GENERATOR SELECTION

CONTENTS

The aim of Section 4 is to prepare the reader for self selection of a.c. generators. The principles involved and some of the design limitations are given. An approach to self selection of "STAMFORD" machines is adopted by considering in turn electrical aspects of the a.c. generator, environmental conditions, specific load situations and some mechanical parameters. Application reports end the section.

Further considerations on earlier Sections taken from independent published papers, seminars, etc.

SECTIONAL DRAWING
TWO BEARING WITH PMG

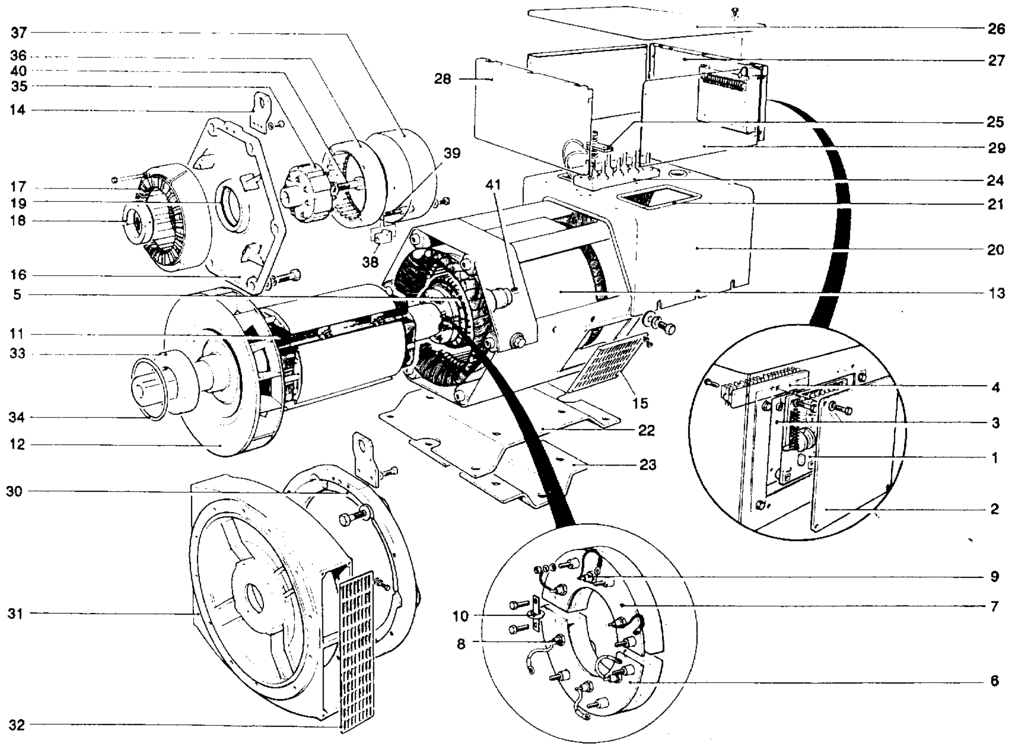


Plate Ref	Description	Plate Ref	Description
1	AVR	25	Terminal Link
2	AVR cover plate	26	Terminal Box Lid
3	AVR mounting bracket	27	End Panel NDE
4	Auxiliary Terminal Panel Assy	28	End Panel DE
5	Exciter Rotor Assy	29	Side Panel
6	Rectifier Assy Forward	30	Adaptor Ring DE
7	Rectifier Assy Reverse	31	Endbracket DE
8	Diode Forward Polarity	32	Screen DE
9	Diode Reverse Polarity	33	Bearing DE
10	Varistor	34	Waved Washer
11	Pressed Rotor Assy	35	PMG rotor
12	Fan	36	PMG Stator
13	Stator/Bar Assy (Wound)	37	PMG Cover
14	Lifting Bracket	38	PMG Clamp
15	Frame Inlet Louvre	39	PMG Pillar
16	Endbracket NDE	40	PMG Bolt
17	Exciter Stator Assy (Wound)		PMG Harness (Not illustrated)
18	Bearing NDE	41	PMG Dowel
19	Bearing O Ring		Droop CT (Not illustrated)
20	Saddle		
21	Frame Grommet		
22	Coupling Bolt		
23	Centre Foot		
24	Main Terminal Panel		

NDE - Non Drive End   DE - Drive End

SECTION DRAWING
SINGLE BEARING WITHOUT PMG

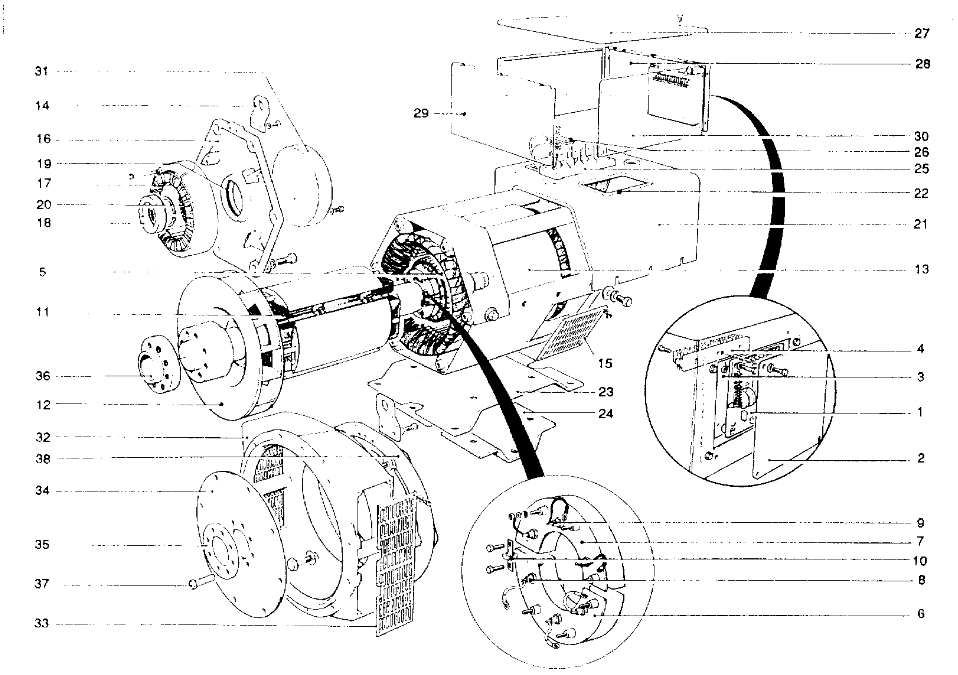


Plate Ref	Description	Plate Ref	Description
1	AVR	19	Bearing O Ring
2	AVR Cover Plate	20	Circlip NDE
3	AVR Mouting Bracket	21	Saddle
4	Auxiliary Terminal Panel Assy	22	Frame Grommet
5	Exciter Rotor Assy	23	Standard Foot
6	Rectifier Assy Forward	24	Centre Foot
7	Rectifier Assy Reverse	25	Main Terminal Panel
8	Diode Forward Polarity	26	Terminal Link
9	Diode Reverse Polarity	27	Terminal Box Lid
10	Varistor	28	End Panel NDE
11	Pressed Rotor Assembly	29	End Panel DE
12	Fan	30	Side Panel
13	Stator Bar Assembly	31	Cover NDE
14	Lifting Bracket	32	End Bracket/SAE Adaptor DE
15	Frame Inlet Louvre	33	Screen DE
16	Endbracket NDE	34	Coupling Disc
17	Exciter Stator Assembly	35	Coupling Pressure Plate
18	Bearing NDE	36	Coupling Spacer
		37	Coupling Bolt
		38	Adaptor Ring DE

NDE - Non Drive End   DE - Drive End

TERMINOLOGY

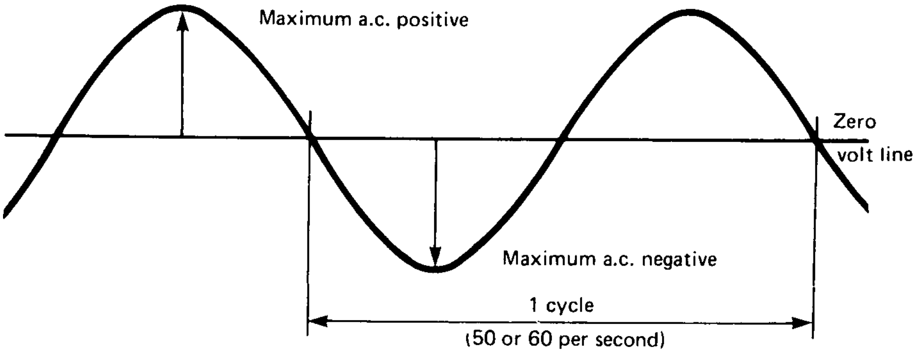
INTRODUCTION

Below is an alphabetically arranged list of terms frequently used in a.c. generator works. A brief definition of each term is given. This is sometimes supplemented by an in depth explanation with any diagrams and formulae for those readers wishing to know more than is given by the basic definition.

The words in ***italics*** are those terms explained in this list.

Terms not listed here will be explained as they are introduced through the manual.

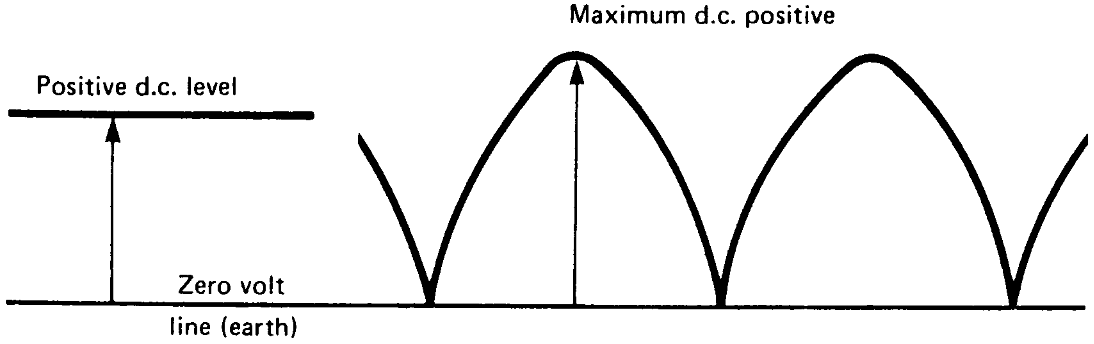
TERMS

a.c.	Alternating current. Both ***voltage*** and ***current*** vary in ***polarity*** at a pre-determined and fixed ***frequency*** - 50Hz in the U.K., 60Hz in the USA. Note: Hz = Hertz = cycles per second. Diagrammatically, a sine wave a.c. supply is shown below.  As can be seen, polarity changes every cycle, so in an a.c. system correct polarity need not be observed. Any waveform shape is considered a.c. providing it changes polarity and repeats itself every cycle. Examples can be square wave, sawtooth wave, sine wave with a large harmonic content as well as the pure sine wave shown. In a.c. power systems it is always the sine wave that is required.
A.C. Generator	Also called "Alternator". Provides electrical ***power*** output from the input of mechanical power; usually at a fixed ***voltage*** and ***frequency***. It comprises a static part and a rotating part which needs to be driven by the ***prime move***. It is usually surrounded by a metal frame and the main materials used are copper wire (for the electrical windings) and lamination steel (for the ***magnetic field*** (circuit).
Armature	Conventionally held to be the main output winding of an ***a.c. generator*** which incorporates a static ***magnetic field*** system and a rotating main output winding. These designs always have sliprings and brushgear in order to transfer the electrical output ***power*** from the main rotating winding to the external circuits.
Automatic Voltage	An electronic unit which maintains the main machine output ***voltage*** at a fixed pre-set level irrespective of load or speed changes. It does this by comparing a reference or set voltage with the actual output voltage and automatically adjusting the ***excitation*** level as necessary. This is a ***closed loop*** voltage control system. This unit is sometimes called voltage control unit or VCU.
Brushless	A design of ***a.c. generator*** without sliprings or brushgear. This design needs a static main output winding with a rotating ***magnetic field*** system. If the magnetic field is to be produced electrically an ***exciter*** is required.

Closed Loop This defines a particular class of control system. In ***a.c. generator*** work it is referred particularly to ***voltage*** control. A closed loop system is one in which the system output is continually monitored and compared with the set requirement. The system input is then automatically and continuously corrected to ensure that no difference occurs between the actual system output and the set requirements. The ***voltage control unit*** performs this function in the a.c. generator. The alternative class of control system is called the ***open loop*** system.

Current The output current (or electrical flow) is determined by the nature of the applied load only. Before current can flow a load must be applied to the ***a.c. generator***. Current is measured in 'amperes', abbreviation 'A'. See also ***kVA***.

d.c. Direct current. Both ***voltage*** and ***current*** are fixed ***polarity*** in d.c. systems. Positive and negative terminals need to be marked and in any wiring correct polarity is observed. ***Magnetic field*** systems which are electrically produced require a d.c. supply. Two examples of a d.c. supply are diagrammatically shown below.



(a) Battery

(b) a.c. supply, full wave rectified

Efficiency The efficiency of any machine or process is a ratio of the amount of useful output energy against the required amount of input energy, usually expressed as a percentage.

In the case of an ***a.c. generator*** the output is easily derived as the ***power*** (kW) figure from the standard output lists. The input is normally derived by summation of the output plus the machine losses. There are a number of machine losses which can be either calculated or measured.

windage and friction loss
iron loss
copper loss
stray loss
excitation loss

From this it follows that the input power required from the ***prime mover*** is higher than the electrical output power of the a.c. generator by an amount corresponding to the machine losses, the actual factor being given by the efficiency figure.

As the machine size increases, so efficiency improves. At 5kW output, typical efficiency figures are about 80% whereas at 500kW output, typically efficiency figures are about 93%.

Exitation An ***a.c. generator*** usually on the same shaft as the main machine. All the electrical ***power*** output produced by the exciter is ***rectified*** and used to establish the ***magnetic field*** of the main machine.

Field See ***Magnetic Field***.

Frequency

The frequency of the ***voltage*** from an ***a.c. generator*** depends on the driven speed and the number of ***magnetic field*** poles, thus:-

$$\text{Frequency (Hz)} = \frac{\text{Speed (rev/min)} \times \text{Poles}}{120}$$

Note: HZ = Hertz = cycles per second (see a.c.)

Therefore for standard frequencies, the most common combinations of speed and poles are given below:-

50 Hz	3000 rev/min	2 pole
60 Hz	3600 rev/min	2 pole
50 Hz	1500 rev/min	4 pole
60 Hz	1800 rev/min	4 pole
50 Hz	1000 rev/min	6 pole
60 Hz	1200 rev/min	6 pole

h.p.

Horsepower, a measure of the rate of doing work, use by primer mover manufacturers, but now being replaced by the S.I. unit, kW - see ***power***. A ‘metric horsepower’ C.V. (cheval vapeur) or PS (pferdestarke) is common in Europe. The relationships are:

1 h.p. = 0.746kW = 33,000 ft lb/min
1 C.V. or PS = 0.735kW

kVA

This unit is always the product of ***voltage*** and ***current*** in ***single phase*** a.c. systems. In the ***three phase*** case an extra constant is involved ($\sqrt{3}$). It is the normal way of quoting a rating for any ***a.c. generator***. It is independent of ***power factor*** and is only used when considering ***a c systems***. It is also normal to specify a kVA level at specific power factortherefore defining the level of real ***power*** capability of the machine and its ***primer mover***:-

i.e. kW = kVA x power factor
= real power capability

This specific power factor is conventionally considered to be 0.8 p.f. lagging, although in practical installations power factors of nearer 0.9 p.f. lagging are usually measured. As systems get smaller, power factors approaching 0.95 p.f. lagging are obtainable in practice. Since quite large outputs are obtained from a.c. generators it is conventional to divide the product of voltage and current by one thousand to obtain the unit kVA.

i.e. 1kVA = 1000VA

In single phase systems kVA $= \dfrac{V_{\text{phase}} \times I_{\text{phase}}}{1000}$

In three phase systems kVA $= \dfrac{\sqrt{3}\, V_{\text{line}}\, I_{\text{line}}}{1000}$

$= \dfrac{3\, V_{\text{phase}}\, I_{\text{phase}}}{1000}$

where $\sqrt{3} = 1.732$

kW

See ***power***.

Magnetic Field

A force set up around a magnet. The best known magnetic field is that of the earth, established by the North and South magnetic poles.

The existence of a strong magnetic field is a pre-requisite of an ***a.c. generator***. The magnetic field can be produced by using a ***permanent magnet*** material or by electrical methods. A d.c. supply is necessary for setting up a magnetic field electrically, commonly called an ***excitation*** supply. The magnetic field strength can be varied by varying the d.c. excitation supply. The number of magnetic field poles must be multiple of 2, as each ‘magnet’ comprises a North pole and a South pole. The most common poleages for a.c. generators are 2 pole, 4 pole or 6 pole. See also ***Frequency***.

Nominal

A range of operating conditions or values within which the machine can be safely and successfully run. See also ***Rating***.

Open Loop This defines a particular class of control system. In ***a.c***. ***generator*** work it is referred particularly to ***voltage*** control. Once an open loop system has been set up its performance cannot be automatically adjusted during operating. There is no check on the output and no continuous correction of the input. The alternative class of control system is called a ***closed loop*** system.

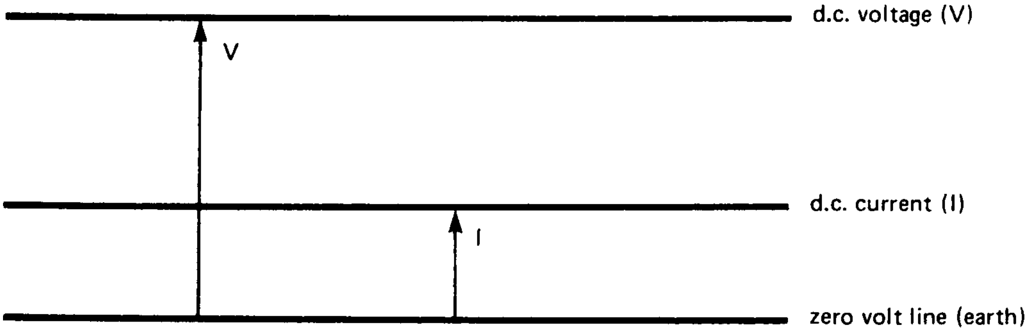
Permanent Magnet A magnetic material which once magnetised, retains its magnetic properties. This can be used as the ***magnetic field*** of an ***a.c. generator***, the most common application being the permanent magnet ***exciter***.

Polarity This term can be applied to d.c. supplies or to ***magnetic fields***. For a d.c. supply the polarity is either positive or negative. In ***a.c***. work the polarity changes every cycle. In a magnetic field the polarity is either North or South. There may be any number of magnetic poles providing the number of Norths and Souths are identical.

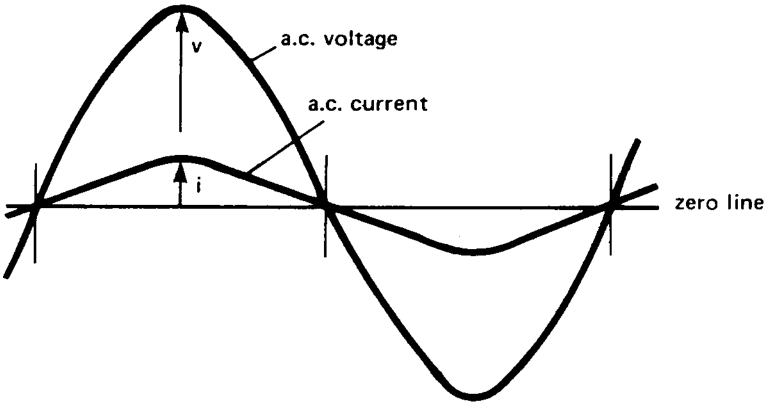
Poles See ***Magnetic field; Polarity***.

Power This is defined as the rate at which work is done. The mechanical ***prime mover*** power input to an ***a.c. generator*** shaft must be enough to sustain the nominal speed throughout all conditions of ***excitation*** power and machine losses. See also ***kVA*** and ***Power Factor***. Below is a detailed description of electrical power.

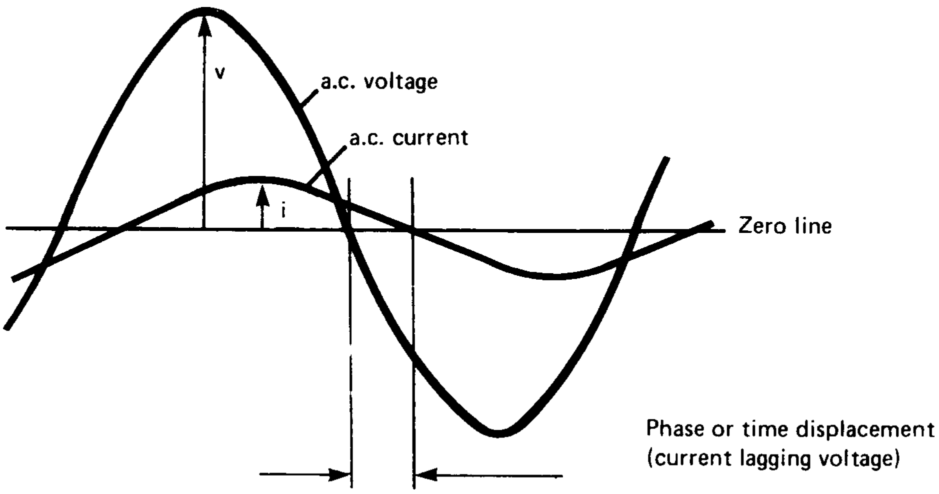
In a d.c. circuit, the power in watts is the product of ***voltage*** and ***current***, i.e. W = V x I.
A diagram of d.c. voltage and current is shown below:-



In an a.c. circuit, the real power in watts is not necessarily the product of voltage and current due to the effect of power factor, i.e. W = V x I x p.f. This is best explained diagrammatically.



In this picture the current and voltage peaks and zeros coincide. They occur at the same instant in time. This is the only case when voltage and current are said to be “in phase!” and where the power factor is unit; 1.0 In other words. It is the only case, in a.c. work, when power is the product of voltage and current, i.e. W = V x I.



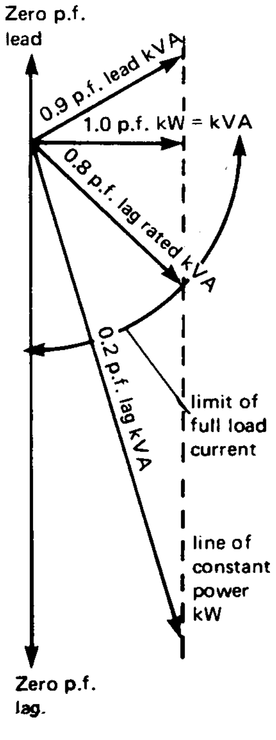
In this case the load applied causes the current waveform to lag behind the voltage waveform by a constant amount, i.e., the voltage peaks and zeros occur at constant time before the current peaks and zeros.

This is the normal situation in a.c. work where a phase or time difference exists between the voltage and current waveforms. The instantaneous real power in watts is always the voltage-current product for that instant in time. Since voltage and current are no longer in phase, the summation of all of the instantaneous powers over one cycle will be less than the summation for the in-phase case.

Hence the power factor figure will reduce from 1.0 to a figure proportional to the amount of phase or time displacement. Consequently, as the phase difference between the voltage and current waveforms increases, the power factor figure will reduce, as will the real power output figure.

Since quite large powers are obtained the unit kW is preferred to the watt (W) where 1000W = 1kW.

Power Factor (p.f)



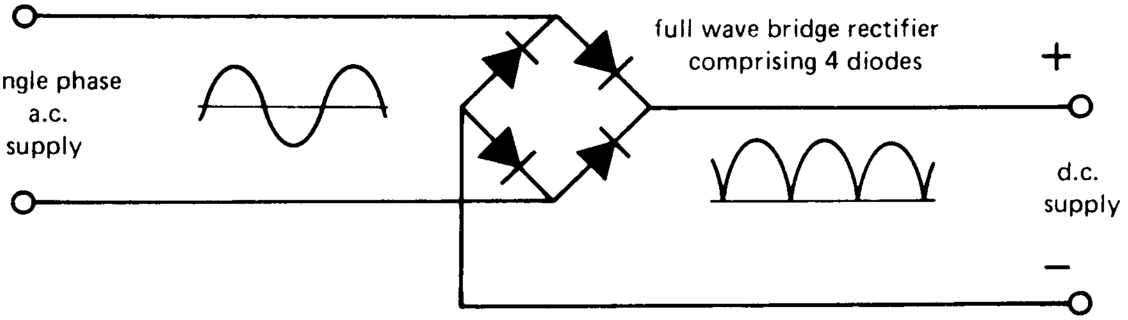
The nature of the load in an ***a.c***. circuit will determine if the ***current*** drawn is in phase or out of phase with the generated ***voltage***. The load again determines if that current waveform 'leads' the voltage waveform or 'lags' the voltage waveform. For normal industrial loads (e.g. motors) the current will lag the voltage by some time interval or phase angle. See also ***kVA*** and ***Power***.

The optimum situation is where current and voltage are in phase. This makes the power factor unity (1.0) and hence the real power (kW) the same as the product of voltage and current (kVA). Conventionally, ***a.c. generator*** work considers a lagging power factor of 0.8. In this case the current will lag the voltage by an amount which causes the real power level supplied (kw) to fall below the kVA level by a factor of 0.8 times.

