Automatic Control Techniques Used on 64-Meter-Diameter Antenna Power Systems

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New power plant equipment installed at DSS 61/63 (Robledo, Spain) and at DSS 42/43 (Tidbinbilla, Australia) was designed to supplement the existing equipment for the additional electrical load of 64-m-diameter antennas recently constructed at these sites. The existing power plant equipment (Section A) at each site consisted of manually controlled generators operating at 480 volts. The new equipment (Section B) uses completely automatic generator control operating at 2400 volts. This report describes the automatic controls and also the techniques used for independent or combined operation of both sections. Features provided for possible future operation with commercially produced power, and future automation of Section A equipment are described.

I. Introduction

The installation of 64-m-diameter antennas at DSS 61/63 (Robledo, Spain) and at DSS 42/43 (Tidbinbilla, Australia) demanded increased power-generating facilities. The existing power plant (Section A) operating at 480 volts at each station was supplemented by new generating equipment (Section B) operating at 2400 volts.

This progress report describes automatic control features of the Section B equipment, which allow combined or separate operation of the two sections. Controls for future parallel operation of the generators with commercially produced power and future automation of Section A during integration of the two power-generating sections are also described.

A brief description of the manual controls performed by an operator in a non-automatic power plant indicates the functions requiring automation and prefaces the description of the automatic control.

II. Manually Controlled Power Plant Operation

At a typical power plant the operator is responsible for the following control operations:

(1) Establishes the power load requirements of the system and determines the required number of engine–generators to provide sufficient generating capacity.

(2) Starts and adjusts the speed of each engine prior to connecting the driven generator to the electrical power system.

(3) Sets the engine–generator speed so that a small difference in frequency exists between the incoming generator and that of the power bus before paralleling. This difference in frequency is indicated on a synchroscope by the speed of its pointer rotation.

(4) Adjusts the incoming generator voltage to coincide with the power bus voltage before paralleling.

(5) Closes the incoming generator circuit breaker to connect the incoming generator to the power system at the precise moment that the generator and power bus are in phase. This is indicated by the synchroscope pointer at the 12:00 o'clock position. This requirement for correct phase relationship is mechanically analogous to meshing two rotating spur gears at the moment when the teeth are in the correct position. To achieve this condition it is necessary to have a slight frequency (i.e., speed) difference between the power bus and the incoming generator voltage so that the phase angle will cycle and pass the "in phase" condition. If an attempt is made to connect the incoming generator out of phase with the power bus, severe overcurrents and voltage dips will occur and the equipment could sustain heavy damage. In the mechanical analogy, the spur gear teeth would be stripped or damaged.

    To back up the operator in this operation a permissive synchronization check relay monitors the phase angle of the running and incoming voltages and prevents circuit breaker closing despite control switch operation unless the phase angle difference is close to zero.

(6) Having synchronized and then paralleled the new generator to the power system, adjusts the diesel engine fuel manually by a governor control switch. The increase in fuel would tend to increase the diesel-generator speed but this is constrained to correspond with the power bus frequency and, instead, the generator increases its share of the kilowatts (real power load) demanded by the power system.

(7) Adjusts the reactive load on the generator by a voltage adjusting rheostat. This rheostat controls the generator field excitation. When the excitation is increased, the voltage of the generator tends to increase but is constrained to correspond with the power bus voltage and instead the generator reactive load (kilovars) increases.

    NOTE: The constraints on generator frequency and voltage depend on the capacity of the power system. The greater the power load, and number of generators running in parallel, the greater the constraints.

(8) Monitors the power generation equipment, making necessary adjustments of governors and excitation as required to share the load kilowatts and kilovars between the connected generators in proportion to their individual power ratings.

(9) Unloads generators and disconnects them as load demand decreases; then stops the diesel engine of the disconnected generator.

III. Automatically Controlled Devices

The automatic control devices used to perform the above operations in Section B of the power plant are discussed below.

A. Power System Sequencer

The power system sequencer (Fig. 1) is built almost completely of solid-state components. It is designed to start and stop the engine–generators as power load increases or decreases. The sequence of starting and stopping of individual machines is manually set by control knobs at the front which allow any machine out of the four installed to be first, second, third or fourth to start. Once preset for starting sequence, the machines stop in the reverse sequence. Following a period of operation of two or three months, the running time of the first engine–generator in the sequence will be greater than the other machines and the sequence will then be manually changed to balance running times. The sequencer is also equipped with control knobs which allow presetting of load kilowatts at which generators will automatically start. Load kilowatt sensing is an integral function of the sequencer.

With one machine generating, the first control knob setting determines the percentage of that machine's power capacity at which a second machine should be started and connected to the power bus to share the load demand. The second control knob setting is set at a percentage of the combined power capacity of the running engine–generators which will start a third machine. The third control knob similarly sets the percentage of the combined power capacity of three engine–generators which will start and connect the fourth machine.

The sequencer presently installed is equipped to handle the four generators presently existing in Section B but can be retrofitted to accommodate the four additional machines in Section A.

B. Automatic Synchronizer

The automatic synchronizer (Fig. 2) is predominantly of solid-state construction. It differs from the synchronizer check relays previously described by incorporating active controls for regulating the incoming diesel-engine speed. When a machine is started by the power system sequencer, the synchronizer automatically assumes control of the machine, brings it into synchronism, and then automatically closes the circuit breaker to connect the generator to the power bus. Following this operation the synchronizer disconnects itself and engine–generator control is passed to its electronic governor and voltage regulator as described later.

Two independent monitors are used in the synchronizer to establish correct synchronizing conditions prior to circuit breaker closing. Both monitors must be satisfied before the generator connects to the power bus. Each monitor checks voltage differential and phase angle difference between the incoming and running generators, and control knobs mounted on the front of the synchronizer permit presetting of acceptable voltage and phase angle tolerances which are suitable for synchronizing. If only one monitor signals that synchronizing conditions are met, the circuit breaker will not close, and an indicator light on the synchronizer will signal a malfunction.

