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SYNCHRONIZATION OF THE DOE/NASA 100-KILOWATT WIND TURBINE GENERATOR WITH A LARGE UTILITY NETWORK

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| 16 Abstract The DOE/NASA 100 kilowatt wind turbine generator system has been routinely successfully synchronized with a large utility network since September 1976. The system equipments and procedures associated with the synchronization process are described. Time-history traces of typical synchronizations are presented indicating that power and current transients resulting from the synchronizing procedure are limited to acceptable magnitudes. | | | |
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SYNCHRONIZATION OF THE DOE/NASA 100-KILOWATT WIND TURBINE GENERATOR WITH A LARGE UTILITY NETWORK

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SUMMARY

The DOE/NASA 100-kilowatt Wind Turbine Generator System has been routinely successfully synchronized with a large utility network since September 1976. The system equipments and procedures associated with the synchronization process are described. Time history traces of typical synchronizations are presented indicating that power and current transients resulting from the synchronizing procedure are limited to acceptable magnitudes.

INTRODUCTION

As part of the national wind energy program under the direction of the Department of Energy, the NASA Lewis Research Center has designed and constructed a 100-kW wind turbine at the NASA Plum Brook Station in Sandusky, Ohio. This wind turbine, designated Mod-0, is the first large wind turbine to be built in the United States in 35 years. The purpose for the machine is the assessment of the technological requirements and engineering problems associated with the design, construction, and operation of large wind turbine electrical power systems which are to be operated in parallel with commercial utility networks.

This report describes the equipment and procedure used in the synchronization of the Mod-0 wind turbine alternator with a network. (The equipment is described in the appendix of this report.) The data recorded during the synchronizing process with the Ohio Edison Company network is included.

The Mod-0 wind turbine system is a horizontal-axis, propeller-type machine. A two-bladed, variable pitch, 125-foot diameter rotor, mounted on a 100-foot truss tower, drives an alternator through a step-up gear box. The rotor is downwind of the tower and rotates at a constant nominal speed of 40 rpm. The alternator is a 125 kVA, 0.8 power factor, three-phase, Y-connected, 1800 rpm, synchronous machine. Figure 1 is a detailed drawing of the components inside the nacelle mounted atop the tower. The rated power output of 100 kW is produced at a wind speed of 18 mph.

The fabrication and assembly of the Mod-0 system is described in reference 1.

The system was designed to meet the following requirements:

1. Production of electric power at a voltage and frequency of the electrical utility of which it is a part
2. Protection of the wind turbine and the utility with standard devices and practices
3. Unattended operation: starting, synchronizing, dropping out of synchronization, and shutting down automatically
4. Operation at remote sites where the environment may impose unusual requirements
5. Electric power of a quality acceptable to the utility while operating in a random power excitation environment (wind)

A block diagram of the Mod-0 wind turbine system is shown in figure 2.

The Mod-0 wind turbine electrical subsystem was first synchronized with a commercial utility network (Ohio Edison Company) on September 15, 1976. Since that time the system has been repeatedly synchronized with and removed from the utility network with no untoward results. Synchronizing torques and currents are small and there has been no evidence of undue stress on the wind turbine system or the network.

The Ohio Edison Company network with which the Mod-0 system is generally synchronized has a capacity many times greater than the capacity of the Mod-0. It provides virtually an infinite bus for the wind turbine.

To demonstrate compatibility with smaller paralleled generating systems, the Mod-0 system has been synchronized with a 187 kVA, diesel driven alternator and also with a 400 kVA natural gas driven generator. Synchronization with these generators presented no problem.

Prior to the first attempt at synchronization of the Mod-0 system with the utility network an analysis of the synchronization of the Mod-0 wind turbine generator with an infinite bus indicated the feasibility of the process (refs. 2 and 3). The analysis indicated that within the frequency tolerance band indicated by the manufacturer of the automatic synchronizer - ± 0.25 hertz frequency difference - the systems would synchronize with maximum electromagnetic torque of 0.30 per unit and maximum alternator current of 0.8 per unit. In this analysis the drive shaft was assumed to be rigid, without the spring coupling and slip coupling actually present in the Mod-0 drive train. From the point of view of transient torques, the rigid drive shaft represents a more severe condition. Therefore, the predicted transient currents and torques were assumed to be conservative and synchronization was undertaken with confidence in its proper performance.

