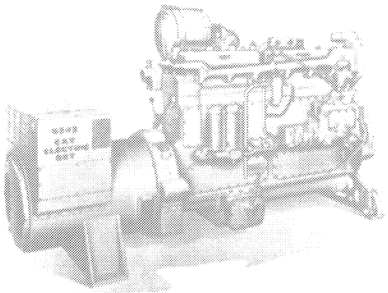
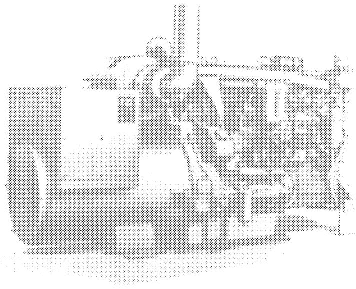
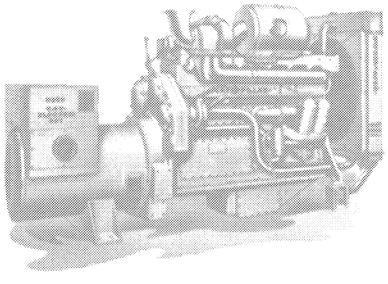
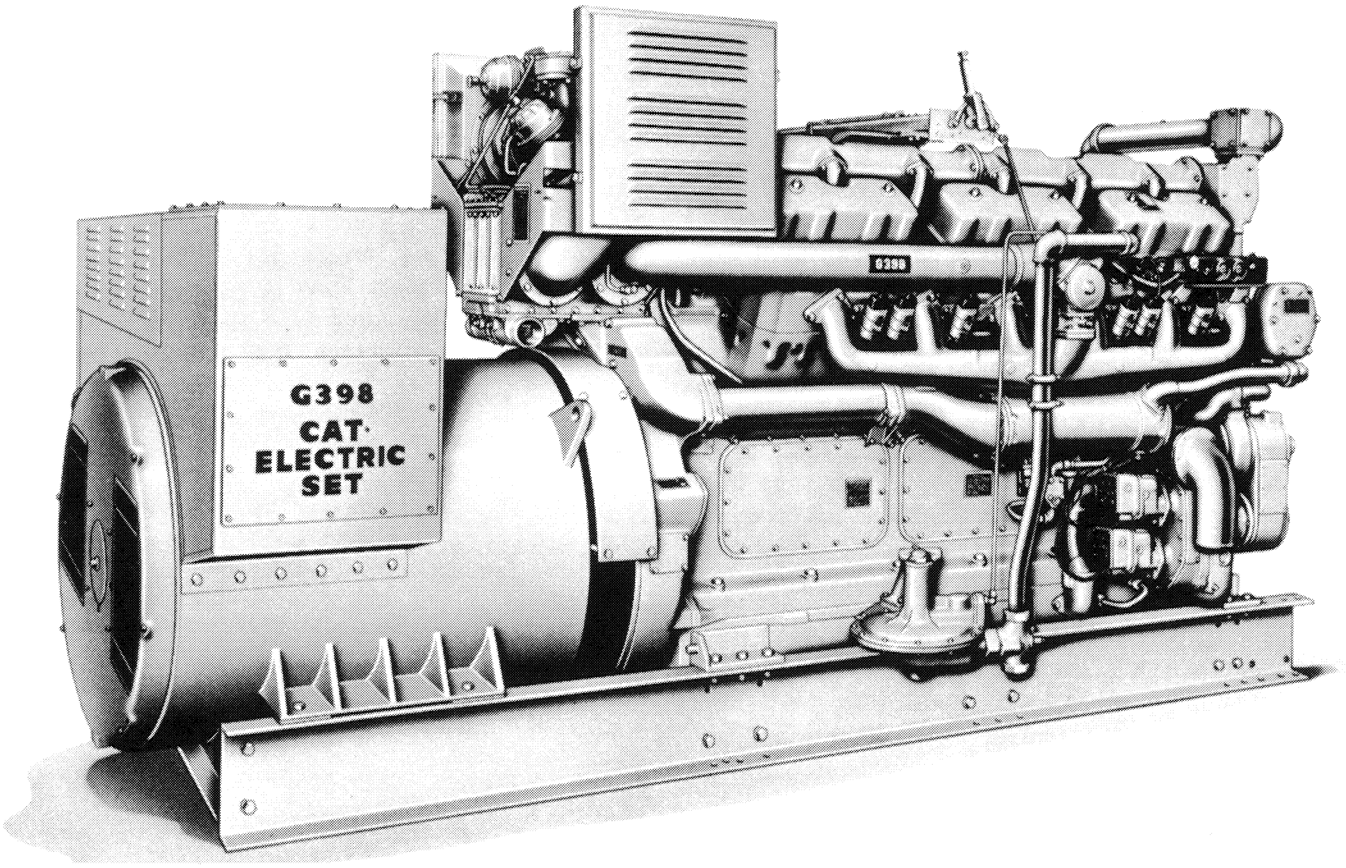
PRINCIPLES OF ELECTRIC SET GOVERNORS, PARALLEL OPERATION, ALTERNATORS AND REGULATORS









– SEE PAGE 14 FOR INDEX –

INTRODUCTION

The operation of a single engine electric set is quite straightforward. When two or more electric sets are operated in parallel, the techniques become more complicated. However, an understanding of the principles and practices described in the following pages should help the operator.

Mechanical and hydraulic governors commonly used with engine electric sets will be described. Their operating characteristics during single unit and parallel operation will also be discussed, with examples of various governor combinations. Electric-hydraulic and electronic governors are given a short description.

Fundamentals of alternating current generators, also called alternators, will be followed by descriptions of single unit and parallel unit operation. This will include bringing a unit on the line in parallel with others, transferring load to the incoming unit, and taking a unit off the line. The function of the voltage regulator in the operation of alternators is described.

GOVERNORS

Types of governors and their characteristics.

Types

A Caterpillar Engine Electric Set is generally furnished with one of the following types of governors:

Mechanical - approximately 3% speed droop - (Fixed)
Woodward UG8 Hydraulic - Adjustable from 0% to approximately 4% speed droop
Woodward PSG Hydraulic - Adjustable from 0% to approximately 4% speed droop

Two types of governors that are being used for special applications are the electric-hydraulic and electronic governors. These are adjustable from 0% to approximately 4% speed droop.

Characteristics

The governors listed above include in their description a value of speed droop. Speed droop is defined as the per cent change in engine speed between no load (high idle) and full load. Speed droop can be calculated using the equation given below.

$$\frac{\text{NO LOAD SPEED} - \text{FULL LOAD SPEED}}{\text{FULL LOAD SPEED}} \times 100 = \% \text{ SPEED DROOP}$$

A schematic of a typical mechanical governor is shown in Figure 1. The basic components are a governor spring, a set of weights, and linkage connecting these components to the engine fuel rack.

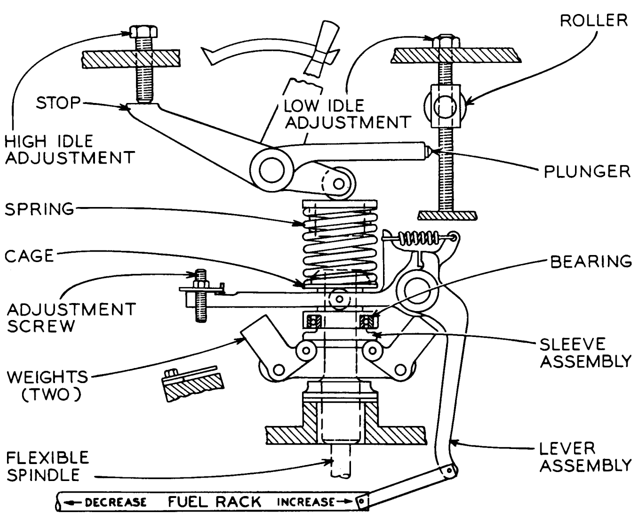


FIGURE 1 – SCHEMATIC OF A TYPICAL MECHANICAL GOVERNOR.

The weights are driven by the engine through gears of an appropriate ratio.

The engine speed control is set for the desired engine speed. This, in turn, compresses the governor spring and the fuel rack moves to a position to supply fuel to the engine. When the engine starts, the weights rotate. Since they are constructed to move under the action of centrifugal force, the weights move out as the engine speed increases. This action causes the toes of the weights to compress the governor spring further. This movement continues until the centrifugal force of the weights is in balance with the force of the compressed spring. When the weights move out against the force of the governor spring, the fuel rack setting is reduced. The engine speed will stabilize at a value where the spring force, weight centrifugal force, and engine speed are in balance.

