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PARALLEL OPERATION OF TWO BRAYTON-CYCLE ALTERNATORS WITH PARASITIC SPEED CONTROLLERS

by Dennis A. Perz
Lewis Research Center
Cleveland, Ohio

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by Dennis A. Perz

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

The experimental paralleling characteristics of two 1200-Hz Brayton-cycle alternators are presented. Since the Brayton power conversion system uses electric speed controllers, the paralleling requirements are somewhat different from those for conventional ground-based power systems. Results include the transient effects of synchronizing the two alternators with various phase-angle, voltage, and frequency differences. Based on these results, the effects of synchronizing differences can be defined, and adjustment requirements of the parasitic speed controllers during synchronizing can be established. Data indicate that parasitically loaded alternators are able to parallel over a wide range of synchronizing differences. However, equilibrium could not be reached in extreme cases where alternator load differences were great and, at the same time, the phase-angle error was large (150° or more).

THE DEVELOPMENT OF DYNAMIC POWER SYSTEMS for space applications has reached the point where the use of multiple generators operating in parallel is of interest. The range of space application of Brayton systems may be extended by using two or more machines rather than just a single machine. The use of multiple generators permits a modular approach to power-system design with the resulting advantages of increased flexibility and reliability and reduced cost.

Much work has been done in the past on multiple-generator systems, both in aircraft and commercial power applications; however, the advanced turbo-alternator systems currently under investigation for use in space (1)* differ from conventional power systems in several ways.

Space power systems use an electric speed contoller in combination with a parasitic load instead of a turbine valve and mechanical governor (2). The electric speed controller applies a parasitic electrical load to the alternator as a function of frequency in order to absorb the constant generated power even when the useful system load varies. The effect of the parasitic load on synchronizing and system stability after paralleling must be determined.

Space power systems also use solid-rotor alternators. The solid-rotor machine does not require brushes for field excitation, is easier to cool than wound-rotor machines, and is considered more reliable. Solid-rotor alternators do, however, have larger rotor inertias than wound-rotor machines for the same output. Since rotor inertia is significant during the synchronizing transient, the effect of the larger value must be determined.

As an initial effort to study the paralleling characteristics of parasitically loaded turboalternators, two alternators from the 1200-hertz Brayton-cycle system (1) were tested. In addition, breadboard versions of system parasitic speed controllers, shunt voltage regulators, and series field modules were used (2).

Transient results of synchronizing the two alternators under several load conditions are presented for various differences in voltage magnitude, phase, and frequency. Of particular interest are (1) the ability of the alternators to parallel in spite of synchronizing differences, (2) the magnitude of the synchronizing transients, and (3) the effects of the

*Numbers in parentheses designate References at end of paper.

parasitic speed controllers on synchronizing.

PARALLELING CONSIDERATIONS FOR PARASITICALLY LOADED TURBOALTERNATORS

Figure 1 is a simplified block diagram of a single-generator parasitically loaded power system. This figure shows the significant power-transfer stages between the prime energy source and the useful system electrical load.

Turboalternator power systems with parasitic loads are designed to operate at a single constant power level. Thus the energy source has a constant output, and no provision is made to control the power input to the turbine. As a result, the total alternator electrical output must also be constant so that nominally constant speed and frequency can be maintained. The useful system load is assumed variable, however, so a frequency-sensitive waste, or parasitic, load is added. The parasitic load, which typically operates over a 2-percent frequency range, offsets any change in the useful load so that the alternator frequency remains nearly constant.

For alternators to be synchronized, they must have the same phase sequence. In addition, any differences in the voltage magnitude, phase, or frequency will produce transients in the form of current, power, and torque surges in proportion to the size of the differences. These transients arise out of the natural tendency of alternators to self-synchronize (i.e., to minimize magnitude, phase, and frequency differences) when tied to a common bus.

In parasitically loaded turboalternator power systems, alternator frequency varies with the amount of parasitic load applied. As a result, when two parasitically loaded turboalternators are to be paralleled, a frequency difference will exist before paralleling if the two machines have unequal amounts of parasitic load. This is likely to be the case.

A further consequence of using a parasitic speed controller is the effect on voltage regulation. As noted in reference (3), a characteristic of presently used speed controllers is that alternator voltage magnitude varies with the amount of parasitic load applied. For the 1200-hertz Brayton-cycle power system, voltage variations of about 3.5 percent of rated voltage were measured over the operating range of the speed controller.