A description of the electric power hardware is included as an appendix to this report.

System Operation Features Affecting Synchronization

Control modes. - The Mod-0 wind turbine system is an autonomous system controlled by a microprocessor type computer. The control system shown in figure 3 operates in three modes: (1) pitch control, (2) speed control, and (3) power control.

In the pitch control mode the rotor blade pitch is moved to a designated angle by directly activating the blade pitch servo. This mode is used at starting to accelerate the rotor from a stopped position to a rotational speed of 5 rpm. It is also used to feather the rotor blade when shutting down the system.

At 5 rpm the speed control mode becomes operative, and remains operative until the system is synchronized to the network generators. In the speed control mode the rotational speed of the output shaft of the gearbox is compared to a controller reference speed signal. When operated as an independent power supply not interconnected with the network, the Mod-0 system uses the speed control mode exclusively after accelerating to 5 rpm.

The power control mode is operative when the wind turbine alternator has been synchronized and is operating in parallel with other electrical generating sources.

All control modes are effectuated by configurations of the same controller, a BAFCO Incorporated, Model 846 Controller, which has been modified to a NASA specification for this equipment. For speed control a proportional plus integral gain is used with the feedback speed signal compared to a reference speed signal to provide the speed error. For power control an integral gain is used with a feedback signal proportional to alternator output power compared to the speed reference to provide the power error signal. A feed forward signal proportional to the wind speed is also actuated in the power control mode when the wind speed is above the rated speed of 18 mph. This signal aids in effecting a reduction in alternator generator power variations due to wind speed changes.

In the power control mode, at any wind speed below the rated value of 18 mph, the controller sets the blade pitch to the angle at which the system generates 100 kW at 18 mph. The blade pitch remains fixed at this setting as the wind speed varies between the cut-in and the rated speeds, the output power varying accordingly from zero to 100 kW. At wind speeds greater than 18 mph, the controller feathers the rotor blades to "spill wind" and thereby limits the output power to 100 kW. A var controller regulates output vars to a constant 75 kilovars.

Drive train. - The drive train which transmits the torque from the turbine rotor to the alternator rotor is illustrated in figure 1. The torque developed by the turbine is applied via the low speed shaft

through a 1:45 speed changer gearbox to the high speed shaft. The torque is transmitted from the high speed shaft to the alternator by a set of pulleys and V-belts. Two special coupling devices are included in the drive train: a spring (Falk) coupling (not shown in the figure) in the low speed portion of the drive train, and an hydraulic slip coupling in the high speed portion. Detailed characteristics of the drive train are described in reference 4

Synchronization Procedure

Starting. - The wind turbine system is automatically activated from a standby shutdown condition by the microprocessor computer when the average wind speed (sensed through a 1 minute filter) has increased to the cut-in value of 10 mph. The rotor blades are pitched from the feathered position to an angle at which sufficient starting torque is developed. At a rotor speed of 5 rpm the control changes from the pitch control to the speed control mode. As the rotor accelerates the reference speed is stepped up until the rotor speed is slightly greater than 40 rpm. At 38 rpm the field contactor of the alternator is closed, the alternator voltage regulator having been set to produce line voltage at the switch gear, a nominal 480 volts.

The network circuit breaker (CB-2, fig. 4) is now enabled. When the frequency and phase differences between the alternator and bus voltages are within the operating limits of the automatic synchronizer, the synchronizer closes, permitting the circuit breaker to close.

The automatic synchronizer of the Mod-0 system locks out at beat frequencies between alternator and bus voltages greater than 0.25 hertz. At a beat frequency of 0.25 hertz, the device output relay will close at -2 degrees after synchronism. At a beat frequency of 0.1 hertz or less, the device output relay will close at +8 degrees before synchronism. Between 0.25 hertz and 0.1 hertz beat frequency a linear angular change from -2 degrees to +8 degrees is assumed.