An electric set engine is customarily set at "High Idle" speed when there is no load on the alternator. Alternators rated 1200 rpm, 60 cycles will be used in the examples that follow. Figure 2

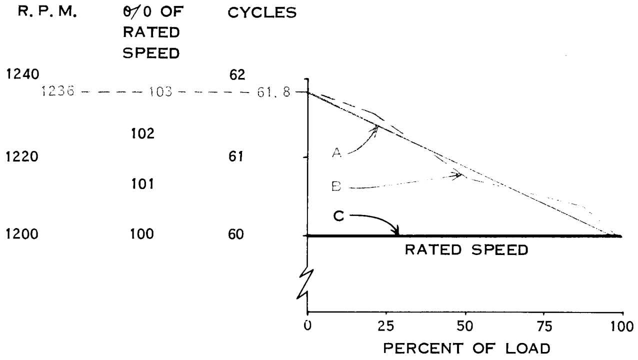


FIGURE 2 – TYPICAL SPEED DROOP CHARACTERISTICS OF A 3% MECHANICAL GOVERNOR. LINE A REPRESENTS AN IDEAL 3% SPEED DROOP CHARACTERISTIC; LINE B AN ACTUAL SPEED DROOP CHARACTERISTIC AND LINE C THE RATED SPEED OR FREQUENCY.

shows the speed droop characteristics of a 3% mechanical governor. In this case, high idle speed is 1236 rpm. Line "A" represents an ideal 3% speed droop characteristic. Line "B" represents an actual speed droop characteristic. Because of friction losses and limitations of materials, a governor speed droop characteristic is never a straight line. This is one reason why the descriptions of speed droop percentage include the word "approximately". The ideal speed droop characteristic figure of 3% will be used in this discussion.

At 0% load, the engine speed or alternator frequency is 103% of the rated value. This represents 61.8 cycles for a 60 cycle system. At 100% load the engine speed or alternator frequency is 100% of rated value. This represents 60.0 cycles for a 60 cycle system. Speed characteristics will be given in per cent of rated frequency of the electrical system, or in cycles. Line "C" of Figure 2 represents rated speed or frequency.

A simple mechanical governor cannot maintain rated speed over the load range. This can only be accomplished with the use of additional governor components which will be mentioned in the description of hydraulic governors. The simple mechanical governor can maintain constant speed if the load does not vary. When load is applied, however, engine speed decreases and the centrifugal force of the governor weights decreases. Therefore, the governor spring is opposed by a smaller force and moves the fuel rack in the direction to give the engine more fuel to carry the load. The engine speed will then increase until the force of the governor weights again balances the force of the governor spring. Figure 3 shows typical changes in engine speed, or alternator frequency when 1/3 load is added and then dropped for a engine electric set with 3% mechanical governor.

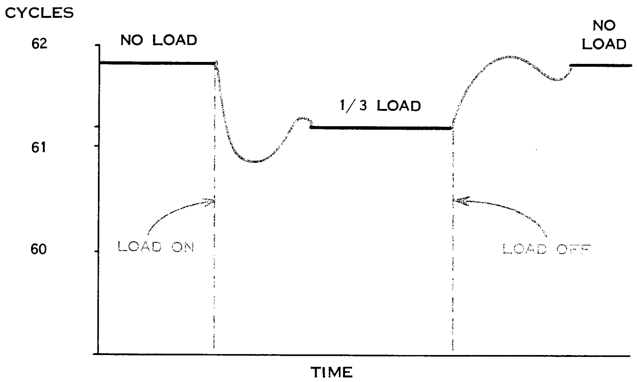


FIGURE 3 – TYPICAL PLOT OF CHANGES IN ENGINE SPEED OR ALTERNATOR FREQUENCY ON AN ENGINE ELECTRIC SET WITH 3% MECHANICAL GOVERNOR WHEN 1/3 LOAD IS ADDED AND THEN DROPPED.

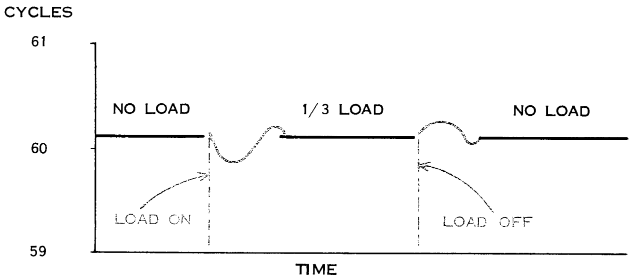


FIGURE 4 – TYPICAL PLOT OF CHANGES IN ENGINE SPEED OR ALTERNATOR FREQUENCY ON AN ENGINE ELECTRIC SET WITH ISOCHRONOUS GOVERNOR WHEN 1/3 LOAD IS ADDED AND THEN DROPPED.

A hydraulic governor is capable of being adjusted to maintain constant speed over the load range. This is called "isochronous" operation. Figure 4 shows a typical speed characteristic curve when load is added and dropped from a engine-electric set with isochronous governor.

An isochronous governor is more complicated than a simple mechanical governor. A detailed description of the principles of isochronous governing is available from such companies as the Woodward Governor Company.

Two other types of governors being used for special applications are the electric-hydraulic and the electronic. The electric-hydraulic governor has basic hydraulic governor components with electrical components added. When a load change occurs, the electrical circuit senses the electrical change and acts through the governor to change the fuel setting to maintain constant speed.

Mechanical and hydraulic governors sense a change in speed as a signal that load has been added or removed and that a change in fuel setting is required (Figures 3 and 4). The electric-hydraulic and electronic governors sense load changes directly and make a corresponding change in fuel setting, thus keeping the speed changes to a minimum. The above description of the electric-hydraulic governor pertains to isochronous governing. These governors can be adjusted for speed droop. However, they are capable of being operated in parallel when both are adjusted for isochronous operation. This is not the case with the regular hydraulic governors. A bulletin from the governor manufacturer describing in detail the operation of the electric-hydraulic governor is considered essential before any governor of this type is placed into operation.

The electronic governor usually consists of the following components:

Hydraulic Pump
Oil Reservoir
Hydraulic Servo-motor
Electric Control Cabinet

The hydraulic pump is driven by the engine. It draws oil from the reservoir and delivers it to the hydraulic servo-motor. Servo-motor action is initiated by a solenoid valve which is operated by power from the electric control cabinet. The servo-motor moves the fuel rack to increase or decrease fuel to the engine as required to maintain the engine speed at the value determined by governor control settings. The cabinet receives signals from the voltage, current, and frequency output of the alternator. Electronic governors can be adjusted for speed droop or isochronous operation, including operation in parallel when adjusted for isochronous operation. A bulletin from the governor manufacturer describing the operation of the electronic governor is essential before any governor of this type is placed into operation.

PARALLEL OPERATION OF GOVERNORS

Parallel operation of mechanical and hydraulic governors will be described; the electric-hydraulic and electronic governors will not be covered here.

When paralleling A.C. Generators, the engine governors must have the same speed droop characteristics if the sets are to divide the load in proportion to their ratings throughout the entire operating range.

It is very important that two basic facts be understood concerning load division between alternators operating in parallel. First, the power supplied to the alternator and thus to the load is a function of the engine. The engine governor settings and the positions of the governor controls determine the amount of power delivered by the engine and the KW load carried by the alternator. If the governor control setting is advanced, the engine and alternator will assume more KW load. Likewise, decreasing the governor control setting will result in a reduction of load on the unit. Any other units on the line will, conversely, either reduce or gain load at the same time, assuming no change in total load or no change in the governor settings of the other units has taken place. Second, the division of power is not determined by alternator excitation or terminal voltage. The Power Factor at which an alternator will operate when paralleled with other alternators is determined by its excitation. For more discussion on this subject, refer to the section on Parallel Operation of alternators.

As mentioned previously, governors furnished with Caterpillar Powered Electric Sets can be either of two types, governors with fixed speed droop (mechanical) or governors with adjustable speed droop (hydraulic). The values of speed droop used are commonly 3% and 0%. Governors with adjustable speed droop can be adjusted so their characteristics match quite closely the characteristics of governors with fixed speed droop. The operating characteristics of the following combinations of governors on paralleled electric sets will be described.

1. Two 3% mechanical governors.
2. One 3% mechanical or hydraulic governor and one 0% (isochronous) hydraulic governor.

In the diagrams that follow, the per cent of rated load of one unit will be shown across the bottom. The system capacity will, however, be the sum of the capacities of the units operating in parallel. Percentage is used in the general cases discussed. For any particular installation this can be converted to kilowatts as shown in the following:

Set A — 100 KW — 100%
Set B — 100 KW — 100%
System — 200 KW — 200%

Set C — 60 KW — 100%
Set D — 100 KW — 100%
System — 160 KW — 200%

Example 1 - Two 3% Mechanical Governors.

The governor speed droop characteristics of these two units are similar. This is shown by lines "A" and "B" coinciding in Figure 5. If both units are started, set for high idle speed and paralleled at no load, the system frequency will be 61.8 cycles or 103% of rated frequency. As load is applied to the system, the frequency will decrease along the speed droop characteristic until the frequency at full load is 60 cycles.