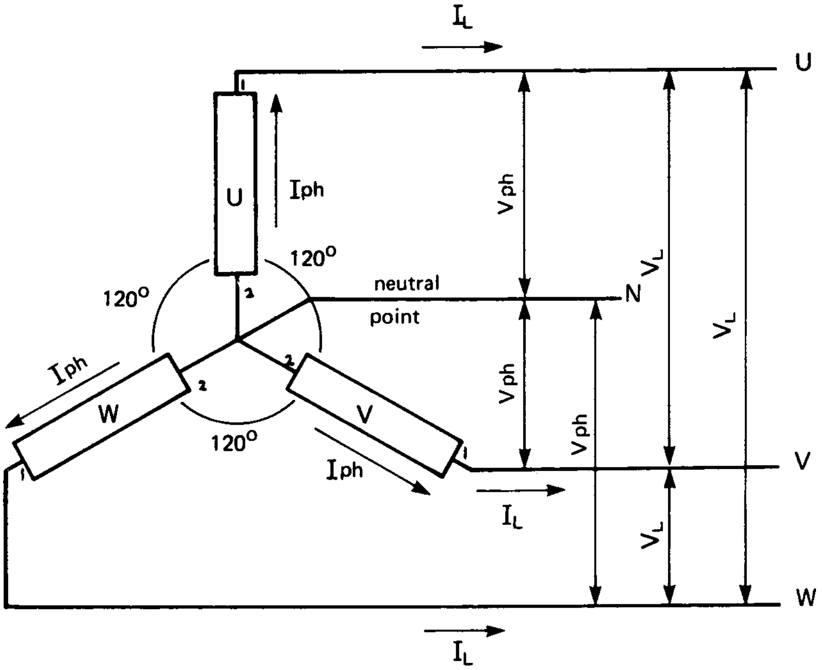
It is possible for a load to demand a current which is almost totally out of phase with the generated voltage. Also that current may be lagging the voltage (inductive or motor loads) or leading the voltage (capacitive loads). This, therefore, completes the range of power factors for a.c. generators from zero p.f. lagging through conventional 0.8 p.f lagging to unity (1.0) p.f. to zero p.f. leading. One aspect of this is that even though only a small real power (kW) is demanded by the load which is well within the machines capability, damage can easily result if the load is a very low power factor load demanding a very high kVA level.

The diagram shows difference power factor-kVA loads all supplying the same real power (kW) level. For normal constant voltage operation the length of the kVA line is directly proportional to load current. The high current overloads at lower power factors can be easily seen from this diagram.

Prime Mover	The method by which mechanical rotational ***power*** is provided to the ***a.c. generator*** shaft to sustain the ***nominal*** speed throughout all conditions of ***rated*** electrical load. It must also supply the ***excitation*** power and machine losses. Examples of such prime movers are diesel engines or gas turbines.
Rated/Rating	A specific continuous operating condition or value at which the machine can safely and successfully function. When the term is used generally it implies the maximum specific continuous operating condition or value. See also nominal.
Rectification/ /Rectified	The conversion of ***a.c***. to ***d.c***. The device which carries out this conversion is a rectifier or diode. There are a variety of rectification systems, one of the most popular is called the full wave diode bridge rectifier. The ***single phase*** circuit for this is shown below:-



Rotating Armature	A type of ***a.c. generator*** in which the main output winding is the rotating member. See also ***Armature***.
Rotating Field	A type of ***a.c. generator*** in which the ***magnetic field*** system is the rotating member. This occurs in all ***brushless*** machines.
Rotor	Generally used to describe all the rotating parts of an ***a.c***. ***generator***. It often refers specifically to the main ***magnetic field*** winding of a ***brushless*** machine. When the main output winding is on the rotor it is frequently called an ***armature***.
Self Excited	A design of ***a.c. generator*** where the source of power for the electrically produced ***magnetic field*** is derived from the main output winding of the machine itself.
Separately Excited	A design of ***a.c. generator*** where the source of power for the electrically produced magnetic field is derived external to the main machine. It may be provided by a completely independent machine or by an extra machine winding on the same shaft as the main machine. See also ***Permanent Magnet*** and ***Exciter***.
Single Phase	Applicable only to a.c. work. Defines a single a.c. ***voltage*** source providing a supply, usually at a fixed ***frequency***.
Speed	See ***Frequency***
Stator	Refers specifically to the main output winding of a ***brushless*** machine. Can also mean the main ***magnetic field*** winding of a ***rotating armature*** machine.
Three Phase	This can be considered as three equal but independent ***single phase*** supplies with one end of each supply forming a common (neutral or earth) point. These three supplies also have a time or phase difference of 120°. A particular 3 phase connection is called the star connection, and is shown on page 7.

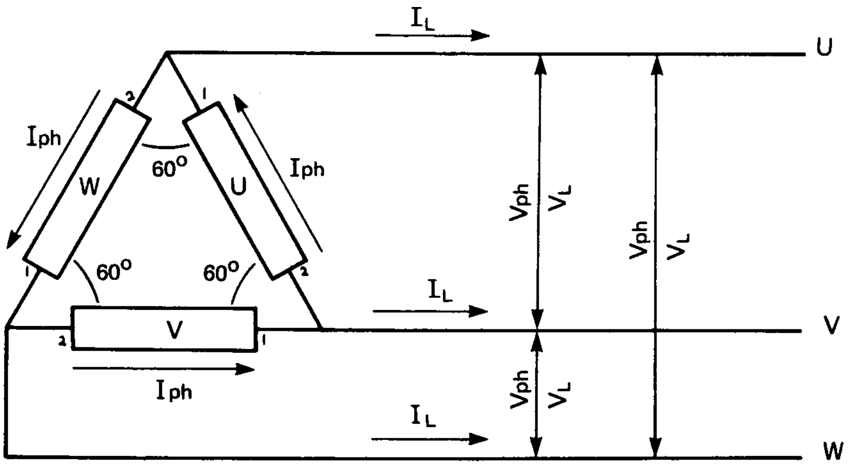


Note: The relationships between the phase and line ***voltage*** and the phase and line ***current*** are:-

voltage:- $\sqrt{3}\,V_{ph} = V_L$

current:- $I_{ph} = I_L$

There is also an alternative way of connecting a 3 phase supply, the delta connection. This, however, does not have a common or neutral point.



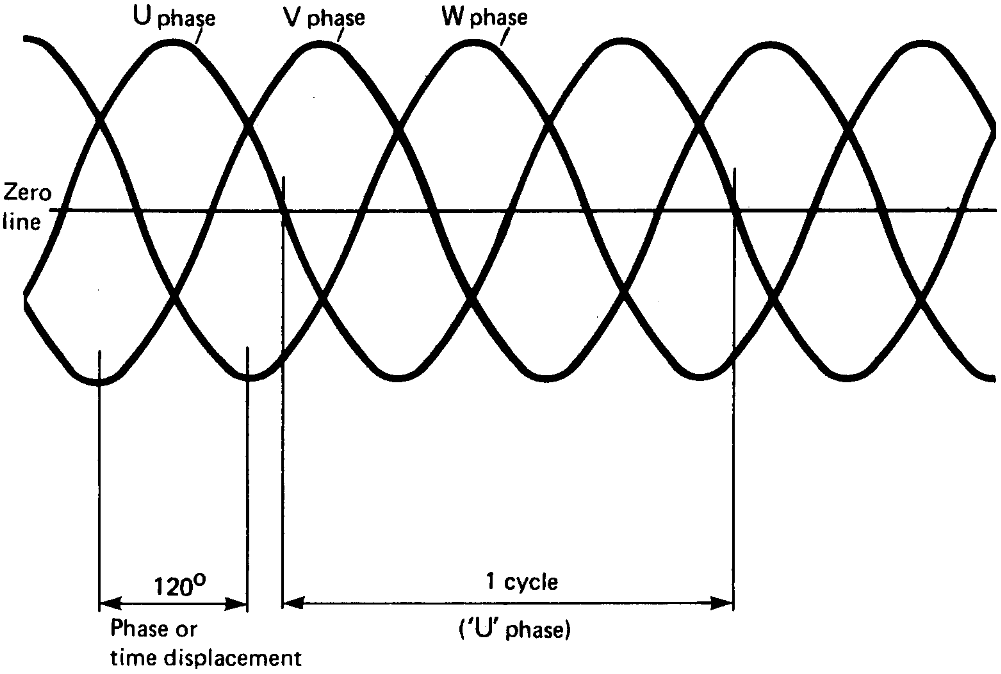
Note: This relationship between the phase and line voltage and the phase and line current are:-

Voltage:- $V_{ph} = V_L$

Current:- $\sqrt{3}\,I_{ph} = I_L$

Three phase cont'd

Whichever method is chosen the open circuit voltage waveforms will be identical, except in magnitude. Below is a waveform picture of a 3 phase sinusoidal a.c. supply:-



In view of the complex nature of the above waveform, any theoretical analyses are first reduced to 'single phase models'.

Note it is only ***a.c.*** supplies that can be connected in this manner. Three ***d.c.*** batteries connected in "delta" merely short circuits all the batteries; and equally, in star, there is no benefit over a conventional single d.c. supply of 3 batteries in parallel.

Voltage

The output voltage (or electrical pressure) of an ***a.c. generator*** depends on the speed of rotation, the number of turns of copper wire in the output winding and the strength of the main ***magnetic field***. The required ***frequency*** limits the speed choice and the turns are fixed in the manufacture of the machine; so the only variable is the ***magnetic field*** strength. The ***AVR*** adjusts this field strength as required by changing the ***excitation*** power supplied to the field.

Voltage Control Unit (VCU)

See Automatic Voltage Regulator.

BASIC DESIGN THEORY

General

One of the simplest ways to remember how every a.c. generator works is to imagine a magnet and a piece of wire. Move one of them with respect to the other, whilst keeping them close together, and a measurable voltage will be induced at the ends of the wire.

Immediately then we see that all a.c. generators must have the following, before an output voltage can be generated:-

a) a magnet - to produce the magnetic field excitation.
b) a piece of wire - usually coils of copper wire.
c) relative movement between these tow - usually a constant rotational speed.

Theory

In its simplest form an a.c. generator is diagrammatcially shown in figure 1. All three criteria stated above are met and a voltage output will be produced. In this case the magnetic field produced is at a constant level from a permanent magnet. This type of machine does have practical applications, particularly when supplying a constant load; for example, a pedal bicycle dynamo.

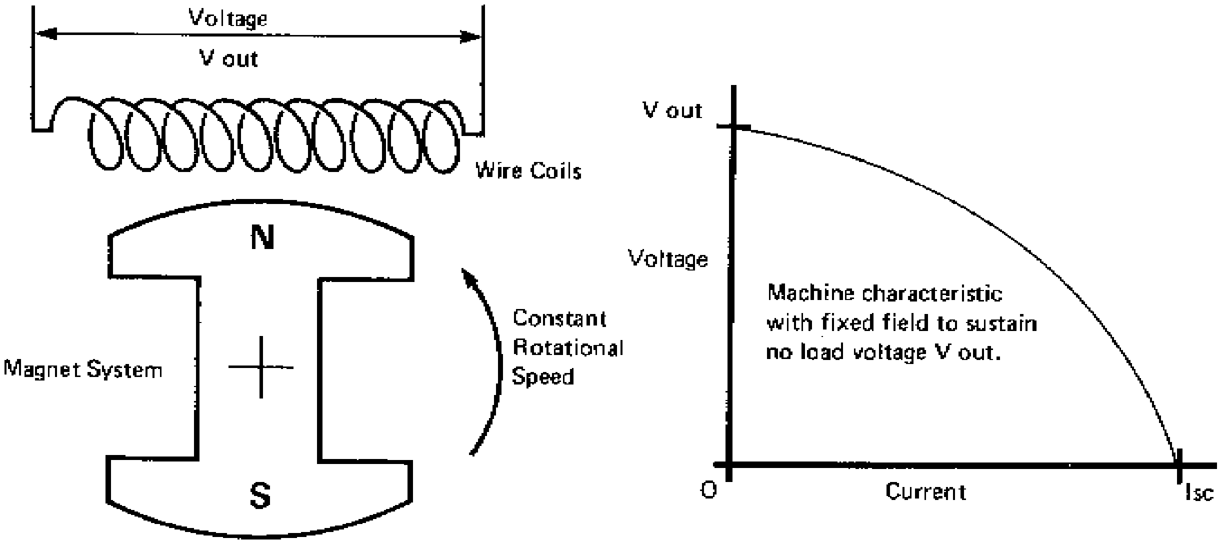


Figure 1

There are two conditions to consider at this point, the no load condition and the on load condition. The no load output voltage level is sustained by the constant magnetic field strength produced and fixed by the permanent magnet. On load, current is drawn from the machine which will cause the output voltage to fall, since the permanent magnet cannot produce a change in the magnetic field strength. The typical relationship between the output voltage and the load current is shown in the graph in figure 1. Typically the relationship is nearly linear between no load voltage (V) at zero current and the short circuit current (Isc) at zero voltage. In order to maintain the output voltage whilst supplying current, the magnetic field strength must be increased as load is applied. It is this requirement that brings us to the next stage of a.c. generator design incorporating the electrically produced magnetic field system. (Figure 2).

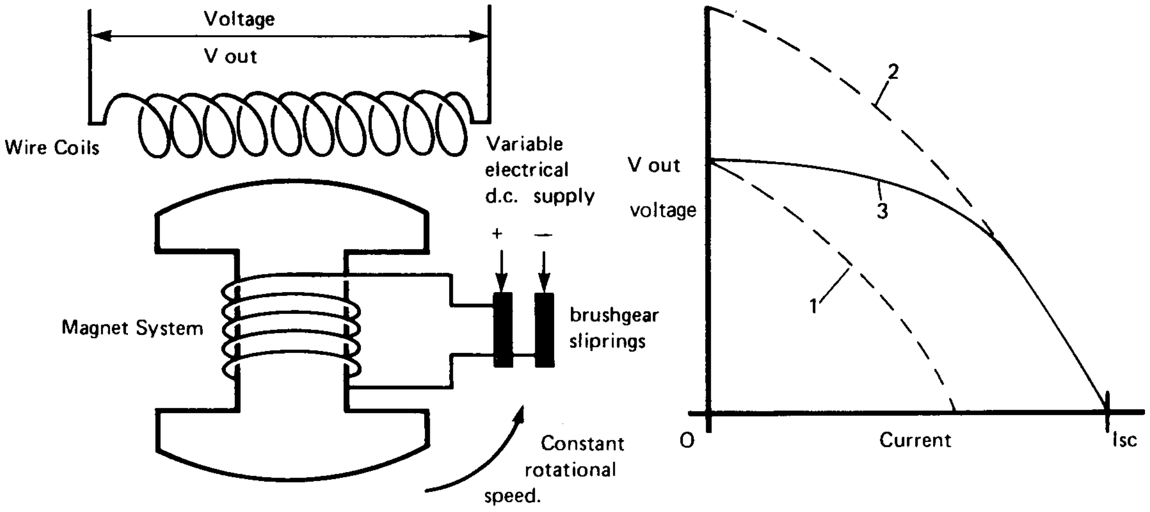


Figure 2

Curve (1) machine characteristic with minimum fixed field to sustain no load voltage ‘V’.

Curve (2) machine characteristic with maximum available fixed field from variable d.c. supply.

Curve (3) typical desired machine characteristic using variable d.c. supply to provide variable field.

Again all the basic criteria are met, except that the magnet is now produced electrically from an external variable d.c. source supply a coil of wire wound on the magnetic material. In order to get the supply to the rotating coil, the coil ends have to be brought to sliprings and the static supply connected to brushgear. The magnetic field strength can be increased by increasing the supply current. When this machine is run on load, we can increase the magnetic field strength in order to maintain the output voltage level. See the graph in figure 2, curve 3.

From here onwards there are many design improvements that can be made. For example a second a.c. generator (an exciter) can be put on the same shaft to make the basic brushless machine; that is a machine without sliprings and brushgear but which still maintains control over magnetic field strength. Also instead of having a manual control over the variable d.c. supply to the field coil, we can provide an automatic control system. These items are discussed later on in this section.

Now let us consider the factors governing the rotational speed and the output voltage.

Speed.

There is a simple relationship between speed, output frequency and the number of magnetic poles forming the main field excitation system of the machine.

$$\text{Output frequency (Hz)} = \frac{\text{Driven Speed (rev/min)} \times \text{No. of magnetic poles}}{120}$$

Obviously the number of magnetic field poles is decided and fixed by the machine manufacturer. Therefor we can see that output frequency is directly proportional to driven speed. In other words the only way frequency can change is due to a corresponding change in driven speed.

Voltage.

The relationships of the machine governing voltage level are more complex.

Output Voltage (V) depends on	1) Driven Speed (rev/min) 2) Number of turns of copper wire in output winding. 3) Strength of magnetic field produced by the main field excitation magnetic poles.

The number of turns of copper wire in the output winding is fixed by the machine manufacturer. Voltage is also affected by driven speed. In fact with a constant magnetic field strength, voltage as well as frequency would be directly proportional to driven speed.

As the speed is fixed to obtain the correct frequency, the only variable left can be used to change and fix the machine voltage level is the magnetic field strength. This is exactly the parameter that the machine's control system does adjust in order to set the voltage level, and compensate for both speed and load current changes. Let us now take a look at the control systems that are readily available.

Control System.

These are two popular methods of voltage control system for a.c. generators, firstly a closed loop electronic system and secondly, an open loop transformer system.

a) **Electronic System.**

This system continually monitors the output voltage an compares it with a reference voltage level set by the user. Once the reference voltage level is set, the automatic voltage regulator (AVR) will automatically compare the actual output voltage with the reference voltage level and if they are different will adjust the magnetic field strength to make the output voltage the same as the reference voltage. This system is therefore an accurate closed loop control by using static magnetic amplifiers (combinations of transformers of transformers and controlled reactors). This system is very reliable although slow in operation and very bulky compared to the electronic systems which have now virtually superseded it.

b) **Transformer Control.**

This system is really in two parts, firstly adjustment for no load voltage level and, secondly, compensation for load current. This system once set up is not normally adjusted. It is an open loop control system; there is no continuous monitoring to adjust the output voltage. It can only provide the amount of magnetic field strength it has been set up to provide.

Machine Types

Previously we have stated that rotational speed must be maintained between the output winding (the 'wire') and the field winding, (the 'magnet'). Also we have assumed that the field winding is rotated with the output winding remaining stationary. This type of machine is logically called a rotating field a.c. generator and an example of such a machine is the Newage Stamford Brushless range. In fact all brushless machines are rotating field types, but as we see in figure 2, not all rotating field type machines are brushless.

The alternative is to rotate the output winding whilst keeping the field winding stationary. This still complies with all the basic requirements for voltage generation and such a machine is called a rotating armature a.c. generator. An example of such a machine was the Newage Stamford 'D' range.

Operation.

In the next part the combined operation of the machine with the control system will be examined in more detail.

OPERATING PRINCIPLES

Introduction

In the preceding theoretical part, the basic a.c. generator and voltage control system parameters were discussed. In this part we shall examine several practical machines with their associated control system. In all cases the basic requirements are the same:-

a) an output voltage is induced between the ends of a conductor (usually copper wire), when the conductor is adjacent to a magnet and there is constant relative motion between them.

b) the output voltage is controlled by variation of the magnet's field strength in order to maintain the output voltage under load and speed changes.

Self-excited, rotating field, brushless, a.c. generator with electronic voltage control system (Stamford Series 4).

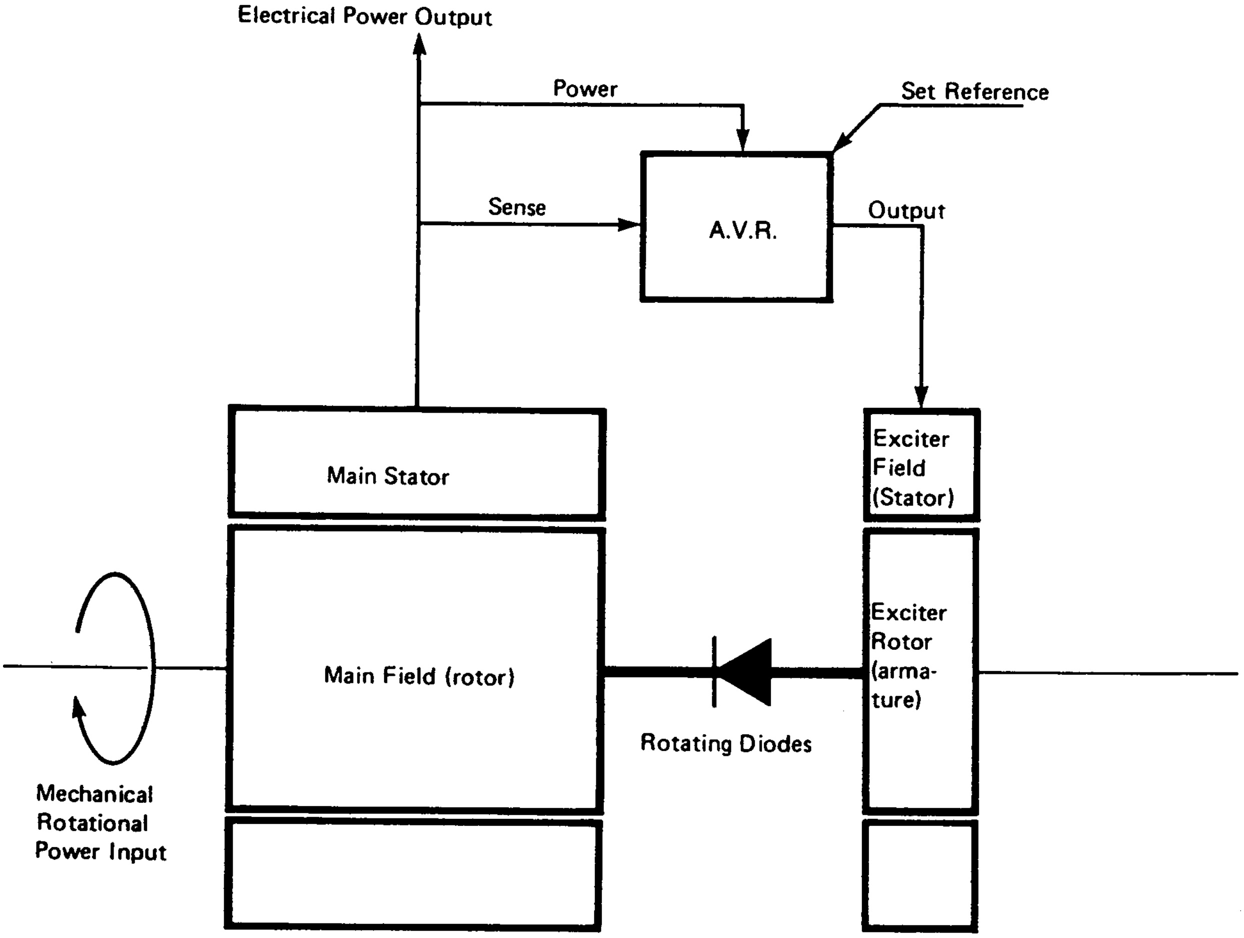


Fig. 1 Block Schematic Diagram

Looking at the title of this machine, it is self exited as the excitation power is derived from the main output winding of the machine itself. Rotating field indicates that it is the main machine's magnetic field system that the prime mover rotates. Brushless means that there are no sliprings or brushgear needed in this type of machine design.

Let us now consider the necessary motion - the mechanical rotational input power. It is this input power that sustains the correct speed under all load conditions. From this input power is derived the electrical power output, the field excitation power and all the machine losses.

Excitation power is supplied to coils of copper wire wound on some magnetic material. A characteristic of these materials is that a magnetic field can be easily set up and controlled in them. In all such materials there already exists a small amount of magnetism even before any electrical excitation supply is connected. This is called 'residual magnetism'.

Referring now to figure 1, with the machine rotor being driven at the correct speed, we have a small magnetic field set up due to residual magnetism, rotating adjacent to coils of copper wire in the main stator output winding. Therefor a small voltage is induced at the ends of the winding and is termed 'residual voltage'. The automatic voltage regulator (AVR) will sense this low voltage and compare it with the 'set reference' voltage level. The 'set reference' voltage level is an externally adjustable voltage level, derived by the AVR corresponding to the value of sensing voltage obtained when the machine is running at nominal speed and at rated output voltage. The AVR will find initially that the sensed voltage is considerably lower than the 'set reference' voltage. The AVR will therefore provide such power as is available from the main stator winding in order to establish the exciter field.

The exciter is made form similar magnetic materials as the main machine, so the exciter field will also have a small amount of residual magnetism. The power from the main output winding, which is rectified by going through the AVR now adds to his residual level to produce a greater magnetic field strength in the exicter field. It is worth noting there that correct polarity must be observed, since, if incorrect, the additional excitation power will subtract from the residual magnetism until zero magnetic field strength is reached. This means that the output voltage will not build up but remain at zero until an external d.c. source is applied to re-establish the exciter field.

With the exciter magnetic field strength increased, the a.c. output voltage from the exciter rotor will also increase. This voltage is rectified by the rotating diodes to provide additional d.c. excitation to the main machine field. This extra excitation adds to the residual level of the main field and produces an increase in output voltage from the main stator. The AVR senses this increase, compares it with the 'set reference' and uses the increased power from the main stator to further increase the exciter field excitation as required.

In this way the main stator voltage is progressively built up until the 'sensed' voltage is the same as the 'set reference' voltage. At this point the exciter field excitation will be stable and of such a value to just maintain the nominal or rated voltage level. This build up process in fact starts during the run up of the set. By the time the prime mover speed is stable, the a.c. generator output voltage will normally be stable and at the correct pre-set level.

Since this is a closed loop electronic voltage control system, a change in output voltage due to load current or speed changes is automatically compensated for by the action of the AVR. This will adjust the excitation under all circumstances in order to achieve minimum error between the 'sensed' output voltage and the 'set reference' voltage. There are, however, upper and lower limits of stable excitation voltage and power than can be provided by the AVR. These limits must be borne in mind during the design of the field systems.

The Newage Stamford Series 4 excitation system is of this type and full details can be found in section 5 of this manual. Also the now superseded machines with a Series 1 excitation system are of this type.