Other lights on the synchronizer allow visual monitoring of the incoming machine status to indicate overspeed, underspeed, overvoltage, and undervoltage.

A feature of the synchronizer is the ability to set the control for circuit breaker closing time, i.e., the short time required for the closing mechanism to respond to its closing signal and physically close its contacts. The synchronizer anticipates the moment of precise synchronism and signals the circuit breaker slightly early so that contact closure is at synchronism.

C. Electronic Power Sharing Governor

Each engine–generator is equipped with an electronic governor control. The fuel setting of the engine is determined by the position of its actuator shaft which is directly proportional to a dc signal from an electronic control assembly. Figure 3 is a block diagram of the fundamental components. This shows that the fuel delivered to the engine, and therefore the electrical power derived from the associated generator, depends on speed and load sensor signals transmitted to the actuator through an integrating and power amplifier. The function of the ramp generator is to control the acceleration of the machine when starting and bringing it up to rated no-load speed prior to synchronizing the generator. Control of the acceleration precludes the possibility of overspeeding the machine on starting.

The normal operation of the power plant, unless interconnected with other power sources, will be isochronous mode (i.e., constant frequency) with load sharing between parallel connected generators. The connection shown in Fig. 3 going to paralleling lines on other machines provides the load sharing function. Mode switching is provided automatically within the control circuits developed for the system.

A short review of fundamentals of stable parallel operation of generators may be of value.

D. Review of Diesel Generators Operating in Parallel

A diesel generator operating singly and supplying electric power independent of any other generator would normally operate in an isochronous (constant speed frequency) mode. The governor would automatically adjust the fuel setting as the power load varies to keep the speed constant (Fig. 4a).

Unless electronic governors are used with forced load sharing provisions, two or more generators cannot be operated in parallel with all generators in isochronous mode. Each machine would attempt to compensate individually for any speed variation and the machines would "fight" each other. The loads on the individual generators would be indeterminate and would swing from no-load up to the maximum load connected to the power bus. This would cause protective gear to operate and disconnect the generators due to overload.

One way of overcoming this instability is to speed droop each of the machines in proportion to the power it is delivering. Any machine tending to take a higher proportion of the load will tend to slow down below the speed of the other generators, but as it is forced to stay in synchronism with the others it will shirk the additional load. On the other hand, any machine tending to deliver less than its proportionate share of the total load will naturally tend to increase its speed. As the speed is contrained to correspond with the power system frequency, this will result in additional load being delivered by the generator (Fig. 4b).

The resulting stability of operation is achieved at the cost of overall power system frequency droop with load. Compensation is usually manually performed by governor control switch.

A second mode of operation that gives stability is to operate all machines in droop except one which operates isochronously. The isochronous machine functions to maintain power system frequency constant (Fig. 4c).

Considering operation under varying power system loads, all machines in the droop mode tend to increase speed as load decreases. The isochronously operating machine shirks its proportion of the load when this occurs, and its share is imposed on the drooped machines to hold them down to system frequency. Conversely, load increase tends to slow down the machines in droop, while the isochronous machine regulates its fuel for the desired speed. The isochronous machine delivers increased load, while the drooped machines shirk any additional load.

The price paid for this solution is that the isochronously operating machine can not be run normally at the same load as the drooped machines. It must have reserve power capacity to supply increased load beyond the preset loads of the machines in droop. Another problem can occur if the total load of the system drops below that normally carried by the drooped machines. This causes the isochronous machine to motor on the drooped machines at a speed above that required for 60-hertz operation.

The most satisfactory solution of the problem can be achieved only by electrically operated governors which are employed in the power systems. Each governor can be set for isochronous operation with its load sensor control interconnected by bus wires to the load sensor circuits of the other machine governors. Any unbalance in generator kilowatt loading causes an error signal on the bus wires which automatically force-shares all generator kilowatts.

E. Voltage Regulation With Cross-Current Reactive Load Control

The voltage regulators installed are of the solid-state type. Their function is to maintain a preset generator and power system voltage value when generators are operating singly or in parallel with others.

With one generator connected to the power system, the voltage regulator action is to control the excitation of the generator and maintain the preset generator voltage under varying load conditions. The function of the voltage regulator is to compensate for inherent generator voltage droop as load increases, by increasing field excitation. This compensation is achieved by comparing the generator output voltage with a reference voltage, and the error difference is amplified and fed to the exciter.

With machines operating in parallel, if the individual voltage regulators attempted to maintain precisely constant individual generator voltage, this would produce unstable reactive load sharing. The problem is very similar in nature to that already described for real power (kilowatt) sharing of isochronous engine–generators. If reactive power is considered instead of real power and the voltage regulator action substituted for the governor action, the similarities in the problem can be noted (Fig. 5).

To prevent "fighting" of the voltage regulators and the resulting reactive power load swings between generators, it is common practice to introduce voltage droop into each generator voltage regulator action. This drooping action is required to give stable reactive load sharing and is therefore introduced into the voltage regulator action as a direct function of the reactive component of the generator total load current.

Figure 6 shows paralleled generators operating with simple voltage regulator droop compensation. The minimum droop to achieve stable reactive power loading is set by the adjusting rheostats to minimize the power system voltage degradation. Manual voltage adjusting control is used to compensate for the droop and bring the power system voltage within acceptable limits.

A better method of maintaining stable reactive load sharing between machines is shown in Fig. 7 and has been used in these power systems. This is achieved by interconnecting the current transformers and voltage regulators of the paralleled generators. The popular term given to this interconnection is "cross-current compensation," and the current transformers are said to be "polygon-connected."