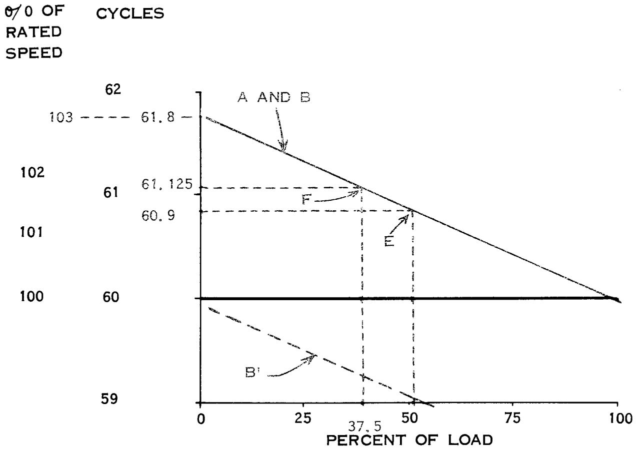


FIGURE 5 – PARALLELING TWO UNITS WITH SIMILAR SPEED DROOP CHARACTERISTICS.

If Unit A had been operating alone carrying full load, the system frequency would be 60 cycles as shown by Line "A" at 60 cycles and 100% load. Now, if the frequency of Unit B is adjusted by the engine speed control to be equal to that of Unit A and the circuit breaker of Unit B is closed, the system would be operating under the following conditions:

1. Unit A is at 60 cycles and 100% load.
2. Unit B is at 60 cycles and 0% load. The characteristic of the governor of Unit B at this time is shown by the dotted line B'.

In order for Unit B to carry load, it is necessary to advance the speed setting of the governor. If it is advanced to the full load position, the governor characteristic of B will coincide with the characteristic of A. Since the load on the system was 100% of one unit, no change was made in total load, and the available capacity is now 200%, the system will operate at 50% load on each unit, and 60.9 cycles for two units of equal capacity (Point E). For units of unequal capacity, the load will be divided in proportion to the ratio of the capacity of each unit to the total capacity, and the system frequency will be determined by the points on the governor characteristics corresponding to these loads. The frequency will be the same for both units since paralleled alternators must operate at the same speed.

If Unit A had been a 60 KW unit fully loaded and a 100 KW Unit B was paralleled with it and the governor adjusted to the full load position, the final load division and frequency would be determined as follows:

a. System load - 60 KW

b. System capacity - 160 KW

SYSTEM LOAD KW RATING FOR UNIT

c. The 60 KW unit will carry $\frac{60}{160} \times 60$ KW = 22.5 KW

SYSTEM CAPACITY KW LOAD FOR UNIT

d. 100 KW unit will carry $\frac{60}{160} \times 100$ KW = 37.5 KW

e. The system frequency can be determined readily from step c or step d. The load carried by each unit is $\frac{22.5}{60}$ or $\frac{37.5}{100}$ which figures out to be 37.5% of the capacity of either unit. Again, using Figure 5 for the governor characteristic of the 100 KW unit and reading up from the value of load (37.5% to point F), we find the system frequency to be 61.125 cycles.

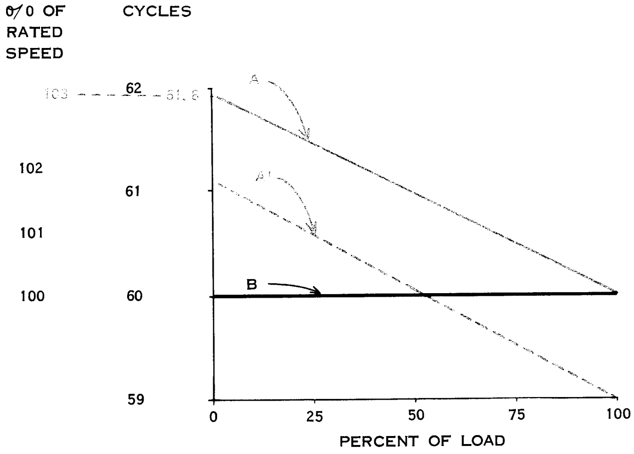


FIGURE 6 – PARALLELING TWO UNITS, ONE WITH A 3% MECHANICAL GOVERNOR AND THE OTHER WITH A HYDRAULIC GOVERNOR SET FOR ISOCHRONOUS OPERATION.

Example 2 - One 3% Mechanical or Hydraulic Governor and one 0% (Isochronous) Governor.

The characteristics of the 3% governor (Unit A) is shown by line A of Figure 6 and the characteristics of the isochronous governor (Unit B) is shown by line B. Only at full load, 60 cycles, do the frequencies of the units have the same value. It is customary to operate a system of this type with a system load greater than the capacity of Unit A. In this way Unit A carries its full load at 60 cycles and the additional load and load swings are handled by Unit B, also at 60 cycles. The system can maintain constant frequency by this method of operation. The system described in example 1 cannot maintain constant frequency with load changes because of the speed droop characteristics of the governors.

In the system described in this example, if the load is less than the capacity of Unit A (which has the 3% governor) and can be carried by Unit B, (isochronous governor) Unit A can be disconnected from the system. If the load cannot be carried by Unit B, the governor setting of Unit A can be reduced to give a governor characteristic such as A' so Unit A will still carry the steady part of the load and Unit B will carry the load swings. If the system load is reduced to the point where Unit A is not operating at the 60 cycle point of its governor characteristic, Unit A will try to motor Unit B and the system frequency may be greater than 60 cycles. The reason for using an isochronous governor in a power system is to maintain constant frequency.

The preceding discussion and examples of governor operation can be summarized as follows:

1. The simplest governor combination for paralleled electric sets is to have a 3% speed droop characteristic for each governor. If a constant frequency from no-load to full-load is required, one governor can be adjusted for isochronous operation. This is called a "lead unit".
2. In order for all paralleled units to accept their full share of the load, the following governor adjustments are required:
   a. The same full load speed.
   b. The same high idle (no-load) speed in the case of mechanical governors or hydraulic governors adjusted for speed droop operation.
   c. Governor controls set to the high idle position so the full governor range is available.
3. Operation of an isochronous governor in parallel with speed droop governors requires the special techniques described in example 2.
4. Any number of electric sets can be operated in parallel. However, only one governor of the group can be adjusted for isochronous operation except in the special cases of electric-hydraulic and electronic governors.

ALTERNATING CURRENT GENERATORS (ALTERNATORS)

An alternating current generator is often referred to as an alternator. This name is used to prevent confusing A.C. generators with D.C. generators. A simple, non-technical discussion of alternating currents and alternators cannot be very comprehensive, but it is hoped that alternator behavior can be made to seem reasonable in the non-rigorous explanations that follow. It may be necessary to read this material several times for complete understanding.

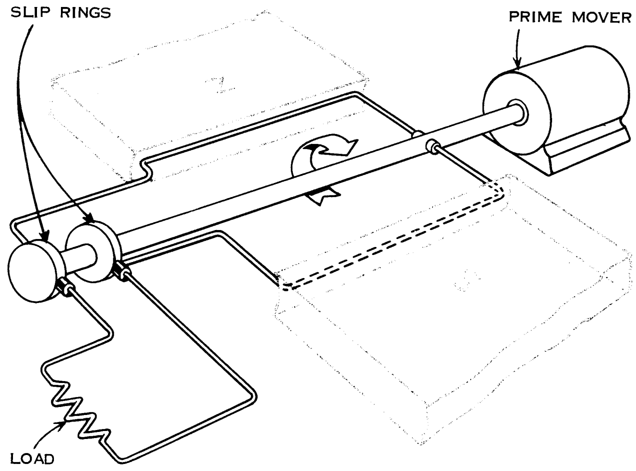


FIGURE 7 – AN ALTERNATOR IN ITS SIMPLEST FORM.

If an electrical conductor (a wire) is passed sideways through a magnetic field, a voltage is generated in it. If a circuit including this conductor is completed, the generated voltage will cause a current to flow. As soon as current flow is established, force is required to move the conductor through the magnetic field. Electrical power is then developed from the mechanical work done during such movement. This is an alternator in its simplest form (Figure 7). Conversely, if some outside source of voltage causes a current to flow through a conductor placed in a magnetic field, force is required to restrain the conductor from moving. If the conductor is permitted to move against a lesser force, mechanical work is done. This is the simplest form of a motor.

Figure 8 is a cutaway view of an alternator. In an alternator, the magnetic field is established by causing direct current to flow through coil A wound on part of the iron structure of the magnetic path — usually, in the larger machines, on the rotating field or "rotor" B. The direct current is generated by the belt driven d.c. exciter F and is supplied to the rotor through brushes bearing on slip rings G. Since voltage is generated whether the conductor moves across the magnetic field or

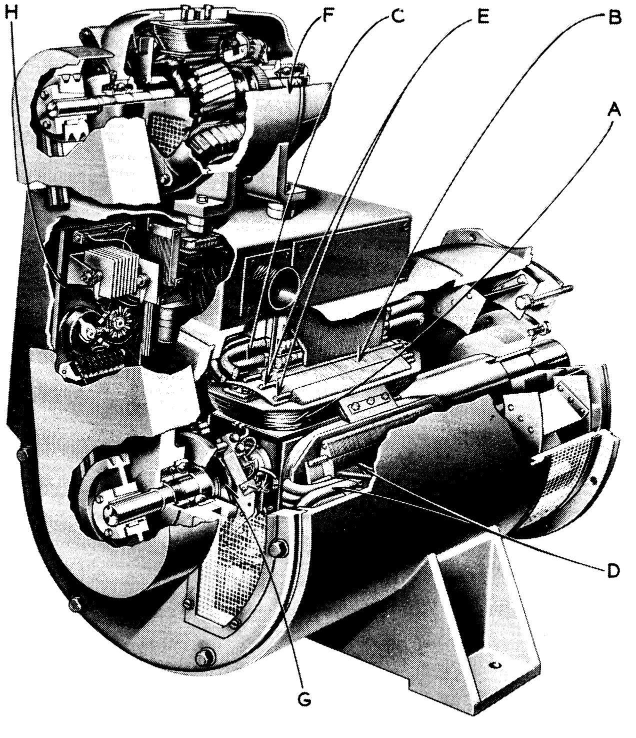


FIGURE 8 – CUT-AWAY VIEW OF AN ALTERNATOR WITH A BELT DRIVEN D.C. EXCITER.

the field across the conductor, the rotor moves the magnetic field across armature conductor C located in the stator D. Amortisseur bars E in the rotor pole faces have several functions, one of which is to improve the wave shape of the output voltage. This alternator has an integral static voltage regulator H. Voltage regulators will be discussed later. Figure 9 shows a simplified schematic of the alternator pictured in Figure 8.

