DESIGN DATA SHEET
DEPARTMENT OF THE NAVY
NAVAL SHIP ENGINEERING CENTER

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FREQUENCY REGULATION OF A.C. SHIP SERVICE ELECTRIC POWER SYSTEMS

Supersedes DDS-6101-3, dated 11 January 1955

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9610-1-a. References

(a) Design Data Sheet DDS9610-3

(b) Military Standard MIL-STD-761

9610-1-b. Scope

It is the purpose of this design data sheet to outline the influence of frequency within the range normally encountered aboard ship on the operating characteristics of shipboard electric auxiliaries and to discuss the significant prime mover characteristics from the standpoint of operation of the electric system.

9610-1-c. Influence of frequency on the operating characteristics of electric equipment

Lighting equipment.—Operation of incandescent lamps is not affected by reasonable frequency variations. Operation of fluorescent lamps is independent of frequency except insofar as the characteristics of the auxiliary equipment are altered.

Heating equipment.—No change in the characteristics of heating equipment will result from abnormal frequency. However, where relays, transformers or other devices are associated with the heating unit, the operation of these devices will be altered as described below.

Motors.—Universal type motors operate independently of applied frequency within the frequency ranges experienced aboard ship. Synchronous and induction motors, however, depend on the rotating magnetic field set up by exciting current and accordingly are influenced by changes in applied frequency. In some applications (such as, a.c./d.c. motor generator sets) the speed change alone caused by a frequency change may be intolerable. The effect of frequency on the operation of induction motors under constant horsepower load and constant voltage is shown in figure 1. Although these curves are for a typical general purpose type motor, they may be applied with reasonable accuracy to all induction motors. Induction motor loads encountered aboard ship may be of the friction and fan type as well as the constant horsepower type. These three loads correspond to constant torque, torque proportional to the square of the speed, and torque inversely proportional to speed, respectively. Total losses of a typical induction motor under these three types of load are approximately as shown in figure 2. Changes in the distribution of loss within the machine will cause actual temperature rise to deviate to some extent from the values to be expected from the total loss curves of figure 2.

Transformers.—Flux in a transformer must change with sufficient rapidity to induce a back voltage in the windings equal to the applied voltage less the resistance and leakage reactance drops. Under negligible saturation and constant voltage, magnetizing current varies inversely with frequency, no load copper loss approximately as the inverse square of frequency, and core losses approximately as the inverse square root of the frequency. However, most transformers in naval service are designed for high normal flux density and operate at high saturation so that the effect of frequency change on exciting current and no load losses is exaggerated. It is impossible to give any general rule as to the magnitude of these effects since the degree of magnetic saturation varies greatly between transformers. It has been estimated, however, that no overheating of standard Navy transformers will occur at frequencies within 5 percent of normal with full load current or at 50 hertz if the load current is less than 75 percent of the transformer rating.

Control equipment.—Shipboard a.c. power systems encompass a large amount of control equipment in switchboards, bus transfers, motor controllers, and the I.C. and F.C. systems. Where transformers are used in these equipments, a substantial increase in temperature rise with decreased frequency may be expected unless load can likewise be reduced. In the case of synchros, relays, and other inductive devices connected directly across the a.c. voltage, an even greater temperature rise will occur because these units are designed for full temperature rise with exciting current only and load current does not mask increased excitation losses. For these reasons, satisfactory operation at less than 95 percent normal frequency should not be assumed unless special provisions for low-frequency operation are made in the design.

Control relays with voltage coils such as those used in automatic bus transfer switches present a special problem of operation at nonstandard frequencies because at a given voltage the flux in the magnetic path changes inversely with the frequency. Hence the calibration of the relay is changed and the actual value of voltage at which it will operate varies inversely with the frequency of the applied voltage. This effect is illustrated in figure 3 which shows the change in frequency reflected as an apparent change in the applied voltage, and provides a basis on which the operation of voltage relays at nonstandard frequency can be predicted. A large resistance may be, and often is, used in series with voltage coils to greatly reduce the effect of frequency on calibration. In contrast to the effect of frequency on voltage relays, current relays are not affected by frequency. Hence, the operation of such equipment as circuit breakers and overload relays, is not affected by ordinary frequency changes.