The method of connection forces reactive power load sharing between generators without accompanying voltage droop.

Referring to Fig. 7 it will be noted that current transformers are connected to their associated voltage regulators in a manner similar to that used for droop control but interconnections (a), (b), and (c) cause a completely different reaction. The individual current transformers generate current i_b. When each current value is the same, this current passes through interconnections (a), (b), and (c), and the current transformers behave as though their secondary windings are short-circuited. The voltage regulator elements E1, E2, and E3 carry virtually zero current, provided the interconnections (a), (b), and (c) have low impedance.

For the case indicated, however, generator 1 is delivering more than its share of reactive power, leading to a difference current (Δi) which is superimposed on the balanced value i_b. Element E1 receives most of Δi and the reactive component of this current is active in causing the voltage regulator to reduce generation excitation.

The remainder of Δi passes through the interconnection (a) to the second voltage regulator, through element E2 in the direction causing increased excitation of generator 2. This current then passes through interconnection (b) and through the voltage regulator element E3, which increases excitation of generator 3 and then completes its circuit through interconnection (c) back to the current transformer. In this case with three machines in parallel, 2/3 of Δi will act through element E1 to reduce generator 1 excitation, and 1/3 of Δi will act through elements E2 and E3 to increase the excitation of generators 2 and 3.

Although it may appear that some of Δi passing through elements E2 and E3 would be shunted by CT2 and CT3, these current transformers represent such high impedances to Δi that their shunting effect is negligible.

The foregoing techniques provide all the normal control functions associated with an automatically operated plant. Further consideration had to be given to the controls to allow parallel operation of the automatic plant with an independent commercial power source if this is considered economically feasible in the future. Also, the design allows parallel operation with the manually operated Section A of the power plant.

F. Parallel Operation of Power Plant With Commercial Power Source

If commercial power is connected to the system, the commercial source will be isochronous. The automated power plant controls will automatically revert to speed droop operation and will carry a preset power load. As described in Subsection D, this provides good, stable operation. The commercial source will provide all variations in power required in excess of that generated by the plant.

To allow manual synchronizing of the two power systems and also to preset the kilowatts provided by the generators, the power plant is equipped with a power transfer control device (Fig. 8). This device is actually a simple dc power supply with manually variable output voltages compatible with the paralleling bus wire voltage levels of the electric governors. The output voltage of the power transfer control is manually set to correspond with the value across the governor bus wires by use of a built-in balancing indicator and then manually switched to the bus wires. Following this, movement of a control knob on the device varies the signal voltage on the bus wires which control all governor fuel settings on the connected engine-generator sets. By this control the power plant-generated frequency can be varied to allow manual synchronization and interconnection with the commercial power source. After interconnection, adjustment of the power transfer control knob allows presetting the kilowatts to be contributed by the power plant.

Reactive power division between the power plant and the commercial power source is treated differently from the kilowatt power division. It is desirable to keep reactive power load from the commercial system to a low value and use the power plant to supply all reactive power. The generators are fully rated to supply all the reactive load at no fuel cost, while commercial power companies charge for reactive power. The power plant equipment is therefore equipped to monitor the reactive power loading of the commercial power source (Figs. 9 and 10).

The monitoring meter is equipped with manually settable contacts which close whenever reactive power flows in the commercial power source interconnection. The contacts drive a motor-operated variable transformer which injects a voltage into the cross-current compensation circuit of the generator voltage regulators as shown in Fig. 9.

When the variable transformer is in the null position, corresponding with its center point, the voltage induced in the cross-current circuit is in phase with phase 2 voltage, and this has no effect on the voltage regulators. When the variable transformer is in other positions, the vector phase angle of the induced voltage changes, and the quadrature component of this voltage acts on the voltage regulators to raise or lower the generator excitations. The resulting effect is to maintain commercial power source reactive power loading within the manual settings of the monitoring meter.

G. Parallel Operation of Power Plant Sections A and B

The present configuration demands that the manually operated Section A be considered as an isochronous power source. This means that the automatic Section B must be operated in the droop mode (governors and voltage regulators). The automatic Section B will deliver a preset portion of the load kilowatts and kilovars while the manually operated section will supply a variable portion of the load as power demand varies.

Complete integration of Sections A and B of the power plant is underway. This will provide a totally automated system, incorporating all the automatic features to both sections of the generator plant. The operation of the integrated system will be isochronous with zero frequency or voltage droop, load sharing of kilowatt and reactive load between generators in proportion to their ratings, and automatic starting and stopping control of all generators.