Delta, the angular difference between the wind turbine generator excitation voltage and the line voltage at the moment of breaker clo-

sure, is a function of the operational speeds of the synchronizer and the breaker. The nominal angular difference as a function of frequency difference (considering the equipment speeds specified by the manufacturers) is shown in figure 5. No direct measure of this angle is available from test data. It is assumed that the angular difference varies randomly between -9.5 degrees and +11 degrees for synchronization of the Mod-0 system with the network.

Shutdown. - The synchronized wind turbine system is normally separated from the network when the wind speed decreases to 8 mph or increases to 40 mph. For wind conditions less than 8 mph the power generated is typically below 3 kW. At the onset of shutdown the load is reduced by moving the rotor blade pitch toward the feathered position. At 3 kW the network circuit breaker and the field contactor are opened. When the rotor blades have reached the feathered position, the hydraulic subsystem is de-energized and the wind generator system is in its shutdown condition.

TEST RESULTS

The strip chart traces of figure 6 were selected from a set of ten synchronization executions to display the variation observed during operation. The traces are time histories of the process of synchronizing the Mod-0 wind turbine system with the Ohio Edison Company power network at Plum Brook Station, Sandusky, Ohio. At this location the wind turbine is working into an infinite bus, effectively. The transformer and line impedance is 0.02 per unit.

Consideration of the strip chart traces indicates the independence of synchronization from the steady wind speed. The range of steady wind speed for the ten test executions was 10-28 mph. Relative differences between closing angles are best indicated by the relative magnitudes of the power transients resulting from the synchronization procedure. Also to be noted is the very short duration of the synchronizing transient. For a 1.0 per unit power pulse the transient is essentially

completed in 0.075 second. (Noise superimposed on the traces of figure 6 is an instrumentation injection.)

Alternator power, current, and reactive volt-amperes were the only signals with measurable transients among 11 which monitored and recorded during synchronization. The following are the signals which were monitored:

1. Alternator power - measurable transients during synchronization
2. Alternator vars - measurable transients during synchronization
3. Alternator current - measurable transients during synchronization
4. Alternator frequency
5. Line voltage
6. Low speed shaft input torque
7. Turbine blade bending moment load (2)
8. Low speed shaft bending moment (2)
9. Yaw drive torque
10. Turbine blade pitch angle
11. Low speed shaft rotational speed

The low speed shaft torque signal trace displayed no discernible transient caused by the breaker closing. The absence of a transient variation in the drive torque signal is attributable to the presence of the hydraulic slip coupling and the Falk spring coupling in the drive train.

The line current did not exceed 0.25 per unit (fig. 6(d)) for the severest power transient observed. Analysis had indicated current transients as large as 0.8 per unit, so test results are well within the predicted upper bound. However, the test current transients were filtered, and the process limited the recorded peak values somewhat. Nevertheless, the traces do demonstrate that no short circuits which would result from synchronization failure or difficulty were produced. Further, the current transients rapidly subsided to zero or very small

magnitudes. Similarly, traces of volt-amperes were limited by an instrumentation filter. No volt-ampere trace peaked at a value greater than 0.1 per unit, and each trace subsided to zero or a very small magnitude rapidly.

The peak power pulse observed was 1.4 per unit.

SUMMARY OF RESULTS

1. In tests performed over a range of wind speeds from 10 to 28 mph, synchronization of the Mod-0 wind turbine system with a large utility network was accomplished with minor transients by means of a speed control and an automatic synchronizer.

2. The transients resulting from synchronization with a large utility network were independent of the steady wind speed.

3. Output power transients were of the order of 0.075 second duration and reached peak values of 1.4 per unit. Recorded current transients were limited to a magnitude of 0.25 per unit.