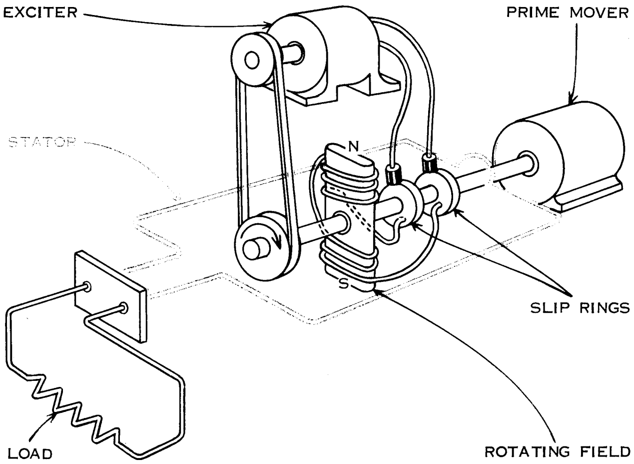


FIGURE 9 – SCHEMATIC OF AN ALTERNATOR WITH A BELT DRIVEN D.C. EXCITER.

When alternate north and south magnetic poles pass a conductor in the stator, as represented in Figure 10A, the direction of the voltage reverses periodically and an alternating voltage is generated. The voltage will rise to a maximum value in one direction, decrease through zero to a like maximum in the other direction, and then rise through zero to a maximum in the initial direction. This is represented in Figure 10B. The variation of voltage from one maximum point to the next maximum point in the same direction constitutes a cycle. Most alternators are designed and the speed of rotation so chosen that a cycle is completed sixty times a second. In some parts of the world fifty cycle power is used.

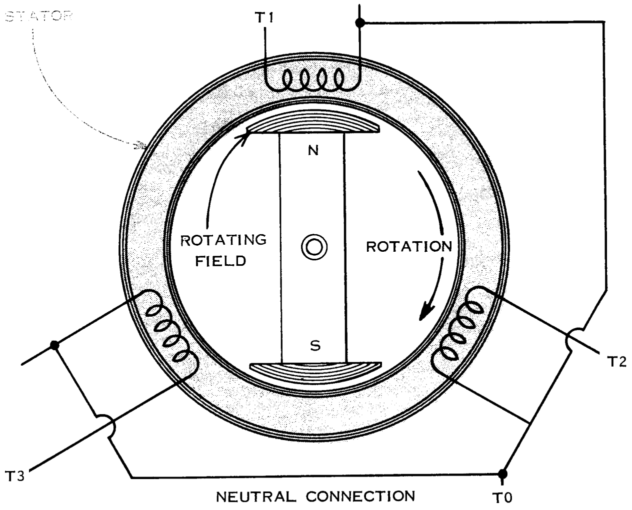


FIGURE 10A – SCHEMATIC OF AN ALTERNATOR WHICH WILL PRODUCE THREE PHASE CURRENT.

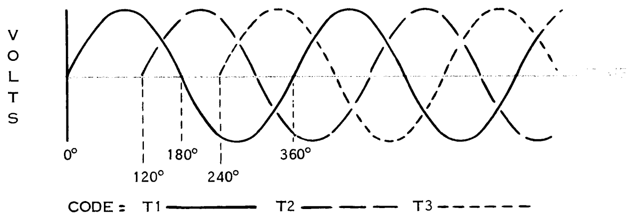


FIGURE 10B – ACTUAL PLOT OF THE THREE PHASE CURRENT PRODUCED.

Frequency, number of rotor poles, and alternator revolutions per minute are related as shown by the following equation:

$$F = \frac{P}{2} \times \frac{RPM}{60}$$

F - Frequency in cycles per second
P - Number of field poles
RPM - Revolution per minute
60 - Sixty seconds per minute

For example, 60 cycle current will be produced by a two pole alternator when rotated at 3600 RPM.

$$F = \frac{P}{2} \times \frac{RPM}{60} = \frac{2}{2} \times \frac{3600}{60} = 60 \text{ cycles}$$

Likewise, 60 cycle current can be produced by a four pole alternator turning at 1800 RPM or by a six pole alternator turning at 1200 RPM.

The conductors of the stator, arranged in coils, can be so placed that the maximum voltage in two separate windings will be reached at different times. For instance, consider again a rotor having one north and one south pole as represented in Figure 10A. A conductor (T1) at a given point in the stator will have a 60 cycle voltage generated in it if the rotor makes 60 revolutions per second or 3600 rpm. Another conductor (T2), placed 120° around the stator in the direction of the rotation will reach its maximum at a later time. If we consider one cycle to include 360 electrical degrees (the passing of one pair of north and south field poles past a given point or conductor in the stator), which in this example is produced in 360 degree rotation of the rotor, the second voltage will reach its maximum value 120° later than the first and may be said to be lagging the first in phase by 120 electrical degrees. If a third conductor (T3) is placed an additional 120° around the stator, the three voltages generated will differ in phase by 120°, as represented in Figure 10B. This is the usual three-phase voltage relationship.

Manual Voltage Control

The alternator requires excitation of the rotating field with d.c. power. This can be obtained from a small d.c. exciter generator as shown in Figures 8 and 9 or from a static source of d.c. power, one type of which will be mentioned later. Alternators with rotating d.c. exciters will be considered in the following description.

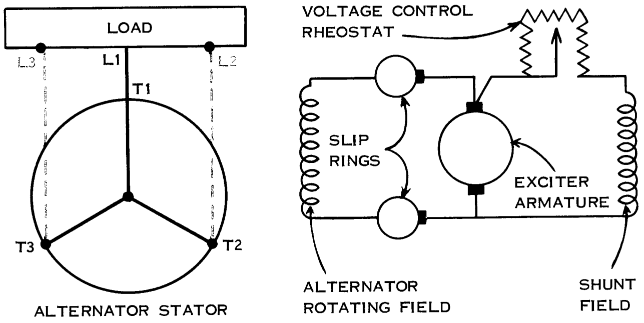


FIGURE 11 – SCHEMATIC OF AN ALTERNATOR WITH ROTATING D.C. EXCITER ILLUSTRATING HOW THE VOLTAGE CONTROL RHEOSTAT CONTROLS ALTERNATOR OUTPUT.

Figure 11 represents an alternator with rotating d.c. exciter. The output of the alternator is controlled by the power available from the engine driving it and the magnetic strength of the alternator rotating field. The engine governor controls the engine power. The exciter output controls the magnetic strength of the rotating field. The exciter output is controlled by the magnetic strength of the exciter shunt field. The magnetic strength of the exciter shunt field is controlled by adjustment of a voltage control rheostat, or variable resistance, in the circuit between the exciter armature and the exciter field.

A single alternator operating at constant speed will deliver a terminal voltage which is almost directly proportional to its excitation or the magnetic strength of its rotating field. When an alternator is developing rated voltage on open circuit, its excitation level is a certain value. If it is desired to raise or lower the voltage, the excitation must be raised or lowered. When the excitation is raised there is more magnetizing power (or field current) available than is required for generation of rated voltage. This power must be expended in some manner. In the case of the single unloaded alternator this magnetizing power is expended in raising the terminal voltage. A very small part of it changes to heat. If the excitation is lowered from the value required to generate rated open circuit voltage, there is a shortage of magnetizing power and the voltage drops. It will require the addition of some magnetizing power to raise the voltage back to the rated value.

When an isolated alternator developing rated open circuit voltage — with the excitation fixed at the value required to develop this voltage — has a load circuit connected to its terminals, the voltage will cause a current to flow through the load. This same current circulates back through the alternator. Since all electrical circuits exhibit resistance to the flow of electric current, there will be a loss in voltage in the windings of the alternator. This voltage drop will be proportional to the amount of current flowing and the impedance of the alternator windings. This loss of voltage due to impedance and current flow resembles the loss in voltage due to a reduction in the magnetic strength of the alternator rotating field.