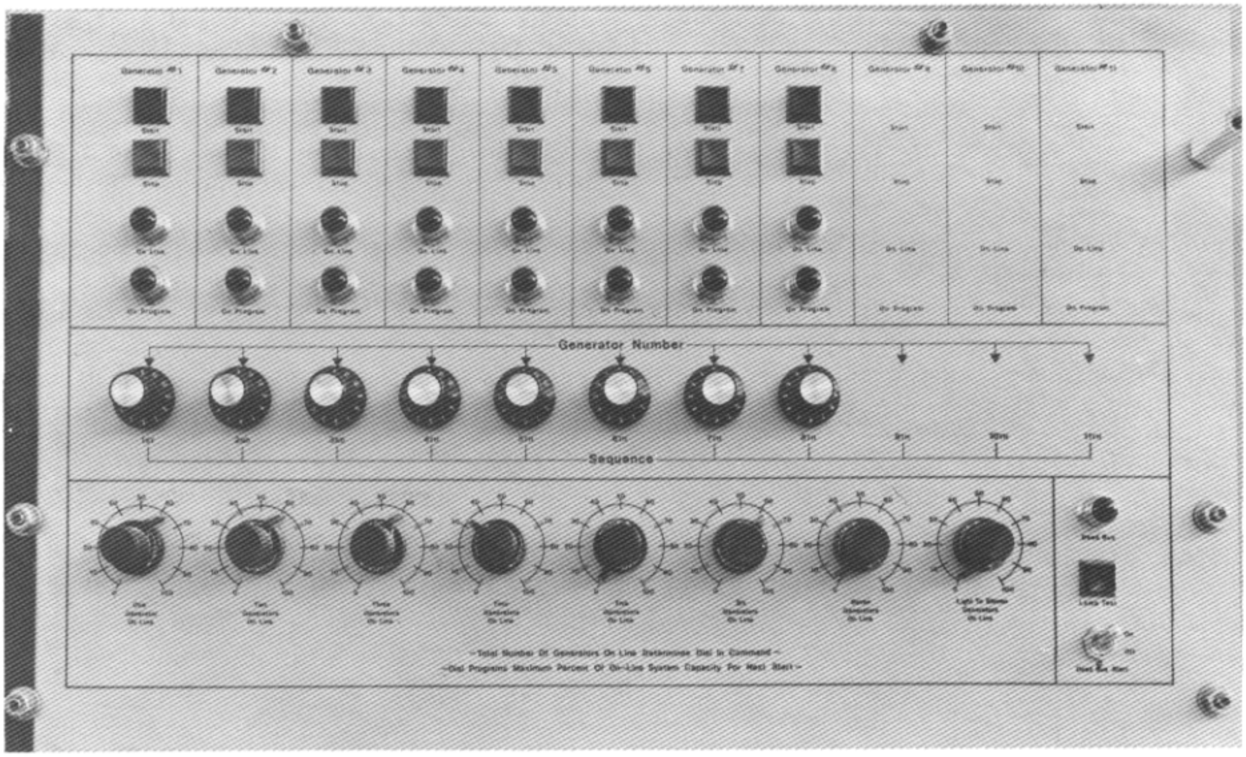


Fig. 1. Power system sequencer

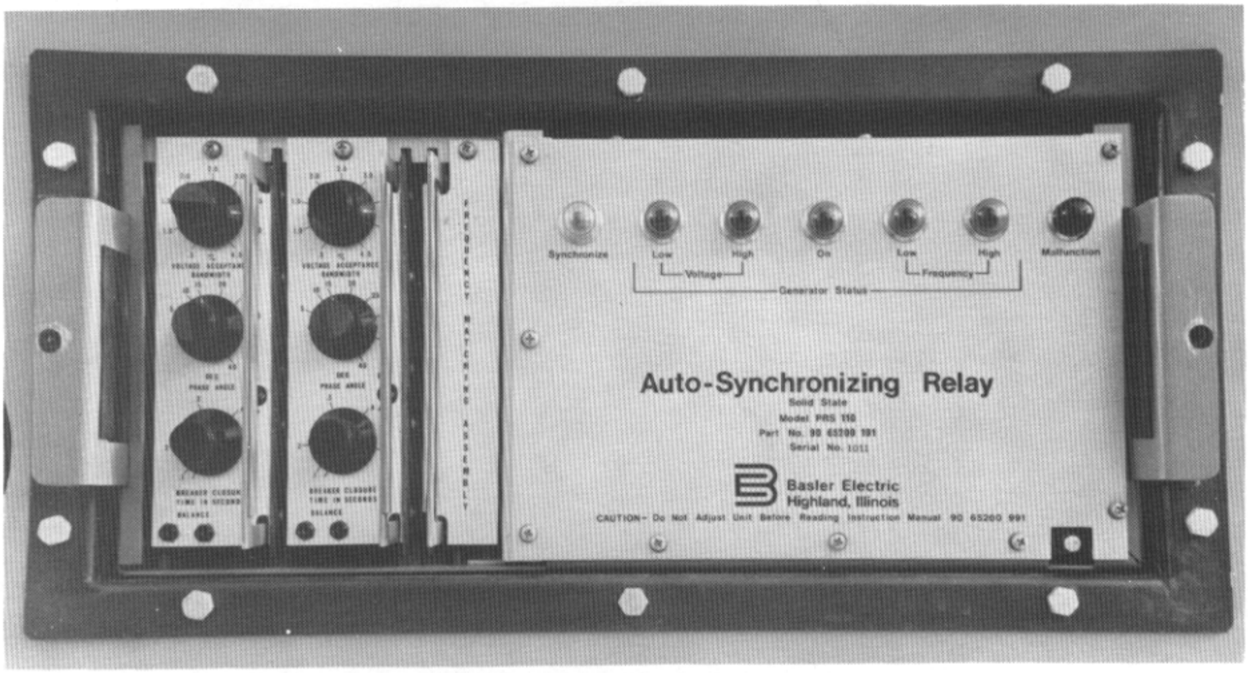


Fig. 2. Automatic synchronizer

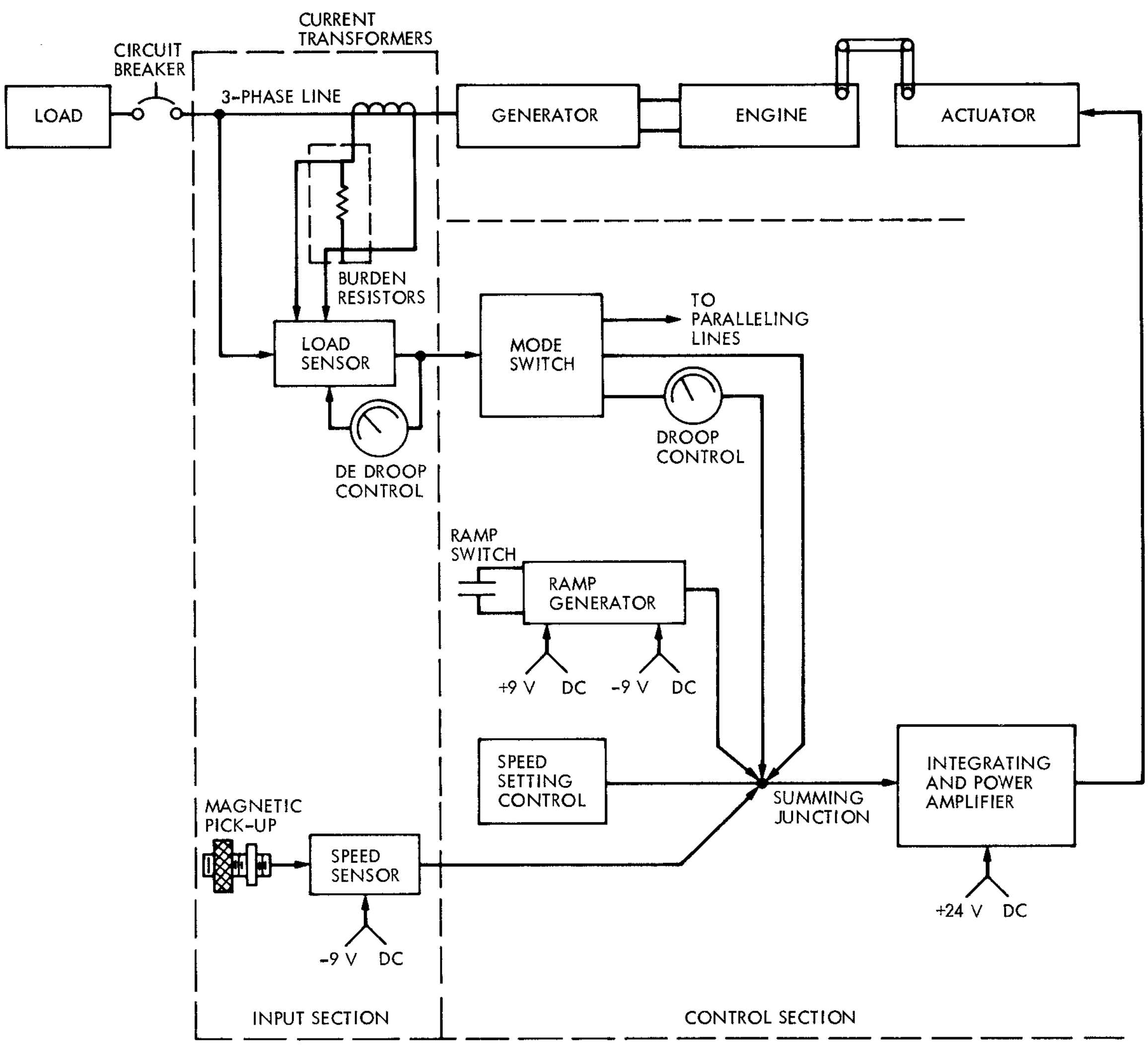