4. No additional blade or shaft loading resulting from synchronization was observed. Power and current transients were the only recorded signals that produced measurable transients on strip charts with standard instrumentation. These signals were within acceptable limits.

APPENDIX

DOE/NASA 100-KILOWATT WIND TURBINE ELEC-
TRICAL EQUIPMENT INVOLVED IN THE
SYNCHRONIZATION PROCESS

The interconnection of the switch gear involved in the synchronization of the Mod-0 wind turbine alternator with the Ohio Edison network is shown in figure 4

Alternator. - The alternator of the Mod-0 system is a synchronous alternator. It is rated 125 kVA continuous, at 0.8 power factor, 480 volts, Y-connected, three-phase, 60 Hz, 1800 rpm. Insulation is Class B with a 40° C ambient and a 70° C rise. Bearings are pre-packed, rolling element type. Electrical characteristics of the generator are shown in table I.

The exciter is a brushless type and is directly connected to the alternator.

Voltage regulator. - The voltage regulator for the Mod-0 wind turbine alternator is a silicon controlled rectifier static device. It provides two modes of operation, automatic and manual. In the automatic mode it maintains the alternator output voltage within two percent of rated value from no load to full load at 0.8 power factor. The regulator maintains output voltage within regulation limits for an ambient range from 0° to 40° C. The unit is a General Electric Model 3300A03 B0054 Static Voltage Regulator.

Network transformer. - The transformer between the wind turbine alternator voltage and the network is an outdoor oil insulated, self-cooled unit. It is rated 300 kVA with 480/7200 V, grounded wye-delta windings. The transformer is coupled to the network through an outdoor oil circuit-recloser rated for 14.4 kV, 560 A. The transformer and recloser, as well as all other switchgear and protection equipment, are located at ground level in or adjacent to the control building which is 600 feet from the base of the tower.

Var controller. - A var controller is used in conjunction with the voltage regulator in the Mod-0 electrical subsystem. The controller is intended to maintain a level of 75 kvars. A Basler Electric SCP240 KVAR Controller is used for this function. The controller provides var control during parallel operation of the wind turbine alternator. The controller senses generator output voltage and current and, based upon these inputs, provides an output to a motor operated control (Basler Electric Motor Operated Potentiometer) to raise or lower the voltage regulator set point. Generator field excitation is correspondingly changed to obtain the desired var load.

Power circuit breaker. - The power circuit breaker (CB-2) is an indoor oilless drawout type, three pole, single throw, 600 V ac, 225 A, 14,000 rms symmetrical ampere interrupting rating. It is equipped with a three-element overcurrent trip device on each pole - long time delay adjustable from 80 to 130 percent, short time delay, 200 to 350 percent, and instantaneous, 10 to 12 times coil rating. The circuit breaker has a closing time of less than 5 hertz for synchronizing.

Synchronizer. - The synchronizer provided for the Mod-0 electrical subsystem is a Westinghouse Type XL automatic synchronizer. This is a solid state device, except for the synchronizing relay, for use in conjunction with a fast-closing (8 cycles or less on a 60 Hz base) circuit breaker.

The synchronizer senses the generator and bus voltages, transformer coupling the sensed voltages. These voltages beat against each other, and the transformer secondaries are so wired that the beat voltage reaches a minimum at an in-phase condition. This minimum is zero volts when generator and bus voltages are matched. Provided that the frequency difference is less than 0.25 hertz and the voltage difference between the bus and generator voltages is less than 15 V ac, the synchronizing relay will close within 8 degrees of synchronism.

REFERENCES

1. Puthoff, Richard L.: Fabrication and Assembly of the ERDA-NASA 100-Kilowatt Experimental Wind Turbine. NASA TM X-3390, 1976.
2. Hwang, H. H. and Gilbert, Leonard J.: Synchronization of the ERDA-NASA 100 kW Wind Turbine Generator with Large Utility Networks. NASA TM X-73613, 1977.
3. Hwang, H. H. and Gilbert, Leonard J.: Synchronization of Wind Turbine Generators Against an Infinite Bus Under Gusting Wind Conditions. Presented at the IEEE Power Engineering Society Tenth Power Industry Computer Application Conference, Toronto, Ontario, Summer Meeting (Mexico City, Mex.), July 17-22, 1977.
4. Sullivan, T. L.; Miller, D. R.; and Spera, D. A.: Drive Train Normal Modes Analysis for the ERDA-NASA 100-kW Wind Turbine Generator. NASA TM-73718, 1977.