Communications equipment.—Frequency affects transformers, synchros, and control relays on communications equipment in the same manner as it affects these units on other equipment. Where the communications equipment contains components which are synchronized with system frequency or rely on system frequency to measure time intervals, such as occur in certain radar equipments, a change in the performance of the equipment as a whole can be expected as a result of the influence of the frequency sensitive component.

9610-1-d. Steady state frequency regulation

General

The frequency regulation of an a.c. system is determined by the characteristics of the prime movers and their governors and not by any electrical characteristics of the generator. The type governor used and the prime mover characteristics which influence system frequency also determine the kilowatt (real load) load division between the various generators and the stability of parallel operation. For this reason, real load (KW) division and system stability must be considered whenever frequency regulation is discussed. The division of reactive power (KVAR) between generators in parallel is controlled by the voltage regulator and is not a function of speed, therefore, in the following discussion only real power (KW) will be considered. See reference (a) for a discussion of division of reactive power.

Two basic governing systems are used on naval generators, that is, the speed governing system, and the speed-load sensing governing system. A discussion of each system follows.

System characteristics using speed governing systems

For stable operation of generating units using speed governing systems, it is necessary that any change in speed will result in a power differential between prime mover input and generator output tending to restore the initial condition of speed. As the load characteristic on practically all naval generators give increased generator output with rising speed, as shown in curve XY figure 4, the only practical prime mover characteristics which will provide stable operation are the flat or drooping speed-load curves within the crosshatched area of the figure. If the prime mover characteristics were slightly rising (line AB, fig. 4) any increase in generator speed would cause a greater increase in power input than output, thereby causing a further increase in speed, and unstable operation would result.

In the case of machines operating in parallel, there must be both stable operation and satisfactory load division. Satisfactory (KW) load division in addition to stable operation, can be obtained with drooping speed-load curves on all units. If a machine having a flat characteristic is operated in parallel with one having a drooping speed-load curve the machine with the flat characteristic will take all load changes and unsatisfactory load division will result.

For this reason, the slopes of the respective speed-load characteristics determine the real load division as well as the stability of operation. Furthermore, the proportion of the load picked up by each machine depends on the inverse ratio of the slopes. It follows that where two dissimilar machines operate in parallel and it is desired to have each share load in proportion to its rating, the slope of the respective speed-load characteristics should be inversely proportional to the ratings. This condition exists when each machine has the same speed droop no load to full load (speed regulation) and the two speed-load curves are similar in shape.

If parallel operation of generators is not required, a very slightly drooping or even flat speed-load characteristic can be provided and very good frequency regulation secured. On the other hand, if generators are to operate in parallel, the slopes of their respective speed-load curves must be inversely proportional to the generator ratings and sufficiently large to give stable operation. In this case stability and load division requirements limit the degree of frequency regulation which can be obtained. As the minimum slope of the speed-load curve is the limiting factor in establishing stability of operation, minimum overall speed droop can be achieved with a straight line speed-load curve. This type curve has the further advantage of giving constant performance characteristics of the paralleled machines over all values of load distribution.

System characteristics using speed-load governor systems

The speed-load sensing governor can be operated as an isochronous governor, as a speed droop governor, or as a "slave" unit to a similar unit which is acting as a "master." As an isochronous governor installed on an engine or turbine operating alone, it will maintain a constant speed for all loads within the capacity of the engine or turbine except momentarily at the time a load change occurs. Paralleled with dissimilar governors or with an infinite bus (shore power), the speed-load sensing governor can be operated as a conventional speed droop governor, and the load carried by the engine or turbine will be a function of governor speed setting and speed droop setting. As a slave unit paralleled with similar governors, the speed-load sensing governor will render proportional real load division with isochronous control.