Fig. 3. Block diagram of electronic governor system

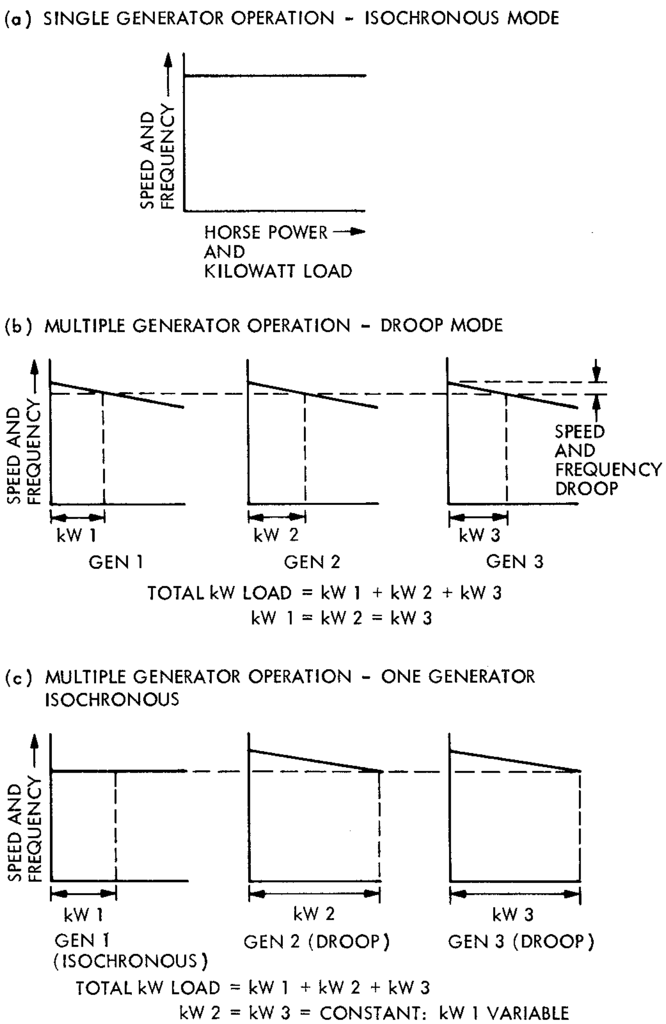


Fig. 4. Diesel-generator operating modes

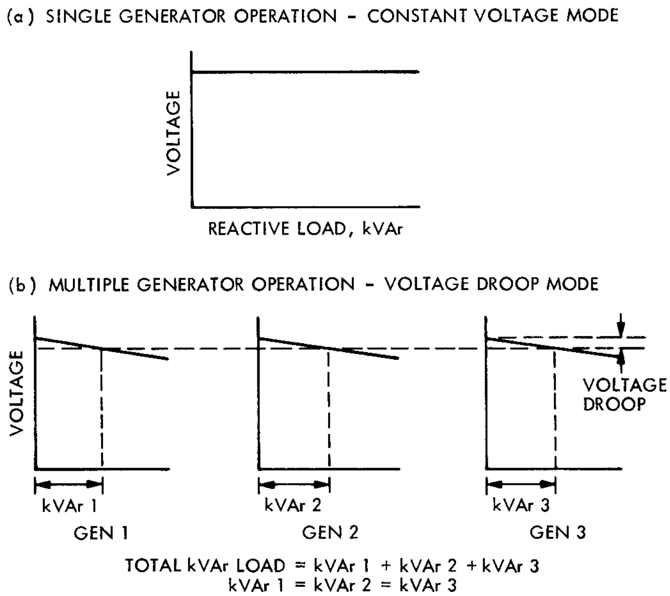