Because of the existence of voltage-magnitude and frequency differences, the question arises regarding the feasibility and practicality of paralleling without regard to synchronizing errors (random paralleling). The advantage gained is that special synchronizing circuitry would not be required. The obvious drawbacks are that (1) the alternators may be unable to synchronize for very large phase and frequency errors, and (2) the peak transient currents and powers may be excessively large and potentially harmful to the machines.

In order for the range of acceptable conditions to be determined for multigenerator operation, the system must be experimentally subjected to the various types of errors possible during synchronizing. It is also of interest to examine any variations in conditions which may occur when the machines are paralleled. For example, the useful-load power factor may be variable, or the total generator loads may be unequal as during system startup.

APPARATUS AND PROCEDURE

The components tested were built as part of the 1200-hertz Brayton-cycle program currently under investigation by NASA. Figure 2 shows the major components used for this test. Two alternators, each with its own voltage regulator and parasitic speed controller, were tested.

ALTERNATORS - The two alternators used were the Brayton rotating unit with rolling element bearings (BRU-U) (fig. 3) and the alternator research package (ARP) (fig. 4). The BRU-R (4) consists of a turbine, alternator, and compressor mounted on a single shaft. The alternator is a modified Lundell design with stationary field coils.

The ARP was built to be electromagnetically equal to the BRU-R alternator. Its original purpose was for experimental determination of alternator characteristics. These data are presented in reference (5). The nominal three-phase rating of the two alternators is 14.3 kilovolt-amperes at a 0.75 power factor. Rated voltage is 120/208 volts, rated current is 39.7 amperes, and rated power is 10.7 kilowatts.

The ARP was coupled to a facility turbine, and both it and the BRU-R were operated with a facility air supply. A servovalve was used at each turbine inlet and was automatically controlled to maintain a preset valve position. Thus, constant power was provided to each turbine for a given valve position.

For the purposes of this test, the compressor wheel on the BRU-R was replaced by a solid disk of equal inertia. The compressor inlet was then sealed to minimize windage losses.

VOLTAGE REGULATORS - As shown in figure 2 the voltage regulators used consist of a shunt field regulator which senses load bus voltage and a series field controller which senses line current. Each excites separate windings in the alternator. Breadboard versions were used, and the operating characteristics are reported in references (3) and (6).

Two modifications to the shunt regulators were incorporated into the original design (2). First a constant volts per hertz reference circuit was added as described in reference (7). The second modification was the addition of reactive load compensation circuits for paralleling. The circuit design used was based on the aircraft system application described in reference (8).

PARASITIC SPEED CONTROLLERS - The speed controllers are breadboard units and are described in references (3) and (6). The speed controllers adjust the load dissipated in a resistor by means of phase control. Phase control is a technique by means of which a solid-state switch (SCR) can be made to conduct current over a controlled portion of each half cycle of the alternator voltage. The effective current is varied, by varying the conduction interval, thereby causing the resistor's parasitic load to change. The speed controller senses alternator frequency, which is proportional to rotational speed, and adjusts the SCR conduction interval accordingly. The two parasitic speed controllers used were adjusted to have similar loading characteristics.

TEST PROCEDURE - The total power on each alternator was set by adjusting the trubine servo-valves. Alternator voltage adjustments were made by potentiometers provided in the shunt regulators. Synchronizing was performed by observing the real time relationship between the two alternator voltages on an oscilloscope. The paralleling contactor was opened and closed manually. All data were recorded on an oscillograph. Accuracy of the data is 5 percent or better. All loads were nominally balanced three-phase.

RESULTS AND DISCUSSION

The data presented here are based on the differences in voltage magnitude, phase, and frequency between the two alternators at the moment the paralleling contactor is closed. For the sake of brevity the following definitions are made:

Δf frequency difference

ΔV voltage magnitude (rms) difference

$\Delta\varphi$ phase difference

For each data point, the maximum rms alternator phase current, maximum average single-phase alternator power, and maximum and minimum rms load-bus voltage variations are presented. The current and power peaks are measures of the torque loads placed on the machines during synchronizing. The voltage swings are indications of the effects the synchronizing transient can have on the useful load.

PHASE-DIFFERENCE EFFECTS. Zero-Power Transient - Figure 5 presents a synchronizing transient with zero load on each machine: $\Delta V = 0$, $\Delta f = 0$, $\Delta\varphi = 145^{\circ}$. When the paralleling contactor is closed, the phase difference immediately goes to zero, as only one voltage can exist on the bus.

The current and power traces show that the system oscillates at its natural frequency and is damped in this case. When the machines are paralleled out of phase, the rotors must adjust their angular position relative to each other in order to reach equilibrium. Depending on their relative angular positions, one machine will motor off the other machine which operates as a generator. Rotor inertia causes an overshoot, however, so that the functions are then reversed — the generator becomes the motor and the motor the generator. This process continues until system damping causes the transient to die out and the proper phase relationship is attained. (By convention, generator power (output) is positive and motoring power (input) is negative.)

