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>..</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
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<td>R</td>
<td>W</td>
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<td>W</td>
<td>B</td>
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<td>W</td>
<td>W</td>
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<td>B</td>
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<td>B</td>
<td>R</td>
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<td>R</td>
<td>R</td>
<td>R</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>..</td>
</tr>
</tbody>
</table>

Figure 1: Double layer lap slot information for 3-phase 6-pole winding in 60 slots

The second important design factor is the magnitude of the rotating field produced by armature currents, i.e. the armature reaction effect defined as follows:

\[
F_{ar} = \frac{2.22 \cdot I_{N} \cdot k_{ar}}{p}
\]  

(3)

The rotating field mmf from the dc pole winding \( F_0 \) combines with \( F_{ar} \) to produce a resultant mmf \( F_r \) which essentially generates voltage. The mmfs are all sinusoidally distributed in space and phasors are used to obtain \( F_r \). Two examples follow. Figure 2 shows the mmf and phasor diagrams for a generator with a lagging load, Figure 3 shows a synchronous motor operation as a lagging load. Thus the relationship between the magnitude and angle of the field and armature reaction mmf's determines the nature of the machine's operating condition.

Figure 2: Field mmfs and resultant phasor diagram for generator with lagging power factor load

Figure 3: Field mmfs and resultant phasor diagram for synchronous motor with lagging power factor
The per unit synchronous reactance of the machine is defined by the ratio:

$$X_{d}(pu) = \frac{\text{mmf (AR)}}{\text{mmf (voltage)}}$$

and is inversely proportional to the airgap length.

For the synchronous machine the leakage inductance calculations are less important than they are for an induction machine (Section 7). Inductance depends on flux linkages per unit current. Inductance formulae are based on idealised flux patterns (Figure 4).

However, these are rarely realised in practice.

![Figure 4: Leakage flux patterns around stator slots](image)

The finite element process has given greater insight into the flux patterns in a machine. Figure 5 shows the magnetic conditions in a 2-pole 500 MW generator on full load.

![Figure 5: Magnetic flux conditions in a 2-pole 500 MW turbo generator on full load](image)
4. LARGE TURBO-GENERATOR EXAMPLE

4.1 Steady state performance

The essential name plate data for a typical 500 MW turbo generator is as follows:

<table>
<thead>
<tr>
<th>Loy Yang A Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 MW, 21 kV, 0.85 power factor (lagging), 588 MVA, 16200 A</td>
</tr>
<tr>
<td>Hydrogen cooled at 4 bar. Star connection.</td>
</tr>
<tr>
<td>2 pole, 3000 rpm, 50 Hz</td>
</tr>
<tr>
<td>Field current (open circuit) - 1200 A</td>
</tr>
<tr>
<td>Field current (rated load) - 4000 A</td>
</tr>
</tbody>
</table>

Table (1) 500 MW generator - Name plate information

Additional data required for power system calculations is shown in Table (2).

<table>
<thead>
<tr>
<th>X_d = 2.4 p.u.</th>
<th>X_d' = 0.26 p.u.</th>
<th>X_d'' = 0.18 p.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_2 = 0.21 p.u.</td>
<td>H = 3.4 sec</td>
<td>T_d0 = 8.6 sec</td>
</tr>
</tbody>
</table>

Note: 1 p.u. Z = 0.75 Ω

Efficiency = 98.8% at 500 MW, 0.85 power factor (lagging)

Table (2) 500 MW generator - Additional data

The simple equivalent circuit for a generator consists of a voltage source and series reactance X_d. For a generator connected to an infinite bus through an additional external reactance X_e the equivalent circuit is shown in Figure 6.

Figure 6: Cylindrical rotor generator equivalent circuit

The phasor diagram depicts the steady state behaviour at any load and gives a measure of torque angle δ and of internal voltage E_o. Saturation issues are ignored in these diagrams. A further construction which allows for saturation is based on the zero power factor characteristic and enables a more accurate estimate of the field current required for given load conditions.