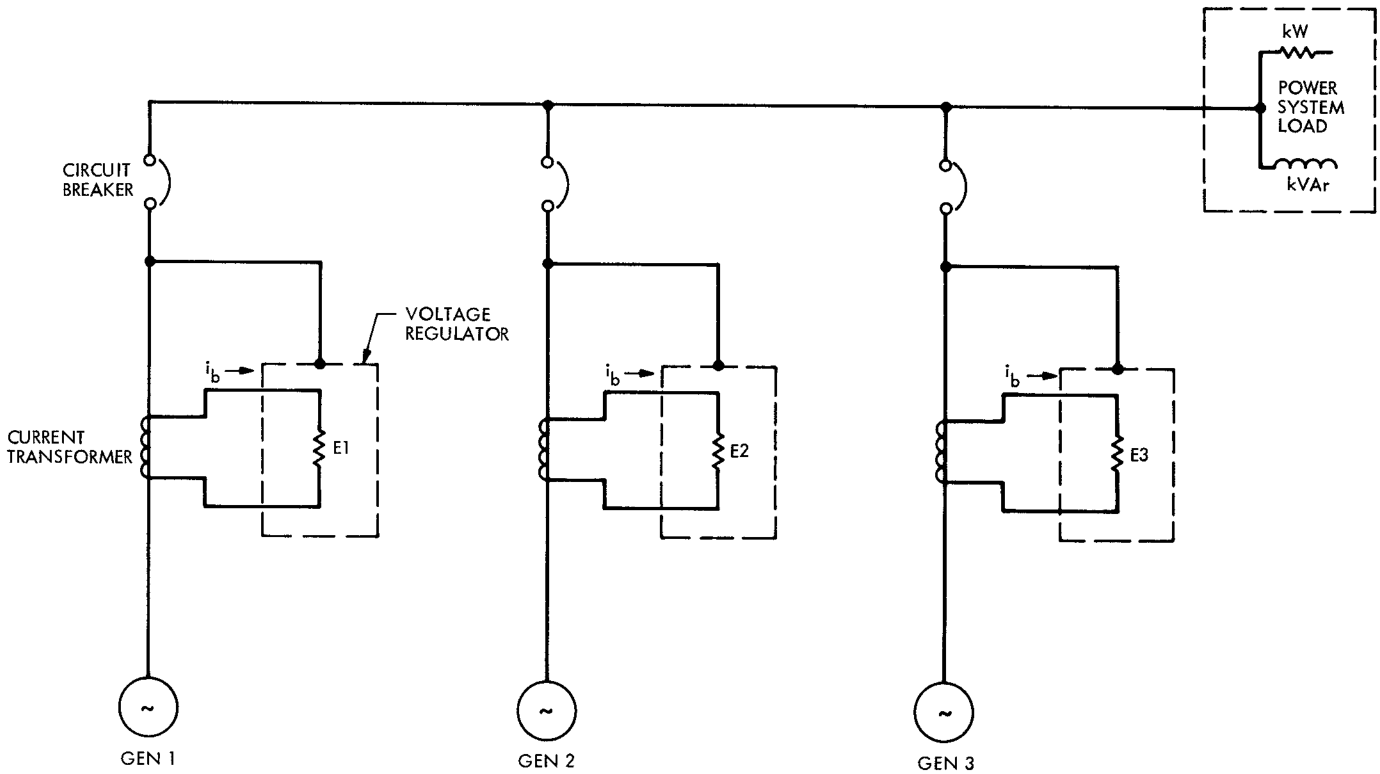


Fig. 5. Kilovar loading of generators



NOTE: REACTIVE COMPONENT OF i_b IN DIRECTION SHOWN REDUCES GENERATOR EXCITATION THROUGH VOLTAGE REGULATOR ELEMENTS E1, E2, AND E3