TABLE I. - MOD-0 WIND TURBINE ALTERNATOR CHARACTERISTICS

General Electric Brushless Generator Model 5SJ4444A23Y53F1

| | |
|--------------------------|--------------------------|
| Base kVA | 125 kVA |
| Base voltage | 480 volts |
| Base frequency | 60 hertz |
| Base ohms | 1.843 ohms per phase wye |

$$R_a = 0.018 \text{ per unit}$$

$$R_f = 0.00405 \text{ per unit}$$

$$X_d = 2.21 \text{ per unit}$$

$$X_q = 1.064 \text{ per unit}$$

$$X_o = 0.0058 \text{ per unit}$$

$$X'_d = 0.165 \text{ per unit}$$

$$X''_d = 0.128 \text{ per unit}$$

$$X'_q = 0.193 \text{ per unit}$$

$$T'_d = 0.145 \text{ second}$$

$$T''_d = 0.0085 \text{ second}$$

$$T''_q = 0.0114 \text{ second}$$

$$T''_{qo} = 0.0623 \text{ second}$$

$$X_{kd} = 0.104 \text{ per unit}$$

$$X_{kq} = 0.146 \text{ per unit}$$

Self-inductance of damper circuits:

$$\text{d-axis} = 2.26 \text{ per unit}$$

$$\text{q-axis} = 1.16 \text{ per unit}$$

TABLE I (Concluded)

Self-inductance of main field:

0.883 henries referred to field

2.33 per unit referred to stator

Mutual reactance between armature and d-axis

damper circuit 2.16 per unit

Mutual reactance between armature and q-axis

damper circuit 1.005 per unit

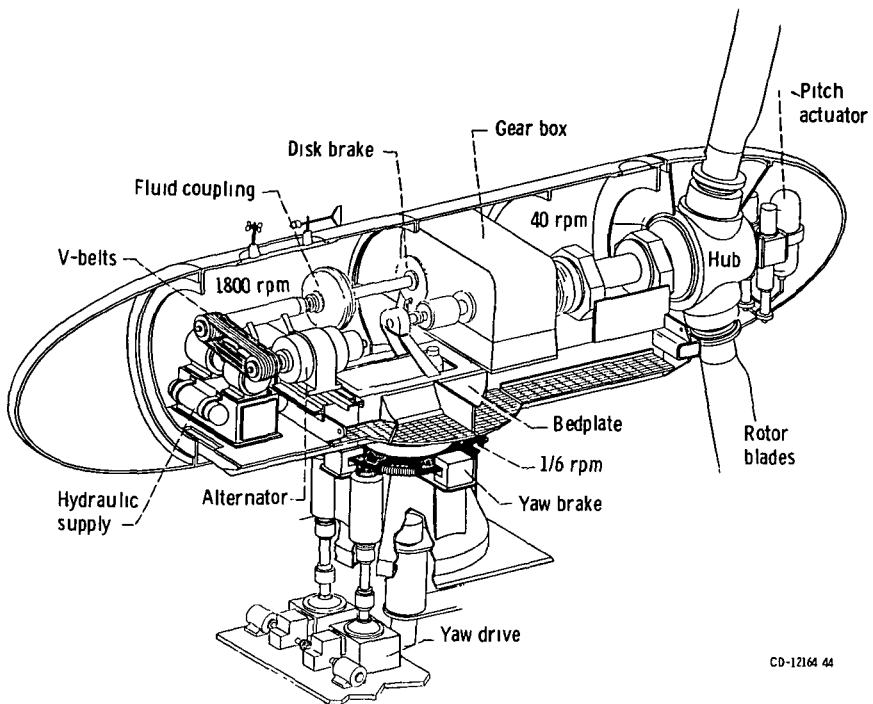
Mutual reactance between field and d-axis

damper circuit 2.16 per unit

Generator field current at rated voltage, no load 16.4 amperes

Number of poles 4

Weight moment of inertia 45.0 lb-ft²



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Figure 1. - Mod-0 wind turbine generator schematic of nacelle interior.