Figure 5 also shows the transient effect on the load-bus voltage (see fig. 2) for the same phase error of 145°. An initial voltage drop occurs, followed by a rise as the alternator currents oscillate and the shunt voltage regulator adjusts. The voltage is modulated as the current surges between machines. As a result, peak voltages well above the 120-volt rating are realized.

Effects of Voltage Magnitude Errors - In figure 6 the combined effects of phase error $\Delta\varphi$ and voltage error ΔV are shown; $\Delta\varphi$ ranges from 0° to 180° and ΔV from 0 to 5 percent. The alternator load is zero. The effects on the extreme values of alternator current, alternator power, and load bus voltage are shown.

Two observations can be made. First, each curve has an extreme value occur near 180°. (Refer to fig. 5 for peak locations.) This is expected because the greater the $\Delta\varphi$, the greater the transient.

The second observation is that little change occurs for a ΔV of 5 percent relative to a ΔV of 0 percent. Since all voltage variations due to the parasitic loads are less than 5 percent, it was concluded that ΔV errors are not significant.

Effects of Alternator Loads - The variation of transient peaks with phase error for a range of equal total alternator loads is presented in figure 7. In each case the total alternator load was 100 percent parasitic (zero vehicle load). Each machine had its own parasitic speed controller, as shown in figure 2.

Results show that maximum alternator rms current and maximum average alternator power occur near 180° and increase with the magnitude of the load. Maximum measured phase current is 113 amperes for 6-kilowatt loads with approximately 180° $\Delta\varphi$. Peak single-phase power for the same condition is 12 kilowatts (36 kW total). These peaks are about six times the original loads and about three times the machine ratings.

Figure 7(c) indicates that voltage maximums and minimums are not affected by magnitude variations in equal alternator loads.

Two other significant points are (1) the machines successfully synchronized for even the most extreme phase errors, and (2) the two-machine paralleled system remained stable even with two parasitic speed controllers operating simultaneously and independently on the same bus.

Figure 8 presents the transient effects of synchronizing alternators with unequal loads. In each case, one alternator was unloaded (0 kW) and the other had only a parasitic load ranging from 3 to 7.5 kilowatts. The most significant result is that although paralleling was successful under most conditions, equilibrium could not be reached for the most extreme phase-angle differences. For a 6-kilowatt load difference, the maximum possible $\Delta\varphi$ is about 160°; for a 7.5-kilowatt load difference, the maximum $\Delta\varphi$ is 150°. In order to determine the cause of this limitation, the test for the 6-kilowatt load difference was repeated several times with the following variations:

(1) The loads on the two alternators were reversed.

(2) The load was changed from phase-controlled parasitic to linear useful at 1.0 and 0.75 lagging power factors.

(3) The load levels were changed from 0 and 6 to 3 and 9 kilowatts.

(4) The reactive load compensators were removed. In each case, the 160° $\Delta\varphi$ limitation appeared. Thus, it appears that the gross alternator load difference is the source of the limitation.

Figure 9 is an unstable synchronizing transient for initial machine loads of 0 and 7.5 kilowatts, $\Delta V = 0$, $\Delta f = 0$, and $\Delta\varphi = 153°$. In contrast to the transient in figure 5, the current and power swings are not damped but are actually increasing in time. The paralleling contactor was manually opened as soon as this condition was determined.

Examination of the phase error trace after the paralleling contactor was opened shows that $\Delta\varphi$ has a frequency of about 35 hertz. This indicates that the two machines have been driven apart in speed at this point compared to the initial $\Delta f = 0$.

EFFECTS OF FREQUENCY DIFFERENCES - The effects of paralleling the two alternators with different frequencies was first looked at for the zero-load case. The open-circuit voltages were equalized ($\Delta V = 0$) and the frequency difference was adjusted with the turbine servovalves. Results show that for frequency differences up to 40 hertz, the synchronizing transient is damped and stable. The 40-hertz difference represents a 3.3-percent error for a 1200-hertz system, and this is greater than the 2-percent frequency regulation of the parasitic speed controller.

To determine the effects of frequency differences on loaded machines, each turboalternator was connected to its parasitic load and the turbine valves were adjusted to give about 6 kilowatts per machine. One valve was then closed in small increments. Each adjustment had the effect of reducing that alternator's load and frequency. After each adjustment, the alternators were synchronized randomly several times. The first case of unsuccessful paralleling occurred for machine loads and frequencies of 6.0 kilowatts at 1216 hertz and 3.6 kilowatts at 1210 hertz. Thus, a frequency difference of only 6 hertz coupled with an initial power difference of 2.4 kilowatts is enough to prevent synchronization. Paralleling was attempted for this condition five times and was successful four times.