Separately excited, rotating field, brushless a.c.generator with electronic voltage control system (Stamford Series 3)

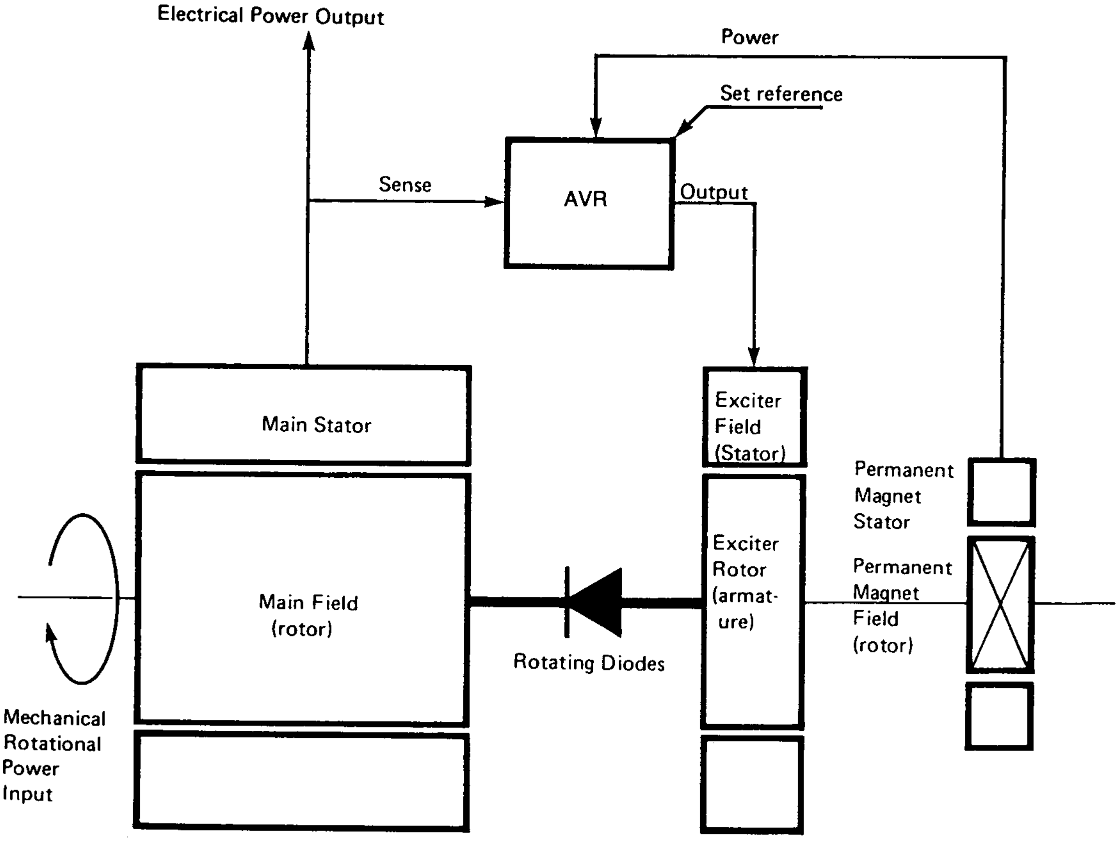


Fig. 2 Block Schematic Diagram

By comparing figure 1 with figure 2 above, we see the two types of machine are very similar. The difference is in the source of exciter field excitation power. In this case there is a separate source of exciter field power from a small permanent magnet field a.c. generator situated on the same shaft as the main machine. Hence the machine title is 'separately excited'.

When running at the correct speed, excitation power is always available independent of load condition. The permanent magnet produces constant magnetic field excitation and rotates close to the permanent magnet machine's output winding. The constant output voltage is then fed to the exciter field winding through the AVR. By comparing the main output 'sensed' voltage with the 'set reference' voltage, the AVR decides on the proportion of permanent magnet machine output to rectify and feed to the exicter field.

The process of initial voltage build up is very positive in this system, as residual magnetism is no longer continually depended upon. The AVR senses output voltage, compares it with the 'set reference' voltage and can apply the full permanent magnet output power rectified to the exciter field if necessary. The exciter rotor output would then increase, establishing a strong main field and therefore a marked increased in main output voltage. The AVR senses and compares voltages and adjusts exciter field excitation until, as in the previous machine type, both output voltage and exciter field excitation become stable.

Another significant advantage of this system is the ability to sustain main field excitation when the main output winding is short circuited. This means the 'sensing' voltage to the AVR is forcibly held at nearly zero by the applied short circuit. Since the difference in the 'sensed' and 'set reference' voltages is now large, the full permanent magnet output is rectified and applied to the exicter field. This sustains the main field excitation which in turn maintains the short circuit current. This facility is advantageous wherever positive voltage build up, high overload capacity, or short circuit current fault discrimination is required. The Newage Stamford HC range a.c. generators with a Series 3 excitation system are of this type and full details can be found in section 5 of this manual. Also the now superseded machines with the Series 2 excitation system are of this type.

Self excited, rotating field, brushless a.c. generator with transformer control system (Stamford — Series 5)

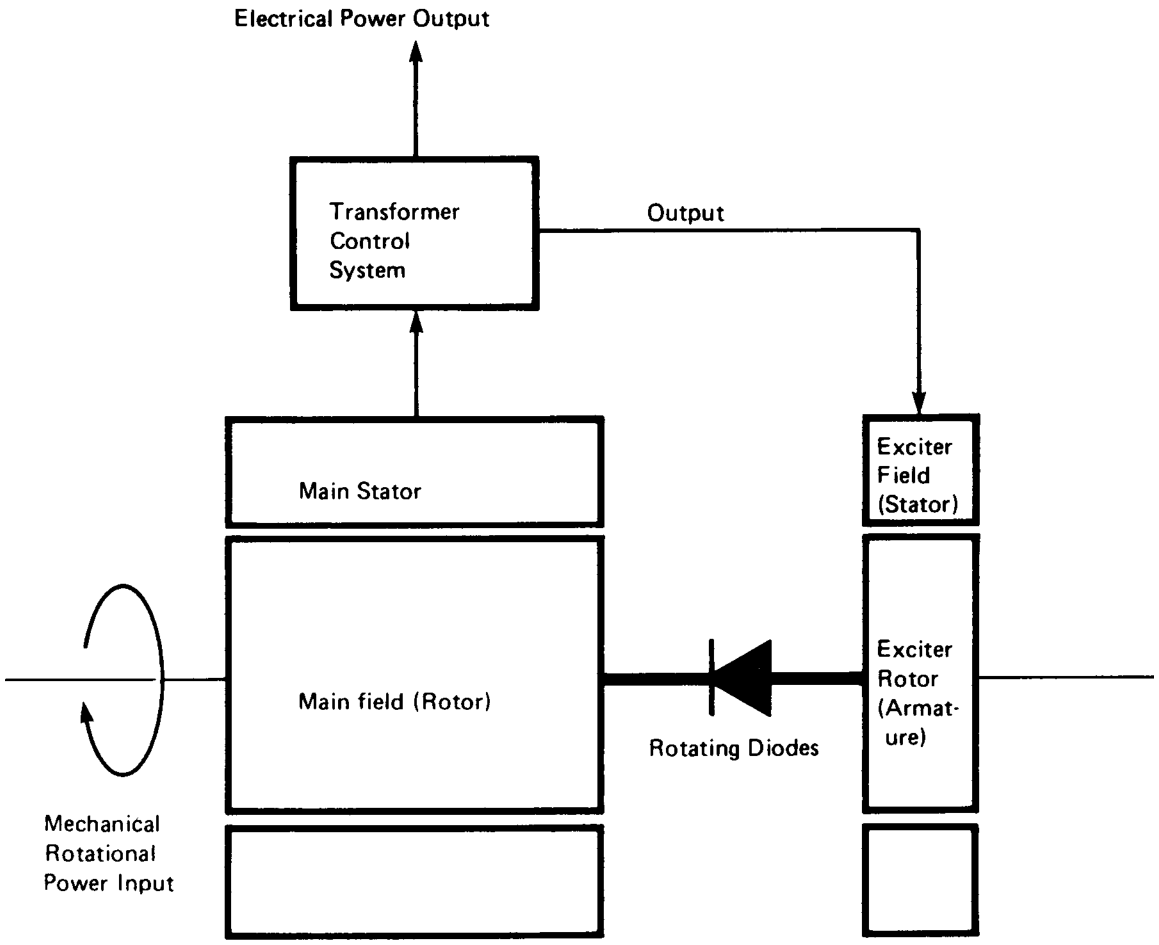


Fig. 4 Block Diagram

This combines the brushless style of machine with the open loop transformer type of control system. (See machines described under figure 1 and figure 3). When rotating, the residual magnetism causes an output voltage, a fixed proportion of it being rectified and fed to the exciter field. Output voltage will be built up in the way described previously until the proportion of output voltage fed to the exciter field is just enough to sustain that voltage. The machine and control gear are designed so that this happens at the nominal output voltage of the machine. Compensation for load current is achieved by using a transformer to obtain a voltage proportional to load current. This voltage is rectified and used to increase the exciter field strength thereby sustaining the output voltage on load. The Newage Stamford a.c. generators with a Series 5 excitation system are of this type.

A.C. GENERATOR STANDARDS

Almost every nation has its own standards authority. Therefore to provide a complete list of all relevant standards for a.c. generators is an impossible task. Some of these national standards are internationally accepted and Stamford a.c. generators can be built to meet the requirements of all such standards. In addition, particular industries have felt their own recognised specifications. Below is a list of those standards and specifications most frequently stipulated.

1. Industrial Standards.

I.E.C. 34-1	International Electro-technical Commission.
BS 5000 Part 99	British Standard
NEMA MG1-22	North American Standard
C.S.A. C22-2	Canadian Standards Association
V.D.E. 0530	West German Electrical Engineers Institute
N.F. C51-100	French Standard
AS 1359	Australian Standard

2. Marine Standards.

Lloyds Register of Shipping	Britain
Det norske Veritas	Norway
Bureau Veritas	France
American Bureau of Shipping	USA
Germanischer Lloyd	West Germany
Polish Register of Shipping	Poland
R.I.N.A.	Italy

3. Specifications.

Various international military specifications.
Telecommunications specifications of many countries including Britain.
Various computer installation specifications.
Automatic semiconductor load specifications (e.g. No Break Sets).
Severe environmental operating condition specifications.
Navigational Radar Equipment supply specifications.
Radio Station Supply specifications.

STANDBY RATINGS TO NEMA MG1-22

In response to a market requirement especially on those areas where American engines are used as the prime movers Newage offer continuous operation standby ratings for their range of brushless a.c. generators. The graph on the next page indicates the principles involved.

These ratings are in accordance with the United States specification NEMA MG1-22.

Extracts from NEMA Standards - Part 22 - June, 1972.

MG1 - 22.40 Temperature Rise.

Machine Part	Method of temperature determination	Temp. rise 40°C ambient Class of insulation system			
		A	B	F	H
Armature windings	Resistance	60	80	105	125
Field windings	Resistance	60	80	105	125

Note IV

Temperature rises in the above table are based upon generators rated on CONTINUOUS DUTY basis. Synchronous generators may be rated on a STANDBY DUTY basis (See MG 1-22, 84). In such cases it is recommended that temperature rises not exceed those in the foregoing table by more than 25°C under continuous operation at the STANDBY RATING.

MG1-22.84 Standby Generator.

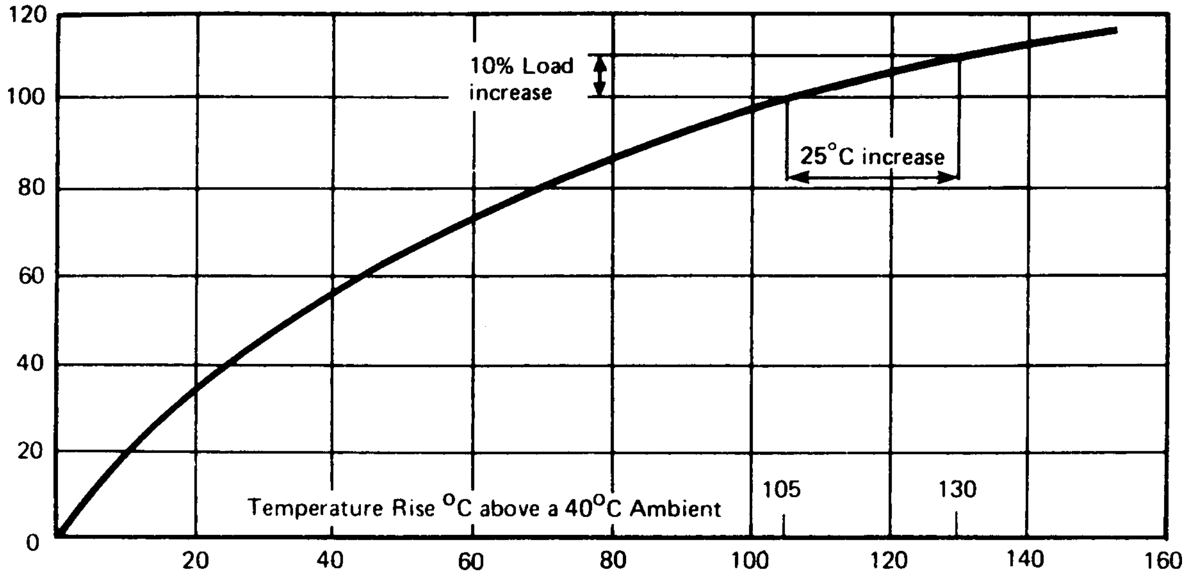
Synchronous generators are at times assigned a STANDBY rating where the application is an emergency back-up power source and is not the prime power supply. Under such conditions, temperature rises up to 25°C above those for CONTINUOUS-DUTY operation may occur in accordance with Note IV of
MG1-22.40.

Operation at these STANDBY temperature rise values causes the generator insulation to age thermally at about four to eight times the rate that occurs at the CONTINUOUS-DUTY temperature rises values, i.e., operating 1 hour at STANDBY temperature rise values is approximately equivalent to operating 4 o 8 hours at CONTINUOUS-DUTY temperature rise values.

Stamford generators are generally insulated with a Class H system throughout. Where prime power continuous duty ratings are used to the full Class H temperature rise no standby rating is offered.

Prime power continuous duty ratings are often quoted to a Class F temperature rise EVEN THOUGH the insulation system is Class H. This may be to comply with certain standards or to meet other operational parameters. In this case a standby rating can be offered.

In general the Class F standby ratings and Class H prime power ratings on Stamford generators are identical. The user then has the choice which standard to quote.



GRAPH 1
Typical Temperature Rise Against Load Curve For Class 'F' Rated A.C. Generator

A C GENERATOR SELECTION - CHECK LIST

1. Basic Data

- ☐ Voltage
- ☐ Phase
- ☐ Frequency
- ☐ Speed
- ☐ Site kVA
- ☐ Site kW
- ☐ Power Factor

Designation	HC, UC, MHC, etc
Bearings	One/Two
Control System	3/4/5/6
Poles	2/4/6

2. Build Type and Accessories

☐ Parallel Droop Kit	
☐ Three Phase Sensing	
☐ RFI Filter Kit	
☐ Anti-condensation Heaters and Voltage	
☐ IP23 Enclosure	
☐ Air Inlet Filters	
☐ Shaft Standard/Special/2nd Extension	
☐ Coupling or Adaptor Type	
☐ Winding Ends Out	
☐ C.S.A. Approval	
☐ Other Approval (specify)	Refer to Factory
☐ Official/Special Inspection	
☐ Special Testing	Refer to Factory
☐ Belt drive	Check side load
☐ Vertical Mounting - special bearings	Refer to Factory
☐ AVR Type	
☐ Special Nameplate	Refer to Factory
☐ Special Foot Mounting	Refer to Factory
☐ Manual Voltage Regulator	
☐ Over Voltage Protection	
☐ Frequency Detection Module	
☐ VAR/PF Controller	
☐ Alternator Protection Module	
☐ Excitation Loss Module	
☐ Diode Failure Detector	

3. Rating Adjustments

☐ Derate for High Ambient Temperature Section 4401
☐ Derate for High Altitude Section 4411
☐ Derate for Temperature Rise Restriction
☐ Derate for Lagging Power Factor Below 0.8
☐ Derate for Leading Power Factor Refer to Factory

☐ Derate for Maximum Overload Condition
☐ Derate for Maximum Voltage Dip Restriction
☐ Derate for High Sustained Short Circuit Current Requirement
☐ Derate and/or Special Build for Thyristor Type Load
☐ Allowance for Future Growth
☐ Derate for Voltages Higher than Normal Top Limit of Winding Refer to Factory

☐ Derate for Voltages Lower than Normal Bottom Limit of Winding Refer to Factory
☐ Allowance for Standby Duty only
☐ Derate for Unbalanced Load Regulation

☐ Final Steady State Machine Rating kW
☐ Final Resultant Power Factor
☐ Final Required kVA for Transient Performance
☐ Final Required kVA for Short Circuit Performance
☐ Frame Size Selection based on limited Rating

4. Typical Test Data

The following typical test figures are normally available on request:-

☐ Open Circuit and Short Circuit magnetisation Curve
☐ Regulation, Phase Sequence, Insulation Resistance and Megger
☐ Heat Run
☐ Efficiency Curves
☐ Efficiency - by Summation of Losses
☐ Waveform Analysis (Distortion, Deviation, T.I.F., T.H.F., Photograph)

SECTION 4311
January, 1990

POWER RATING

The most fundamental factor governing the correct sizing of an a.c. generator is the power rating. By consideration of the electrical load likely to be applied to the a.c. generator, the user can estimate the required power rating. This is usually done by adding together the kW ratings of the individual parts of the load to arrive at a total kW power rating figure.

Initially every possible load should be included. In addition an allowance for future growth typically between 15% and 20% is common practice. This total kW power rating can now be checked with standard published output lists and an a.c. generator frame size selected. For standby or emergency service, only the essential loads need to be included.

Having established the power requirement and possible frame size we need now to look at the specific supply details, environmental conditions and performance criteria required when supplying this particular load. This next stage is the ‘fine tuning’ to ensure that exactly the right size of machine is chosen for the application.

It should be noted that standard published output lists usually quote a kVA rating as well as a kW power rating, and is relating these a power factor of 0.8 lagging is assumed:-

i.e., kW = 0.8 x kVA

Also general different ratings may be quoted for the same machine. Typically three ratings may be quoted.

a) Continuous Maximum Industrial Rating - this is the rating to which all others are referred. All performance criteria and technical data will be based on this rating, unless instructions to the contrary are given. When working at this rating all quoted performance figures will be met.

b) Standby Duty Rating - this is a higher rating than the continuous maximum industrial rating. It permits a greater continuous output from he machine providing that worsened performance criteria, increased temperature rise and reduced lifetime are acceptable.

C) Continuous Marine Rating - this is a lower rating than the continuous maximum industrial rating. All standard performance criteria are met and bettered, but at a 50°C ambient temperature, rather than the 40°C ambient temperature considered for industrial applications. The overall actual temperature of the windings are insulation remains constant

EFFICIENCY AND DRIVE POWER

The selection of a suitable size of prime mover for an a.c. generator is governed by the electrical power output supplied to the load and the efficiency of the a.c. generator. The relationship is given below:-

$$\text{kW drive input} = \frac{\text{kW output}}{\eta\ a}$$

Where:-

“kW drive input” defines the prime mover power rating in kilowatts
“kW output” defines the electrical power supplied to the load (usually the continuous maximum industrial power rating of the a.c. generator).
“ η a” is the efficiency in ‘per unit’ of the a.c. generator.

To convert kW input into Horsepower (h.p.) or Cheval Vapeur (C.V.)/Pfedestarke (PS) the following conversations constants should be used.

$$\text{h.p.} = \frac{\text{kW input}}{0.746}$$

$$\text{C.V. or PS} = \frac{\text{kW input}}{0.735}$$

In special circumstances the prime mover size may need to be larger than specified above, to copy with particular overload or transient conditions. Consideration of motor load starting torque can be especially relevant when determining prime mover size.

The efficiencies of Stamford a.c. generators are given in individual data sheets in Section 6.

TEMPERATURE AND TRANSIENT PERFORMANCE

A simple description of the approach to a.c. generator selection is that the chosen machine must be capable of supplying the steady state loads and the transient or motor starting loads within the temperature and voltage limits for that application. It is these temperature and voltage limits we shall look at now.

Temperature

A C. generators are designed and insulated to operate on full load within a maximum permitted temperature. It is the quantity of active material in the machine (lamination steel and copper) that primarily affects the temperature at which the machine operates when on a specific load. The insulation system must retain its properties over this operating temperature range for the lifetime of the machine.

Losses in the copper windings are due to the flow of load current through the winding and the winding have electrical resistance. These losses create heat and hence cause the winding and insulation temperature to increase, which in turn means that the winding resistance will also increase. If excessive loads are applied the insulation temperature may increase beyond the temperature class normally specified, as in the case of Standby Duty Rating defined in specification NEMA MG1-22. Continuously applied highly excessive loads will quickly lead to a winding burn out. There is definite relationship between machine insulation operating temperature and degrading of the insulation materials (insulation lifetime).

Insulation materials are assessed on their ability to retain their insulating properties up to a maximum specified temperature for a specified lifetime. A usually accepted insulation lifetime is 100,000 hours of continuous operating at the maximum permitted temperature specified. The table below (simplified from BS4999 Part 32) gives the standard insulation classes available and the associated maximum permitted temperature rises, (i.e., actual temperature minus ambient temperature).

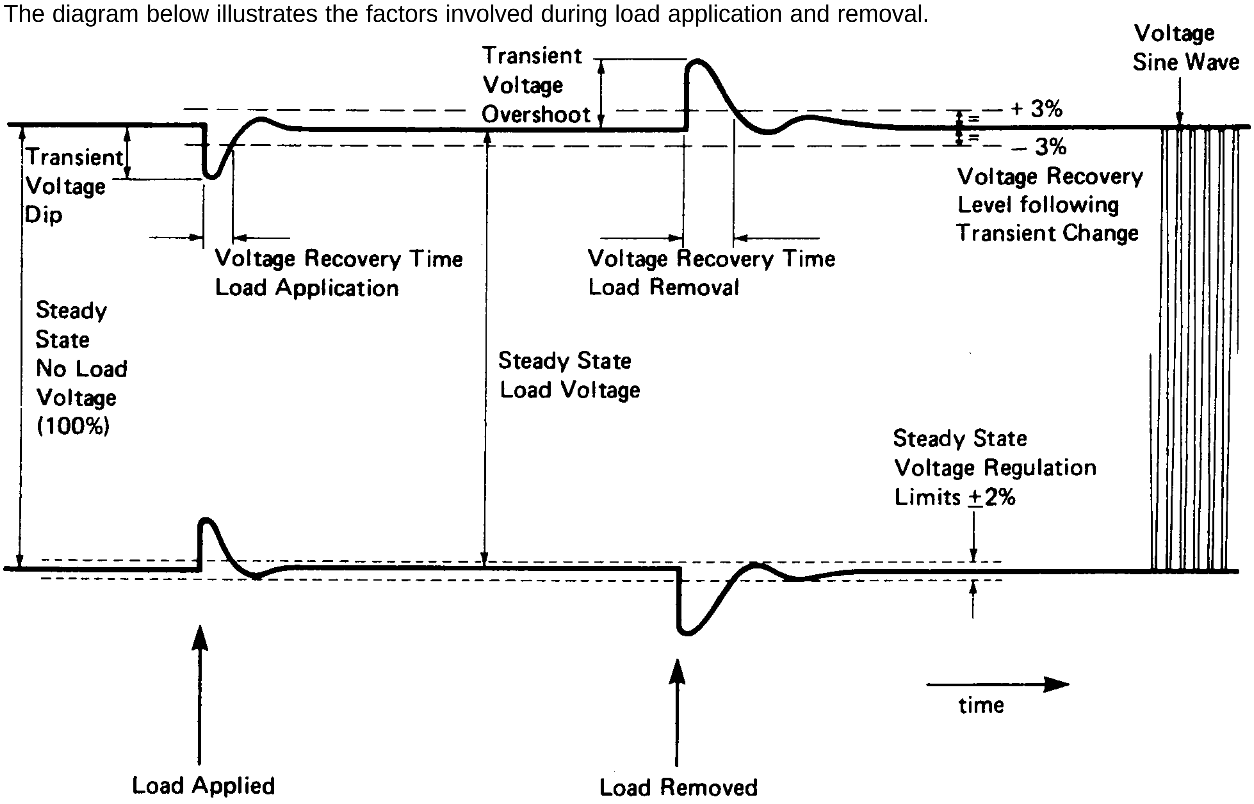
Insulation Class of Material	**A**	**E**	**B**	**F**	**H**
Maximum permissible temperature rise (°C) based on an ambient temperature of 40°C and the standard lifetime period.	60 (measured by change in winding resistance)	75	80	105	125

Transient

When a load is suddenly applied to an a.c. generator the voltage will fall instantaneously to a level dependent upon the amount of load applied. The AVR will monitor this voltage dip and increase excitation to restore voltage level to nearly the original value, within a fraction of a second. Similarly on load removal there is a voltage over-shoot and the AVR reacts reducing the excitation.

See diagram on page 2.

The diagram below illustrates the factors involved during load application and removal.



NOTES:

1. Voltage waveform envelope is shown as the heavy line.
2. This diagram is not to scale and is intended to bring out the features mentioned in the text.

These factors are described below and the standard performance of Newage 'Stamford' machines is also given.

a)	Transient Voltage Dip	- the amount of transient voltage decrease due to the sudden application of a specified load usually expressed as a percentage of the original voltage level.
b)	Recovery Time	- the length of time taken for the voltage level to recover to within 3% of the original value.
c)	Transient Voltage	- the amount of transient voltage increase due to Overshoot the sudden removal of a specified load usually expressed as a percentage of the original voltage level.
d)	Steady Stage Regulation	- a measure of the maximum permitted steady voltage changes over a wide variety of machine conditions (includes machine hot to cold variations: no load to full load applied, power factor 1.0 to 0.8 lag).