Fig. 6. Generator voltage regulators in droop mode

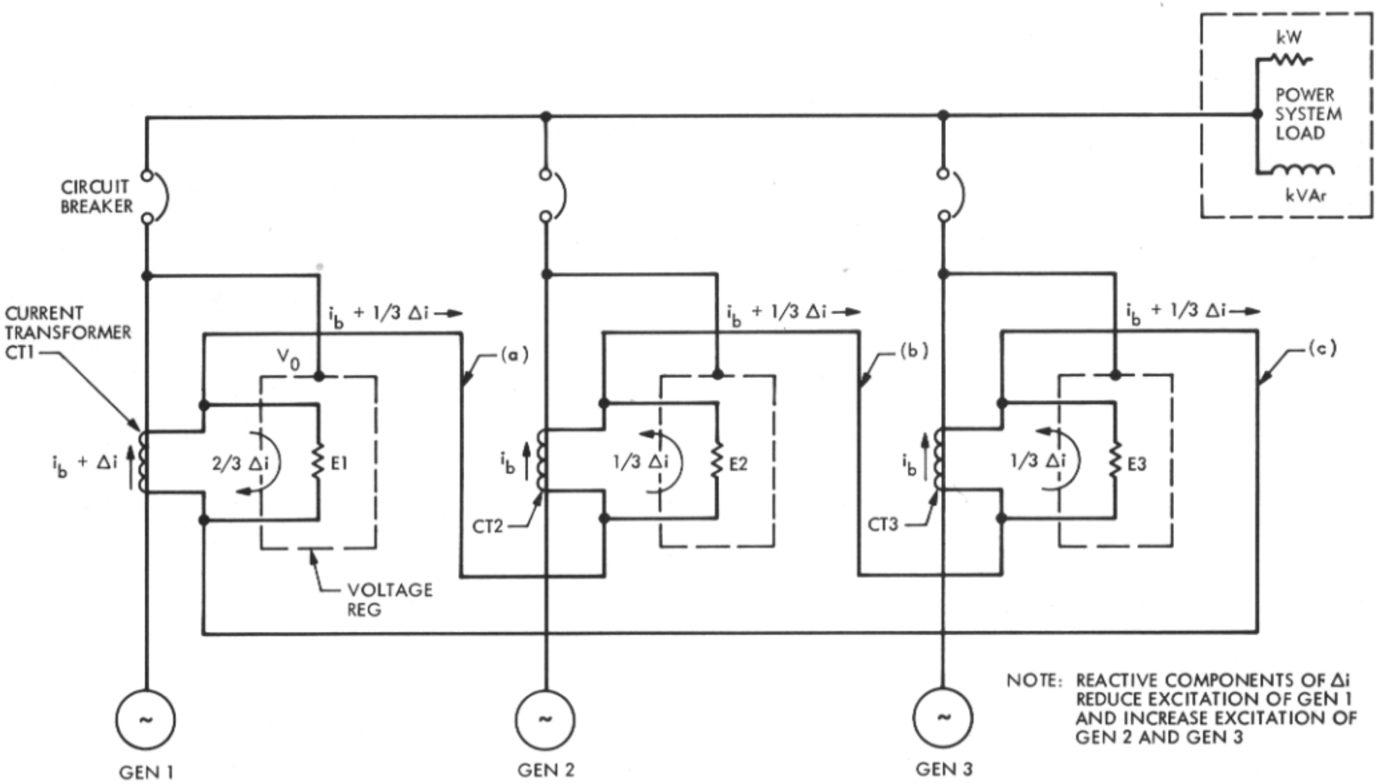


Fig. 7. Generator voltage regulators with cross-current compensation

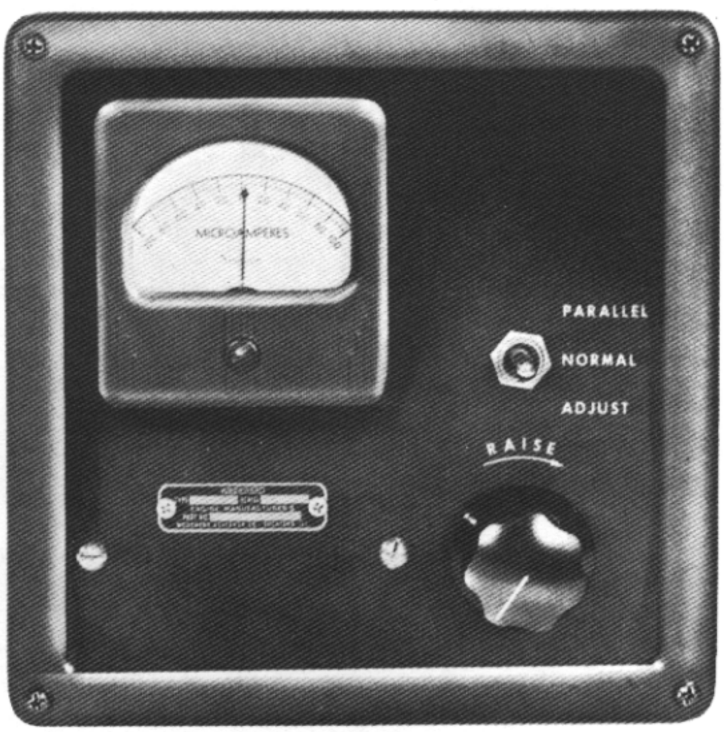


Fig. 8. Power transfer control

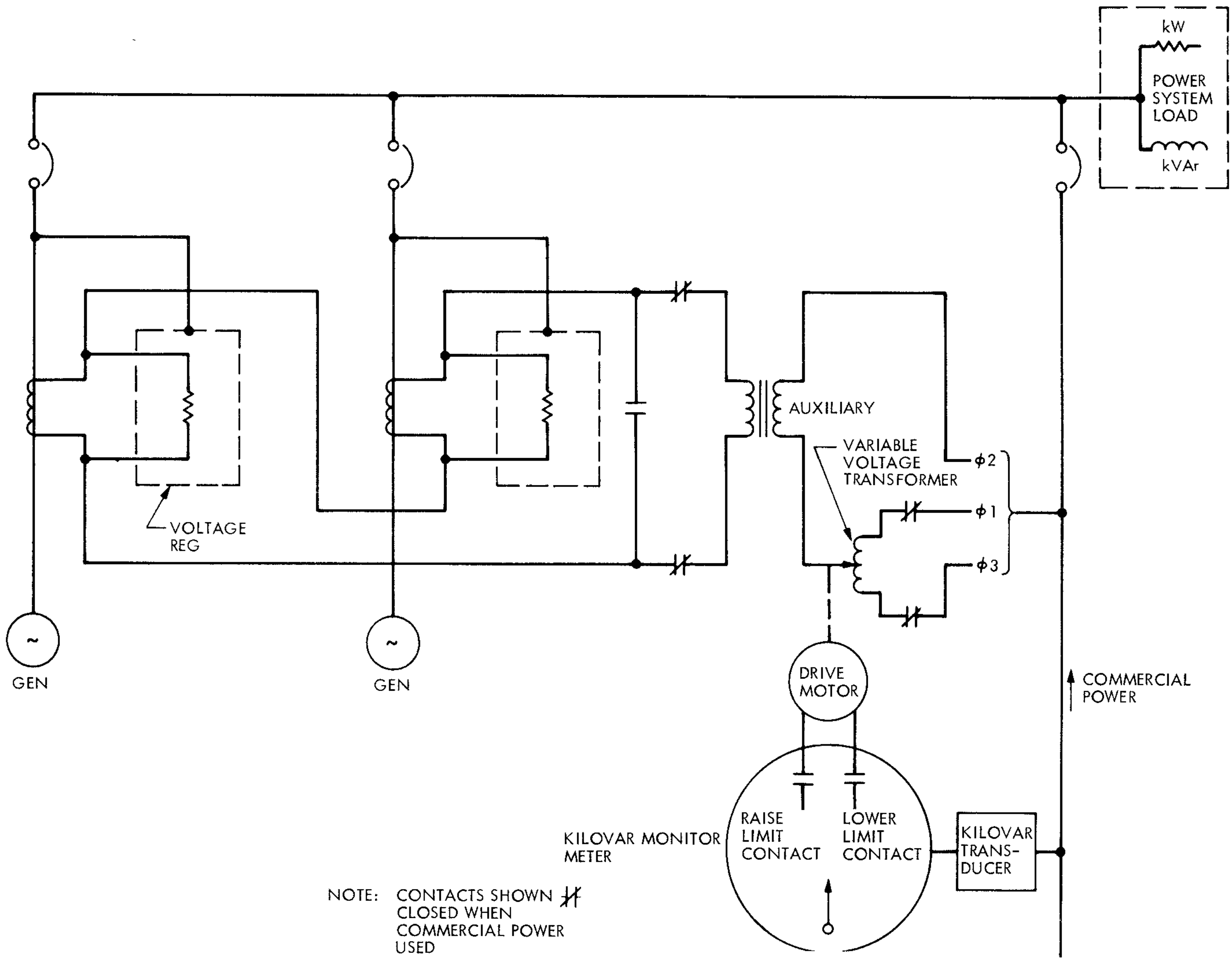