The phasor diagram illustrates the phasor equation:

E_o = V + I X_d

(5)

The phasor diagram for a 500 MW generator operating at rated load, 0.85 power factor lagging is shown in Figure 7.
Figure 7: Phasor diagram in p.u. for 500 MW generator on full load

Numerical calculations of electrical power $P_e$ and torque $T$ use the relationships:

$$P_e = \frac{V E_o}{X_d} \sin \delta$$
and
$$T = P_e / \omega$$

The generator reactive power $Q$ is given by:

$$Q = \frac{V E_o \cos \delta - V^2}{X_d}$$

The phasor diagram can be converted to real and reactive power axes to provide the following performance diagram for the same 500 MW generator operating at rated load.

Figure 8: Performance diagram in p.u. for 500 MW generator showing full load operation

- $V = 1.0$
- $E_o = 3.1$
- $I X_d = 2.4$
- $\delta = 42^\circ$
- $\phi = 32^\circ$

- $P = 0.85$
- $Q = 0.53$
- $X_d = 2.40$
- $\delta = 42^\circ$
- $\phi = 32^\circ$
The performance diagram can conveniently include limits of performance to guide the staff when operating the generator at other than rated load. The limits are as follows:

- Stator MVA limit: heating, stator insulation temperature (Reference [4])
- Rotor field limit: heating, rotor temperature
- Stability limit: torque angle ∆, instability
- Turbine limit: shaft power
- Boiler limit: boiler operation - instability

Figure 9 shows these limits on the 500 MW generator performance diagram.

Figure 9  Performance diagram for 500 MW generator showing operational limits of performance

The manufacturer's performance diagram for the generator with the data set out in Tables (1) and (2) (or as named, reactive capability chart) is given in Figure 10.
LOY YANG POWER: REACTIVE CAPABILITY CURVE

Figure 10: Manufacturer's reactive capability chart for 500 MW generator

4.2 Transient and unbalanced behaviour

In the transient or unbalanced state, the behaviour of the generator can be predicted by calculations based on the following machine parameters.

- Transient and subtransient reactances \( -X_d' \) and \( X_d'' \).
- Transient and subtransient time constants \( -T_d' \) and \( T_d'' \).
- Sequence impedances for unbalanced calculations \( -Z_1, Z_2, Z_0 \).
- Dynamic constants, inertia (H) and damping coefficient (Kd).

From these constants, a range of calculations can be carried out, including:

- Unbalanced loading and the negative sequence limit on the rotor field
- Fault studies, 3-phase, 2-phase, 1-phase, 2-phase-to-ground faults
- Swing calculations, dynamic response, peak currents and torques
- Sudden loss of load characteristics
- Asynchronous-behaviour requiring additional induction-machine-type-information for rotor behaviour at given slip

The sudden three phase short circuit is a test required by most customers to determine sub-transient and transient parameters. A test oscillogram is given in Appendix C.
The first 500 MW sets were commissioned in the UK in 1965 and 660 MW units became standard from about 1974. The introduction of water cooled stator windings earlier in 1956 made these large outputs possible (Appendix D). Many large 4-pole generator units were built in the 70’s for US power stations but these have not become standard sets. There had been moves to build sets rated beyond 660 MW up to 900 MW. Russia has 2-pole generators rated at 1200 MW. The size of the power system has to be considered before a decision can be taken on the upper rating magnitude of a standard set. Table (3) shows the cooling methods for generators with various ratings.