In certain applications, a voltage dip better than our standard may be required - for example a 10% voltage dip on application of full load. The most effective way of achieving this is to provide a bigger a.c. generator. To assist in the correct selection of machines capable of this improved performance, graphs of applied load against voltage dip are included in Section 6 of this manual. Sometimes, when only small improvements to voltage dip are required, a special winding can be designed to give the correct performance without going to a larger machine. For this, reference to the factory is necessary.

As with temperature, the standard transient performance should be considered first. Any improvement required in transient performance should have technical or economic justification.

CONTROL SYSTEM

Stamford a.c. generators can be fitted with a choice of control system.

The selection of control system is made from three alternatives, designated and described briefly below:-

Series 3 system
- available where a sustained short circuit is required.
- a separately excited system deriving magnetic field power from a permanent magnetic exciter mounted on the main shaft; and controlled by an electronic AVR.
- a high performance closed loop control system.

Series 4/6 system
- a self excited system depending for its operation on residual magnetism, deriving its magnetic field power from the main output winding itself; and controlled by an electronic AVR.
- a closed loop control system.

Series 5 system
- available on small generators.
- a self-excited system depending for its operation on residual magnetism, deriving its magnetic field power from the main output winding itself and controlled by a current compounding transformer.
- an open loop control system.

TEMPERATURE

Ambient Temperature

Ambient temperature can be defined as the temperature of the surrounding air at a particular location. The internationally accepted standard value for this is 40°C. All design work and most ratings of a.c. generators are based on this figure. The ambient temperature measured should be that of the cooling medium. In the case of an air cooled machine such as a Newage Stamford a.c. generator, this would be the air inlet air temperature. This may be higher than the surrounding air ambient temperature due to the heat generated by the prime mover within the confined space of an engine house.

It is essential that the total actual temperature does not exceed the limits set by the class of insulation used; see Section 4341. In some cases, especially marine machines, ambient temperatures higher than 40°C are encountered. It follows then, that a machine operating in an ambient temperature greater than 40°C, must be de-rated to ensure that total actual temperature does not exceed the specified maximum.

The converse of this is also true; that by reducing temperature a greater output can be obtained from an a.c. generator for the same actual temperature. This is permitted in most standards down to an ambient of 30°C.

Outputs are normally quoted at 40°C. These outputs must be multiplied by the following factors for higher ambient temperatures.

Temperature (°C)	**Multiplier**
45	**0.97**
50	**0.94**
55	**0.91**
60	**0.88**

ALTITUDE

Up to 1,000m (3,300ft) above sea level, the change in air density is insufficient to radically alter the thermal transfer properties of the air. Above 1,000m the effectiveness of the air is reduced sufficiently to make de-rating necessary. Standards are agreed that to avoid overheating due to this reduction in coolant effectiveness, machines operating at high altitudes must be de-rated.

This section gives the necessary de-rating factors for altitudes from 1,000m to 4,000m (3,300ft to 13,200ft) above sea level.

Unlike ambient temperature, the converse is not permitted. No greater output is allowed from a machine operating at sea level to one operating at 1,000m above sea level.

For altitudes above 1,000m outputs must be multiplied by the following factors:

Altitude (m)	Multiplier
1,500	0.97
2,000	0.94
2,500	0.91
3,000	0.88
3,500	0.85
4,000	0.82

HUMIDITY

Humidity is a measure of the moisture content of the air in which a machine is situated. It is normally measured as ‘relative humidity’ (rh) where 100% rh is air fully moisture saturated (i.e. the point at which condensation occurs, see Note 1) and 0% rh is air absolutely dry. (See Note 2).

For successful operation in the high humidity levels found in tropical regions, machines are said to be ‘tropicalised’. This involves correct choice of the insulating materials and careful assessment of the impregnation varnish system and methods.

All Newage Stamford a.c. generators are tropicalised as standard.

NOTE:

1. **For consideration of condensation see section 4431 “Anti-condensation heaters”.**

2. **Definition of relative humidity is the ratio of the pressure of the water vapour actually present in the atmosphere to thepressure of the water vapour which would be present in the same atmosphere if the water vapour were saturated; temperature remaining constant.**

SECTION 4431
January, 1990

CLIMATE AND ENVIRONMENT

In previous sections 4401, 4411, 4421, we have considered temperature, altitude and humidity as separate independent elements. This is not the case in practice since climate and environment depend on various combinations of these and other elements. Other elements may include:-

atmospheric contaminants such as gases and various chemicals.
salt water (sea) spray
dust or sand laden atmospheres
solar radiation and wind.
rainfall and icing

We must now look, therefore, at combinations of all the above elements which make up particular climates and environments. Then we must ensure the a.c. generator will adequately cope with the particular conditions without breakdown.

Certain accessories can be added to the generator to provide adequate protection against particular problem climates and environments. These may include any of the following:-

Anti-condensation heaters.

Condensation occurs due to the change of water vapour into liquid, (i.e., greater than 100% rh, see Section 4421). The point at which this change occurs is dependent upon actual water vapour pressure and particularly upon temperature. Consider a hot machine shut down at the end of a day shift. During the night the ambient temperature can reduce quickly but the machine surface temperature will reduce much more slowly. At dawn ambient temperature may rise quickly, probably to a level greater than the machine surface temperature which will begin to rise towards ambient temperature only slowly.

Depending upon the actual water vapour pressure present in the local atmosphere, condensation may occur in the machine at any time after the ambient temperature exceeds the machine surface temperature. If the water vapour pressure is near or at saturation then condensation will occur during the rapid rise of ambient temperature at dawn.Condensation or dew will form on all surfaces which are cooled than ambient temperature.

To avoid this, anti-condensation heaters can be fitted which will ensure the winding temperature remains a few degrees above the ambient temperature and hence no condensation will form. Note that the anti-condensation heaters should be on only when the set is off, and they should be switched off whilst the set is in use. They can be fitted to a machine at any time.

Drip-proof Louvres.

The standard machine is drip-proof, i.e., vertical drips of water cannot enter the machine. Should the machine be used on uneven terrain (or the sea) then protection against water drops up to 60°C from the vertical can be provided by fitting drip-proof louvres. These louvres can be fitted at any time. A derating of the generator output (normally 5%) may be necessary.

Air Filters.

Some site conditions are such that the air may be heavily laden with a very fine dust or sand, to an extent where the air passages become blocked. If moisture is also present then the dust may become saturated and so accelerate the insulation breakdown. Under these conditions we strongly recommend the fitting of inlet air filters. The sizing of these is important to avoid airflow restrictions and advice should be sought from the factory or the machine purchased complete with the necessary air filters.

The general recommendations given above are intended for guidance in consideration of any particular climate or environmental condition. If the machine specifications call for operation in a specific climate or a particularly arduous environment, reference should be made to the factory. A detailed description of the climate or environment will be required before we can offer our recommendations.

GENERAL COMMENTS ON LOAD CONDITIONS

Section 4.5 is concerned with the effect of load upon the a.c. generator and on correct generator sizing. The majority of a.c. generator applications are in supplying electricity to standard loads such as lighting, heating, ventilation, and an infinite variety of motor drives. These loads, and loads of a more complex nature, are considered in the sections following these general comments. However any doubts about sizing should automatically mean reference to the factory.

Some specialised loads such as computers and transmitting stations may demand very specific performance parameters. In these cases advice from the factory should be sought. Were are specification exists for any particular load or installation, it is always advisable to forward a complete copy of the factory for examination. As a result of such an assessment it is sometimes possible to incorporate design changes to provide a more economic machine which still meets the specification.

In arriving at a total load figure it is always wise to select the standard rating larger than that estimated. This despite the fact that all the loads may not be operating at the same time and hence a smaller machine could have been selected. Future operating conditions and future growth are very difficult to estimate. An allowance of 15% to 20% excess capacity designed into a set now is a small price to pay compared with the cost of a completely new larger unit that may be required to drive additional loads in a few year's time. The exceptions are sets solely for emergency service, when only the essential loads need be included.

There are two basic conditions to check when sizing machines. The steady state condition, which is mainly concerned with normal operation of the machine within temperature rise limits; and the transient condition, which examines voltage deviations when suddenly applying high current loads (e.g. during motor starting). It is essential that both these conditions are checked as a rating sufficient for the stead state condition is often not large enough to meet motor starting or voltage dip requirements. Calculation methods and examples for both conditions follow. The base unit for the two conditions is also different. The steady state calculation normally uses kW output from the a.c. generator as the base unit, which can also be used to ensure that the correct power size of prime mover is selected, without overload. Transient calculations are conducted to the base of kVA. Note that without exception.

$$KW = kVA \times \text{power factor}$$

It is the nature of the applied load that dictates the system power factor. Loads that operate at or very close to unity (1.0) power factory include most forms of lighting, all hearing elements, rectifier and thyristor type loads; in fact any load which does not include an induction coil (motor). Generally, all domestic loads can be considered as unity power factor since any motors (washing machine, refrigerator, etc.) represent only a small part of the load, being normally fractional horsepower motors. For all remaining load types, some knowledge of operating power factor is required, which for motors depends a great deal on their size and power rating.

Newage Stamford a.c. generators perform satisfactorily at any power factor in the range of 0.8 p.f. lag to unity p.f. Operation at leading power factors usually demands a derate and reference to the factory must be made if leading power factor loads are under consideration. Lagging power factors below 0.8 p.f. also require the machine to be de-rated.

Under certain circumstances a high level of fluorescent lighting load should be considered with caution. Some are manufactured uncompensated with operating power factors as low as 0.5 p.f. lag, although the majority are capacitor corrected to around 0.9 p.f. lag. The two most disturbing effects of fluorescent are the waveform distortion created by high third harmonics in the current waveform and the switching transient created by the 'starter' equipment. These can adversely affect other connected leads and where doubt arises advice should be sought from the factory.

In considering the various load conditions following, reference is made to typical performance figures. It must be noted that any attempt to be specific can be done with the true performance figures for the load in question. Full and detailed technical information of current consumed under both starting and running conditions must be obtained from the manufacturer of the load.

In considering motor loads for example, design data should be sought from the motor manufacturer. If any doubt or difficulty arises in sizing the a.c. generator, that data should be submitted to us for assessment. The need for this is clearly demonstrated in considering the example of a motor load rated at 44kW. For product standardisation reasons for the motor manufacturer may supply a 50kW motor for this load; and will have therefore 50kW starting characteristics demanding a much higher starting current that the quoted 44kW.

This point is raised to draw the attention of the end customer to the need for obtaining full information about the load. Without such information only typical or generalised assessments on a.c. generator sizing can be made using the data and tables given in the remainder of this manual.

CONSTANT OR STEADY STATE LOADS - THREE PHASE, BALANCED

A balanced three phase load is one which demands identical power and current from each of the three phases of the a.c. generator, i.e., the load is equally shared or balanced between three phases.

The total constant or steady state load is derived by adding together all the individual constant or steady state loads. The same unit of load rating obviously must be used throughout, usually kW. Load ratings can be given in current (A, amperes); horsepower (h.p.); kVA; or in kW. Conversion formulae are given below:-

$$\begin{aligned} \text{kW genr} &= \text{kW load} \\ &= \text{kVA} \times \text{p.f.} \\ &= 0.746 \times \text{h.p.} \\ &= \frac{\sqrt{3} \times \text{volts} \times \text{current}}{1{,}000} \times \text{p.f.} \end{aligned}$$

where kW genr = output power from a.c. generator
kW load = input power to load in kW.

$$\text{kVA} = \frac{\sqrt{3} \times \text{volts} \times \text{current}}{1{,}000}$$

p.f. = power factor derived from data given in 4501
or assume 0.8p.f. lag
h.p. = input power to load in h.p.
volts = rated line to line voltage
current = rated line current.

These formulae give the output power from an a.c. generator based on the input power required by the load. This is true of all loads except motors. Motors are usually rated for their shaft output power. Therefore an extra 'motor efficiency' term is required in these cases; thus:

$$\begin{aligned} \text{kW genr} &= 0.746 \times \frac{\text{h.p (output)}}{\eta\ m} \\ &= \frac{\text{kW (output)}}{\eta\ m} \end{aligned}$$

where h.p. (output) = motor shaft output power rating in h.p.
kW (output) = motor shaft output power rating in kW
η m = motor efficiency in per unit.

Having derived the total kW loading on the a.c. generator required to supply the load, then an estimate of prime mover output can be made, thus:-

$$\text{kW (prime mover output)} = \frac{\text{kW genr}}{\eta\ \text{genr}}$$

where η genr = a.c. generator efficiency in per unit.

By this calculation the minimum kW rating of an a.c. generator has been determined. All the above assumes a standard ambient temperature of 40°C and standard altitudes of less than 1000m. If higher ambient temperatures or altitudes are required, then derate factors must be applied to this calculated minimum kW rating. A check through kW rating is not listed then the next higher kW output frame size of machine should be selected. This will ensure that the a.c. generator selected will supply continuously the full rated load within the temperature rise limits of the machine design.

The effect of power factor must now be checked. If all the individual loads are between 0.8p.f. lag and unity p.f., then no adjustment to the selected frame is required. If any one load is outside these limits, then the resultant steady state power factor should be calculated by vector additions of all the loads. Again, if this resultant is within the range 0.8 p.f. lag and unity p.f., no adjustment is required. If it is outside this range, then a derate factor must be applied to the calculated minimum kW figure and a new frame size selected, based on the new kW rating figure.

CONSTANT OR STEADY STATE LOADS - THREE PHASE, UNBALANCED

An unbalanced three phase load is one in which the load is not equally shared by all the three phases of a machine. This frequently occurs in practice due to single phase loads being applied across one or rwo phases of a three phase machine.

Only one of the formulae given in 4511 changes for single phase loading, where the constant $\sqrt{3}$, is removed thus:-

$$\text{kW genr.} = \frac{\text{volts x current}}{1{,}000} \text{ x power factor}$$

However in assigning values to the terms in all these formulae, it is the single phase values that must be considered. Great care must be taken to ensure that the values selected are the correct ones. In particular the voltage value should be given special consideration since in a 3 phase star connected machine:-

$$\text{volts (line to line)} = \sqrt{3} \text{ x volts (line to neutral).}$$

In the delta connected three phase case, single phase loads can be connected only from line to line, since there is no neutral point.

When connecting single phase loads to a three phase a.c. generator it is advisable to distribute the loads over the three phases as evenly as possible. Using the formulae from 4511, with the above notes, the total 'worst case' single phase and two phase loadings can be calculated. To obtain the equivalent 3 phase rating for 'kW genr', these single phase and two phase calculated loadings must be multiplied by 3. This will ensure that no part of the main output winding is overloaded by carrying too much load current.

The final point about unbalanced loads is that as the amount of unbalance increase, the voltage regulation and voltage balance between phases worsens.

For example of this type of clrculation see Section 4595.

CONSTANT OR STEAD STATE LOADS - SINGLE PHASE

Some three phase machines can be reconnected to provide a single phase supply. More often, if a single phase supply is all that is required, a machine with a specially wound single phase winding is supplied.

Whichever is the case, the total constant or steady state single phase load is derived in exactly the same way as the three phase case.

The necessary conversion formulae are given in section 4511 with one change. For single phase calculations the constant $\sqrt{3}$ is removed thus:-

$$\text{kW genr} = \frac{\text{volts x current}}{1{,}000} \text{ x power factor}$$

From this all single phase load ratings can be calculated to a common base of kW.

In this case there are no factors to multiply by in order to obtain the total kW loading. The final calculated kW load figure is compared directly with the standard output lists to obtain the correct minimum frame size of machine, as before. Remember to look up the single phase rating lists. If there is no single phase rating list available please refer to the factory.

TRANSIENT OR MOTOR STARTING LOADS

Preceding sections dealt with constant or steady state loads and were concerned the temperature rise. In this section it is the transient performance that is discussed, in particular during motor starting. By far the most common problem in correct sizing of an a.c. generator concerns the starting of induction motors.

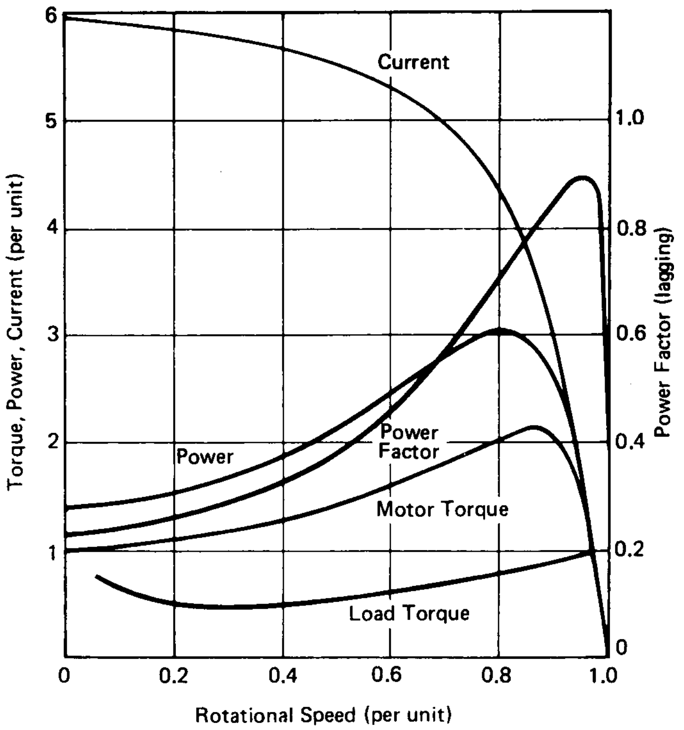
In order for a motor to start to rotate, the magnetic field of the motor must be built up to create sufficient torque. During the starting period a very large current is demanded form the power source. This is known as starting or locked rotor current. The level of starting current can vary greatly depending upon the motor design. Six times motor full load current can be considered a usual starting current for the most three phase motors. In applying this level of load to an a.c. generator, the output voltage disruption may be quite severe. Momentary transient voltage dips in excess of 40% are possible. Consequent effects of this on other connected loads may be experienced. For example, lighting may dim or even go out altogether; other motors may stop due to insufficient holding voltage on the control contactor coils or release of undervoltage protection relays. Therefore, for most applications a maximum voltage dip ought to be specified. Generally the maximum voltage dip should not exceed 30%; and in the absence of any prescribed limit this is the figure normally assumed.

An a.c. generator inherently has a characteristic which resists any change in voltage. Time is required for the machine's magnetic field system voltage to rise or decay to compensate for load or output voltage changes. Such long time lags (in order of a second) are not acceptable with today's fast acting voltage control systems. To reduce this time lag to acceptable limits (in order of 1/10th second), it is necessary to force a lot of current into the field, forcing the voltage to change quickly. This forcing current is about 3 times normal full load field current. The majority of voltage control systems operate in this way and the effect is called 'field forcing/ For brushless machines this means that the exciter, the main field and the control system must be liberally rated for normal load conditions. Under severe overload conditions, after the initial voltage dip, the high field forcing will rapidly cause the output voltage to return near to the normal value.

Provided other connected loads can tolerate a high transient voltage dip, this characteristic is ideally suited for loads consisting mainly of direct on line started induction motors. The initial voltage dip may be the cause of insufficient starting torque, but then the field forcing rapidly increases the voltage towards nominal levels which means an increase in available motor starting torque. This starting torque increase should rapidly become sufficient to start the motor rotating. Therefore in this specific situation it is not the voltage dip characteristic that is of most interest as is normal, but the steady state relationship between voltage and load. It is this that must be examined to see if sufficient starting torque will become available. These overload curves are shown in individual data sheets in section 6.

The per unit overload capability of a.c. generators does not alter when connected for 3 phase or single phase operation. Hence single phase motor can be started as readily as 3 phase motors, providing the same basic rules are applied. The maximum overload capability of the Newage Stamford range of a.c. generators is given in both the standard publications (Section 2) and in the technical data sheets (Section 6). In all instances the maximum current drawn by the load during starting must never exceed the stated overload capabilities given for a specific a.c. generator. Note that these overload capabilities are always referred to the standby industrial continuous maximum ratings. Derated machines, for example marine machines, should have any motor starting calculation based on the equivalent maximum industrial rating and then, if required, be referred back to the marine rating. In other words, the overload capability in 'per unit' terms appears higher for marine machines than for industrial machines because of the derate, although the actual overload capability (in amperes or kVA) remains the same in both cases.

Below is a graph of typical performance characteristic of an induction motor when operated at a nominal constant voltage level; i.e. a mains supply giving no voltage dip on motor starting.



From this graph, we see that the motor power factor is very low on start. The a.c. generator overload capabilities given, are valid for any lagging power factor in the range zero to unity. If the machine has a connected base load at a high power factor (say 0.9 lag) and a motor is then started (at around 0.2 Lag); then the power factor of the two loads should be taken into account by vector addition, in order to correctly estimate any overload during start. However, since in these cases an arithmetic addition always gives a larger answer than the vector addition, then it is safe to do the overload capability check by using arithmetic addition of the base load, and the motor start load instead of the true vector addition.

Another point to notice from the graph is the peak power requirement needed from the prime mover. This can be up to 3 times full load power (kW) of the motor being started, and this has to be supplied by the prime mover, instantaneously as the motor passes through about 80% speed. Should the prime mover be unable to develop sufficient power for this, the prime motor being started will crawl low at speed determined by the balance between the power developed by the prime mover and the power required by the motor. Normally the energy stored in the fly-wheel of a diesel engine is sufficient to overcome this problem on starting motors that are small compared to the size of the prime mover. However on starting comparatively large motors, the difficulties here are complex and it is not always appreciated that the prime mover under these circumstances can be the cause of many motor starting failures!

There are a number of ways to reduce the dip level on starting motors. Consideration of the best sequence of starting, if there are many motors or groups of motors, is vital. Simply by rearranging the sequence it is sometimes possible to utilise a smaller a.c. generator. It is possible to design machines specifically for motor starting duty. These are basically low transient reactance machine and may have a lower than normal steady state rating for a given size of a.c. generator, but this can still be economic where the load is totally direct-on-line started motors. However, simply using a larger machine in order to reduce voltage dip is not economic when compared with the cost of some form of reduced voltage starting. This need careful assessment of the application, to decide if a type of reduced voltage is acceptable. The starting current drawn reduces as the square of the reduction in voltage, but at the same time, starting torque is also reduced by the same amount. Hence any high inertia load must be approached with care before deciding to attempt a reduction in a.c. generator size by using a reduced voltage starting method. The various methods of motor starting are discussed in the next section.

For an example of a motor starting problem see Section 4595.

This system required that all 6 ends of the 3 phase motor are brought to terminals. Through two contractors or a changeover switch, the windings are initially connected in 'star'; then usually after a preset time delay or when the motor has run up to a steady speed, the windings are reconnected into 'delta'. This is the normal running condition at full line volts.

This mean that:-

(a) the starting voltage is reduced to $1/\sqrt{3}$ of V_L since $V_L = \sqrt{3}V$ line to neutral

(b) starting current is also reduced to $1/\sqrt{3}$ of the D.O.L. value since $I \alpha T_M$

(c) starting kVA is reduced to 1/3 of the D.O.L. value since kVA αV_L^2

(d) starting torque is reduced to 1/3 of the D.O.L. value since $T_M \alpha V_L^2$

Assuming, as with the D.O.L. case:-

per unit over load capability	= 2.5 p.u.
D.O.L. starting current	= 6.0 x 1_M
motor efficiency	= 90%

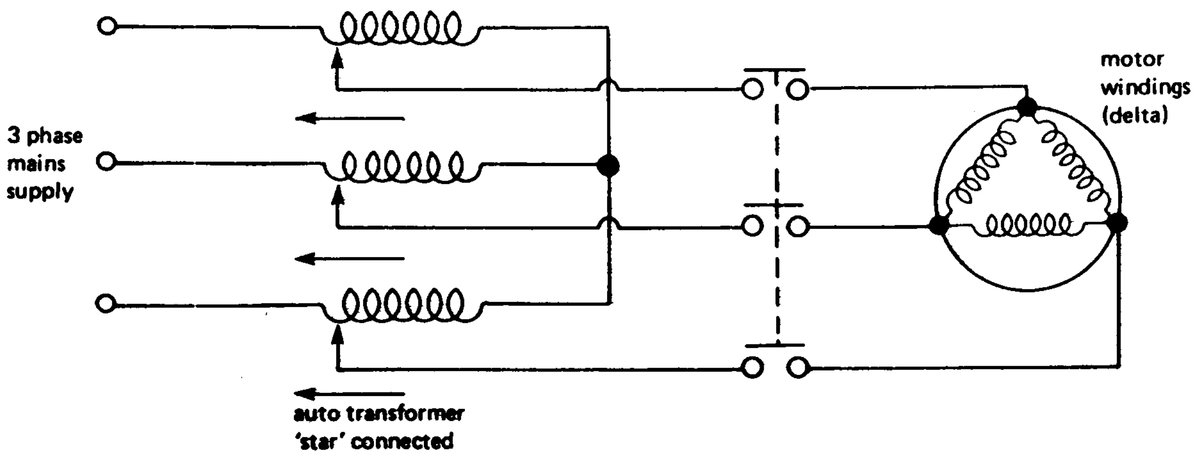
Then the value of the ratio of S can be calculated from

$$\text{kW genr.} = \frac{6}{3 \times 2.5 \times 0.9} \quad kW_M$$

ratio $\underline{S = 0.889}$

Note: For values of S less that 1.0, this implies that the a.c. generator kW rating can be less than the motor kW rating for starting purposes. This is true, but of course the a.c. generator would be unable to supply the motor with its full load continuously rated steady state power! In other words, values of S less than 1.0 are not practical.