Impedance exists in A.C. circuits in the same manner as resistance exists in D.C. circuits. The characteristics of an impedance is a combination of resistance and reactance. In D.C. circuits, the voltage drop across a circuit is equal to the current in amperes flowing through the circuit multiplied by the resistance in ohms of the circuit, $E = IR$. In A.C. circuits the voltage drop across a circuit is equal to the current in amperes flowing through the circuit multiplied by the impedance in ohms of the circuit, $E = IZ$.

If the connected load is not greater than the rated load of the unit, the voltage can be returned to rated value by increasing the excitation of the alternator. This is done by reducing the resistance on the exciter field. This results in more excitation in the exciter. The exciter voltage increases and more current flows through the alternator field. This increase in current causes an increase in the magnetizing power (field current) of the alternator rotor and, correspondingly an increase in the alternator generated voltage. The voltage will rise toward the rated value. Of course, more current will flow through the load and the alternator as the voltage increases, but a setting of the exciter field control can be made which will result in the alternator operating at rated voltage when connected to a load if the load is not greater than rated load.

If the exciter control should be advanced beyond the point at which the increased excitation will compensate for the voltage drop at the alternator terminals, the voltage will rise past the rated value. This indicates that too much magnetizing power is being supplied to the alternator rotor. The excess is expended in increasing the terminal voltage.

Automatic Voltage Control

The changes in the control of the exciter field circuit can be made to occur automatically by the use of a simple automatic voltage regulator which has a circuit connected to the alternator terminals

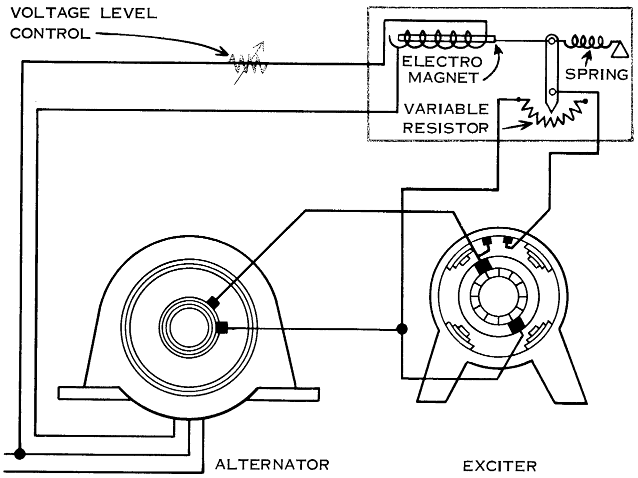


FIGURE 12 – SCHEMATIC OF AN AUTOMATIC VOLTAGE CONTROL REGULATOR.

as shown in Figure 12. Usually the alternator voltage is used to energize an electromagnet. The pull of the electromagnet is opposed by a spring. Both the magnet and the spring can act to move the control arm of a variable resistance element in the exciter field circuit. If the terminal voltage decreases, the pull of the electromagnet weakens and the spring pulls on the control arm, moving it in the direction to decrease the resistance in the exciter field circuit. This permits the excitation of the alternator to increase and the voltage increases. Conversely, if the voltage is too high, the pull of the electromagnet increases and the control arm moves in the direction to decrease the excitation and thus decrease the terminal voltage. The opposing forces of the spring and the electromagnet are in balance when the alternator voltage is the value set by the voltage level control.

Detailed descriptions of various automatic voltage control arrangements including static regulators (which consist of electronic circuitry with no moving parts) are available from Caterpillar Tractor Co.

PARALLEL OPERATION OF ALTERNATORS

The operation of one electric set is not complicated. Increase the governor setting and the speed increases. Decrease the governor setting and the speed decreases. Increase the voltage level setting and the voltage increases. Decrease the voltage level setting and the voltage decreases. When two or more electric sets are connected in parallel, making changes to governor or voltage regulator settings gives entirely different results.

In order for two alternators to be operated in parallel, several conditions must be met. They are:

1. Same number of phases.
2. Same phase rotation.
3. Same frequency.
4. Same voltage.
5. Same voltage droop.

As discussed in the section on governors, it is not necessary for the mechanical or hydraulic governors to have the same speed droop. However, it is necessary for all the governors of units being paralleled to have 3% speed droop except one. This one governor can have 0% speed droop and be used to control the frequency of the system. The paralleling operation is performed with the assistance of a synchroscope or synchronizing lights to show when the frequencies of the alternators are the same. With the synchroscope, paralleling is performed with the pointer, in a vertical position. With synchronizing lights, paralleling is performed when the lights are dark. Refer to the Operation and Maintenance Instructions for the electric sets being paralleled for more details.

When alternators have been paralleled at no load and no operations have been performed except closing the circuit breaker, the machines are "floating" on the line with no power being transferred either between them or to a load. When a load is connected to the system, power is supplied from the paralleled units. If they all have the same rating and governor speed droop characteristics, the load will be divided equally among them. Any differences in kilowatt loading should be equalized by adjusting the governor controls. To increase the kilowatt load on a unit, the governor control should be advanced farther in the direction to increase speed. To decrease the load, the control should be moved in the direction to decrease speed. For small movements of the governor control, the change in system frequency will be negligible or zero. However, changes in kilowatt load among the engines may be appreciable. To insure balanced kilowatt loading of several electric sets, a separate kilowatt meter for each one is extremely helpful.

There is a misconception that an alternator operating in parallel can have its kilowatt load changed by changing its excitation or magnetizing power. It seems logical that if the voltage level control setting is increased there will be an increase in kilowatt loading of the alternator in a manner similar to that experienced when an alternator is operating by itself. This is not true.

If the magnetizing power of an alternator is increased beyond the value required to maintain the voltage of the alternator at the same value as the system voltage while the alternator is delivering the amount of power determined by the engine governor setting, the excess magnetizing power goes out from the alternator into the system as MAGNETIZING POWER. This fact shows up as an increase in amperes being furnished by the alternator. Figure 13. There is no increase in kilowatt output since the kilowatt output is determined by the governor setting. The alternator power factor is lowered. (Power Factor is briefly described below. For a detailed description, refer to the addendum on page 15.)

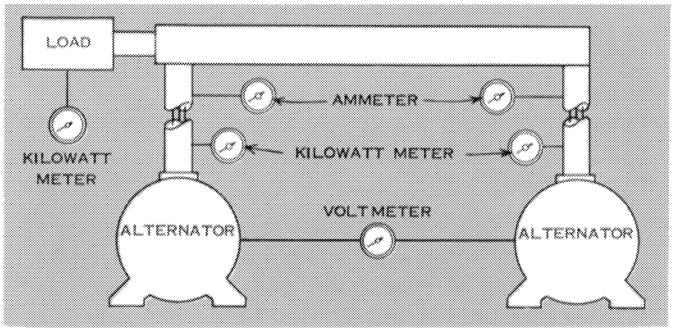


FIGURE 13 – CONSIDER AN OVER EXCITED ALTERNATOR OPERATING IN PARALLEL INTO A RESISTIVE LOAD. THE RESULT WOULD BE AN INCREASE IN LINE AMPERES. SAMPLE METER READINGS FOR THIS ALTERNATOR MIGHT BE AMMETER – 100, VOLTMETER 220, AND KILOWATT METER 30.5. NOTE THAT THE PRODUCT OF VOLTS TIMES AMPERES TIMES 1.732 (CONSTANT FOR THREE PHASE GENERATION) IS 38.1 KILOWATT AND EXCEEDS THE KILOWATT OUTPUT BY A SUBSTANTIAL AMOUNT. THE AMPERES REQUIRED FOR 30.5 KILOWATTS AT UNITY POWER FACTOR AND 220 VOLTS ARE 80. THE EXCESSIVE AMPERES INDICATED ON THE METER REPRESENT MAGNETIZING POWER CIRCULATING IN THE SYSTEM. THESE ARE CALLED REACTIVE AMPERES OR CIRCULATING CURRENT.

Three-phase power in a purely resistive circuit, such as one having only incandescent lamps or heaters, is defined as the product of volts, amperes and a constant. As an equation, this would be stated as Watts = V x A x 1.732. Three-phase power in a circuit having resistance and inductance, such as one having lamps and motors, is defined as the product of volts, amperes, a constant, and power factor. As an equation, Watts = V x A x 1.732 x (P.F.). The power factor of a system varies between 1.0 (unity) for a system with all resistance and no inductance and 0 (zero) for a theoretical system with all inductance and no resistance. If there were such a thing as a perfect inductance with no resistance, no power would be required to circulate amperes through the system. This is shown by the equation W = V x A x 1.732 x (0). If the major portion of a load is resistive and a small portion is inductive, the equation might look like this: W = V x A x 1.732 x (.8). Most induction motors operate at a power factor near .8 when loaded near their rated horsepower. If a load operates at a power factor less than unity, it indicates that there is some inductance in the load. This inductance requires magnetizing current. This magnetizing current is necessary to form a magnetic field, but it does not contribute directly to the performance of useful work. The best example of this is the squirrel cage induction motor. This motor has no separate excitation source to form a magnetic field so it draws magnetizing or reactive amperes from its power source to form a magnetic field. It also draws active amperes to transform into shaft horsepower from rotation of its rotor.