SUMMARY OF RESULTS

Two 1200-hertz parasitically loaded turboalternators were subjected to a variety of synchronizing transients in which voltage magnitude, phase, and frequency differences were varied. Results were generally favorable in that the machines were able to synchronize over a wide range of conditions. Some limitations do exist, however.

The following results hold for equal frequencies and equal open-circuit voltage magnitudes:

1. The two machines successfully paralleled with equal loads of 0, 3, and 6 kilowatts for any phase difference.

2. When initial machine loads are unequal, synchronizing is not always successful. For a load difference of 6 kilowatts, the maximum permissible phase error for successful synchronizing is 160°. For a load difference of 7.5 kilowatts, the maximum error is 150°.

3. Paralleling the two machines, each with its own parasitic speed controller and for equal loads of 3 and 6 kilowatts, results in stable synchronizing and steady-state operation with any initial phase difference. After paralleling, the two-machine system operating with two independent parasitic speed controllers remains stable.

4. For equal loads of 6 kilowatts and a synchronizing error of 180°, the worst transients resulting in successful paralleling occurred. The measured rms phase current was greater than 110 amperes and the peak three-phase power was 36 kilowatts. These peaks are about 600 percent of the levels before paralleling and about 300 percent of the alternator ratings.

5. Additional testing showed that open-circuit voltage errors up to 5 percent and frequency errors over 3 percent did not significantly affect the no-load synchronizing capability of the two machines.

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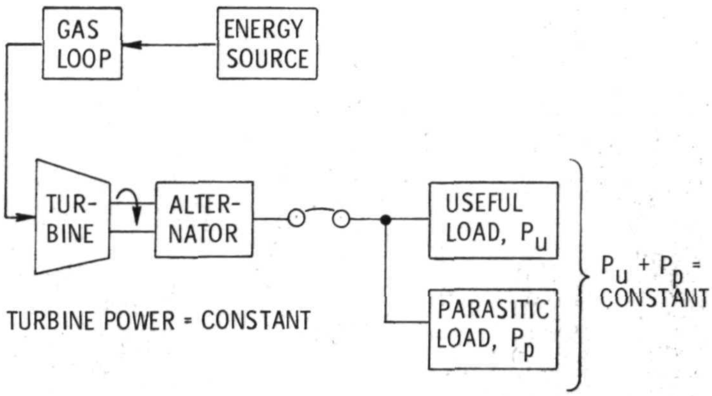

FIG. 1. Power flow in turboalternator power system with parasitic speed controller.

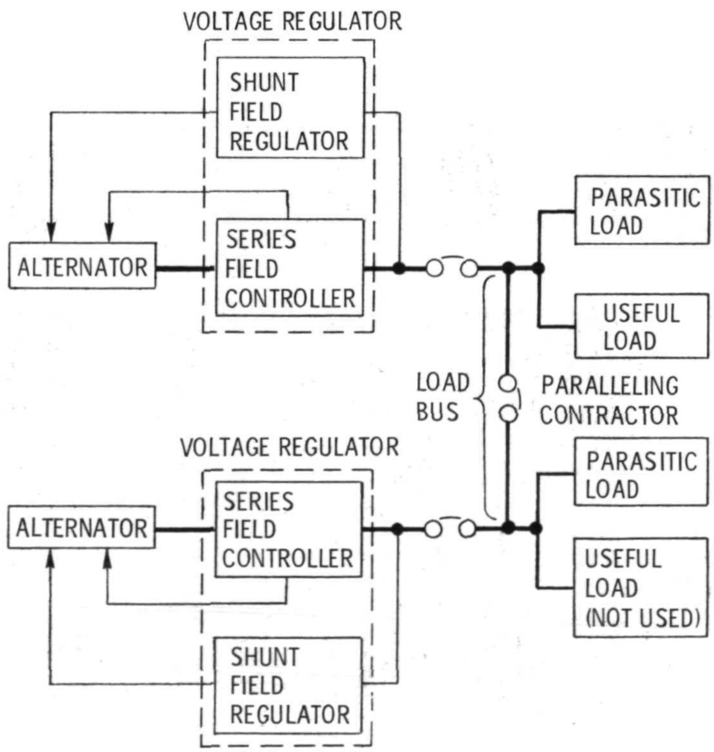

Fig. 2. Major electrical components of a two generator power system.