Auto Transformer Starting



Whereas the star/delta system uses contactors and requires a 6 ends out motor winding to achieve a fixed, reduced voltage motor start; this method can be used with any type of motor and uses an auto transformer with fixed voltage taps along its winding. The basic idea is that a low line voltage is tapped off the auto transformer and fed to the motor on start. As the motor speeds up, the tap position is changed in any number of steps, increasing the line voltage until the full line voltage is directly across the motor terminals. Commonly used taps are 65% and 80% of full line voltage. Using the same form of calculation the following can be derived:-

assume:- a.c. generator overload capability 2.5 p.u.
motor start current 6.0 p.u. efficiency 0.9 p.u.

Tap position	65%	80%	100% (as D.O.L.)
Reduction in line starting voltage	35%	20%	0%
Starting current is reduced to % of D.O.L. value	65%	80%	100%
Starting kVA and staring torque are both required to % of D.O.L. value	42%	64%	100%
Value of ratio S is	1.12	1.71	2.67

Again, as with the star/delta case, check that the full load motor run kW is less than the selected a.c. generator frame size kW rating, to ensure that the a.c. generator is capable of supplying the steady state continuous maximum running power requirement of the motor.

For an example of a motor starting problem see Section 4595.

CONVENTIONAL MOTOR STARTING METHODS

Throughout this discussion the following symbols will be used:-

I = full load current of a a.c. generator at maximum rating.

I_M = running full load motor current.

kW genr. = rated full load kW of a.c. generator

kW_M = rated full load shaft kW of motors

S = ratio of a.c. generator kW requirement per kW motor rating.

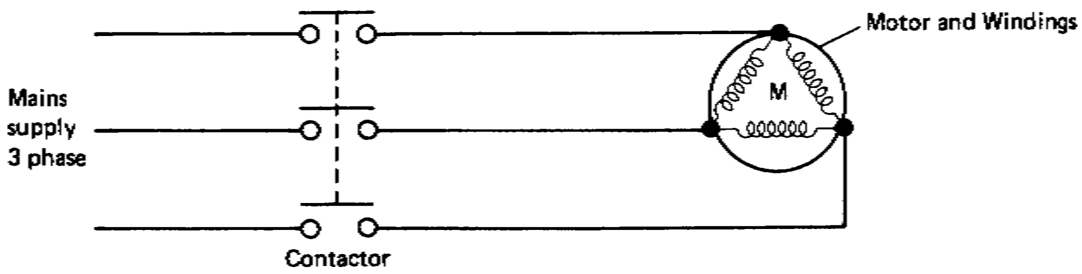
T_M = starting torque required by motor.

V_L = line voltage.

$\cos \varnothing$ = load power factor.

h_M = motor efficiency.

Direct-on-line (D.O.L) Starting



In this case the full line voltage is switched directly to the motor terminals. The motor winding normally is connected delta. The maximum starting torque is available with this method, but a very high starting current is required.

Assumptions:-starting current is 6 times motor full load current.

N.B. Some motor manufacturers specify 7 or 8 times and any calculation would need the correct figures inserted; hence the earlier warning to obtain full technical details from the motor manufacturer (Section 4501).

a.c. generator overload capacity is 2.5 p.u.

Then under starting conditions: $2.51 \geq 61_M$

From this we can derive a ratio of a.c. generator kW rating per kW motor rating.

Since $I = \dfrac{\text{kW genr.}}{\sqrt{3}\, V_L \cos \varnothing}$ and $I_M = \dfrac{\text{kW}_M}{\sqrt{3}\, V_L \cos \varnothing_M}$

We get $2.5 \times \text{kW genr.} = 6\, \dfrac{\text{Kw}_M}{\eta_M}$

and assuming a motor efficiency, η_M, of 90%

$$\text{kW genr.} = \frac{6}{2.5 \times 0.9} \times \text{kW}_M$$

$$= 2.67\ \text{kW}_M$$

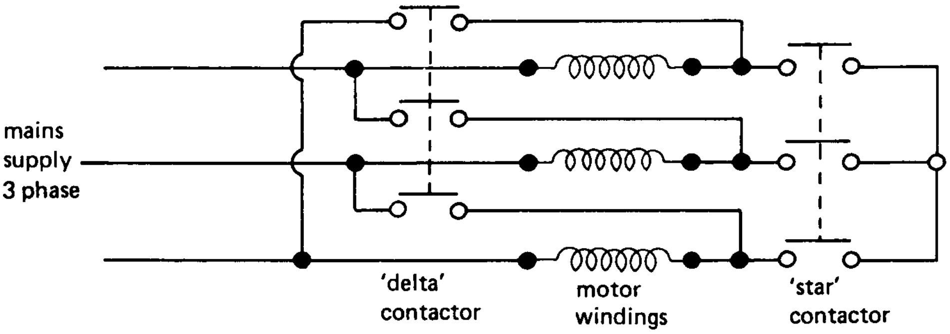
ratio <u>S = 2.67</u>

Similarly ratios for different values of overload capability, motor start current and motor efficiency can be calculated.

The voltage dip during a 3 phase D.O.L. motor start should be considered. If starting current is known this can be converted to starting kVA (multiply by voltage x √3 for a star (Wye) connected motor). The voltage dip curve on the appropriate generator data sheet (Section 6) may then be used to read off the transient dip. If the dip is beyond a specified limit a larger generator must be chosen.

If starting current is not given a good working assumption is to take 7.1 x hp rating of the motor (9.5 x kW rating) as the starting kVA value. This is equivalent to the most severe case for a NEMA Code G motor.

Star - Delta Starting



Since $I = \dfrac{\text{kW genr.}}{\sqrt{3}\, V_L \cos \varnothing}$ and $I_M = \dfrac{kW_M}{\sqrt{3}\, V_L \cos \varnothing \quad {}_M}$

We get $2.5 \times \text{kW genr.} = 6 \dfrac{Kw_M}{\eta_M}$

and assuming a motor efficiency, η_M,of 90%

$$\text{kW genr.} = \frac{6}{2.5 \times 0.9} \times kW_M$$

$$= 2.67\ kW_M$$

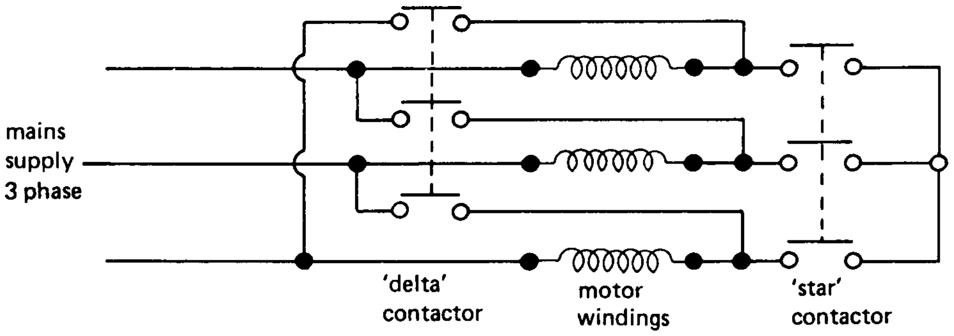
ratio $\underline{S = 2.67}$

Similarly ratios for different values of overload capability, motor start current and motor efficiency can be calculated.

The voltage dip during a 3 phase D.O.L. motor start should be considered. If starting current is known this can be converted to starting kVA (multiply by voltage x √3 for a star (Wye) connected motor). The voltage dip curve on the appropriate generator data sheet (Section 6) may then be used to read off the transient dip. If the dip is beyond a specified limit a larger generator must be chosen.

If starting current is not given a good working assumption is to take 7.1 x hp rating of the motor (9.5 x kW rating) as the starting kVA value. This is equivalent to the most severe case for a NEMA Code G motor.

Star - Delta Starting



EXAMPLES OF SELECTION FOR VARIOUS LOAD CONDITIONS

The following examples cannot hope to cover every possible calculation method, but they do demonstrate an approach for your guidance. Some are taken from actual enquiries whilst others are devised to demonstrate specific points.

Example One

This example was devised to consider many different load conditions simultaneously. The supply required is assumed to be 415V 3 phase 50Hz.

LOAD DETAILS

Single Phase 240V

(a) 72 fluorescent light fittings each 100W and power factor corrected to 0.95 p.f. lag.
(b) 7 heaters each requiring 20A.
(c) 4 x 5 h.p. motors, started simultaneously Direct-On-Line (D.O.L.).

Single Phase 415V

(d) 5 welding sets each rated at 11A primary current 0.4 p.f. lag.

Three Phase 415V

(e) 3 x 3 h.p. machine tool motors started in sequence D.O.L.
(f) 1 x 80 h.p. motor started by auto transformer at 80% tap but with a poor full load power factor of 0.6 p.f. lag.
(g) 1 x 80kW motor started star/delta with a locked rotor current of 750A.

LOAD ANALYSIS

Now let us consider each load in turn.
For the single phase loads ((a) to (d)) we shall calculate the ‘worst case’ single phase loading for each item and then multiply by 3 to obtain the equivalent 3 phase loading, (Section 4512). This assumes that one of the 3 phases always carries the highest single phase load of each item. This is unlikely to occur in practice as the total loads should be connected as balanced over the 3 phases as possible; however, it is a valid assumption for the purpose of a.c. generator sizing.

LOAD (a)

72 fittings over 3 phases can be balanced at 24 fittings per phase.

Steady State

Hence maximum single phase load is:

24 x 100 = $\underline{2.4\text{kW}}$ (Section 4512)

and $\dfrac{2.4}{0.95} = \underline{2.5\text{kVA}}$

Transient

There is no transient condition given for consideration

LOAD (b)

7 Heaters over 3 phases means one phase must supply 3 heaters

Steady State

Hence maximum single phase load is:

$3 \times \frac{\underline{240 \times 20}}{1000} = \underline{14.4\text{kVA}}$ (Section 4512)

From Section 4501, heaters can be assumed to run at unity power factor; hence load = $\underline{14.4\text{kW}}$

Transient

There is no transient condition to consider

LOAD (c)

4 motors over 3 phases means that one phase must supply 2 motors

Steady State

Hence maximum steady state phase load is given below.

From manufacturer's data; 5 h.p. single phase motor typical performance figures are:

Efficiency = 0.78 p.u. rating.
Power Factor = 0.8 p.f. lag

Steady State Load is:

$2 \times \frac{\underline{5 \times 0.746}}{0.78} = \underline{9.6\text{kW}}$ (Section 4512)

and $\frac{\underline{9.6}}{0.8} = \underline{12.0\text{kVA}}$

Transient

For the one phase with 2 motors starting simultaneously, from Section 4522:

D.O.L. Start Factor = 7.1

Hence Start kVA = D.O.L. Start Factor x h.p. rating.

= 7.1 x 5 x 2

= $\underline{71\text{ kVA}}$

LOAD (d)

5 welding sets across one pair of 415V lines given a 'worst case' of one pair of lines having to supply 2 welding sets.

Steady State

Hence loading is:

$2 \times \frac{\underline{415 \times 11}}{1000} = 9.1\text{kVA}$ (Section 4512)

and 9.1 x 0.4 = $\underline{3.6\text{kW}}$

Transient

No transient condition details are given for consideration

LOAD (e) - 3 x 3 h.p. 3 phase motors.

Steady State

From manufacturer's data, the typical full load running performance is:

Efficiency = 0.78 p.u.
Power Factor = 0.8 p.f. lag

Then the steady state loading is:

$3 \times \frac{3 \times 0.746}{0.78} = 8.6\text{kW}$ (Secction 4511)

and $\frac{8.6}{0.8} = \underline{10.8\text{kVA}}$

Transient

For the transient or starting condition, only one of these motors will be started at any one time since they are started in sequence. In the absence of actual starting performance data: Section 4522 gives the maximum D.O.L. start kVA; thus:

3 x 0.746 x 7.1

= <u>15.9 start kVA</u> per motor started

LOAD (f) - 1 x 80 h.p. motor.

Steady State

From manufacturer's data

Efficiency = 0.91 p.u.
Actual Power Factor(given)
= 06. P.f.lag

Then steady state loading is:
$\frac{80 \times 0.746}{0.91} = \underline{65.6\text{kW}}$ (Section 4511)

and $\frac{65.6}{0.6} = \underline{109.3\text{kVA}}$

Transient

The transient or starting kVA derived from Section 4522 gives the maximum D.O.L. start kVA thus:

80 x 0.746 x 7.1 = 424kVA

For auto transformer start at 80% tap (Section 4522)

Start kVA = $424 \times (0.8)^2$

= <u>271 start kVA</u>

LOAD (g) - 1 x 80kW motor

Steady State

Again from manufacturer's data we obtain:

Efficiency = 0.91 p.u.
Power Factor = 0.91 p.f. lag

Hence the steady state loading is:

$\frac{80}{0.91} = \underline{87.9\text{kW}}$ (Section 4511)

and $\frac{87.9}{0.91} = \underline{96.6\text{kVA}}$

Transient

The D.O.L. starting kVA required is calculated from the locked rotor current given; thus: (Section 4511)

$\sqrt{3} \times \frac{415 \times 750}{1000} = 539\text{kVA}$ for D.O.L start

For star/delta starting (Section 4522) the kVA on start is reduced to 0.33 of the D.O.L. value:

Therefore start kVA = $\frac{539}{3} = \underline{180\text{ start kVA}}$

LOAD SUMMATION

We can not analyse these results and derive a final rating for a suitable a.c. generator. We shall make some further assumptions, and whenever such a calculation as this is attempted, it is essential that all assumptions made, are clearly detailed and passed on to the final customer. In this case assume:-

(i) no two loads will be switched on simultaneously

(ii) generally, the loads come on in the sequence given.

(iii) for sizing purposes the effort of power factor (vector addition) during transient or motor starting loads is ignored since arithmetic addition of the loads will always give a larger kVA load figure than the vector addition.

Summation of Single Phase Loads

Load	Steady State			Transient	
1	kVA 2	kW 3	p.f 4=3/2	Start kVA 5	6
(a)	2.5	2.4	0.95	-	
(b)	14.4	14.4	1.0	-	
(c)	12.0	9.6	0.8	71.0	
(d)	9.1	3.6	0.4	-	
Total	38.0	30.0	0.79		

This total single phase loading represents the worst possible case, as we have assumed that one particular phase always carried the highest unbalanced load current for each single phase load considered. In practice it is likely that the individual loads would be more evenly distributed between the three phases. However, for the purposes of sizing and in the absence of actual load connection data, this is a valid assumption. The steady state total single phase ratings can now be multiplied by 3 to obtain the equivalent 3 phase rating.

Regarding the start kVA load of (c), this again is the worst case single phase surge kVA. The make up of load (c) is such that on start there is unbalanced surge kVA. Therefore the total 3 phase surge kVA on starting load (c) will be less than 3 times the worst case 71kVA. This product (213kVA) is in turn less than the highest 3 phase balanced start kVA which, from the table below, is 271kVA. Hence this single phase start kVA may in this case be ignored when considering the 3 phase summation table below.

Summation of Three Phase Loads

Load	Steady State			Transient	
1	kVA 2	kW 3	p.f. 4=3/2	Start kVA 5	Total Load at Start kVA 6
equiv. 3 phase for (a), (b), (c),(d)	114	90.0	0.79		
(e)	10.8	8.6	0.8	15.9	114 + 15.9 = 129.4
(f)	109.3	65.6	0.6	271	114 + 10.8 + 271 = 395.8
(g)	96.6	87.9	0.91	180	114+10.8+109.3+180=414.1
TOTAL	330.7	252.1	0.76		‘worst case’ is 114+10.8+96.6+271 = 492.4

In the previous table we have assumed that all the single phase loads are applied together with the transient condition ignored as discussed above.

The highest load which must be sustained is given in Col. 6 on the application of load (f), 437.8 kVA. The machine selected must always have a overload capability greater than the largest kVA figure given in Col. 6. Indeed the order of load switching can be vital. To achieve the minimum size of a.c. generator based on 'overload' performance (Co. 6), the loads must be applied in descending order of start kVA's (Col. 5). That is the largest start kVA load must be switched on first and the smallest last. This is the ideal situation for load switching sequence, although rarely achieved in practice.

In this particular example, the 'overload' figures (Col. 6) are not significantly higher than the steady state total kVA. Therefore in this instance, it is unlikely that the switching sequence is that important. Hence we shall consider the worst case for 'overload', that is when load (f), the largest start kVA, is switched on last. This would give a total load on start kVA as follows:-

$$114+10.8+96.6+271 = \underline{442.4 \text{ kVA}}$$

DERATE FACTORS

It is at this point in the calculation that any steady state derate factors must be applied. In this case the final power factor is below 0.8 p.f. lag, hence a derate is required. Interpolating from available date for 0.76 p.f. lag:

derate factors = 0.98

Also any derates for high ambient temperature, restricted temperature rise or high altitude must be applied. In this example we shall assume that the ambient temperature is 45°C; that as the machines are insulated with 'Class H' materials, the associated temperature rise (125°C) is acceptable; and finally that the altitude is below 1000m. Looking at the available data; the derate factor is 0.97 (section 4401)

Applying these derate factors, the selected a.c. generator must be capable of supplying a steady state kVA requirement of

$$\frac{330.7}{0.98 \times 9.97} = \underline{347.9\text{kVA}}$$

It is worth noting that if the derate required for transient performance demands a greater 'kVA' size of machine, then these steady state derate factors do not need to be applied as well. In other words either the steady state derate factors or the transient performance derate factors are applied; whichever gives the larger 'kVA' requirement. It is extremely unlikely that both sets of derate factors should be applied. An assessment of transient performance is given below under the heading 'Voltage Dip Restriction'.

STANDARD SIZING

(a) Steady State

From the summation tables we arrived at a total site load requirement of 330.7 kVA, 252.1 kW, 0.76 p.f. lag.

Applying the steady state derate factor, the kVA requirement was changed to 347.9 kVA. It is this figure that is looked for in the standard output lists given in Section 2.

(b) Transient

Again from the summation tables the maximum start kVA transient requirement is 271 kVA.

The 271 kVA transient load must be checked against the voltage dip curve for the generator selected to determine the % transient voltage dip.

If this level of voltage dip on starting the largest load is acceptable, then the frame size chosen also remains acceptable from a transient performance point of view.

(c) Input Power

The a.c. generator shaft input power is the same as the prime move shaft output power and can be estimated. The a.c. generator efficiency figures are given in the data sheet.

From Section 4511:

$$\text{prime mover shaft power output} = \frac{\text{a.c. generator kW output rating}}{\text{appropriate a.c. generator efficiency}}$$

POWER FACTOR CORRECTION

In general, any load with total power factor ‘leading’ needs careful consideration in selecting a suitable frame size of machine to supply it. Section 4501 recommends ‘ refer to factory’ in such cases.

Power factor correction capacitors operate at almost zero power factor leading and are used to correct the overall low lagging power factor of a complete installation to a value unity power factor but still lagging. This is usually done to reduce tariff charges for industrial consumers of electricity.

Let us look at the effect of adding a 35 kVAr capacitor power factor correction bank to the load installation considered in this example.

The final steady state load figures, from the summation tables, are:

330.7 kVA, 252.1 kW, 0.76 p.f. lag.

Hence the kVAr component = 252.1 x $\tan^{-1}$0.76)
= 215.6 kVAr

With the introduction of 35 KVAr of capacitors at zero p.f. led, the kVAr component reduces to

215.6 - 35 = 180.6 kVAr

Hence the new steady state loading figures are:

(i) the <u>252.1 kW</u> remains the same, as the real power requirement does not change.

(ii) power factor $=\cos(\tan^{-1}\left(\frac{108.6}{252.1}\right))$ =0.813 p.f.lag.

(iii) the kVA $= \frac{252.1}{0.813} = \underline{310.1\ \text{kVA}}$

Notice now that no derate is required for power factor since, with the power factor correction bank installed, the system power factor lies within the range unity to 0.8 p.f. lag. Therefore the required rating must be considered at 0.8 p.f. lag, since this is the standard condition for rating all a.c. generators.

That is, the nameplate rating and site rating becomes:

$\frac{252.1}{0.8}$ = 315.1 kVA; 252.1 kW; 0.8 p.f. lag.

Assuming the same ambient temperature, temperature rise and altitude as before, we arrive at the machine rating of:

$$\frac{315.1}{0.97 \times 1.0 \times 1.0} = \underline{324.8\ \text{kVA}}$$

Notice the addition of the power factor correction bank can reduce the size of a.c. generator required to supply these loads under steady state conditions.

The major problem with power factor correction banks is that, when all other loads are switched off, the power factor correction banks normally remain connected. This represents a purely zero power factor leading load to the a.c. generator and as such we have already recommended 'refer to factory'. One effect of having a comparatively large bank connected to an a.c. generator is for the terminal voltage of the a.c. generator to rise dramatically. Voltages in excess of 500V have been recorded from a nominal 415V machine in such cases.

However, as a general guide, providing the capacitor bank rating is not greater than about 10% of the a.c. generator rating, then no real problems of this nature should be encountered.

In this case we have:

$$\frac{35\ \text{kVAr capacitor bank}}{325\ \text{kVA}} \times 100 = 10.8\%$$

Example Two - from an actual enquiry

Details given:- Base load of 30 kW with a 5 h.p. and a 7 h.p. motor started together D.O.L. followed by a 25 h.p. motor started D.O.L. However, under emergency conditions all loads may come together. Maximum voltage dip 25%. Please advise a.c. generator frame size for the application.

Assumptions:- This enquiry is typical in that much basic data is missing. Assumptions have to be practical and realistic, but there is not need to make things difficult:

(a) supply 415V 3ph. 50Hz.

(b) speed 1500 rev/min hence 4 pole machine.

(c) 30 kW base loads is 1.0 p.f., balanced over 3 phases and without any ‘start’ surges.

In this instance the start sequence is unnecessary, since the worst case is when all loads are applied simultaneously under emergency conditions.

In the absence of actual motor starting data, see Section 4522 where a 7.1 factor is assumed.

5 h.p. (= 3.73 kW) Factor = 7.1 D.O.L. Start kVA = 35.5
7 h.p. (= 5.22 kW) Factor = 7.1 D.O.L. Start kVA = 49.7
25 h.p. (= 18.7 kW) Factor = 7.1 D.O.L. Start kVA = 177.5
Base Load 30

TOTAL 292.7 kVA

Arithmetic addition is permitted since this will give an answer greater than the true vector addition which accounts for power factor.

The voltage dip curves of the individual data sheets must be checked until the smallest generator that gives a dip of not more that 25% at 415V, 50Hz is found.

Then check to ensure continuous steady state kW rating is satisfactory.
Load = 30 kW + 5 h.p. + 7 h.p. + 25 h.p.

The motors are rated for shaft output h.p.; therefore to obtain the input power requirements the motor efficiency is required. An assumption of typical efficiency of 0.83 for small motors and 0.89 for the 25 h.p. motor was made hence:-

$$\text{Load} = 30 + \frac{(5 \times 0.746)}{(0.83)} + \frac{(7 \times 0.746)}{(0.83)} + \frac{(25 \times 0.746)}{(0.89)}\ \text{kW}$$

$$= 30 + 4.5 + 6.3 + 21.0$$

$$= 61.8\ \text{kW}$$

Note: In these cases where it is likely there is no problem with the steady state condition, a quick approximate check without consideration of motor efficiency will suffice. Only when there is likely to be difficulty does the full calculation need to be completed as above.

Example Three

To illustrate motor starting procedures.

Let the supply be 208V 3ph. 60Hz and the load is always a total of 80kW of motors. However, at different times the actual loads can be one of the following:-

(a) 4 x 20kW motors started in sequence D.O.L.
(b) 2 x 40kW motors started in sequence D.O.L.
(c) 1 x 80kW motor started D.O.L.

Voltage dip not to exceed 30%.

Consider case (a)

In the absence of actual starting data, refer to Section 4522 for maximum D.O.L. start kVA = 9.5 x kW rating = 190 kVA for each motor.

Typical power factor = 0.89 p.f. lag.
Typical efficiency = 0.88 p.u.

Now with 3 motors running

$$\text{run kVA} = 3 \times \frac{20\text{kW}}{0.89 \times 0.88} = 76.7 \text{ kVA}$$

Starting the 4th motor gives start kVA = 190 kVA

Total kVA (neglecting effort of power factor) = 266.7

For voltage dip limited to 30% or better, look at the voltage dip curves in the individual data sheets of Section 6.

Check the steady state load to ensure that the selected generator is large enough.

$$\text{Steady state load} = 4 \times \frac{20\text{kW}}{0.88} = 91\text{kW}$$

Check overload capability:-

Maximum demanded by load = 250.7 kVA. Check against the overload capability of the generator selected.

Consider case (b)

Going through a similar procedure as case (a) we get:-

40kW motor D.O.L. start kVA = 380 kVA
typical power factor = 0.91 p.f. lag
typical efficiency = 0.91 p.u.

Now with one motor running; kVA = 48.3

Starting second motor; kVA = 380

Total (neglecting effect of power factor 428.3

Consider case (c)

80kW motor start kVA D.O.L. = 656 kVA
typical power factor = 0.92 p.f. lag
typical efficiency = 0.92 p.u.

Again the generator can be selected by using the dip curves of the data sheet.

Note from this that a single motor supplied by a single a.c. generator may demand a much larger a.c. generator than may be thought, since it must be capable of supplying the large kVA required by the motor starting.

Once again consider the unlimited voltage dip. Can a smaller machine be used, and if so what would be the voltage dip?

ROTATING DIODE PROTECTION

FOREWORD

The rotating diodes on Stamford a.c. generators are protected by a surge suppresser, connected in parallel with the field winding.

This device has the advantage over normal field discharge resistors of using no power during normal operation and clamps the peak transient voltage to a predetermined level.

The following report shows the reason for fitting this form of protection and gives the results of particularly severe tests carried out to show the effectiveness of such a device.

Introduction

During sudden load changes in the stator winding there is flux change within the machine creating a transformer type reaction between the main stator and the rotating field.

This energy has to dissipate through the rotating rectifiers and can, dependent upon whether or not the diode is conducting or blocking, cause damage to the diodes.