The ratio of active amperes to total amperes is the same as the power factor value. Active and reactive amperes are not simply added to get total amperes. The mathematics entailed are beyond the scope of this presentation. The ammeter in the alternator switch-gear shows the value of amperes resulting from active and reactive amperes flowing at the same time.

Returning to the paralleled alternator, if the magnetizing power of an alternator is increased beyond the value required for the alternator to deliver power to the system at the power factor value of the load, the excess magnetizing power flows into any other alternators supplying the system and, as a result, their exciters reduce their excitation or magnetizing power since THERE IS ONLY ONE TOTAL VALUE OF MAGNETIZING POWER REQUIRED FOR ANY ONE SYSTEM. This value is fixed and is determined by the power factor of the load. All alternators in the system should share it proportionately.

The method used to control the magnetizing power of an alternator is called "voltage droop". It has been explained previously that speed droops in governors is used to divide the kilowatt loading of engine-driven alternators. An engine that tends to speed up and carry more than its proportionate share of the load will then tend to slow down and drop this increase in load or conversely, an engine which tends to drop part of its proportionate share of the load will, with a governor having speed droop, tend to speed up and again pick up its proportionate share of the load. Also, remember that active power (KW) loading is determined by the governor setting and the regulator controls reactive or magnetizing power. If an alternator should increase its magnetizing power in excess of its proportionate share for the system, it is necessary to reduce the exciter output of this unit to bring its level of magnetizing power back to the proper value.

The increase in magnetizing power shows up as an increase in line amperes so the use of a circuit sensitive to line amperes should furnish the necessary control. This circuit should act to reduce the magnetizing level of the alternator as the line amperes increase. Since, for an individually operating alternator, this would cause a decrease in voltage, the circuit is called a "voltage droop" circuit. It generally operates as follows: An increase in line amperes causes a voltage to be generated in the secondary of a current transformer. This voltage is added to the alternator voltage impressed on the regulator. The regulator senses the increase in voltage and acts as though the alternator terminal voltage is too high. It reduces the magnetizing power of the exciter field by reducing the exciter voltage and correspondingly reducing the power to the alternator field and the magnetizing power of this field. Since the voltage of a paralleled alternator cannot change, but must remain the same as the bus voltage, the reduction in magnetizing power acts only to reduce the magnetizing amperes being furnished by the alternator. Conversely, if the magnetizing power of the alternator is too low, this circuit acts, within its capacity, to cause the voltage regulator to increase the magnetizing power of the paralleled alternator so it will be furnishing its share of magnetizing power to the system. A voltage droop adjustment causing a 3% to 8% drop in voltage from no load to full load at rated power factor is usually required for satisfactory division of ampere loading. The largest amount of droop that can be tolerated by the load should be used to insure stable operation.

Voltage droop circuits can mistakenly be connected in reverse. In this case, the voltage from the current transformer secondary subtracts from the voltage of the alternator terminals. The regulator acts as though the alternator voltage were too low and increases the magnetizing power of the alternator. This causes the ampere output of the alternator to become excessive. The increase in amperes acts to increase the voltage subtracting from the alternator voltage impressed on the regulator and the regulator continues to act to increase the magnetizing power of the alternator. This power can increase to the limit of the capacity of the exciter. The current can easily exceed the rating of the alternator. The circuit should always be checked against the regulator manufacturer's instructions. Proper connection of the voltage droop circuit can also be checked when the alternator is loaded individually in the process of adjusting the amount of voltage droop prior to paralleling the alternator. If the voltage falls when a load having a lagging power factor is connected to the alternator, the droop circuit is connected properly. If the voltage rises, the circuit is connected improperly. Reversing the wires at the current transformer primary or secondary will usually correct the situation. Returning to the paralleled alternator, when the voltage droop is adjusted to control the ampere output of the alternator so the magnetizing power delivered by the alternator to the load will not exceed the proportionate value for the alternator, then the power factor of the alternator output will be the same as the power factor of the load.

If the alternator should furnish more than its share of magnetizing power, its power factor would be lower than that of the load. If it furnished less than its share, its power factor would be higher than the power factor of the load. Notice that things seem to be backward in the above statement? This happens because power factor decreases as magnetizing power increases, and vice versa. It is possible to have a paralleled alternator operate at such a low magnetizing level that magnetizing power must flow into it from the system in order to keep the alternator voltage at the same value as the bus voltage. In this case, the alternator is said to be operating at a leading power factor. By definition, an alternator delivering magnetizing power is operating at lagging power factor whereas an alternator receiving magnetizing power is operating at a leading power factor. Also, by definition, a motor receiving magnetizing power from its power source is operating at a lagging power factor whereas a motor delivering magnetizing power to its power source is operating at a leading power factor. This latter case is somewhat rare and is represented by a synchronous motor operating with its magnetizing level higher than that required to furnish only the magnetizing power required to keep the motor in synchronism and carry its connected load. Leading power factor motors require special design characteristics for which a premium price is usually charged.

In order to cause the paralleled alternator to deliver power to the system, the engine governor control must be advanced so the engine will tend to speed up. This operation has already been described in the section on governors. The engine-alternator combination will not actually speed up. The alternator rotor will advance several electrical degrees from the no-load position. This advance is made with respect to the neutral or center of the north and south poles of the rotating magnetic field. The alternator rotor continues to rotate in synchronism with the rotating field produced in stator by virtue of its being connected to the system. As the governor is advanced, the alternator will start to deliver power. It will also deliver magnetizing power if the system requires it. When the governor control has been advanced to the high idle position, the unit is capable of delivering power over its full range from no-load to full-load depending on the requirements placed on it by the system. The governor speed droop characteristic acts to cause the engine to deliver its proportionate share of the load. If the engine tends to take more load, it will tend to slow down and drop this additional load. If the engine tends to drop some load, it will tend to speed up and take some load. It requires some imagination to visualize these operations and understand them. Also, the alternator voltage droop characteristic acts to cause the alternator to deliver its proportionate share of magnetizing power to the system and the load. If the alternator magnetizing power tends to rise above its proportionate value, the voltage droop circuit acts to decrease the magnetizing level of the alternator to its correct value. If the alternator magnetizing power tends to fall below its proportionate value, the voltage droop circuit acts to increase the magnetizing level of the alternator to its correct value.

Most electric power stations have limited capacity so consideration must be given to the limitations of the installation. These limitations include slight variations in frequency and voltage, and limited power. Under these conditions, changes in load will result in small changes in frequency as governors operate along their speed droop characteristics and small changes in voltage as regulators operate along their voltage droop characteristics. The sudden application of large blocks of load will cause dips in frequency and voltage. The size of these blocks of load must be checked against the capacity of the system since too large a load suddenly applied can cause the system voltage to dip low enough that some loads may be disconnected automatically by low voltage protective devices. Also, slight discrepancies in the adjustment of governors or voltage regulators can result in frequency being high or low, voltage being high or low, load unbalanced, or unequal division of amperes between generators. A full complement of switchboard instruments including voltmeter, ammeter, kilowatt meter, and frequency meter for checking each generator is extremely helpful in balancing the operation of paralleled alternators. This is particularly true for a power plant with more than two generators operating at any one time.

Under the conditions described above, an engine-alternator unit will automatically follow the load variations and continually deliver its proportionate share of the load requirements. A small amount of practice by an operator coupled with a study of the various operating steps and their effects on each other, will build confidence and bring understanding of the equipment to the operator.

LOAD TRANSFER AND DISCONNECTION OF PARALLELED ALTERNATORS

When two or more electric sets are operating in parallel and it is known that the total load will be less than the capacity of all the units and will not cause an overload if the number of paralleled units is reduced by disconnecting one or more units, the load can be transferred to an adequate number of units and the others disconnected from the load. The following discussion is an explanation of the actions of governors and regulators on engine-electric sets during load transfer and the disconnection of one or more units from parallel operation. This discussion will cover the operation of two units. If more than two units are operating, the same principles apply to the complete system.

If the system were initially started with the units unloaded before being paralleled, the speed of each engine would be rated speed plus speed droop as shown at points A and D of Figure 14. The voltage of each unit would be rated voltage plus voltage droop as shown by points G and K. With these conditions, the circuit breakers can be closed to place the units in parallel. When the system is loaded, the engine speed will follow the governor speed droop characteristics and the alternator voltages will follow the regulator voltage droop characteristics. With 50% load on each unit, the engine speeds (and the frequency of the system) will be as shown by points E and F, and the voltage of the system will be as shown by points L and M. At full load on each unit, the engine speed and the

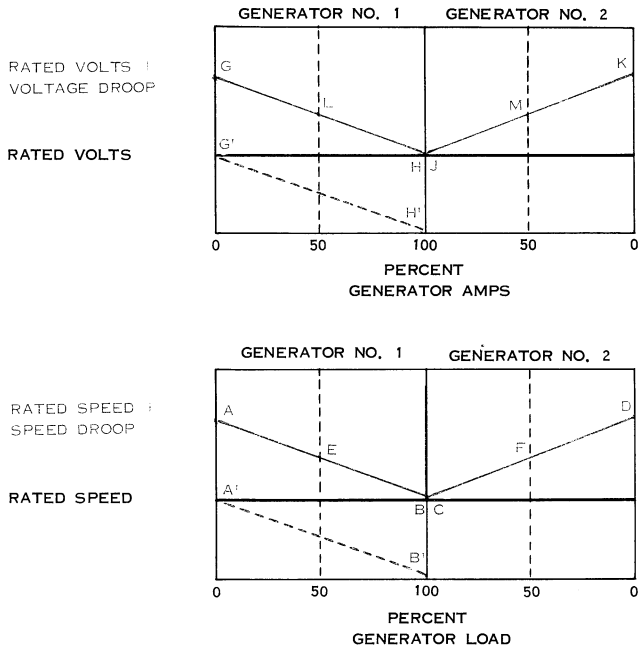


FIGURE 14 – LOAD TRANSFER AND DISCONNECTIONS OF PARALLELED ALTERNATORS.

frequency of the system will be as shown by points B and C and the voltage of the system will be as shown by H and J.