<table>
<thead>
<tr>
<th>Type</th>
<th>Ratings [MVA]</th>
<th>Type of cooling</th>
<th>Rev/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stator winding</td>
<td>Rotor winding</td>
</tr>
<tr>
<td>50 WT20H</td>
<td>to 350</td>
<td>H₂ indirect</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT20H</td>
<td>to 350</td>
<td>H₂ indirect</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>50 WT22H</td>
<td>to 400</td>
<td>H₂ indirect</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT22H</td>
<td>to 450</td>
<td>H₂ indirect</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>50 WT21E</td>
<td>200-600</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT21E</td>
<td>200-700</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>50 WT23E</td>
<td>400-950</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT23E</td>
<td>500-1050</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>50 WT25E</td>
<td>950-1300</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT23D</td>
<td>1050-1300</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>50 WT35S</td>
<td>800-1100</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
<tr>
<td>60 WT35S</td>
<td>800-1500</td>
<td>H₂O direct</td>
<td>H₂ direct</td>
</tr>
</tbody>
</table>

Table (3) Cooling methods for turbo generators

(Reference [8]: ABB Review 1/89 - Design features of large turbo generators)

In recent years there have been moves away from the large generator ratings. Gas turbines with smaller rating are becoming increasingly used because of their short delivery time, their special role in supplying peaking power on top of a given base load and their use in combined cycle systems. These systems have a much higher overall efficiency, raising the efficiency from near 40% to over 60%. Also, generators for small power systems have a lower rating.

There has been considerable discussion recently about returning to completely air cooled generators which have non water cooled armature windings and which are simpler and cheaper to manufacture. The operating efficiency of these new generators is lower than that for H₂ cooled sets by from between 0.3 and 0.5%. Completely air cooled sets up to 300 MVA are being manufactured. The armature windings are not water cooled.

Comparing a H₂/H₂O cooled generator (Reference [4]) with an air cooled generator at say 220 MVA (Reference [5]), for the air cooled generator:

- Rotor diameter increases
- Core length increases
- Design current densities are lower
- Overall efficiency is about 0.5% lower

4.4 Generators for peak load duty

Generators which operate essentially at constant load for long periods are likely to be less stressed than generators which run up once or twice a day to supply peak loads on the system (Reference [7]).
The additional mechanical and thermal fatigue on the generator components can affect the plant reliability (Table (4)). In converting a base-load machine to peak load service a number of components in the rotor, stator and exciter would need to be examined and possibly replaced.

<table>
<thead>
<tr>
<th>Components</th>
<th>Stresses</th>
<th>Mechanical: start/stop</th>
<th>Thermal: load cycling start/stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>Winding</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Cu and insulation)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>End-winding support</td>
<td></td>
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<tr>
<td></td>
<td>Bar support in slot</td>
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<tr>
<td></td>
<td>Core and pressplates</td>
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<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>Body and shaft ends</td>
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<td></td>
<td>Teeth, wedges,</td>
<td></td>
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<tr>
<td></td>
<td>Winding</td>
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<td></td>
<td>(Cu and insulation)</td>
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<tr>
<td></td>
<td>Winding leads and</td>
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<td></td>
<td>lead-in studs</td>
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<tr>
<td></td>
<td>Retaining rings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sliprings and brushes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>Stator cooling-water</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>system</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Sealing-oil system</td>
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<td></td>
<td>Gas plant</td>
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<td></td>
</tr>
</tbody>
</table>

Table (4) Additional stresses on individual turbo generator components due to load cycling and start/stop operation

(Reference [7]: ABB Review 2/89 - Converting large base-load turbo generators for peak-load duty)

5. LARGE SALIENT POLE HYDRO-GENERATOR EXAMPLE

Salient pole generators are used for all low speed, multi-pole designs and are also used for small diesel sets (generators 4-pole or greater). These generators are widely used in industry for example as standby plant and for remote private power stations. The salient pole construction is cheaper than the cylindrical rotor construction, required only for high speed 2-pole and 4-pole rotors. The theory for a salient pole generator is more complicated because there are two reactances $X_d$ and $X_q$ which are required to predict the generator's performance. For a cylindrical rotor generator $X_d = X_q$ while for a typical salient pole machine $X_d \approx 2 X_q$.

The phasor diagram, power-torque equation and performance diagram are given for the salient pole generator defined by the following data.