If, however, this condition occurs when the diodes are in a blocking state then the energy developed in the field windings will produce a high voltage across the main diodes and unless this energy is absorbed in some alternative path the diodes can be destroyed.

Alternative Paths

The alternative path can take the form of a field discharge resistor connected in parallel with the main field winding. The effectiveness of this depends upon the resistance value in relation to the field resistance, and we find that this should not exceed 15 : 1 for the circuit to be effective. This system has the disadvantage that is absorbs power during normal operation, and has no definite voltage clamping level. (Not used on Newage Stamford a.c. generators).

The alternative path can however, take the form of a surge suppresor, again connected in parallel with the main field winding. This component is effectively a high resistance path during normal operation and as such does not absorb any power. However, during a transient voltage condition this component will ‘avalanche’ at a pre-determined level, introducing a low resistance path that allows the energy to be dissipated without causing any damage to the rotating diodes (fitted as standard on Newage Stamford a.c. generators).

Tests

Tests were conducted to show the protective ability of the surge suppresser and the results were shown on pages 3 and 4.

The nature of the test chosen was the paralleling 180 electrical degrees out-of-phase of an a.c. generator with the mains. This gives rise to the highest overload characteristic likely to cause failure of rotating diodes due to high transients in the field system.

This particular test although more severe than the normal excessive load changes caused by the effect of short circuits, capacitors on fluorescent lights etc,. can occur in practice where unskilled operators are uncertain of the normal rules of paralleling procedure.

When two a.c. generators are paralleled out-of-phase heavy mechanical loads are applied to the couplings etc., and severe electrical loads to the a.c. generators. The worst condition for the a.c. generator is 180 electrical degrees out-of-phase whereas the maximum stresses are applied to the engine and coupling at 120 electrical degrees.

When two a.c. generators are paralleled 180 degrees out-of-phase, a voltage of twice the normal phase voltage is presented to the combined low impedance of the two machines. A very high current will therefore circulate in the stators for a short time unit the resultant synchronising power pulls the machines into step. By transformer action current is developed in the main field windings. When examining the field circuit the 3 phase bridge rectifier can be considered to be a half wave diode, conducting for one half cycle and blocking the current on the next reverse half cycle. A high voltage transient will therefore appear at the field terminals and hence at the rotating diodes.

If the diodes are if insufficient rating or no form of surge suppression is supplied, breakdown of the rotating diodes can result.

Test Results

1. An a.c. generator without any diode protection was paralleled to the mains 180 degrees out-of-phase and a voltage trace across the diodes recorded a transient of 1600 volts (see pate 3 Fig. 1). Two diodes failed during this test.

2. The a.c. generator was then fitted with a field discharge resistor of 80 ohms in parallel to the main field and again two diodes failed (see page 3 Fig. 2, 3 & 4).

3. The discharge resistor was replaced with a 50 ohms resistor and then the transient level was reduced to 1100 volts (still considerably above the normal diode rating of 840 V PTIV) (see page 3 Fig. 5).

4. A selenium surge suppresser was then used instead of discharge resistors across the field windings.

   When the a.c. generator was paralleled 180 degrees out-of-phase no voltage transient exceeded 410 volts (see page 4 Fig. 6-13).

Conclusions

To protect effectively the rotating diodes from damage caused by high load changes or misuse and to do this economically some form of discharge path is required.

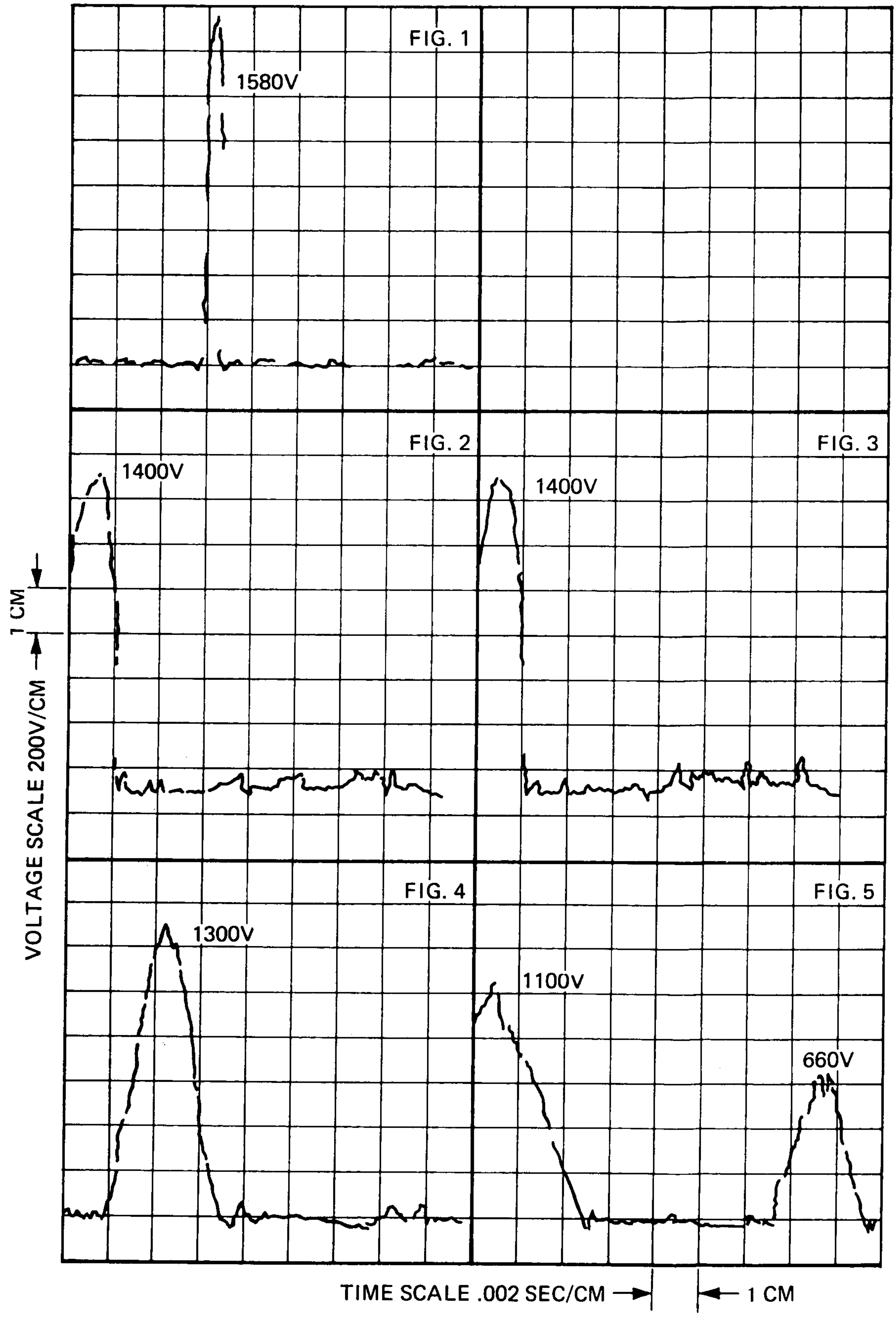
The use of a surge suppresser was the final choice due to:-

a) Its ability to chop transients from 1600 volts to less than 450 volts.

b) Its characteristic that during normal operation its is a high resistance path and therefore does not absorb power.

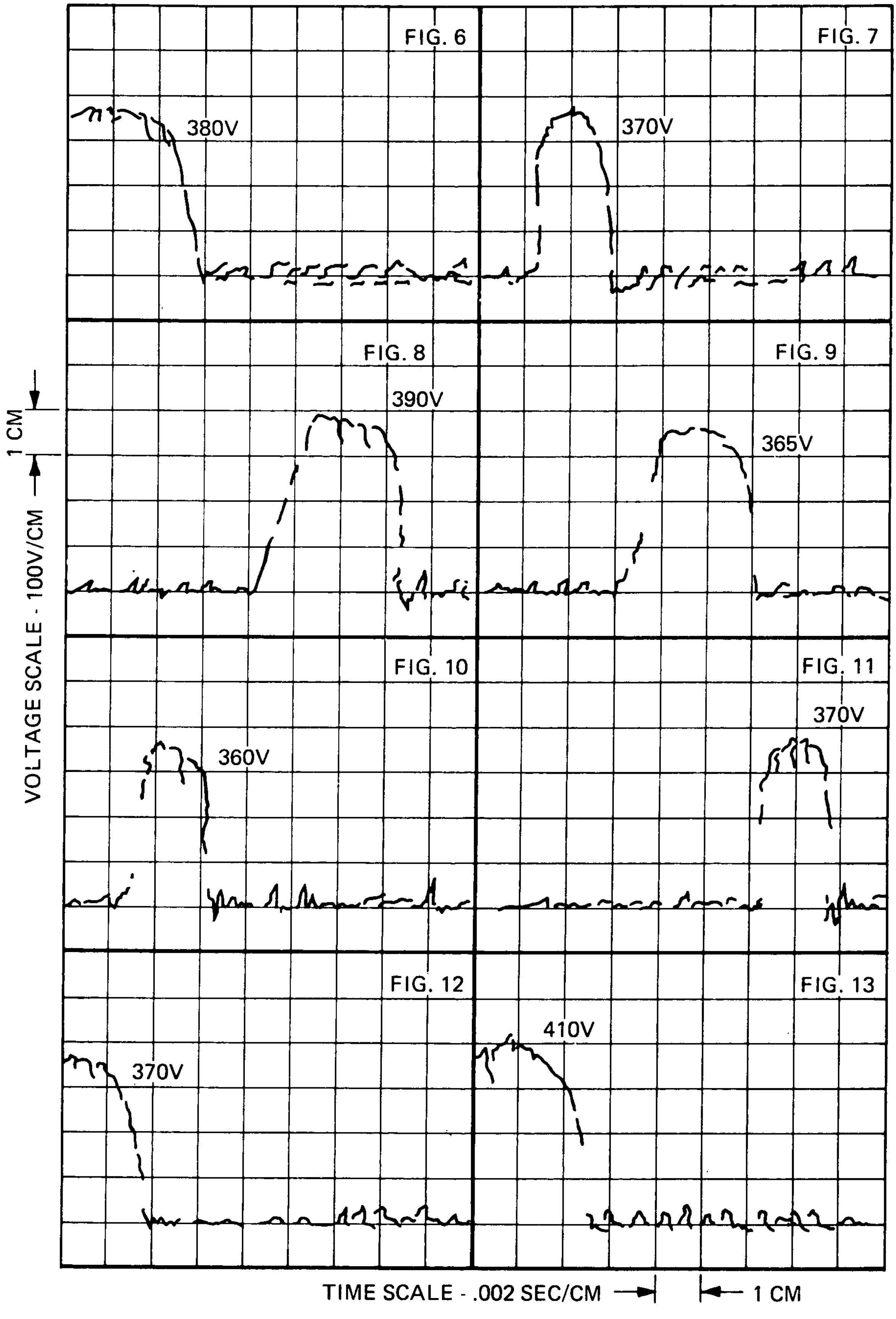
ROTATING DIODE PROTECTION TEST RESULTS

Figs 1 — 5
Main Field Transient Voltages (See text on page 2)



ROTATING DIODE PROTECTION TEST RESULTS

Fig. 6 — 13
Main Field Transient Voltages with AEG Type D — 7 Plate Polarised Surge Suppressor Fitted



PARALLEL OPERATION OF A.C. GENERATORS

1. INTRODUCTION AND THEORY

No one aspect of the a.c. generator set operation causes more misunderstanding than the parallel operation of two or more a.c. generators.

This report will explain the reasons for paralleling, the method by which it is carried out, the setting up procedures and possible problems which may arise.

Paralleling Operation may be necessary for the following reasons:-

(i) To increase the capacity of an existing system.
(ii) Size and weight may preclude the use of one large unit.
(iii) allow non-interruption of the supply when servicing is required.

In order to parallel a.c. generators satisfactorily, certain basic conditions have to be met. These are as follows:

(i) All systems must have the same voltage.
(ii) All systems must have the same phase rotation.
(iii) All systems must have the same frequency.
(iv) All systems must have the same angular phase relationship.
(v) Systems must share the load with respect to their ratings.

A minimum amount of instrumentation is required to ensure the above information is satisfactorily monitored, comprising an ammeter, a wattmeter and a reverse power relay. A voltmeter is not specified for each system because it is preferred to use one voltmeter on the distribution or synchronising panel with a selector switch for each system. This eliminates any possible meter inaccuracies.

A reverse power relay, although contributing a larger proportion of the instrumentation cost, is essential as any engine shut down, from low oil pressure, over-temperature etc., will result in other systems motoring the failed set with consequent overload the remaining systems.

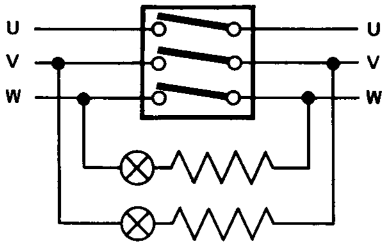
Only one frequency meter is required with the facility of being switched to the busbar of the incoming system.

A synchroscope and/or lights, are required to detect the angular phase displacement. If lights are used three different connections are possible. For paralleling with the lights dim, they must be connected across like phases or like lines (single phases), i.e. U-U, V-V or L1-L1. For paralleling with lights bright they should be connected across unlike phases, i.e. U-V etc.

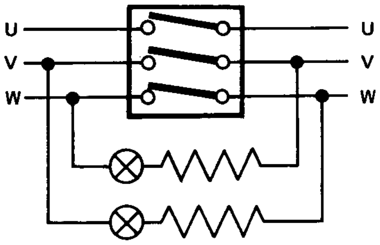
If a three lamp system is used with the lamps connected across U-W, V-V and W-U the lamps will ‘rotate’ and give the indication which machine is running fast. Synchronism is reached with two lamps bright and one dark and in some respects this connection gives a closer visual indication of the point of synchronism. Note the lamps should be rated for at least twice the machine voltage or if will be necessary to connect two or three in series. A preferred method is a resistor/lamp combination.

The following diagrams illustrate the connections:

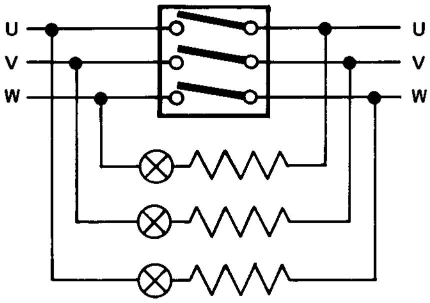
LAMPS DIM



LAMPS BRIGHT



LAMPS BRIGHT/DIM



Note: If the neutral is solidly linked, then only one set of lamp/resistors is required because the return path is through the neutral link. This, of course, only applies to the lamps dim and lamps bright connection, and not to the three lamp connection.

Load Sharing

The most important aspect of parallel operation is load sharing. The total load, comprising a kW or active component and a kVAr or reactive component, must be shared by the systems in proportion to their normal ratings.

The kW component is adjusted by purely mechanical means and requires relatively fine speed control of the prime mover. It is advisable to fit a limited range governor to avoid ‘ misuse’ of the speed control.

The kVAr component is a function of the a.c. generator excitation. When machines are in parallel, the magnitude of the field excitation cannot directly influence the output voltage. It does, however, adjust the internal power factor at which a particular machine operates. For instance, an over-excited a.c. generator will draw lagging current whereas an under-excited a.c. generator will draw leading current. If a difference in excitation exists, then circulating currents will flow, limited only the internal machine reactance. This current will appear as a zero p.f. leading or lagging current dependant on the machine excitation and will either subtract or add to the total current that each machine supplies. Reactive current, either leading or lagging is, by virtue of the 90° phase displacement, quite commonly described as being in quadrature.

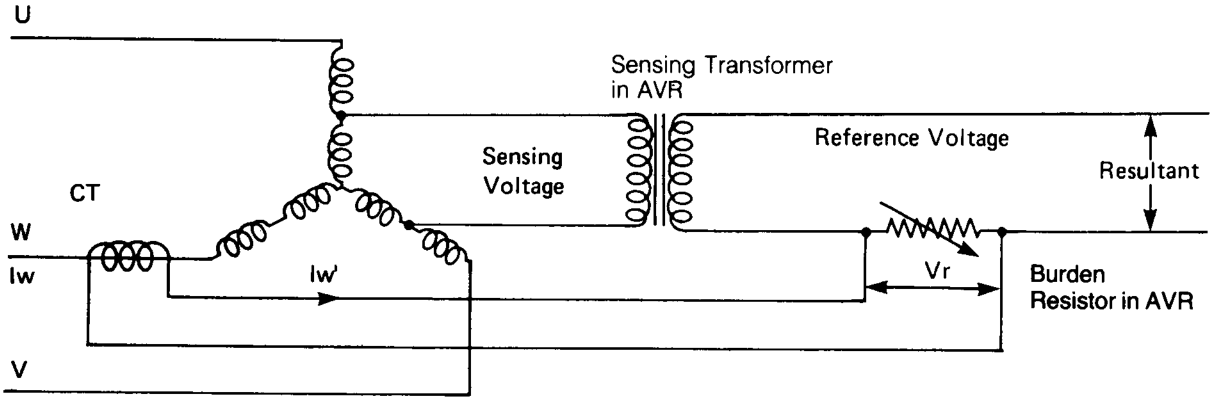
Means must, therefore, be provided to sense this reactive current and limit is to an acceptable level. Hence a quardrature droop kit. This comprises a current transformer (CT) connected to the AVR burden resistor and the following paragraphs and vector diagrams describe and illustrate its action.

On a 2 phase sensed Stamford a.c. generator, the reference or sensing voltage is obtained from the two phases U and V. The CT is wired in W phase and its output dropped across the burden resistor within the AVR. The burden resistor in connected such that the voltage produced across it adds vectorially with the sensing voltage.

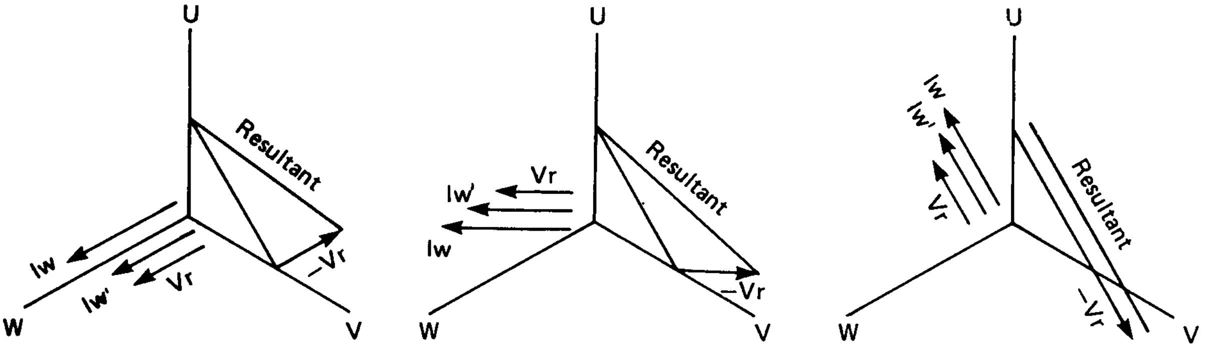
Examination of the vector diagram shows that at 1.0 p.f. the small voltage produced across the burden resistor adds at right angles to the sensing voltage. This produces little change in the sensing voltage and therefore little change in the terminal voltage.

The effect is more marked at 0.8 p.f. but only marginally so. At zero p.f., however, the additional voltage is in phase with the sensing voltage, producing a much larger change.

Droop Kit Wiring Diagram



Vector Diagrams



Unity p.f.

0.8 p.f.

Zero p.f.

The artificially high voltage now seen by the sensing circuit causes the machine excitation to be reduced. Sufficient voltage is produced to ensure that when full load current at zero p.f. is flowing, the terminal voltage will droop by 5%. This should be sufficient to limit the circulating current to a satisfactory level which in any case should not exceed 5% of the normal maximum current.

In short, the machine supplying more thank its share of the reactive current has its excitation reduced. As an under-excited a.c. generator draws less reactive current, the excitation balance and hence power factor balance in restored.

2. GENERAL NOTES ON SETTING UP PROCEDURE

These notes should be read in conjunction with the notes on page 6 and 7 where a simplified step by step procedure is given.

Stable parallel operation and accurate load sharing between no load and full load can only be obtained when the initial voltage settings and the droop kits are correctly set up. It is also most important that the governor characteristics are similar otherwise incorrect kW load sharing can result when either increasing or reducing load.

To check the no load voltage settings, run each machine singly at the normal no load frequency, i.e. 51.5 Hz for 50 Hz operation or 62 HZ for 60 Hz operation. The rated voltages should now be set to within 1% of each other. In the case of machines fitted with hand trimmers, this is a simple operation. Where no hand trimmer is fitted adjustment is made directly on the AVR.

Quadrature Droop Equipment

The most important aspect of initial setting up procedure concerns the droop kit. Most of the troubles allied to poor parallel operation originate from droop kits. They are either incorrectly adjusted for the level of voltage droop or are incorrectly connected such that a rising voltage characteristic is obtained. If a machine is specified for parallel operation at the time of ordering, then the droop kit supplied will have been set up on test. So long as the terminal markings and connections are followed, no problems should result.

NOTE: Reversal of the transformer or reversal of the secondary connections to the transformer will result in a rising voltage characteristic which is completely unstable during parallel operation.

Where machines have to be modified to incorporate a droop kit at a later date, ensuring a drooping voltage characteristic appears to be of the greatest difficulty. As previously stated, the droop kit is correctly adjusted when the terminal voltage droops 5% with a zero p.f. or reactive current equal to the full load current being supplied.

SETTING THE DROOP CIRCUIT

Remember: The generator Droop kit can control only the KVAr sharing and circulating current. The sharing of kW load is determined by engine governors.

The droop DT on 3 phase machines is connected to the droop input terminals S1-S2 and is adjusted by the droop potentionmeter which is mounted on the AVR circuit board. The droop can be increased by turning the potentionmeter in a clockwise direction.

On single phase machines the droop CT is connected across a burden choke. The droop is varied by changing tappings on the burden choke.

For both the two phase and three phase sensed machines the operation is the same in that any circulating current between machines produces a voltage across the burden resistor or choke which directly adds to or subtracts from the sensing voltage fed into the AVR. This makes the excitation system sensitive to circulating currents and ensures correct sharing of the KVAr load. The larger the droop voltage is set, the more flexible becomes the excitation system to reduce circulating currents and ensure KVAr load sharing. In most cases a 5% droop on the output voltage at full load zero p.f. (Power Factor) lag, is satisfactory. This droop is only measurable with the machine running alone (i.e not parallel). This setting degrades the voltage regulation by about 1% at full load unity p.f. and about 3% at full load, 0.8 p.f. When a unity power factor load (kW) is applied the voltage produced across the burden resistor/choke adds vectorially at right angles to the sensing voltage and has a minimal effect. When the machines are run individually, the droop circuit can be switched out by short-circuiting auxiliary terminals S1 and S2 to obtain the normal close regulating characteristics of the machine.

NOTE: MX341 and SX440 with separate 3 phase sensing units. The droop adjustment is on the 3 phase sensing unit. Access to the unit is gained by removing terminal box lid.

Generally a zero power factor load will not be available. A 5% droop at 0 p.f. can be set accurately by measuring the voltage across S1 and S2 on the auxiliary terminal block.

The optimum position for the ‘DROOP’ setting potentionmeter on the AVR can be found as follows:

1. Apply full load amperes to machine, at any power factor including 1.0.

2. Measure voltage across the AVR terminals S1-S2, which is also the output from the C/T.

3. Using the following formula, calculate the position of the droop potentionmeter as a percentage rotation from FULLY ANTICLOCKWISE.

$$\text{Position of Droop Potentionmeter (0-100\%)} = \frac{\text{*Constant X 100}}{\text{Voltage across S1-S2}}$$

*Constant

For AVR type SX440, MX341 = 0.7
For AVR type MX321 = 2.0

NOTE: If the formula produces a figure of more than 100%, check that you have the correct C/T for the size of the load current.

Single Running Operation of Machines with Parallel Droop

The voltage is required to droop at least 2½ % for satisfactory load sharing in parallel. If better regulation is required for single machine operation a shorting switch must be fitted across the parallel droop current transformer.

This switch should be mounted on the instrument panel, clearly marked ‘PARALLEL RUNNING’, in the open circuit position.

3. STEP BY STEP SETTING UP PROCEDURE

The points detailed below are meant as a general guide only. If any doubts exist as to the reason for the various tests, further reference should be made to the preceding notes. Obviously, all machines must be correctly wired in accordance with the appropriate connection and wiring diagram.

(a) Run No. 1 a.c. generator on no load at rated speed. Check a.c. generator voltage and adjust where necessary.

(b) Check phase rotation of No. 1 a.c. generator.

(c) Run No. 2 a.c. generator and proceed as items a and b.

(d) With Nos. 1 and 2 a.c. generators running on no load, switch in synchroscope or lights.

(e) Adjust speed until synchroscope rotates very slowly or lights slowly brighten and dim.

(f) Check finally that voltages are equal or within 1% of each other. Adjust as required.

(g) Close breaker at synchronism; observe ammeters for circulating current. If in excess of 5% recheck no load voltage settings and droop kits for polarity (reversal).

(h) Increase load until full load appears on each a.c. generator when in parallel. Some adjustment to one engine governor may be required to ensure balanced kW meter readings.

(i) Check the ammeter readings with the kW meters equal. They should be within 5% of each other.

(j) If the ammeter readings are outside %5, the machine with highest current is over-excited and therefore requires more droop to compensate. Increase the droop resistance.

(k) With full load current on each a.c. generator reduce the external load in 20% increments. At each loading, observe kW meter and ammeter readings down to 20% full load. Any variation of either instrument beyond 5% of each other requires correction.

(l) Unequal kW sharing implies a faulty prime motor, most likely the governor.

(m) Unequal ammeter readings at the full load end of the range imply incorrect levels of droop.