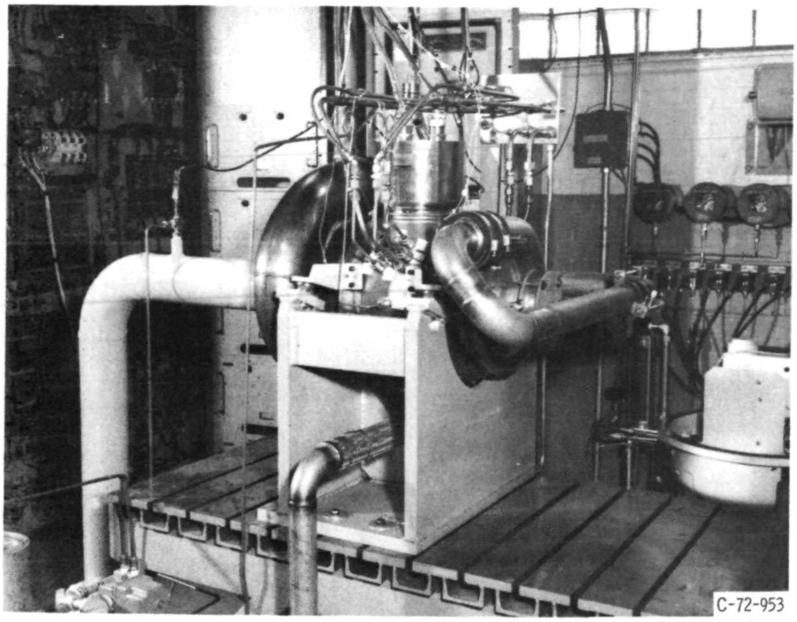

Figure 3. - Brayton rotating unit (BRU-R).

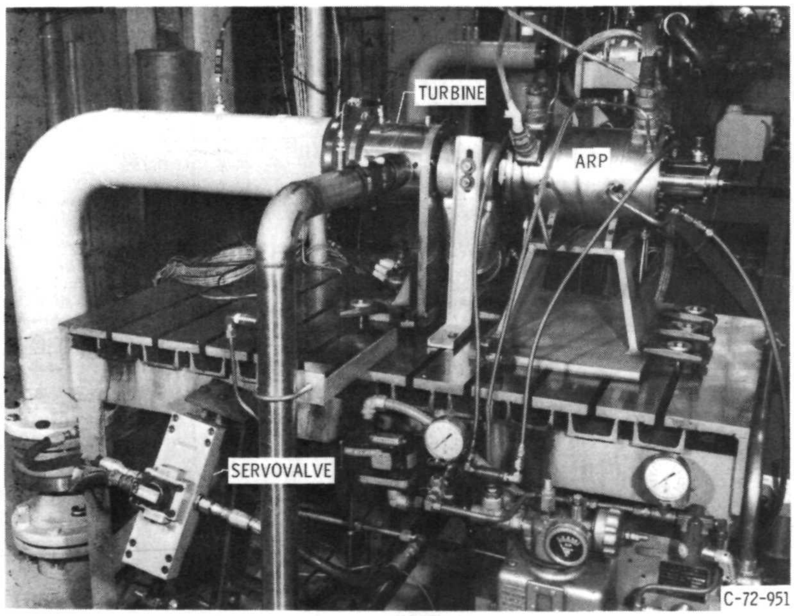

Figure 4. - Alternator research package (ARP).