Fig. 9. Simplified circuit of modified cross-current compensation of generator voltage regulators when commercial power connected

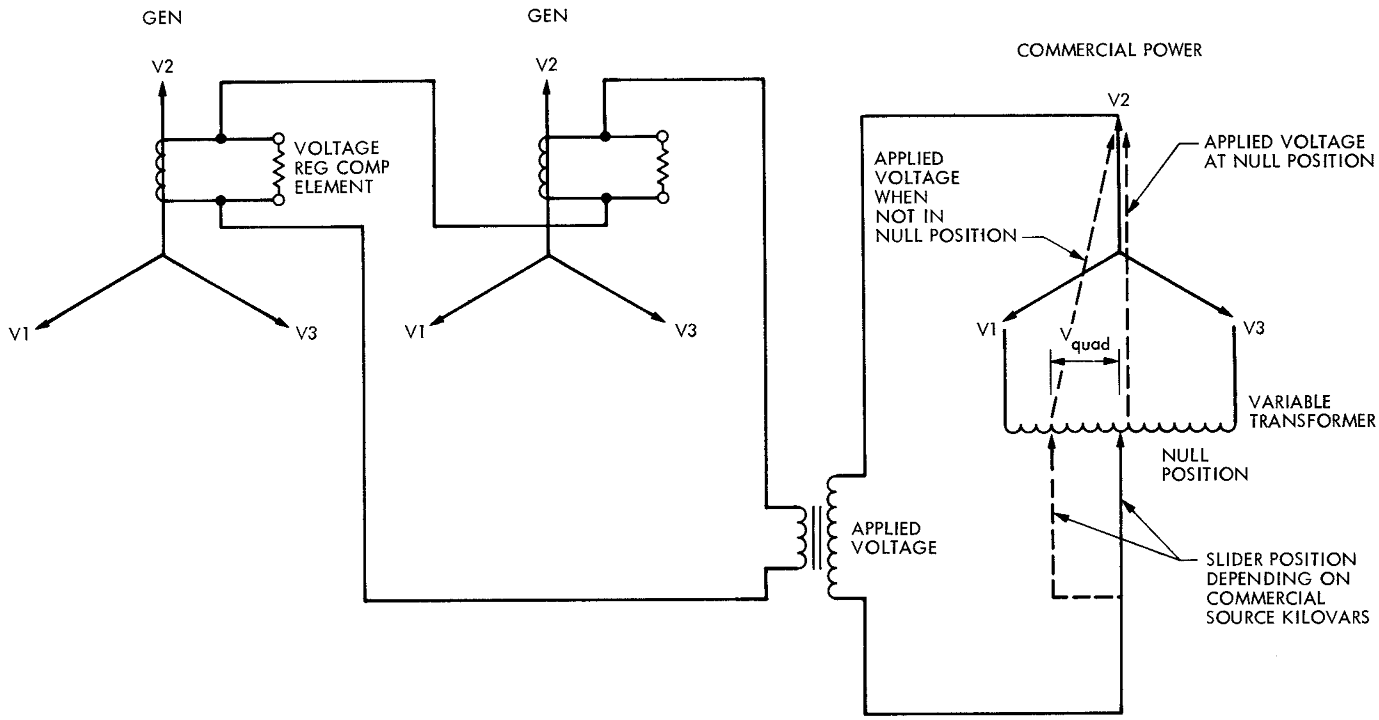


Fig. 10. Voltage vectors applied to voltage regulator cross-current compensation circuits