<table>
<thead>
<tr>
<th>Dartmouth Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 MW, 15.5 kV, 0.9 power factor (lagging), 167 MVA, 6200 A</td>
</tr>
<tr>
<td>Air cooled, star connected, Class F (epoxy mica)</td>
</tr>
<tr>
<td>28 pole, 214.2 rpm, 50 Hz</td>
</tr>
<tr>
<td>Field current (open circuit) - 586 A</td>
</tr>
<tr>
<td>Field current (rated load) - 1324 A</td>
</tr>
</tbody>
</table>

Table (5) 150 MW salient pole generator - Name plate information
Table (6) 150 MW salient pole generator - Additional data

The phasor diagram at full rated load is as follows:

\[ I_d = 0.82 \quad X_d = 1.58 \]
\[ I_q = 0.58 \quad X_q = 0.84 \]
\[ E_o = 2.17 \]
\[ \delta = 29^\circ \]
\[ \phi = 26^\circ \]

Figure 11: Phasor diagram in p.u. for 150 MW generator on full load

The power \((P_e)\) and torque \((T)\) formulae are as follows:

\[ P_e = \frac{V E_o}{X_d} \sin \delta + \frac{V^2(X_d - X_q)}{2 X_d X_q} \sin 2\delta \quad (8) \]

\[ T = \frac{P_e}{\omega} \quad (9) \]

\[ Q = \frac{V E_o \cos \delta}{X_d} - \frac{V^2(X_d \sin^2 \delta + X_q \cos^2 \delta)}{X_d X_q} \quad (10) \]
At full load it can be calculated that:

For $V = 1$ p.u. $I = \text{p.u.}$ Power factor angle $\phi = 25.8^\circ$

Torque angle $\delta = 29^\circ$ $I_d = 0.82$ p.u. $I_q = 0.58$ p.u.

Internal voltage $E_o = 2.17$ p.u.

Power $P = 0.9$ p.u. Reactive Power $Q = 0.44$ p.u.

The performance diagram at full load is given in Figure 12.

![Performance diagram](image)

Figure 12: Performance diagram in p.u. for 150 MW generator showing full load operation

The manufacturer's performance diagram is given in Figure 13.
6. SUPERCONDUCTING GENERATORS

The use of Nb-Ti wire at liquid helium temperature as a super conductor (SC) is now well established. The S-C generator has a rotor wound with Nb-Ti wire and contained within a liquid helium environment. If the technical difficulties of maintaining a high vacuum between the rotor and the stator as well as supplying liquid helium to the rotating member can be resolved over an extended period, a commercially available S-C generator would be smaller, lighter and 1% more efficient (99.5% instead of 98.5%) than a conventional generator. Also the natural reactance of the S-C generator is lower than the conventional generator. A S-C generator will have $X_q \approx 0.4$ p.u., airgap flux density = 5-6 Tesla and a $T_{do'} \approx 20,000$ sec ($T_{do'}$ = field inductance + field resistance).

Figure 14 shows the cross section of a S-C generator which would typically have its volume 40% of the volume of a conventional generator with the same rating. The overall losses at rated load are about 40% of the conventional generator because of zero rotor loss and low windage and load loss.
Figure 14: Cross section of generator with S-C rotor field winding

There have been several attempts to build a commercial S-C generator but these projects have lost support during recent years. However, a consortium of seven Japanese electrical manufacturers led by Super-GM, is currently working on a 70 MW S-C generator as a demonstration unit (Reference [1]).

The 3-phase, 10 kV, 0.9 power factor, 2-pole, 60 Hz, 3600 rpm generator has a stator which has an airgap winding, is water cooled and an $X_d = 0.4$ p.u.. Three experimental rotors are being constructed for the single stator, each with a different design and response time. The generator is due for completion in 1997.