If it is known that the steady load on the system for a period of time will be 50% or less of the total capacity of the alternators, it may be desirable to transfer the load to one unit and disconnect the other unit from the system. In this case, the unit still operating will be loaded to 100% or less of its rating. Note that in the preceding paragraphs, the two units were paralleled with the governors at their high idle settings. In order to transfer the load to just one unit, for example Unit Two, the governor control of Unit One is moved in the "reduce speed" direction until the k.w. meter for alternator one indicates zero k.w. In the event that there are no k.w. meters for the installation, then the ammeter for alternator one should show a minimum indication which is not necessarily zero amperes. At this point, Unit Two is carrying all the load and, if this load is 100% of the rating of the unit, the speed of the system will tend to be at point C and the voltage of the system will tend to be at point J.

What has occurred in the above paragraph is that the governor characteristic of Unit One has been moved down to the points A' and B' (Figure 14) and this unit is floating on the line, but carrying no k.w. load; however, as the load was increased on Unit Two, its speed followed the governor characteristic line from point F to point C. As the load increased on Unit Two, the voltage of the alternator tended to follow the voltage droop characteristic from point M to point J. Also the voltage of alternator one tended to follow its voltage droop characteristics from point L to point G. This tendency for the voltage of the unloaded unit to rise as the k.w. load on the unit is reduced can result in an indication of amperes on the ammeter for alternator one even though the unit is delivering no k.w. to the system. What has occurred is that the voltage droop circuit of the regulator has tended to increase voltage as the load on the alternator is reduced. This is accomplished by the exciter furnishing additional magnetizing power to the generator. This magnetizing power is in excess of that required to maintain rated voltage in the system and magnetizing amperes are delivered to the system. These magnetizing amperes are shown by the indication of the ammeter for alternator one. If this indication is a fairly small value such as 20% or less of alternator rated amperes, the circuit breaker for Unit One can be opened and the unit disconnected from the system.

If the amperes indicated on the ammeter for alternator one are greater than 20% of the alternator rated amperes, or if the device for disconnecting the unit from the system is a knife switch, it may be desirable to reduce the magnetizing amperes to a much smaller value before disconnecting the unit from the system. This is accomplished by reducing the setting of the voltage level control of alternator one. Turning the voltage level control in the direction to reduce the voltage will reduce the magnetizing power of the alternator and the voltage droop characteristics of alternator one has been moved down to the points G' and H'. Under these conditions the engine is floating on the system as shown by A' and is delivering no power to the system, and the alternator is floating on the system as shown by G' and is delivering no magnetizing power to the system. Under these conditions Unit One can be disconnected with a minimum of disturbance to the system and Unit Two will be carrying the complete load. If the voltage or the frequency of Unit Two has varied from the desired values during this operation, they can be corrected by minor adjustments to the governor and the voltage level controls.

SWITCHGEAR INSTRUMENTS AND REGULATORS

Instrumentation used with alternators can vary from none to very complete instrumentation. Single unit operation can be accomplished without instruments. This is very common. The engine governor is adjusted for the high idle speed which will result in rated speed at full load. The alternator regulator is normally adjusted for zero voltage droop. The regulator voltage level control may be set for rated voltage with a very precise regulator or for a slightly higher voltage if there is some inherent voltage spread in the regulator characteristic. The unit is then connected to the load lines. As long as the governor and voltage control settings are not changed, the unit can be operated without instruments.

Parallel unit operation cannot be accomplished without instruments because of the necessity of having equal voltages and frequencies before the units are paralleled. Minimum instrumentation would be a voltmeter for each unit and a set of synchronizing lamps. It is customary to provide an ammeter for each unit as a check on the output of each unit. The power output of each unit is not indicated by the ammeters since currents for kilowatts and magnetizing power are indicated simultaneously by the ammeter. If the governor or voltage regulator adjustment is not correct, it is difficult to determine which is in error and to make the proper adjustment, particularly during operation. It is usually necessary to remove the load, take the units out of parallel, make the necessary adjustment, and reparallel the units. Additional instrumentation makes this unnecessary.

The installation of a kilowatt meter for each unit is useful in setting governor controls, particularly when adding or removing units during continuous operation of an electric plant. The kilowatt meter indicates the power output of the unit. By varying the governor speed control setting, any unit can be made to furnish any desired amount of power up to its full rating. Loads can be divided equally between units of the same rating or proportionately for units of different ratings. Kilowatt meters are particularly useful if the power plant is operated with a lead unit adjusted for isochronous operation. The load on each unit is clearly seen. Overloading the system can be prevented by starting additional units before changes in total load cause overloading of the system.

Two other useful meters for power plant operation are the power factor meter and the kilovar meter. The power factor meter indicates the power factor of the power delivered by an alternator. If there is not a set of load instruments, the power factor of each alternator is the same as the load power factor if all the alternator power factor meters indicate the same value. If these power factor meters show different values, the magnetizing power of the alternators is not in proportion to their ratings.

Assume an .80 power factor load and two units on the line. If Unit One indicates .70 power factor and Unit Two indicates .85 power factor, Unit One is delivering too much magnetizing power and the excess is causing Unit Two to operate at a higher power factor; this is indicated by the power factor of Unit Two being greater than the load and the power factor of Unit One being less than the load. Power factor can be equalized between the units by reducing the magnetizing power of Unit One. This is accomplished by reducing the voltage level setting of Unit One. The power factor of a paralleled unit is increased by reducing the voltage level setting of its alternator. The power factor is decreased by increasing the voltage level setting of an alternator. The power factor of all other units in the line will vary in the direction opposite to that of the unit being adjusted. If the three-phase load in a system is not balanced within ten per cent, the indication of a power factor meter may be in error by approximately .05.

Magnetizing power is also called wattless or reactive power. It can be measured by a reactive kilovoltampere meter. This meter is similar to a kilowatt meter, but it measures reactive or magnetizing power instead of active power. Equal or proportionate indications by KVAR (kilovar) meters indicate equal power factors. Indications of KVAR meters are not influenced by unbalanced loads.

INDEX

ADDENDUM

CHECK YOUR P.F.I.Q.*

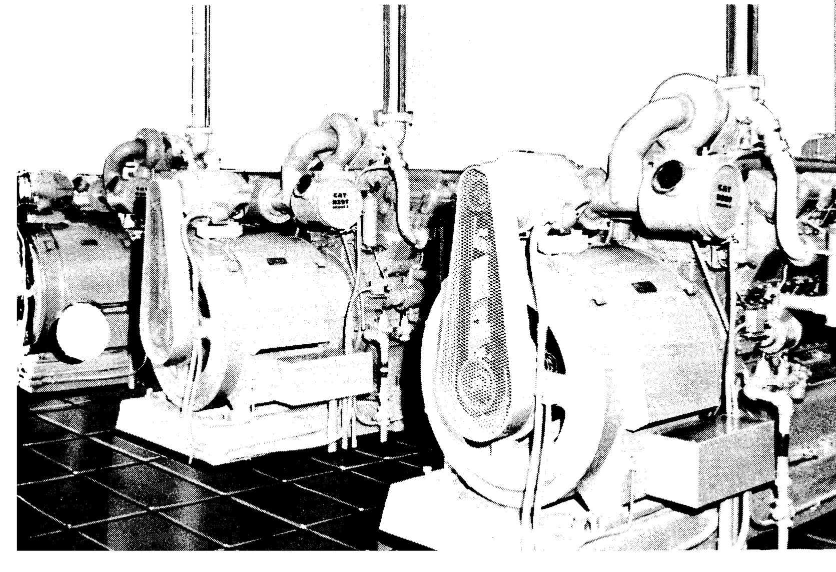
*Power Factor Intelligence Quotient

POWER FACTOR, voltage, efficiency, KVA, phase, amperage and KW. All these terms seem to have a specific mystery about them. They are terms whose definitions are generally misunderstood and often misquoted. This lack of complete understanding is reflected in such questions as, "If an A.C. generator is rated 240 volts and 300 amperes at 0.8 power factor, why can't the generator produce 240 volts and 300 amperes at 1.0 power factor?" Very simply, the answer to this question is — the generator is capable of this output, but it is possible the engine will not be set to deliver enough horsepower to permit the generator to carry the load at rated speed. To help clarify these terms and to explain further the simple solution to this problem, let us explore a typical engine generator setup.