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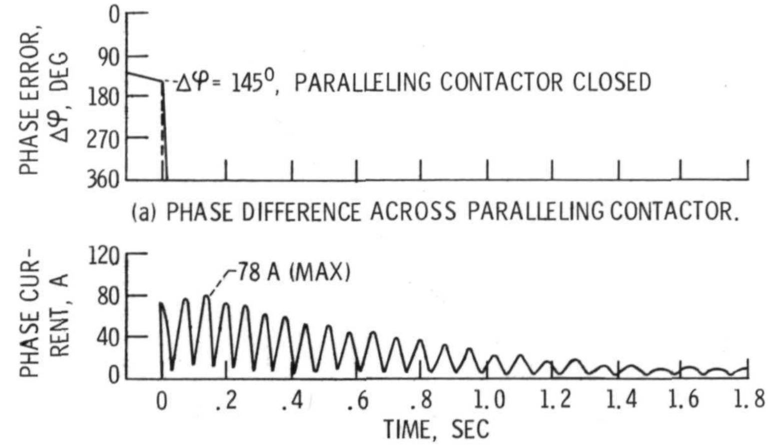
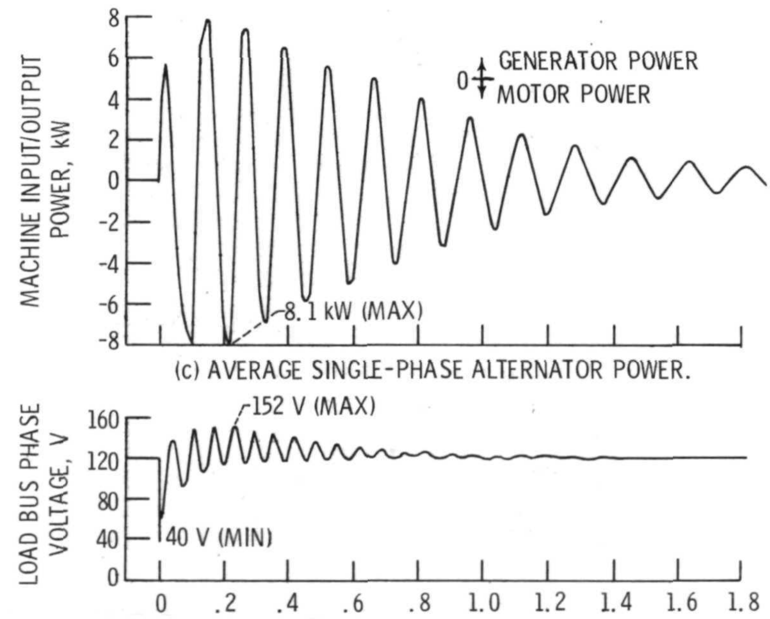


(a) PHASE DIFFERENCE ACROSS PARALLELING CONTACTOR.

(b) RMS ALTERNATOR PHASE CURRENT.

Figure 5. - Synchronizing transient for zero alternator load, zero voltage magnitude error, zero frequency error, and 145° phase error.



(c) AVERAGE SINGLE-PHASE ALTERNATOR POWER.

(d) RMS LOAD BUS PHASE VOLTAGE

Figure 5. - Concluded.

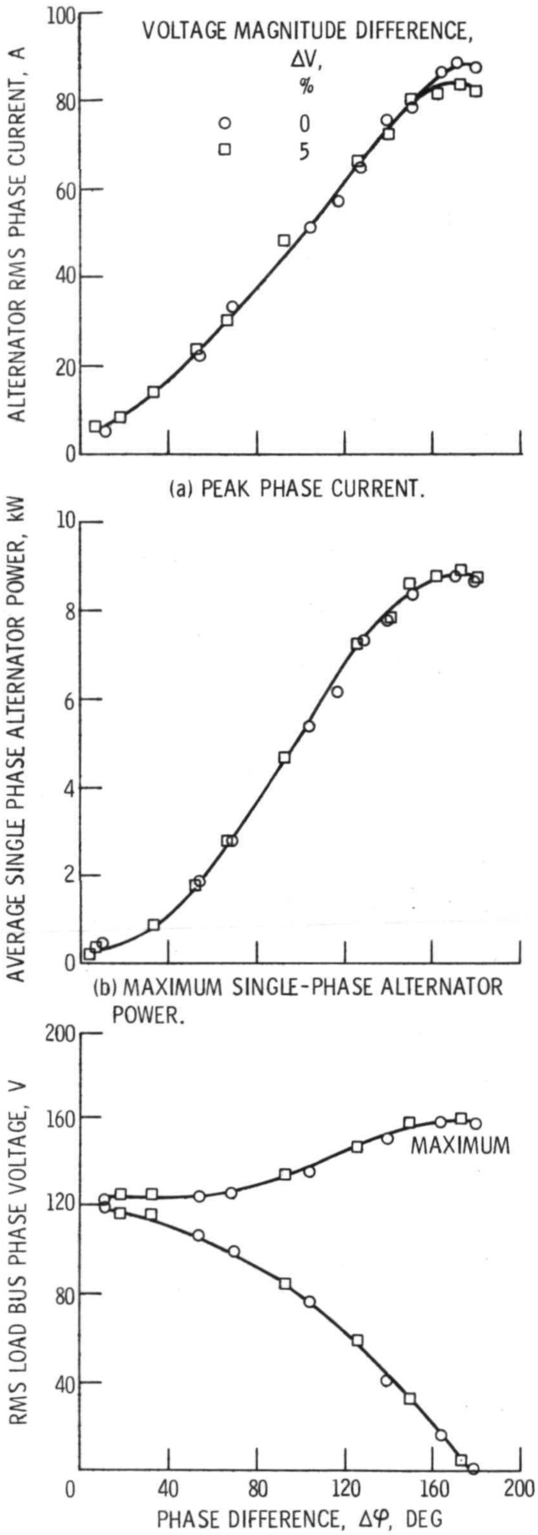


Figure 6. - Peak transient effects of paralleling alternators with 0 kilowatt loads and unequal phase voltages.