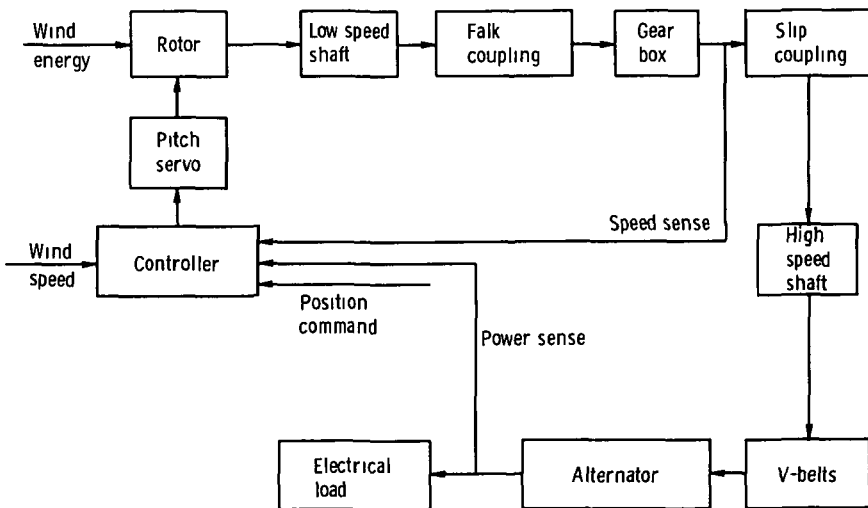


Figure 2. - Block diagram of Mod-0 wind generator system.

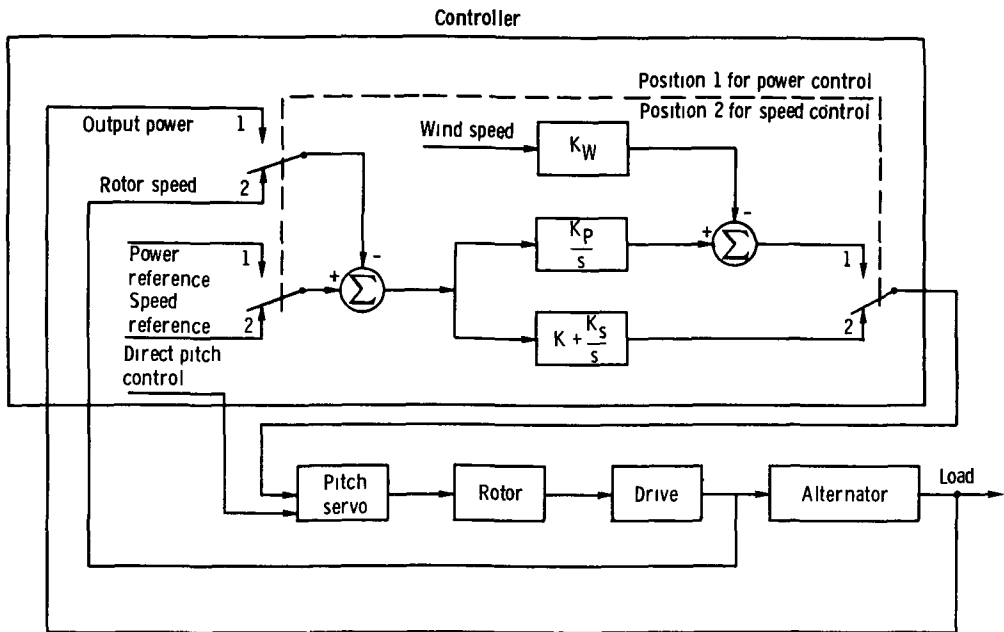


Figure 3. - Control modes of Mod-0 wind turbine generator.