The speed-load sensing governor senses and responds to the electrical load and the rate of change of electrical load as well as to generated frequency (i.e., speed). Load change precedes the speed error that would result if the input to the prime mover were not readjusted, therefore, governor action resulting from load change, in effect, anticipates a speed change and readjusts the input to the prime mover before an appreciable change in speed occurs. As a result speed deviations are on the order of 25 to 50 percent less than that which would be obtained with speed sensing alone. The speed-load sensing governor system also senses and responds to the difference in (KW) load between paralleled units, and permits each engine or turbine to assume its proportional percentage of load while maintaining zero steady-state speed regulation.

Motor-driven generators

Motor-generator sets are used aboard ship to supply systems requiring electrical power at voltages and frequencies other than that supplied by the ship service generators, to supply systems requiring closely regulated voltage and frequency and to supply vital systems on loss of the ship service generators (no break power supplies).

The droop of the speed-load curve of induction motors renders them inherently stable when used as prime movers for a.c. generators. This is illustrated in figure 5 which shows the characteristics of typical induction motors. As shown in the figure, the overall speed change from no load to full load is only a few percent unless a high-resistance motor is used.

Even though induction motors have good speed-load characteristics, they may not in themselves provide the close regulation required for operation of sophisticated electronic equipment. To satisfy the needs of electronic equipment, the frequency regulated motor-generator set is used. These sets usually consist of a squirrel cage induction motor or a wound rotor induction motor driving a synchronous generator, plus several control components and sensing devices. The sensing devices sense the output frequency, and either the input or output voltage, or both input and output voltages, and through the use of control components (such as saturable reactors, resistors and silicon-controlled rectifiers, or a combination of these devices) regulation of the input and output power is achieved so that the regulated power to the load is within the required limits.

9610-1-e. Transient frequency regulation

Kilowatt load fluctuations such as those due to motor starting, switching, or other disturbances, cause sudden changes in the power demand on generator prime movers. Where the prime mover is an electric motor without speed control, the frequency will approach the steady value in a manner similar to that shown in figure 6A. Usually the inertia of the unit is small and the new steady speed is rapidly approached. Figure 6B represents the relation between the power supplied by the generator (load power) and the power taken by the system (motor power) for motor-generator sets using standard induction type motors. It can be seen that the system load buildup does not become equal to the applied load until a short period after load application. The system load never exceeds the applied load disregarding, of course, the m-g set losses. The difference between the input and output power during the early part of the load cycle is compensated by a similar exponential continuance of load on the system for some time after the load has ceased.

In the case of governor-controlled prime movers, such as diesel engines, turbines, and speed-controlled motors, the response of the governor elements and governor-controlled mechanisms are each faster in response than the generator prime mover. If the governor-controlled mechanism were moved immediately to its steady-state position the response of the prime mover would be sluggish. The usual practice is to over-respond and force prime mover response. To obtain fast recovery a prime mover response that exhibits less than critical damping is employed. Critical damping or overdamping will prevent overshoot but at the expense of recovery time; hence, the overshoot is intentionally accepted in a tradeoff to obtain faster recovery than critical damping would provide. Figures 7 and 8 show test results on the governor operation of typical diesel engines and turbines controlled by speed-sensing governors.

The response time as stated in 9610-1-d can be improved by using the speed-load sensing governor, although the degree of improvement obtained depends greatly on the characteristics of the prime mover. The speed-load sensing governor when operated as an isochronous governor has the added advantage of returning the speed to the original setting after the transient excursion as shown in figures 9A and 9B. Governors are adjusted at the factory for maximum response consistent with stable operation and the use of flywheels or special generator design to secure large rotating inertia results in an undesirable increase in machine size and weight as well as creating a possibility of torsional vibration problems. Special machines have the further disadvantage of not complying with established standards. For these reasons, the problem of avoiding excessive frequency disturbances can best be avoided by system design that avoids the use of equipment that would cause large kilowatt load surges, the basic cause of frequency disturbance.