7. **INTRODUCTION TO INDUCTION MOTORS**

The induction motor remains the outstanding electrical machine for normal loads and for drives. The theory of induction machines is familiar and the torque-slip, current-slip characteristics set the profile of the motor. The following torque-slip equation is a reminder of the theory.

\[
\text{Torque} = \frac{3V^2 r_2/s}{\omega_s \left[ r_1 + \frac{cr_2}{s} \right]^2 + (X_1 + cX_2)^2} \quad (11)
\]

The motor's behaviour at starting direct-on-line is particularly important because of the effect of current peaks on system voltage (voltage dips) and of the effect of excessive transient torque on the rotor conductors and on the load.
The fixed frequency asynchronous speed machine still has an important role but the converter fed, variable speed (constant V/f) induction motor has become increasingly important for medium output applications.

In purchasing an induction motor, the following are key issues:

Variation of current, torque, efficiency and power factor with slip.
Direct-on-line (DOL) starting behaviour - peak transient current and torque and locked rotor current. A starting current oscillogram should be supplied (Figure 15).
• Compliance with specified Standard.
• Insulation system used in the stator winding setting the temperature rise.
• Ventilation system used and its compatibility with the motor's required operating environment.
Rotor bar and endring assembly construction. This is the most vulnerable part of a squirrel cage machine, especially if the machine is subjected to frequent starts (Figure 17).
Noise level from fans, ventilation air and ventilating ducts.
Bearing vibration levels.
Servicing specification.
For variable speed applications the behaviour changes of the machine (efficiency, vibration, current) are important as discussed below.

![Figure 15 Line current during DOL starting of large induction motor](image)

For drive applications the induction motor is fed by a non-sinusoidal set of voltages as determined by the nature of the converter (PWM, 6-pulse or 12-pulse). The motor performance is not affected, apart from a small decrease in efficiency and a possible increase of operating noise. Operating current waveforms become non sinusoidal as illustrated for a 6-pulse converter (Figure 16).
Figure 16: Induction motor current with square wave voltage source

Figure 17: Typical cage-end crack in induction motor rotor

8. INDUCTION MOTOR DESIGN

In a similar way to a synchronous machine the dimensions of an induction machine are characterised by the airgap diameter D and its length L. The familiar output equation which relates the motor kVA to these dimensions and to electric and magnetic loading factors, $\bar{ac}$ and $B_m$ is as follows for a machine operating at speed $N$:

$$kVA = k_1 D^2LN \cdot \bar{ac} \cdot B_m$$  

(12)
Inductor motors have evolved by operating at a higher temperatures (increased \( \Delta T \)) or with higher performance core steel (increased \( B_m \)) giving a higher \( \text{kW/kgm} \) ratio. Some key design issues are now discussed.

### 8.1 Magnetic circuit

The finite element process enables designers to know more about the distribution of flux density throughout the magnetic circuit. The slot and tooth design can, for example, be adjusted with more certainty. Figure 18 shows the results of a finite element study on an induction motor design to examine leakage flux and leakage reactance.

![Figure 18: Flux conditions in 4-pole induction motor on load showing leakage flux paths](image)

### 8.2 Airgap length

The airgap length is a critical decision because it should be kept short to reduce magnetising current and to increase power factor. On the other hand a short airgap will increase the risk of rotor radial movement, known as "unbalanced magnetic pull", and the risk of magnetic noise.

### 8.3 Slot design

The choice of stator slots \( S \) links with the standard theory of stator winding design. The number of rotor slots \( R \) is selected in relationship with \( S \) for a \( p \)-pole machine as follows:

\[
R = S \pm k_1 p + k_2
\]  \hspace{1cm} (13)

The value of \( R \) selected controls the properties:

- at starting, at rated load, core loss, noise and reactance

For example, an induction motor with \( R = S \) will not start and will be excessively noisy.
Total leakage reactance

The combined stator: rotor leakage reactance $X_t = X_1 + cX_2'$ controls the performance of the induction motor. The per unit value is related to fundamental design parameters defined earlier as follows:

$$X_t(\text{pu}) = k \frac{ac}{B_m} \frac{p^p}{L}$$  \hspace{1cm} (14)

$P$ is the leakage path permeance.