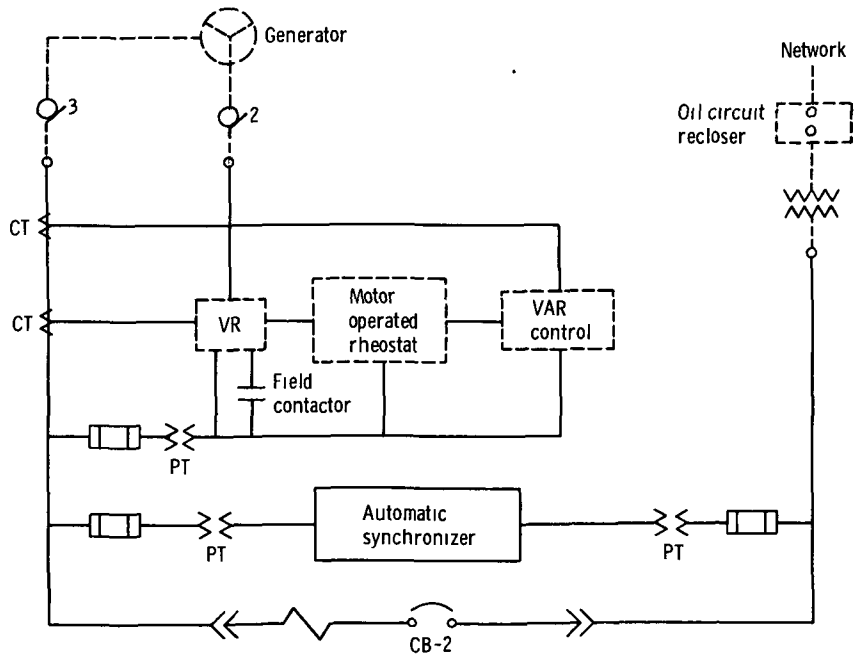


Figure 4. - Power one-line of Mod-0 wind turbine showing synchronizing elements.

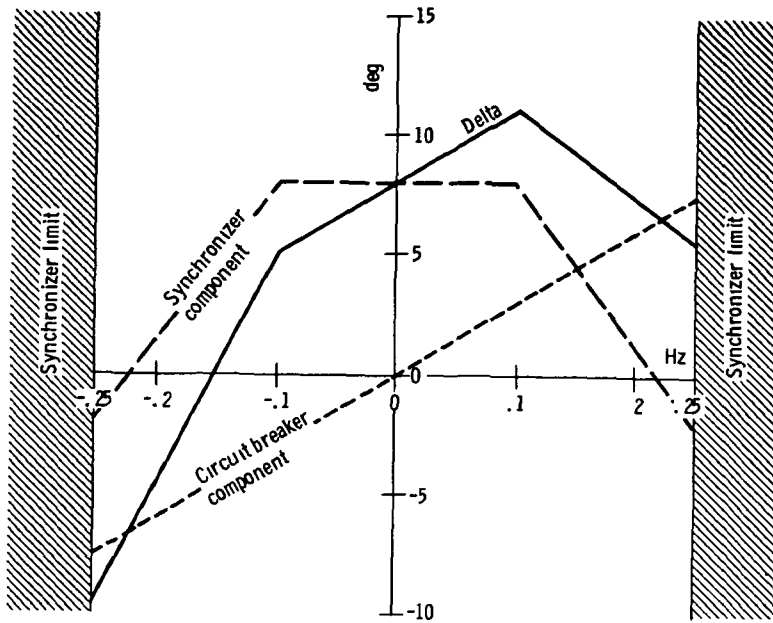


Figure 5. - Nominal angular deviation, delta, between generator and bus voltages at synchronization as a function of frequency difference