(n) Unequal ammeter readings approaching the no load condition imply incorrect voltage settings.

4. WORKING PROCEDURE

The most likely procedure that occurs in practice concerns the paralleling of additional machines to already loaded sets. For instance, if a set is supplying a load equal to 75% of its output and further load is anticipated, the resident engineer may decide to spread this load over two sets. A procedure somewhat on the lines of the following is required.

The incoming set is started and run at the no load frequency. The synchroscope/light switch is closed connecting the incoming machine and the busbar via the synchroscope or lights. As the incoming machine is fast, the synchroscope will rotate in the 'fast' direction or the lights will brighten and dim at a rate dependent on the frequency difference. The speed of the incoming machine should be reduced by actuating the motorised governor in the slow direction. When the frequencies are nearly equal, the speed of rotation of the synchroscope or the changes in brilliance of the lights will slow enough to enable the set contactor to be closed when the voltages are in synchronism. This will be at the twelve o'clock position on the snychroscope or with lights bright or dim dependent on which connection is used.

In order that the incoming machine may now take its share of the load, the governor control should be held in the speed raise position until the desired load is indicated by the kW meter and ammeter. Conversely, if too much load is applied it can be reduced by holding the governor control in the speed lower position. It is most important that the total load be shared in respect of their normal ratings the meter readings should be compared with the nameplate data. In any event, unequal load sharing requires correction to avoid mechanical problems which occur when diesel engines are run light for any considerable time.

It is important to differentiate between unbalanced loading caused simply by the operator failing to spread the load equally over the two sets, and by circulating currents unbalancing the ammeter reading.

For example: consider two - 100 kVA a.c. generators in parallel with no circulating currents supplying 150 KVA 0.8 p.f.

With load distributed equally, meter readings would appear as follows:

	VOLTS	AMP	kW	kVA	p.f.
Machine No. 1	400	108	60	75	0.8
Machine No. 2	400	108	60	75	0.8

If the load were distributed unequally, again with no circulating currents, the following figures could appear:

	VOLTS	AMP	kW	kVA	p.f.
Machine No. 1	400	144	80	100	0.8
Machine No. 2	400	72	40	50	0.8

If now the same unequally distributed load is being supplied, but circulating currents are present, meter readings something on the lines of the following could be observed:

	VOLTS	AMP	kW	kVA	p.f.
Machine No. 1	400	192	80	133	0.6 Lag.
Machine No. 2	400	62	40	43	0.93 Leading

Machine No. 1 is now supplying 133 kVA at 0.6 p.f. considerably in excess of its normal rating. Continued operation under this loading would cause the overload protection circuit to trip or the main stator and the rotor to fail. Machine No. 2 is operating so under-excited that it is operating at leading power factor and at a much reduced kVA.

This will in no way damage No. 2 a.c. generator, but in itself implies that No. 1 a.c. generator is very heavily overloaded. A leading power factor condition is particularly difficult to detect except when individual power factor meters are fitted. The normal instrumentation of ammeter, voltmeter and kW meter cannot indicate such a load condition.

5. DIFFICULTIES:

Some of the paralleling problems that can occur are detailed below. Probable causes are also shown:

(a) Oscillating kW meter, ammeter and voltmeter.
Cause: Engine governing; replace by known serviceable unit.

(b) Unbalanced ammeter readings. kW meters balanced and stable.
Cause: Circulating current through incorrect voltage settings, droop kit connections reversed or insufficient droop.

(c) Unbalanced ammeter readings on no load or rapidly rising currents as soon as the breaker is closed.
Cause: Incorrect voltage settings or droop kit connections reverse.

(d) Unbalanced kW and ammeter readings as load increased or decreased.
Cause: Dissimilar governor speed regulation.

(e) Unbalanced ammeter readings as load increased. KW meters balanced.
Cause: Droop circuit settings not identical or one droop kit reversed.

Apart from the above problems, certain peculiarities may exist which are in no way detrimental to the operation of the sets. They may, however, confuse the operator into thinking a fault exists.

The most common query results from voltage oscillation during the initial paralleling procedure.

When an additional set is being connected to the busbars with the synchroscope/lights switch in the on position, a point may be reached where the incoming machine voltage starts to fluctuate. This only occurs when the frequency difference is at its greatest. As the frequencies approach each other, no further instability is noticed. This is not, however, a function of the stability circuit within the AVR, but relates to ‘pick up’ problems associated with the switchboard wiring.

6. NEUTRAL INTERCONNECTION

It should be noted that paralleling of all the system neutrals can under certain circumstances lead to overheating or possible stator burn outs.

This is particularly evident when machines of a dissimilar type/manufacture are paralleled. Differences in generated waveshape may cause large harmonic circulating currents through the interconnected neutrals.

The neutrals of dissimilar machines must, therefore, never be connected. On the other hand, neutrals of like machines may be connected.

7. PARALLELING WITH THE MAINS

For parallel operation with the mains utility we recommend the use of our Nupart VAr/p.f. controller, since this permits the user optimum control of locally generated power factor, leading of lagging.

THREE PHASE SHORT CIRCUIT DECREMENT CURVES

1. INTRODUCTION

When a fault occurs in a power network, the current which subsequently flows is determined by the internal e.m.f.'s of the machines in that network, by their impedance's, and by the impedance in the network between the machines and the fault.

The current flowing in a synchronous a.c. generator immediately after the occurrence of a three phase short circuit, that flowing a few cycles later, and the sustained or steady state value differ considerably because of the effect of armature reaction on their air gap flux in the machine. The current decays relatively slowly form its initial value to its steady state value.

Selection of circuit breakers for a power network depends not only on the normal operating current but also on the maximum current it may have to carry momentarily and the current it may have to interrupt at the voltage on the line in which it is situated. Therefore it is always necessary to determine the initial value of current when a fault occurs on a system in order to select a breaker having sufficient momentary rating.

In general, sub-transient reactance's of a.c. generators are used to determine the initial current flowing on the occurrence of a short circuit, thus fixing the interrupting capacity of circuit breakers. For the purpose of stability studies, where the problems lies in determining whether a fault will cause a machine to lose synchronism with the rest of the system if the fault is removed only after a pre-set time interval, transient reactance's apply.

These reactances are determined from the open and short circuit magnetisation curves, and the sudden applied short circuit oscillogram tests. This report is concerned only with the explanation of the sudden applied short circuit oscillogram.

2. ARMATURE CURRENT DURING THREE PHASE SHORT CIRCUIT

Consider a generator with negligible resistance, separately excited and running on open circuit. On short circuiting its terminals the e.m.f. is provided with a closed path comprising the stator windings, and a short circuit current is circulating through them.

Initially, this short circuit is a function of the e.m.f. and the leakage reactance of the machine and immediately assumes a large value. It is also considerably affected by the instant in the cycle at which short circuiting occurs. For example, if the short circuit is applied at an instant near a voltage zero, the initial short circuit current is almost double the value of that when short circuit is applied at an instant in the cycle near voltage peak.
After a few cycles, the effect of armature reaction causes a gradual reduction of e.m.f., and hence short circuit current, to the steady state value determined by the synchronous reactance of the a.c. generator.

Figs. 1a and 1b show the decay of current peaks produced by the gradual rise of armature reaction:-

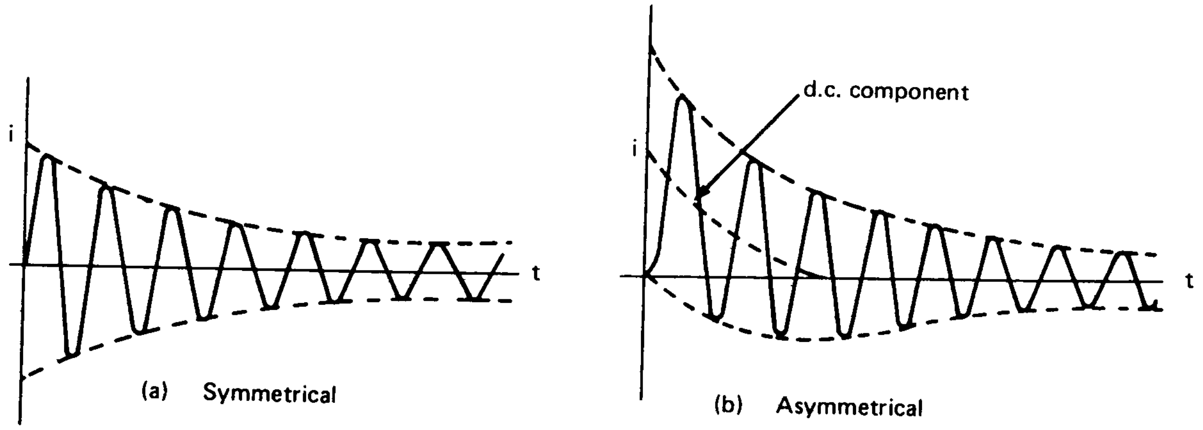


Fig.1 Armature Short Circuit Currents in Synchronous Generator

Briefly, the short circuit current under fixed, external separate excitation is comprised as follows:-

(i) the a.c. component which initially is a function of the leakage reactance, and attenuates slowly to become the normal steady state short circuit current.

(ii) The d.c. component, the magnitude of which is determined by the instant in the cycle at which short circuit occurs, being zero at the instant when the voltage passes through peak value (symmetrical short circuit), or a maximum at the instant when the voltage passes through zero (asymmetrical short circuit) attenuating rapidly away after only a few cycles.

3. DEVIATION OF REACTANCE FIGURES

If three phase short circuit is applied at the terminals of a previously unloaded a.c. generator running at a rated speed and an oscillogram is taken of the current in any one of the phases, in all probability, unless the short circuit is applied at exactly the peak of the e.m.f. waveform, an asymmetrical short circuit current trace will result.

The d.c. component causing asymmetry can be graphically or mathematically eliminated , leaving the symmetrical a.c. component current envelope as shown in Fig. 2 (curve ‘cm’). By graphical construction, curves ‘bm’ and ‘dm’ can be plotted, this representing the transient component of the short circuit current and the fully asymmetrical current envelope respectively. Line ‘am’ represents the steady state short circuit of the a.c. generator.

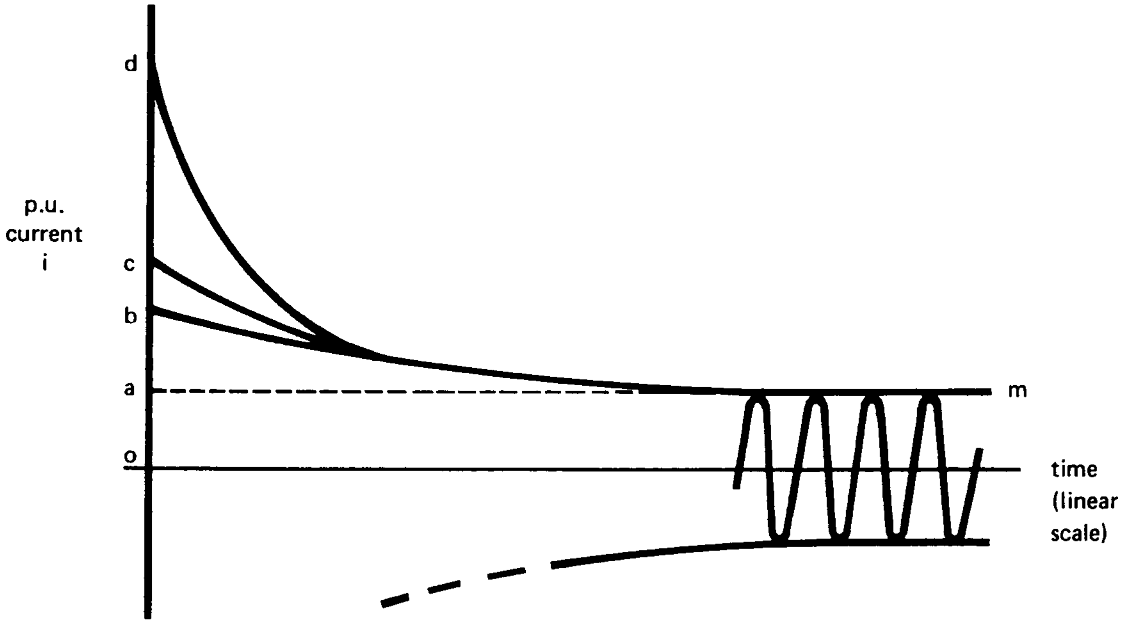


Fig. 2 A.C. Generator Short Circuit Decrement Curves (Separate Excitation)

If each curve is extended back to time zero, the current values measured in per unit r.m.s. and with open circuit voltage set at the rated value (1.0 per unit) prior to applying the short circuit, then the following are obtained:-

a) 1/oa = Per unit direct-axis synchronous reactance, Xd.
b) 1/ob = Per unit direct-axis transient reactance. Xd’.
c) 1/oc = Per unit direct-axis sub-transient reactance, Xd”.
d) Magnitude od represents the initial value of a wholly asymmetrical short circuit current and equals approximately 2 x oc.

4. SHORT CIRCUIT CURRENT DECREMENT CURVES

The curves published for Stamford machines are given in the Section 6 data sheets. The characteristic shape is given in Fig. 3 below.

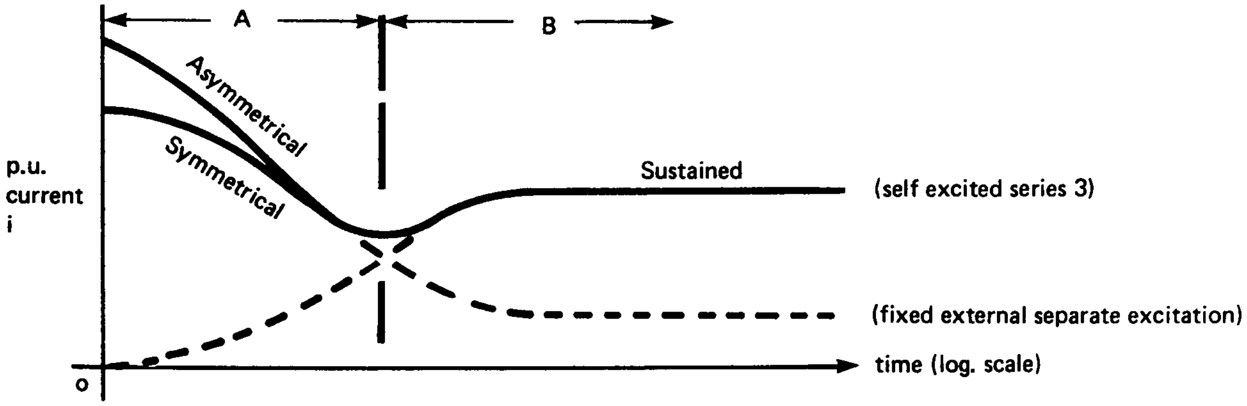
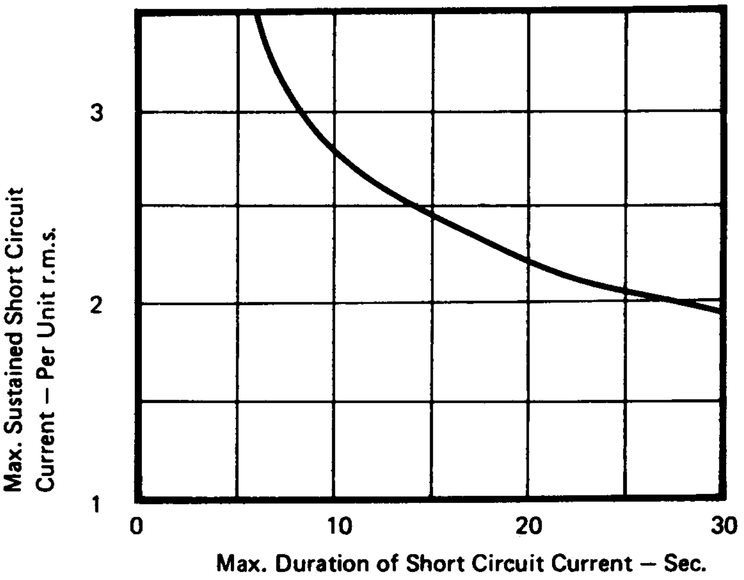


Fig. 3 Characteristic Shape of Three Phase Short Circuit Current Decrement Curve

This curve comprises two distinct and independent parts. The period A represents the early part of the curve shown in Fig. 2. This is governed by machine reactances and the level of voltage set on machine prior to the short circuit being applied. The period B shows the current forcing effect of the AVR or transformer used and is limited only by the maximum output of the excitation system.

5. DURATION OF MAXIMUM SUSTAINED SHORT CIRCUIT CURRENTS

In order to present circuit breakers with enough current to effect a trip in event of a short circuit fault, it is necessary to increase the steady state short circuit current level, usually to a value well in excess of 1 per unit, (period B in Fig. 3). Due to the detrimental effect a high sustained current will eventually have on short circuited stator windings, it is desirable to impose limits on the time allowed before the circuit breakers must interrupt to prevent overheating damage to the a.c. generator. These limits are given in Fig. 4.



NOTE

Per unit values based on Max. kW output at rated frequency, and the mid point of the standard winding voltage range.

Fig. 4.

CONTROL FOR GENERATORS IN PARALLEL

When designing generators and control circuitry for generating sets operating in parallel there are several important aspects to be considered. For the machine, the fundamental factors to be considered are output waveform characteristics, field damping and damage due to mal-synchronising. The waveform of the machine needs to be analysed for third and multiples of third harmonic content, particularly where paralleling of the neutral is required.

If the waveform contains these harmonics, it may be necessary to fit a reactor in the neutral link to reduce the flow of harmonic currents. For stable parallel operation, a fully interconnected field damping winding is required as this reduces oscillations due to forced torsional vibrations.

The most important aspect of parallel operation is correct synchronising. Before two generators or supplies can be connected in parallel they must be synchronised; the frequency, phase angle and magnitude of the phase voltages must be matched.

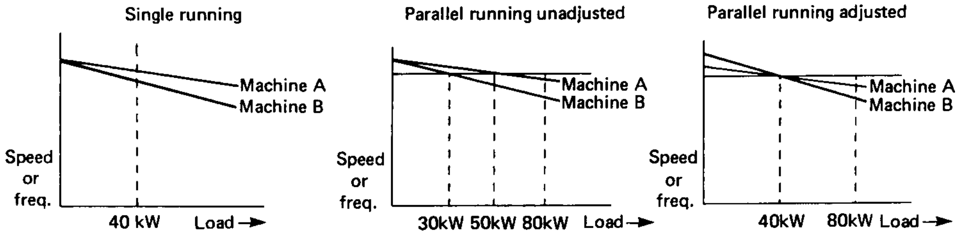


Fig. 1 Power load sharing by two identical machines as a function of engine governing.

Normally the voltage of the incoming set is adjusted slightly above that of the other supply or generator so that the incoming set immediately takes up load. Failure to meet these criteria can result in mechanical damage of couplings if the vibration of phase angle is wide.

It should be noted that if paralleling is carried out at 120 degrees out of phase, the coupling torque can be 10 to 12 times full load torque depending on the ratio of engine and generator inertias. Unless adequate protection is fitted, damage to rectifiers feeding the main field can also be sustained from transient field voltages when the paralleling circuit-breaker is closed with the generator out of synchronism.

Simple Synchronising

Other methods are available to simplify correct synchronisation and the simplest way is with synchronising lamps to indicate when phase angles are similar. This system depends on the skill of the operator to see that frequency and voltage levels match, and more important, skill and ‘feel’ for closing the paralleling circuit-breaker. In many instances unskilled operators are required to parallel generators, and as a first stage to eliminate the need for operator skill, check synchronisers are available. These monitor the phase angle, voltage and frequency each generator and, via an electronic circuit, light an indicating lamp when all three parameters are within acceptable limits. It is then safe the parallel and the operator can manually close the circuit-breaker. With this type of equipment various tolerance settings are available on all parameters, but there is still an element of skill in the operation. However, such skill is unnecessary with an automatic check synchroniser which monitors the same parameters as the manual check synchroniser. If the parameters are outside the tolerance limits set, a control single is generated which may be used to adjust the appropriate parameter so that paralleling can be made safely.

Generally, with automatic voltage regulator (AVR) controlled generators, once the voltage level has been set there will be no diviation other than that due to speed change; and it is therefore only necessary to include control circuits to correct engine speed. Where automatic synchronising is used, with sets for mains peak lopping or for adding sets in a mutli-generator installation, a time delay is needed to avoid unnecessary starting and stopping during short term load variations. A time delay, when used on multi-generator main failure installations, can present a problem in the length of time taken to get all sets de-excited and exciting after all engines have reached full speed. Minimum time delay is therefore achieved and problems associated with rapid synchronisation removed. For this application it is necessary to have a generator which can be suitably switched on the excitation side. It is also necessary to incorporate controls of engine speed to ensure all sets are running before excitation is applied. Synchronisation against the mains using de-excitation can be made but this requires a series reactor to reduce field transient voltages and high torque loads to the coupling. This is subsequently short circuited.

It is possible with two similar generators, to synchronise a second or third generator on to the bus of an already operating generator as the source impedance would be much higher than that of the mains thus reducing the chances of failure due to transient voltages or torques. The correct synchronisation of machines is essential to prevent damage to the machine. Once sets are synchronised and paralleled each has to share its proportion of the load with regard to the reactive current and true power. True power load sharing is purely a function of engine governing, Fig. 1, whereas reactive current sharing is a function of the excitation control system.

The minimum instrumentation to ensure load is being shared correctly is a single voltmeter plus wattmeters and ammeters for each generator. A frequency meter is also desirable generally and essential for manually controlled sets. Totally automatic installations utilise electronic synchronisation and, in general, for these applications the engine speed will automatically be controlled.

Quadrature droop

As previously mentioned, the voltage control when an AVR system is used, is normally not additionally controlled from the synchroniser but should, if the generator is likely to be paralleled with mains or different generators, be fitted with a quadrature droop circuit which ensures generators share reactive load.

The method used for load sharing depends on the control system employed. Broadly, regardless of generator type, (i.e. brushless or slip-ring), control systems can be identified as (a) static control or (b) AVR control or (c) a combination of AVR and static.

Fig. 2 shows a block diagram of a typical static excitation system. This system has an inherent drooping characteristic at low power factors which is suitable for load sharing in parallel operation and generally, generators with this type of control can be paralleled easily with similar generators by the setting of regulation characteristics or paralleling fields.

Generators with other control systems however, are not as readily paralleled, as the drooping characteristics may be non-linear with load increase.

Fig. 3 depicts two basis AVR systems, one having excitation power derived from main stator windings the other having power derived from a separate source. The AVR system maintains constant voltage regardless of load. A drooping characteristic is required and this is achieved by use of quadrature droop equipment which gives the required effect by modifying the sensed voltage signal the AVR. Quadrature droop effects the regulation whether machines are operated singly or in parallel unless switching circuits are employed to short is out for single operation. AVR controlled generators with a separate power source require the quadrature droop, but if isolation between the AVR circuits and the stator exists, they can be made to share load by paralleling fields. This feature allows greater versatility of paralleling the other control systems, for example the static system.

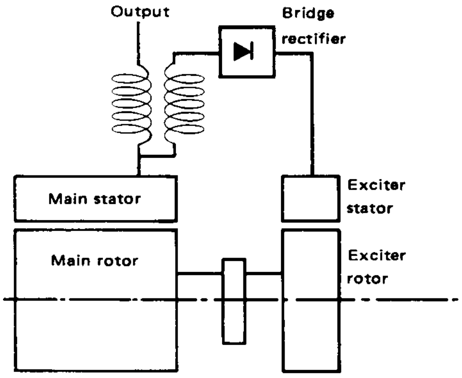


Fig 2. Static excitation system

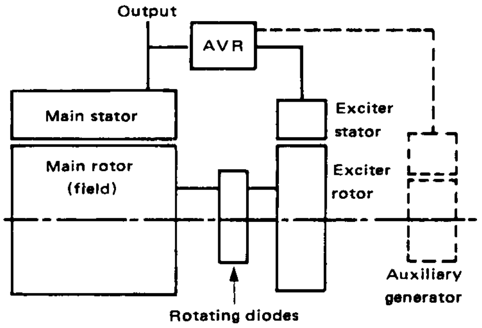


Fig. 3. Possible basic AVR schemes using either excitation power from main stator winding or from a separate auxiliary source (dotted).

Matching of excitation voltages by using resistors is likely to be required and the ratio of no load excitation to full load excitation must be considered for each generator if load sharing is to be achieved over the range no load to full load. Use of paralleled fields does not affect the voltage regulation in single operation. For an excitation system employing both AVR and static components the field winding consists of two sections, one fed from an AVR and one fed from current transformers. The AVR can be used in a divert mode but it is general for arrangements using an AVR to employ a quadrature droop system for load sharing.

Generally, when generators of the same type are paralleled together and the machines are designed with an effective damping winding, satisfactory operation will be achieved. For operation with different makes of generator using AVR control, quadrature droop is necessary, as it is operation in parallel with the main network. Operating AVR controlled generators with static controlled generators requires special consideration. Control circuitry referred to has been purely for excitation control. Overall control of an installation requires equipment such as under/over voltage protection, under/over frequency protection.

The degree of protection and synchronising equipment depends entirely on the application, and whether the installation will be manned by skilled or unskilled operators, or be automatic.

PROTECTION DEVICES

If the generator in an engine driven generator set is to be properly protected the characteristics of the protection equipment must be matched to the characteristics of the generator. It is not practical to consider all possible fault conditions when selecting the protection equipment for the generator so, in general, the generator short-circuit characteristics has been used to determine suitable protection equipment.

The fault current that flows in a generator is dependent on the generator impedance and excitation system, and the impedance of the network between the generator and the fault. Faults that occur remote from the generator will, in general, be in circuits whose rated current is small relative to the generator output current, and sufficient fault current will be available to operate protection equipment. When a fault occurs at or near the generator terminals the fault current depends solely on the generator, impedance and excitation system and since the current rating of the distribution network at this point is equal to the generator output current, the level of fault current related to circuit rating will be lower.