Taking, for example, a naturally-aspirated D342 Electric Set, we will investigate the characteristics of both the engine and generator. In starting, we will make a few assumptions and explain a few terms. First, we will assume the generator to be 90% efficient, which is about an average for generator efficiency. This efficiency indicates that if 100 horsepower were applied to the generator shaft, only 90 horsepower could be extracted from the generator as electrical energy. The 10% loss within the generator is due basically to bearing friction, windage, and heat losses. We can further define one horsepower as being equal to 0.746 KW of electrical power and that KW (kilowatts or 1000 watts) is equal to KVA (kilovolt-amperes or 1000 volt-amperes) times the power factor.

The naturally-aspirated D342 Electric Set is rated 100 KW at 1200 rpm. For an engine to deliver 100 KW from a 90% efficient generator, the following horsepower is necessary.

$$\frac{\overset{\text{KW output required}}{100}}{\underset{\text{90\% efficient}}{0.9} \times \underset{\text{0.746 KW per hp}}{0.746}} = \underline{\underline{149 \text{ horsepower}}}$$



Now we have established that to produce 100 KW from a 90% efficient generator, 149 horsepower will be required. This does not include any capability for overload.

The D342 N.A. Electric Set Engine, set for 1236 rpm high idle and 1200 rpm full load, has a factory rack setting of 0.180. This produces a parallel operation rating of 170 horsepower without fan. The engine is then capable of driving a 90% efficient generator with the following rating (again without including any capability for overload):

$$\underset{\text{Horsepower available}}{170} \times \overset{\text{90\% efficient}}{0.9} \times \overset{\text{0.746 KW per horsepower}}{0.746} = \underline{\underline{114 \text{ KW}}}$$

Actually, this engine is capable of powering a generator rated at 114 KW. Standard generator ratings do not include a 114 KW rating, so a 100 KW generator will be used. This also gives the unit a capability for small overload.

The nameplate data for this sample generator are:

KVA	**125**	**Amperes**	**- 300-150**	**RPM**	**- 1200**
KW	**100**	**P.F.**	**- 0.8**	**Phase**	**- 3**
Volts - 240-480		**Cycles**	**- 60**		

Considering these items one at a time; first, KVA is equal to the rated voltage times the amperage times 1.732 (or $\sqrt{3}$ — a constant required for three-phase

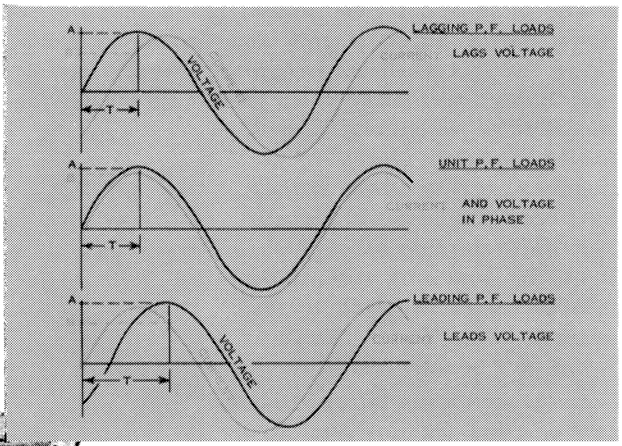


FIGURE 1—*In the illustration, note that for either leading or lagging power factor loads at time (T), voltage is at its peak (A) and current is less than peak (B). KW (or true power) is then the result of voltage (A) times current (B), whereas KVA (or apparent power) is equal to peak voltage times peak amperes. Therefore, it can be seen that KW equals KVA only at unity power factor.*

generation) divided by 1000 (because KVA means 1000 VA).

Using the nameplate information, the KVA for this particular three-phase generator would be:

$$\frac{\overset{\text{Volts}}{240} \times \overset{\text{Amperes}}{300} \times \overset{\text{Constant}}{1.732}}{1000} = \underline{\underline{125\ \text{KVA}}}$$

As previously stated, KW equals KVA times power factor. Therefore, the KW output of this generator equals 125 x 0.8 or 100 KW. One can readily see that, at unity or 1.0 power factor, KVA would equal KW. Further investigation of power factor would reveal it to be, "The ratio for expressing what part of the apparent power (KVA) flowing in an AC circuit is true power (KW)," or P.F.=KW/KVA.

Power factor can be either leading or lagging depending on the load. Figure 1. A leading power factor can be caused by an excessive amount of capacitors connected to the load, a lightly loaded synchronous motor, or an induction motor being driven by its load. Lagging power factor loads are comprised mostly of induction motors. Unity power factor loads are composed of electronic devices and resistance loads such as lights and heaters.

Standard industrial generators are rated 0.8 P.F. lagging since the average industrial load includes motors and other equipment which operate at this power factor. The maximum value for power factor is 1.0 and the minimum is 0.0. The most common value range is from 1.0 to 0.8 (lagging). Leading power factor information is also included here although it will seldom be encountered in practice. The letters in the column of the table labeled "GRAPH LINE" furnish a cross reference between the tabulated data and the information in the graph. (Figure 2).

The table and its companion graph indicate how power factor affects engine and generator loading. Using the aforementioned engine, generator data and performing the necessary calculations with the previously described equations, various loaded conditions (including the rated 0.8 lagging power factor) have been simulated and plotted. Now, with the aid of this graph, it can be seen why the simple solution could be given to the original power factor question. It can now be seen that:

1. At any power factor in excess of rated (in this case anything over 0.8), the output of the electric set is limited by the engine horsepower.
2. At any power factor less than rated, the output of the electric set is limited by generator amperage.

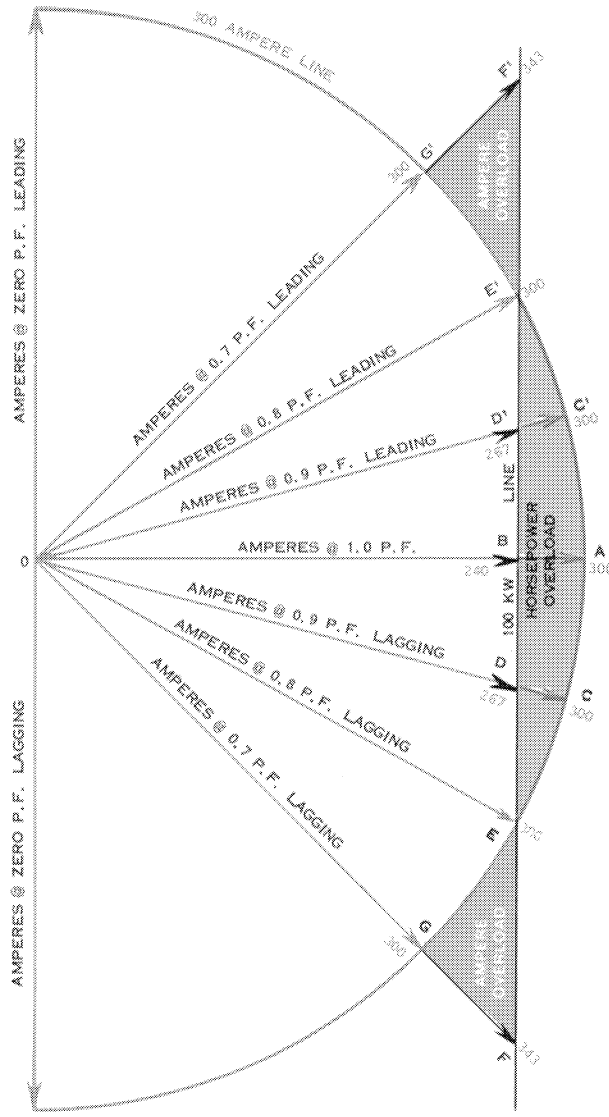


FIGURE 2—*Chart showing how power factor affects engine and generator loading. The engine is rated 149 horsepower at 1200 rpm. The three-phase generator is rated 240 volts, 300 amperes and 0.8 power factor (lagging) at 1200 rpm.*

Power Factor	Engine HP	KW Output	Amps	Graph Line	Comments
1.0	186	125	300	O-A	Rated amperes. 37 horsepower overload.
1.0	149	100	240	O-B	Less than rated amperes. Rated horsepower.
0.9	167	112	300	O-C or O-C'	Rated amperes. 18 horsepower overload.
0.9	149	100	267	O-D or O-D'	Less than rated amperes. Rated horsepower.
0.8	149	100	300	O-E or O-E'	Rated amperes. Rated horsepower.
0.7	149	100	343	O-F or O-F'	Ampere overload. Rated horsepower.
0.7	130	87	300	O-G or O-G'	Rated amperes. Less than rated horsepower.

PREPARED AND EDITED BY CATERPILLAR TRACTOR CO., PEORIA, ILLINOIS, U. S. A.
Caterpillar, Cat and Traxcavator are Registered Trademarks of Caterpillar Tractor Co., Peoria, Illinois, U.S.A.

Not to be reprinted without written permission from Caterpillar Tractor Co.

LITHO IN U.S.A.