Squirrel cage design

The squirrel cage controls the effective value of rotor resistance $R_2$ which, unlike stator resistance $R_1$, is also a fundamental performance parameter. The depth and shape of the rotor bar controls the value of $R_2$ and $X_2$ over the operating frequency range $0 < f < 50$ Hz.

9. INDUCTION MOTOR EXAMPLE

A 3-phase, 6-pole, 6600 V, 1312 kW, 50 Hz squirrel cage induction motor has the following characteristics at rated load.

- Rated current: 133 A
- Rated power factor: 0.91
- Rated efficiency: 95%
- Rated speed: 995 rpm
- Rated slip: 0.005
- Airgap length: 2 mm
- Temperature rise: 60°C

The torque-speed characteristic (Figure 19) shows that:

- Maximum torque = 2.3 p.u.
- Starting torque = 0.5 p.u.

For a direct-on-line start the peak starting current is 680 A (5 p.u.) and the locked rotor current is 620 A.

Also from the locked rotor test the total leakage reactance:

$$X_t = X_1 + X_2' \approx 0.2 \text{ p.u.}$$
Figure 19: Torque speed characteristic for 1312 kW induction motor

The above information is sufficient for most applications. The manufacturer would have both design and measured values of the equivalent circuit constants from which greater detail of performance can be accurately calculated.

The torque-speed characteristic is linear at rated load. This characteristic shows that the slip at full load is small (therefore rotor resistance is low) and that the starting torque (also low) shows little evidence of deep bar effects. From the inertia of the load and the rotor, the run-up time can be calculated.

10. INDUCTION GENERATORS

If an induction machine is driven at a speed higher than synchronous speed, i.e., the slip s becomes negative, the machine becomes a generator. As the generating load increases, the slip increases perhaps to -0.05 at generator full load. Induction generators are therefore asynchronous. The generators must be connected to a power system which will supply the machine with the necessary reactive power.

Induction generators have become important because they are the dominating generator used for wind systems. For example, a 750 kW wind generator will usually have a conventional 750 kW squirrel cage induction generator connected to the blade system through a gear box. Other than for wind generation applications, induction generators are rare.
CONCLUSIONS

The developments of generators and motors have moved slowly over the years because of their size and the high cost of possible failure. There has been evolving progress with insulating materials, excitation methods stemming from the invention of the PN diode and SCR, improvements in electrical and mechanical component steels. The stator water cooling innovation in 1956 lead to the development of high output generators.

The synchronous generator remains the overwhelming choice for generating electricity although there has been a move away from large rated generators to smaller rated generators. The low overall efficiency of the turbo generator which is near 40%, is a problem being overcome by the development of combined gas fuelled, heat and power units with overall efficiencies near 60% and with combined gas turbine, steam turbine and heat units with overall efficiencies near 80%. Even though the synchronous generator was invented in 1886 and its steady state and transient behaviour have long been understood, there is still no serious generating alternative available. The problems caused by hydrogen leakage and conductor water leakage, particularly in generator mid life, have lead to a new series of air cooled generator designs with anticipated higher reliability.

South and East Australia is moving to a national grid system with generator owners bidding for generation opportunities. The market gives the impression of a need for a flexible mix of generators rather than base-load generation linked to the vertically integrated electricity companies that are now being disaggregated. The bulk of Australia's large generators are built for continuous operation with infrequent starts. It would seem that to give these generators a base-load future will require ranging market bids to ensure the constant load profile that gives the generators their present high reliability.

Induction motors have replaced direct current motors for most variable speed applications and, along with their continued role in near fixed speed applications, induction motors are dominant for drive applications below 5 MW. Difficulties with maintaining a uniform airgap in larger induction motors have meant that synchronous motors are used for large rating applications (> 10 MW) either as fixed speed or as variable speed when used with a converter bridge.

REFERENCES


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Appendix B  4-pole salient pole rotor and rotating diode bridge rectifier assembly (ABB)
Appendix C  Sudden short circuit oscillogram for 2470 kVA exciter (AEI)
Appendix D  Conductor water cooling for 500 MW generator (AEI)