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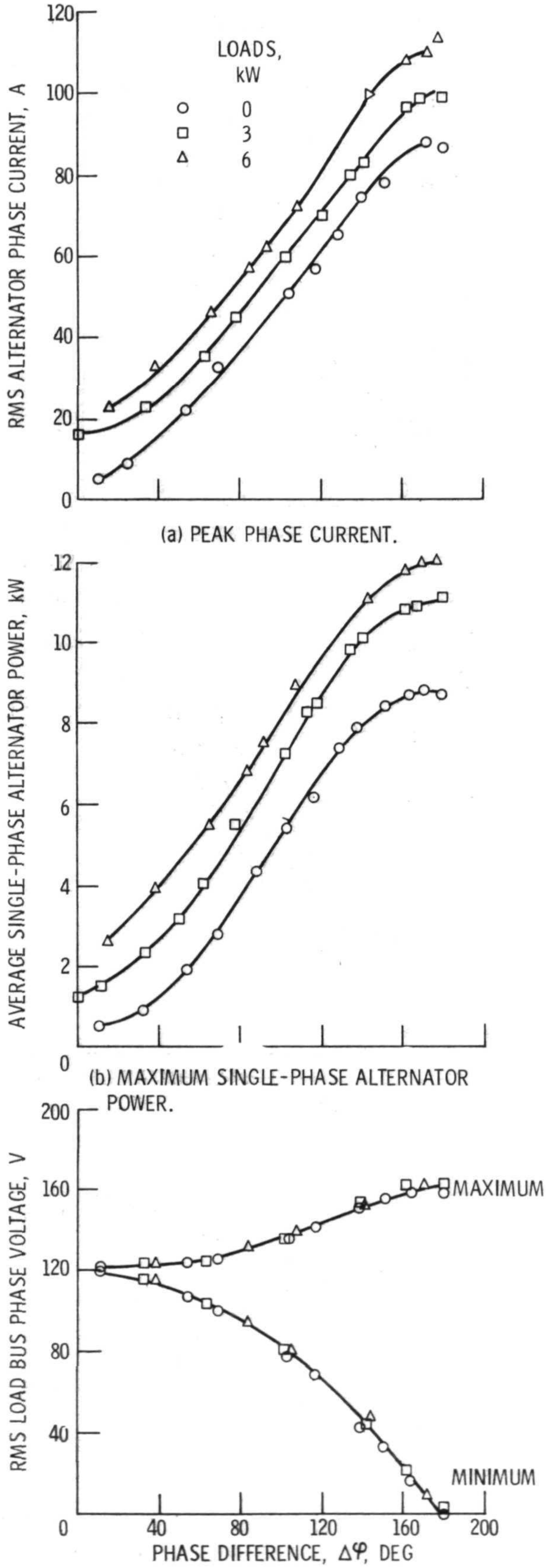
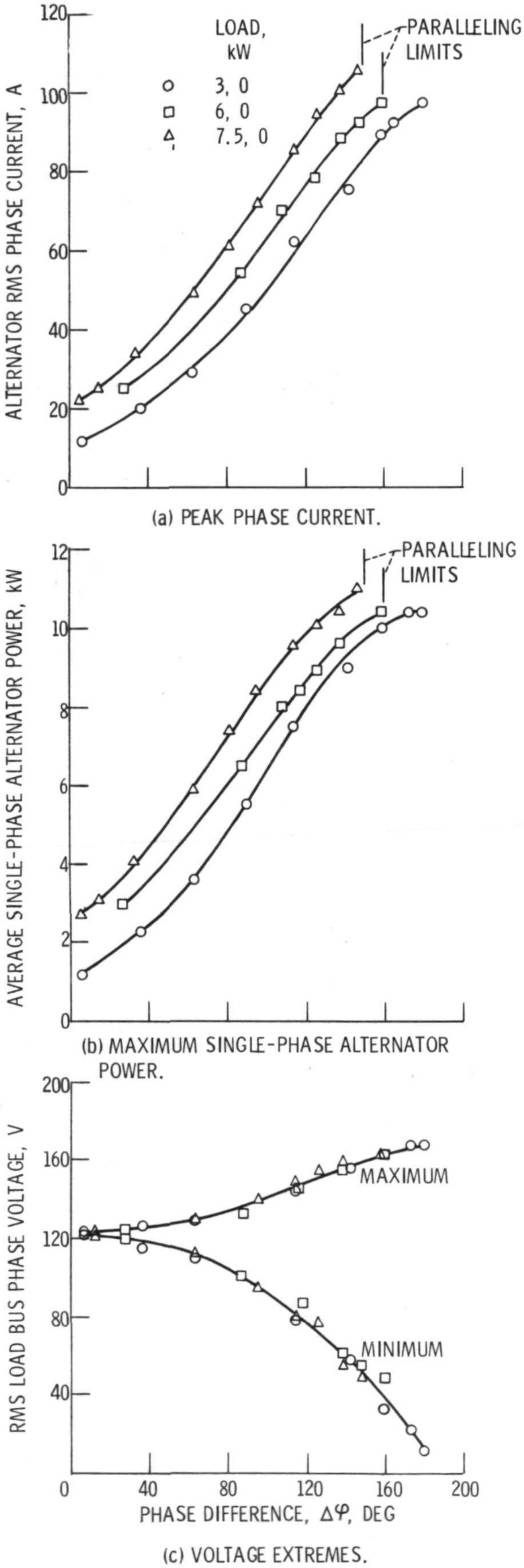