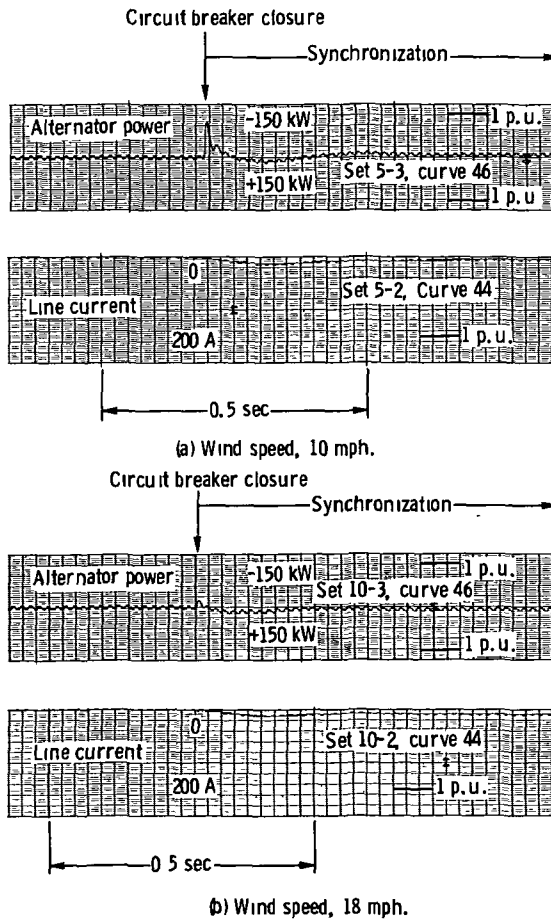


Figure 6. - Synchronization of Mod-0 wind turbine system.

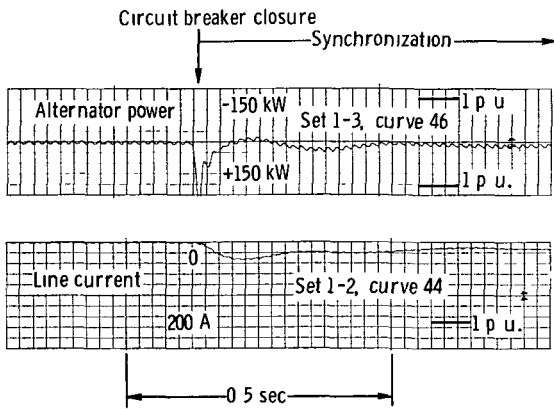
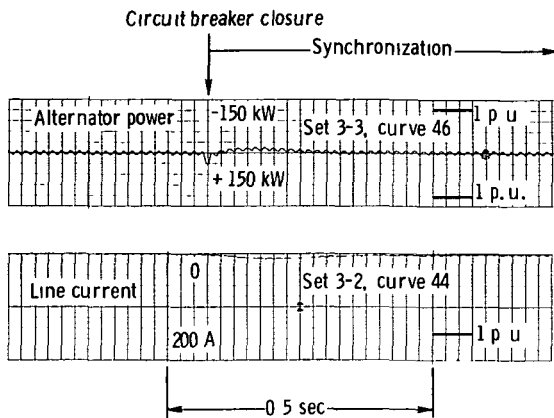


Figure 6. - Continued.

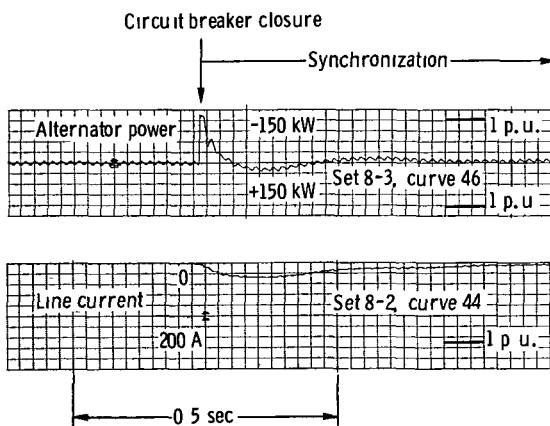


Figure 6. - Concluded.

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