9610-1-f. Summary

Transient and steady-state frequency conditions influence the operation of nearly all shipboard electric auxiliaries. In the case of transformers, synchros, and similar devices, this effect is primarily one of increased heating with the consequent possibility of damage to the equipment. In lights, motors, relays, and other devices the principal effect is one of maloperation. For the frequency ranges normally encountered in naval service, these effects are small and require little consideration. Under special conditions, such as the use of 50-hertz shore power, the influence of frequency may be great and steps should be taken to prevent damage (such as lowering the voltage).

The degree of frequency regulation that can be achieved in shipboard power systems is limited by considerations of stability and, in the case of machines in parallel, load division. A flat speed-load characteristic may be successfully used on isolated generating units and generating units having speed-load sensing governors. Units without speed-load sensing governors require speed droop of 3 to 5 percent, no load to full load, for good parallel operation.

When diesel engine-driven generators are operated in parallel with other generators, consideration must be given to the possibility of excessive load fluctuation from engine torque pulsations. If a natural frequency of oscillation of a voltage regulator, governor, or the electromechanical system of the machines in parallel, is close to the impressed frequency of engine torque pulsations, excessive load fluctuation can be expected. This condition must be avoided by careful system planning.

Transient frequency disturbances, resulting from sudden load application or removal constitutes a possible source of difficulty where frequency sensitive auxiliaries and large load changes are encountered. Momentary loss of frequency, even for a few seconds, such as when an automatic bus transfer switch operates, can cause a serious loss of data to navigational or guidance systems. No break power supplies, which transfer to an auxiliary source of power, such as batteries, without any interruption can be provided for these critical systems. In general, however, load disturbances to be expected aboard ship, the inertia of the generating units, and the sensitivity of connected equipment, are such that the effect of frequency transients is not significant. See reference (b) which lists transient frequency limits for the various shipboard electrical systems.

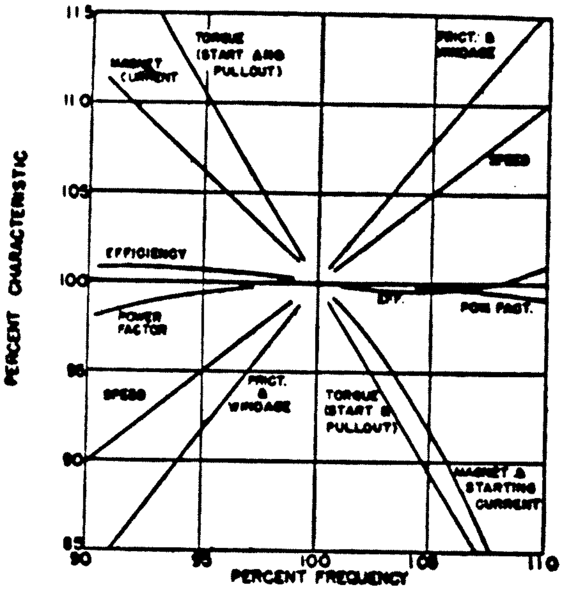


Figure 1.—Effect of frequency on induction motor characteristics.

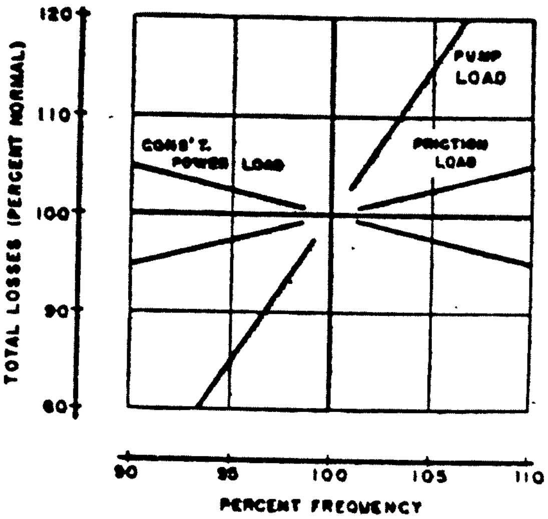


Figure 2.—Effect of frequency on induction motor losses.