(c) Voltage extremes.

Figure 7. - Peak transient effects for paralleling alternators with <u>equal</u> loads.



(a) PEAK PHASE CURRENT.

(b) MAXIMUM SINGLE-PHASE ALTERNATOR POWER.

(c) VOLTAGE EXTREMES.

Figure 8. - Peak transient effects for paralleling alternators with unequal loads.

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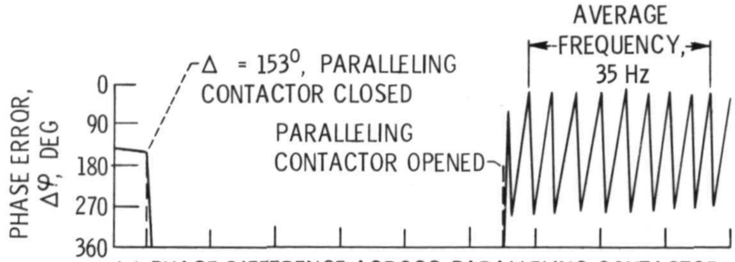
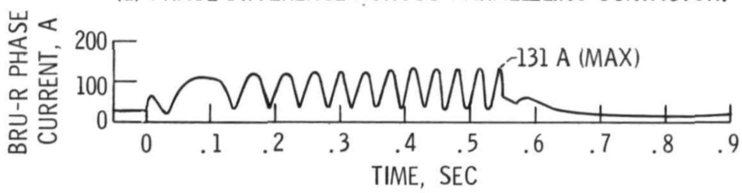
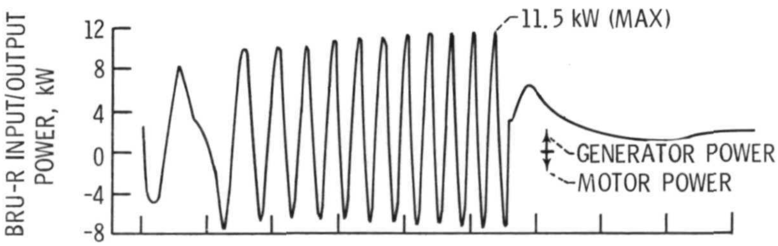


(a) PHASE DIFFERENCE ACROSS PARALLELING CONTACTOR.

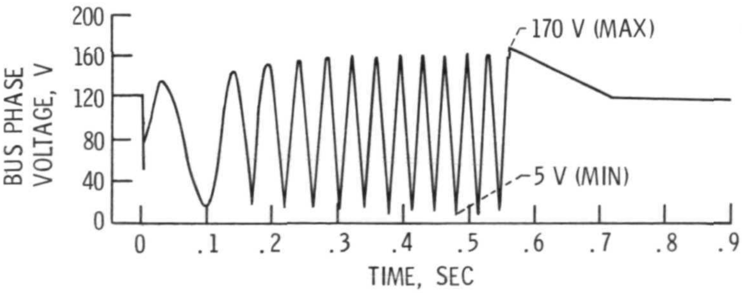


(b) RMS ALTERNATOR PHASE CURRENT.

Figure 9. - Synchronizing transient for 7.5-kilowatts parasitic BRU-R load, 0-kilowatt ARP load, zero voltage magnitude error, zero frequency error, and 153° phase error.



(c) AVERAGE SINGLE-PHASE ALTERNATOR POWER.



(d) RMS LOAD BUS PHASE VOLTAGE.

Figure 9. - Concluded.

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