The basic design parameters of industrial generators have, in recent years, changed to take advantage of better insulation materials and automatic voltage regulators, the prime object being to reduce the cost per kVA output of power units.

The result of this has been that the active material, I.e. iron and copper, is reduced for a given kVA output, giving a machine with an inherently higher impedance. This means that when the generator is subjected to fault conditions, the level of fault current related to generator rated current is reduced. For high fault current an inherently low impedance generator design (or derated machine) is required. The lower levels of fault current make the selection of suitable protection equipment more critical, particularly equipment which is required to operate very early after the application of a fault, e.g. a circuit-breaker operating on magnetic trip. Typical three-phase short circuit decrement curves for industrial generators are illustrated in Fig. 1. Dependent on the time during the voltage cycle at which short circuit is applied, the peak current will vary between the maximum and minimum levels shown. The minimum corresponding to the symmetrical fault and the maximum to an asymmetrical fault.

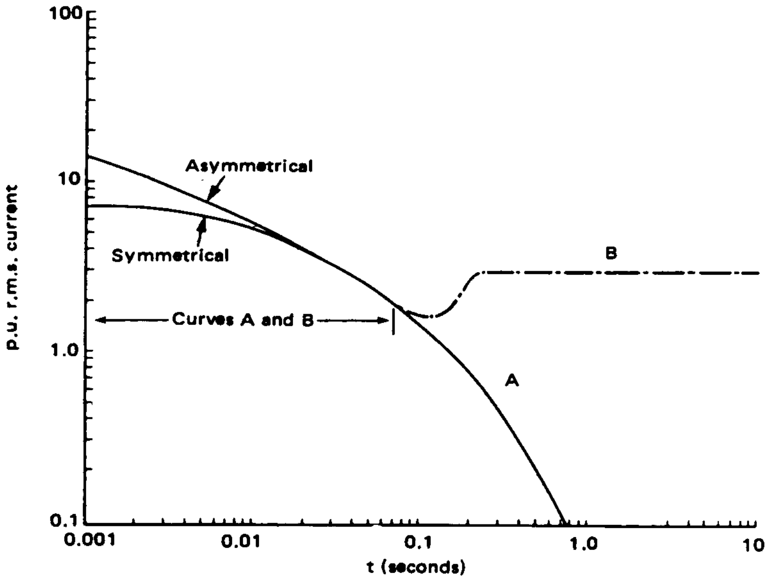


Fig. 1. – Short-circuit current characteristics of (curve A) a typical self-excited machine and (curve B) a machine giving sustained short-circuit level.

Typically a peak current of seven times the generator rated current is achieved on application of a three-phase symmetical circuit. The curves also illustrate variations of short-circuit with time which is important feature in the selection of suitable protection equipment. The initial peak level short circuit is purely a function of the generator electrical design, whereas the level of the curve after, say, the first tenth of a second is dependent on the excitation system employed.

The full lime curve A is that of a self-excited machine. The excitation power is derived from the generator output without current compounding and results in no sustained short-circuit current. Generators which have current compounding, special short-circuit equipment or a separate excitation source, such as a permanent magnet generator, produce a sustained short-circuit and the curve B (broken line) show the typical level of sustained short-circuit current for which excitation systems are designed.

Self-excited generators, as illustrated by curve A, Fig. 1 are not capable of sustaining a short-circuit and therefore no special protection against short circuit is required, since the generator is inherently self-protecting under these conditions. Fault conditions in the network remote from the generator, which may in themselves be short circuits, yet serve only to reduce the total load impedance as seen by the generator, can create overload conditions. Since most self-excited generators utilise excitation systems allowing excitation forcing for up to 2.5 x overload at zero power factor, to give motor starting characteristics, overload created by remote faults can be sustained, so to that suitable protection must be provided.

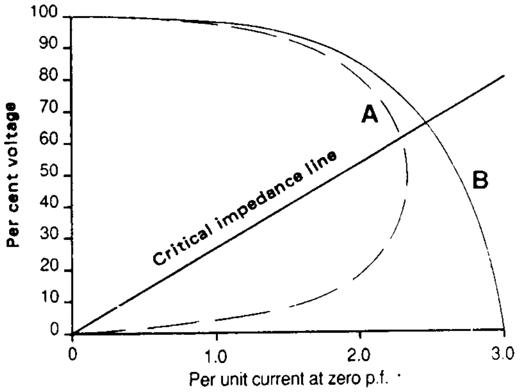


Fig. 2. — Overload characteristic of a self-excited generator (curve A) and load impedance line for maximum overload condition; and the curve (B) for machines with sustained short-circuit current.

In Fig. 2, curve A shows a typical overload characteristic of self-excited machine, together with load impedance line representing the maximum overload condition. Basically, the load impedance values higher than the critical impedance, protection is inherent. The curve shown is drawn for zero power factor load and can therefore only be used to illustrate the generator characteristics. It is not possible to determine the degree of self-protection from this characteristic; the purpose of its inclusion is to show that whilst a self-excited generator may protect itself against a full short circuit it will not always be protected against overload due to system faults. Because no sustained short-circuit current exists; discrimination in the operation of sub-circuit protective equipment is limited to those circuits which, under fault conditions, do not reduce the load impedance of less than the critical value.

Generators having current compounding, special short-circuit equipment or a separate excitation source, have instantaneous peak currents exactly as the self-excited generators, but decaying to a sustained current level, as illustrated in curve B in Fig. 1 Short-circuit conditions at or near generator terminals with this type of machine would, if they existed for more than a few seconds, cause overheating of the generator windings leading to insulation damage and ultimate failure of the windings. (A generator giving three times the normal current on short-circuit will have nine times the full load winding loss). The overload characteristic shown in Fig. 2 curve B clearly shows the no self-protecting characteristic exists and therefore these machines require short-circuit protection. The sustained current characteristic allows better discrimination in the protection of sub-circuits.

Protection can be achieved by a circuit-breaker with thermal or magnetic trips (or both) or fuses. For adequate protection, the chosen device must operate on the fault current provided in a time short enough to prevent damage to the generator windings.

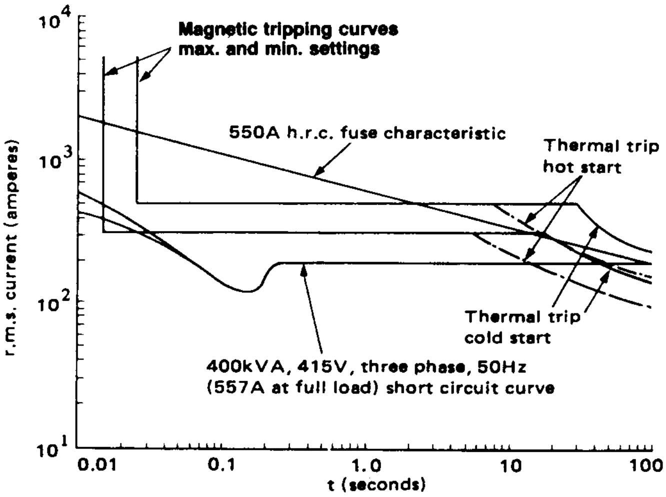


Fig. 3. — Generator short-circuit characteristic compared with the appropriate fuse and circuit-breaker characteristics

Fig. 3 shows typical characteristics of a circuit-breaker, fuse and generator, the fuse and circuit-breaker being selected to suit a generator rating. The characteristics have been plotted on the same graph to illustrate more clearly the degree of protection provided. It will be seen that for early rupturing the fuse requires fault current well in excess of that provided by the generator and it is obvious that if the same generator were equipped with an excitation systen that gave no sustained current, the fuse would never rupture.

With a sustained current of three times full load current the fuse will take 90-100 seconds to rupture. This time is far too long for a short circuit to exist and renders the fuse useless as protection for the generator. The circuit-breaker curves shown are typical of a breaker having both magnetic and thermal trips and indicate the range of settings available by adjustment of the breaker, In this case the transient fault current provided by the generator is just in excess of that required to trip the breaker on magnetic trip, with trip setting in minimum position.

The curves show that if the breaker did not operate on the transient current, then tripping would occur on the thermal trip which would give better protection than a fuse, although still inadequate. Ten seconds is a reasonable maximum time for a short circuit to exist.

Even though it appears from Fig. 3 that adequate protection can be achieved by use of a circuit-breaker, there are limitations to be considered in practice.

Typically the circuit-breaker magnetic trip requires at least five times the breaker rated current to operate. A typical generator transient short-circuit current will have decayed to less than five times full load current in the first few cycles thus making the selection of a suitable breaker difficult. Circuit-breakers are, of course, designed for use on the mains supply where high instantaneous fault current are available.

In addition, the magnetic trip setting usually has an accuracy of ± 20 percent. Ratings of circuit-breakers will not always coincide with the rating of the generator which means that possibly a breaker of higher rating that required must be used. The rating of the breaker considered in Fig. £ was, in fact, ideally suited to the generator rating and this was only just suitable using the criteria of short circuit clearance. In practice, of course, it is more likely that faults occurring at or near the generator terminals will be phase to phase, or phase to earth faults, and under these circumstances both generator and circuit-breaker will have different decrement curves and circuit-breaker operation under these faults is less reliable. The previously assumed criterion of short-%circuit clearance has, therefore, its limitations and from the generator point of view it becomes desirable to have a back-up protection which will overcome these.

Overload and fault conditions on a generator are reflected in the excitation requirements and therefore the excitation voltage level provides the ideal reference for protection equipment. Brushless generators having an auxiliary a.c. exciter are particularly suitable for protection by interruption of the excitation, since the exciter field power requirements are low and rotating diodes act a freewheel diodes for the main field, thus avoiding high transient field voltages.

The Series 3 control system, fitted to the Stamford generator, is powered from an integral permanent magnet generator and incorporates a circuit which de-excites the generator, thereby providing back-up protection, and includes automatic resetting on run-down of the generating set. The excitation voltage is continuously monitored an other protection equipment arrange to trip the excitation, thus collapsing the generator output, when the load conditions creating over-excitation, whether they be overload, distribution network faults, failure of rotating diodes, failure of voltage regulating equipment, or breakdown of excitation during the motor starting. This also allows discrimination in the time of operation of other protection equipment.

VOLTAGE REGULATORS (AVRs) PERFORMANCE AND CONTROL

This section describes in general terms the operation of solid-state electronic automatic voltage regulators used on present day brushless a.c. generators, covering their effect on machine performance for both self-excited and separately excited systems. Full details of each Newage AVR are given in Section 5 of this manual.

INTRODUCTION

During the development of the a.c. generator there have been many types of voltage regulator used in the control of the excitation system. These include the closed loop systems based around various types of automatic voltage regulator (AVR) and the open loop systems based around combinations of reactors, transformers and capacitors.

The AVR has seen many improvements in its performance, reliability and size since the days of the vibrating reed, carbon pile and magnetic amplifier regulators. This has been mainly accomplished by advancements in the electronics field and, in particular in silicon semi-conductor technology which has produced a range of diodes, transistors, thyristors, triacs and, more recently, in thick film technology and integrated circuits. All these devices together with improvements in resistors and capacitors, are now used in the solid state electronic regulators fitted to present day brushless a.c. generators.

This Section will specifically concentrate on two closed loop AVR controlled systems designated ‘self-excited’ and ‘separately-excited’. The Section covers the basic parts of the AVR for both systems together with their own common accessories and the effect they have on the machine performance.

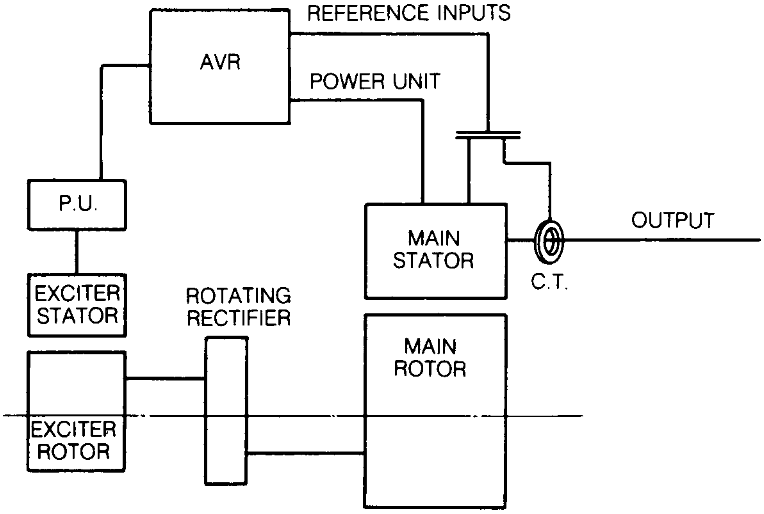


FIG. 1 - SELF-EXCITED AVR CONTROL SYSTEM

Fig. 1 shows the basic components of a brushless generator together with the AVR and its common accessories. The AVR takes its supply from the main stator windings to feed both the power input and reference input. By the control of the exciter stator field current the main stator output voltage is maintained to close the limits with varying load power factor.

Separately-excited AVR control system

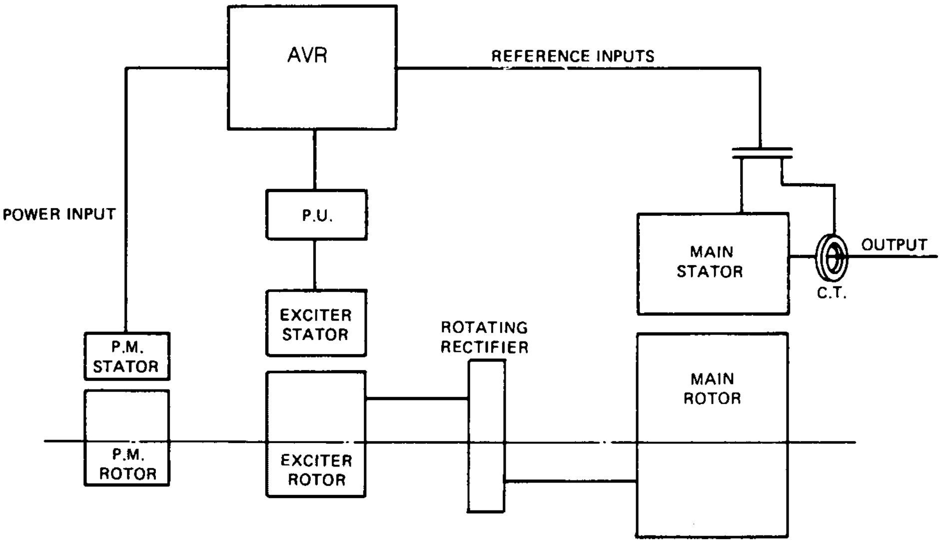


FIG. 2 - SEPARATELY-EXCITED AVR CONTROL SYSTEM

Fig. 2 shows the basic components of a separately-excited AVR control system. The major difference from fig. 1 is that the power input is fed from a separate source, in this particular case a permanent magnet generator. This provides a fixed source impedance which is not affected by external load circuits and gives near constant excitation power under all operating conditions.

The AVR

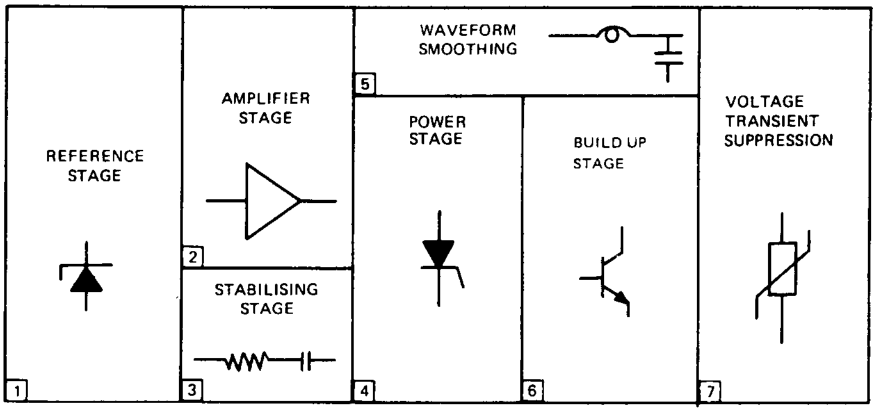


FIG. 3 - THE AVR BLOCK DIAGRAM

Fig 3. Shows the basic AVR block diagram split into various stages. The self-excited system requires all seven stages, whereas the separately-excited system only requires the first four stages.

1) *Reference stage* - This low power high impedance circuit, usually containing a chain of resistors, which includes a variable resistor to adjust the output voltage. The circuit is rectified and filtered and contains zenor diode to act as a voltage reference device. In cases where a common line exists between the field winding and the sensing input, it is desirable to fit an isolation transformer to prevent earth leakage currents from affecting the machine performance.

2) *Amplifier Stage* - This is coupled between the reference and power stages and, as its name implies, amplifies the sensing signal using an operational amplifier i.c. This then provides thesignal to operate the power stage.

3) *Stabilising Stage* - To maintain a high performance it is necessary to have a high d.c. gain in the amplifier stage and during transient changes low a.c. gain to ensure fast response and stable operation. Sudden changes in the power stage are monitored and then fed back into the amplifier stage.

4) *Power Stage* - This usually comprises a number of power diodes with either a thyristor or transistor to control the output current into the exciter field.

5) *Waveform Smoothing* - On the self-excited system where the AVR power is supplied from the main stator output voltage, it is preferable to fit and l.c.r. circuit to reduce any voltage spikes on the output waveform. The choke also acts as a di/dt limiter and the capacitor/resistor as dv/dt limiter to the power semi-conductors.

6) *Build-up State* - With self-excited systems it is necessary for the AVR to operate from the residual voltage of the machine. This is achieved using a combination of mosfet and thyristor technology for maximum sensitivity and ruggedness.

7) *Voltage Transient Suppression* - High voltage transients can be and are generated across the main stator windings from external load sources and again it is preferable on the self-excited system to fit a voltage transient suppression devices to protect the power semi-conductors. This can take the form of a.c.r. network or an available device which absorbs the transient power spike to provide the necessary protection to the semi-conductor components.

Effect on machine performance

1) *Voltage Build-up*- Fig. 4 shows a typical speed/voltage build-up characteristic for both self-excited and separately-excited AVR control circuit. The separately-excited system allows the AVR to pick up extremely fast and as such limits the voltage overshoot to within 5% of the nominal voltage. In the case of the self-excited system, the voltage overshoot during build-up even with a high, permanently connected load across the main stator winding.

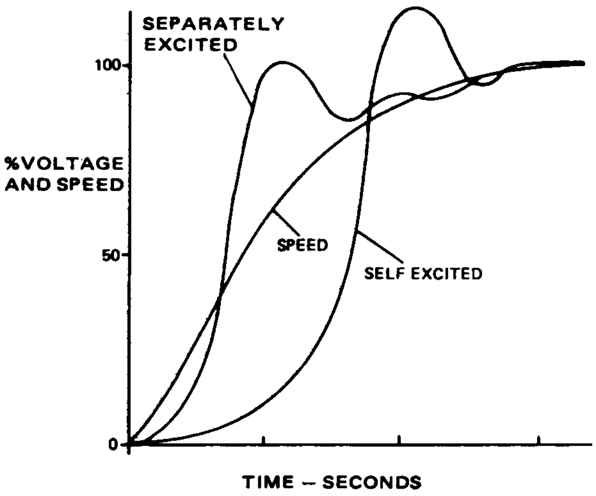


FIG.4 - TYPICAL O/C SPEED/VOLTAGE BUILD-UP CHARACTERISTIC

2) Voltage Regulation - Fig. 5 shows the various sensing circuits used in the AVR. The voltage regulation varies, usually between ±0.5% to ±2%, depending upon the sophistication of the AVR and the amount of distortion of the generator waveform from no load to full load.

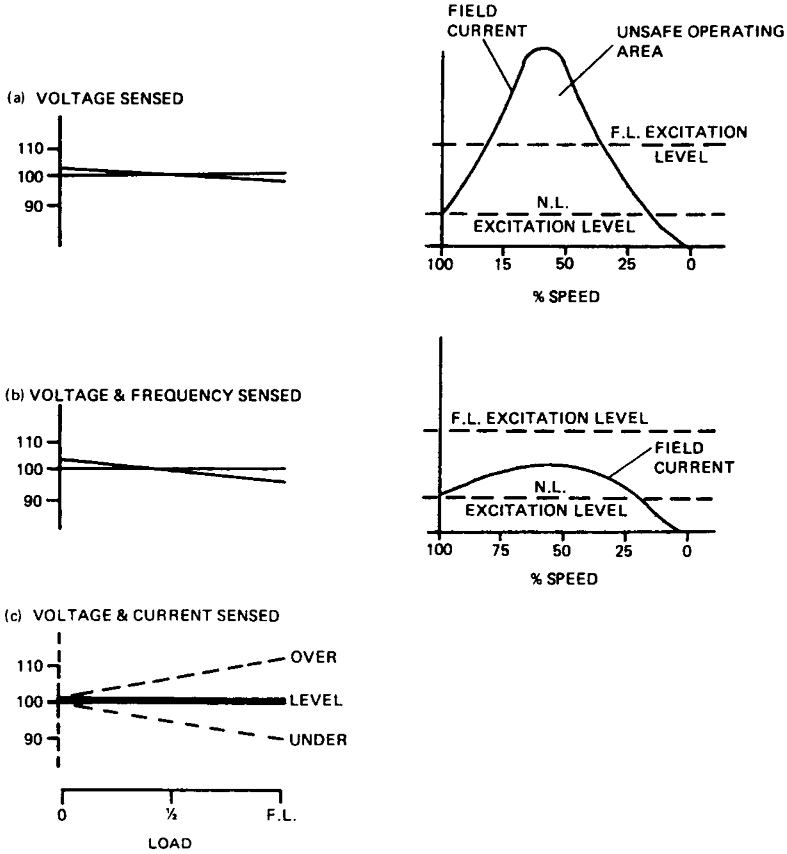


FIG. 5 — VOLTAGE REGULATION

Fig. 5a refers to a voltage sensed AVR which has a very ‘hard’ characteristic to any speed changes. The power available to the AVR is in order of 2.5 times the normal full load condition to allow the machine to react to high overloads during the motor starting. This power is very noticeable during rundown or slow speed operation, where the machine passes through a high saturation level forcing the rotor field current into an unsafe operating area if maintained for any length of time. A typical characteristic is shown in Fig. 5A.

To overcome the above problem, many AVRs are both voltage and frequency sensed. This gives a much softer characteristic and excitation levels above the machine’s capabilities are eliminated as shown in Fig/ 5B. Frequency sensing not only reduces excitation forcing during rundown and slow speed operation, but also assists the engine to recover its speed during high kW load changes.

To both the voltage sensed AVR and voltage frequency sensed AVR can be added current sensing. This provides more flexibility in setting the machine voltage as load is applied to give either level compounding, over-compounding or under-compounding at the generator terminals is required to overcome voltage drop in large cable runs; or to under-compound the generator voltage at zero p.f. loads to help reduce circulating currents between machines when operating in parallel. (droop kit).

3) *Overload Performance* - Fig. 6 shows the steady state overload/short-circuit characteristics of the self-excited and the separately-excited AVR control system. The self-excited system at a load of approximately 2 to 2.5 times full load will bend under and collapse on short circuit to zero. The separately-excited system will sustain a higher over-load and maintain a short circuit current in the order of 3 to 4 times full load. The latter is more desirable where the load consists of a number of sub-circuits where fault discrimination is desirable or where high motor-starting loads are found.

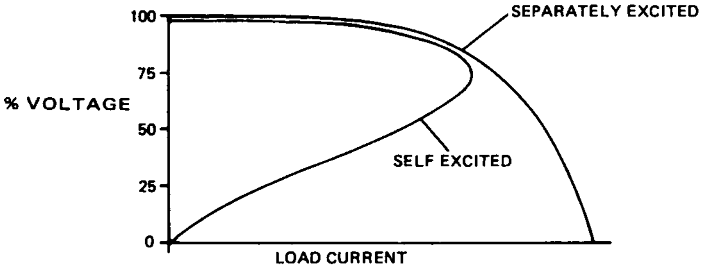


FIG. 6 — STEADY STATE OVERLOAD/SHORT CIRCUIT

Fig. 7 shows a typical transient voltage dip characteristic for both systems. As the self-excited systems derives its power input from the main stator voltage, the higher the load the more voltage dip and less forcing voltage is available to the AVR control circuit. This is the reason for the separation of the two curves at the higher overload. In the case of the separately-excited AVR control circuit, full field current forcing is maintained under all load and fault conditions.

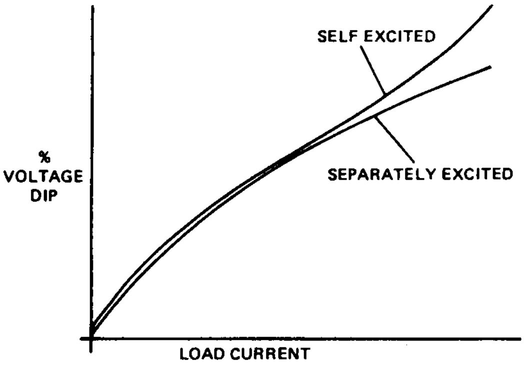


FIG. 7 — TRANSIENT VOLTAGE DIP CURVE

4) *Over-excitation Protection* - The AVR control system is designed to allow the generator to respond to high overloads for motor starting and the excitation power under the control of the AVR or incorrect operation of the machine, there is a possibility that the excitation system can be overloaded causing failure to the rotor system. To protect against over-excitation, a device can be fitted which monitors the excitation and will de-energise the exciter field if the field current is maintained at a level which will damage the machine. Sufficient discrimination must be built in to allow normal overloads to be accepted and ensure normal overload protection devices can operate. The over-excitation protection can take the form of a solid state circuit or a circuit breaker fitted with a timing device.