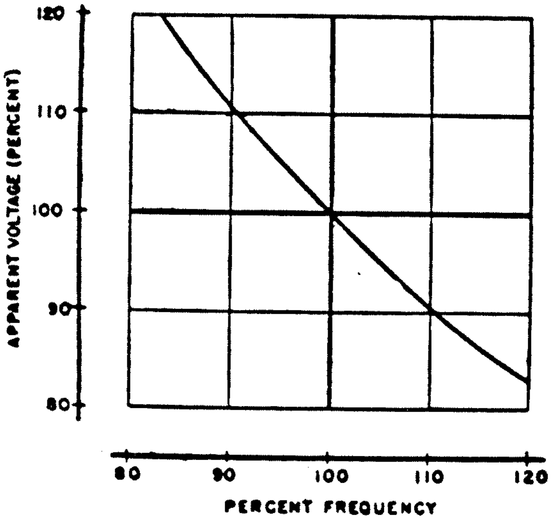


Figure 3.—Influence of frequency on relay operation.

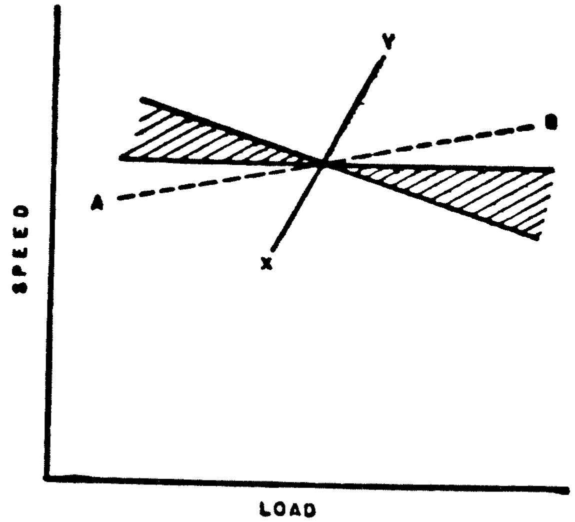
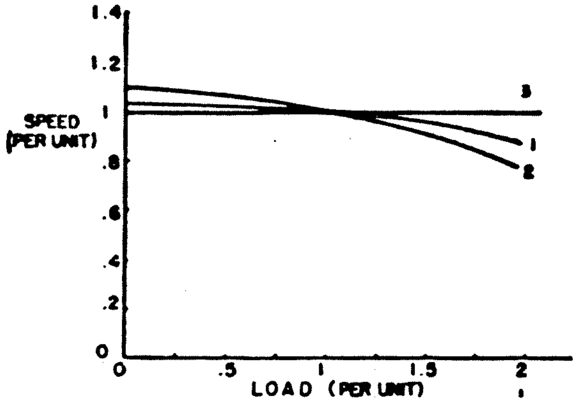


Figure 4.—Speed-load characteristics, prime mover and load.



1. Induction motor - General purpose
2. Induction motor - High resistance
3. Synchronous motor or speed regulated induction motor

Figure 5.—Speed-load characteristics, induction motor.

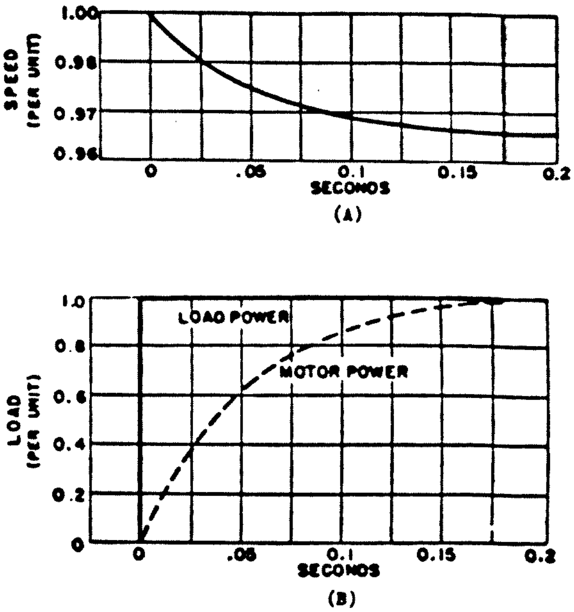


Figure 6.—Sudden load application to a motor.

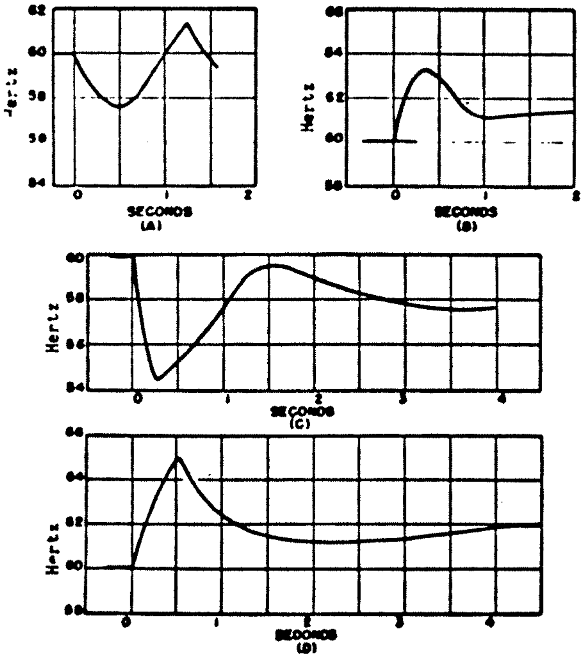


Figure 7. - Frequency transients, diesel generator with speed sensing governor

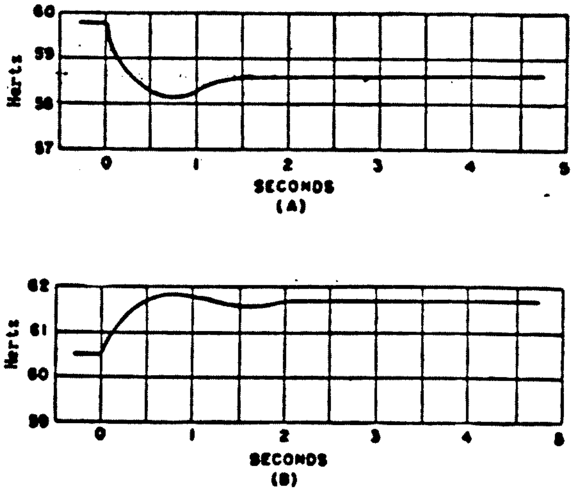


Figure 8. - Frequency transients, turbine-generator with speed sensing governor

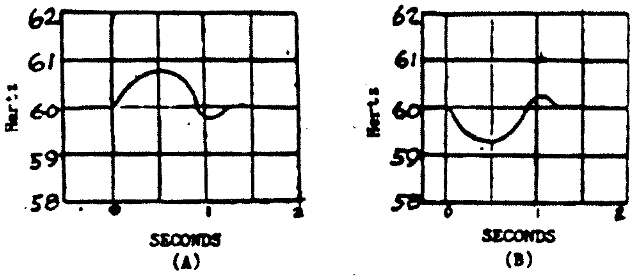


Figure 9. - Frequency transient with speed load sensing governor with isochronous operation