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DESIGN AND TEST OF A CONTINUOUS DUTY PULSED AC GENERATOR

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Abstract

Specially designed synchronous ac generators can provide a high energy pulse power source capable of supplying energy to various pulse forming networks. One such generator, which is the subject of this paper, is presently being used as the prime power source for the Repetitive High Energy Pulsed Power Module (RHEPP)[1] at Sandia National Laboratories.

The generator has been designed to operate continuously in two distinct modes. In the first mode the generator can supply 50-kJ, 9.5-kV, 11,000-amp, 1-msec pulses continuously (500 kW average power) with a rep rate from 1 to 10 Hz. In the second mode, 20.8-kJ, 9.5-kV, 1,052-amp, 4-msec pulses can be supplied continuously (5,000 kW average power) at a rep rate of 240 pulses per second. The latter mode is being used in the RHEPP application at a reduced energy and voltage level. The generator was successfully tested in 9/89 to verify the performance at its maximum rating. Test results are presented along with details of the generator design and its applications.

Introduction

There is an increasing need for high energy pulse power sources to serve many different high energy industrial and defense applications. Rotating machines, being both rugged and insensitive to both overload and electromagnetic interference, are well suited for this purpose. A properly designed motor-generator set acts as both a buffer between the pulse forming network and the electric utility grid and as the first stage of pulse compression. Rotating machine power is directly converted into high power pulses without the need for intermediate power conversion. The pulsed ac generator, with properly designed parameters, becomes an integral part of the pulse forming network. It can be applied to systems requiring single pulse or continuous duty operation. The peak energy can easily be controlled by varying the generator voltage which is a direct function of the field excitation current.

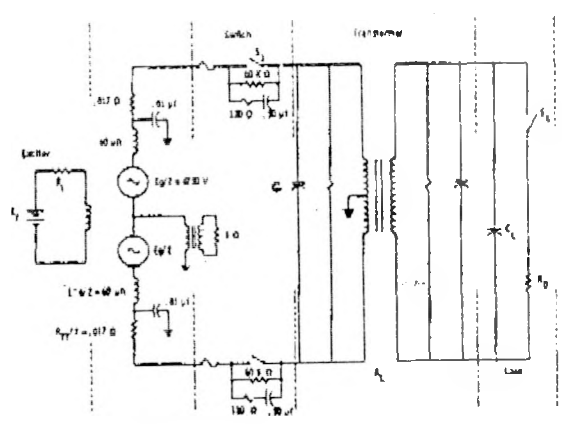

Fig. 1. Use of the pulsed ac generator in a high energy high voltage low rep rate system.

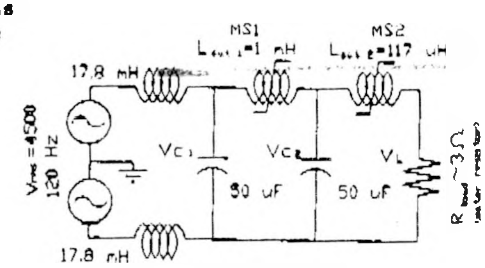

Fig. 2. Test circuit for use of the pulsed generator in a magnetic pulse compression system.

Generator Requirements

The main requirements for the pulse power supply are reliability, continuous duty operation, high voltage, high repetition rate, and flexibility. Reliability is the key requirement. Users want a "wall plug" they can use as a power supply to test various pulse forming networks and component technologies such as thermal management, system modeling, etc. Use of highly developed electrical machine theory and easy switching duty (switches can open and close at current zero) makes a pulsed ac generator system well suited for this power supply.

The subject machine has been designed for two modes or types of operation. Mode 1 operation is with high voltage and energy for low repetition rate systems. Mode 2 is for use with high average power magnetic pulse compression systems (see Figures 1 and 2). Table I gives the main generator system parameters for these two modes of operation along with the values of the SNL RHEPP system currently in operation. The generator has been tested unloaded at its maximum rating for both modes of operation.

In each mode, the pulsed ac generator is part of an ac-resonant charging circuit when connected in series with capacitor C and inductor L. In Mode 1 the internal inductance of the generator is matched to the capacitance of the load to have a natural frequency fr equal to the reciprocal of the desired charging time, t_w. That is, $f_r = 1/(2\pi\sqrt{LC}) = 1/t_w$. The energy of the pulse is given by $\xi = (1/2)C\,V_c^2$, where Vc is the capacitor voltage and equal to twice the generator voltage when losses are neglected.

In the Mode 1 system a solid state switch S1 is required. The switch is closed as the generator voltage passes through its peak value. The entire circuit operation is described in detail in [2]. The repetition rate is from 1 to 10 Hz at maximum generator voltage and pulse energy.

Table I — Pulsed AC Generator Operational Characteristics

	Mode 1	Mode 2	SNL RHEPP
• Energy per Pulse, KJ	50	20.8	2.5
• Continuous Rep-Rate, pps	1-10	240	240
• Peak Generator Output Voltage, kV	9.5	9.5	6.4
• Peak Generator Output Current, Amps	11,000	1,052	220
• RMS Generator Current	780	780	142
• Pulse Width, msec	1	4	4
• Peak First Stage Capacitor Voltage, kV	18.5	16	10
• Average Output Power, kW	500	5,000	600
• Series Res. Inductance, mH	.12	9.4	35.2
• Series Res. Capacitance, μF	202	187	50

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In Mode 2 operation which is described in detail in [1], the system inductance L is matched to the capacitance C of the load to have a natural frequency fr equal to the running frequency of the generator, f_g, i.e., $f_r = 1/(2\pi\sqrt{LC}) = f_g$ = (number of generator poles) x (revolutions per minute)/120. The resonant voltage Vc1 on the capacitor C1 causes the first magnetic switch to saturate at the positive and negative peaks (bipolar mode). Thus, two output pulses are delivered to the load for each cycle of the generator yielding a repetition rate of 2 fr. The energy ξ per pulse is given by $\xi = (1/2)C1Vc1^2$ where $Vc1 = (\pi/2)Vg$. In this mode of operation the average power is approximately equal to the generator's maximum average power. This results in a higher generator rating for Mode 2 type of operation. This is explained as follows. The maximum generator voltage and thus the field excitation current is the same for both modes of operation. This voltage is limited by the machine magnetic circuit and the ohmic heating in the generator field excitation winding. The generator output or armature current is vastly different in the two modes as shown in Figure 3, but the RMS value is 780 Amps for both modes. The RMS value of the generator current sets the ohmic losses and thus temperature in the armature winding. This temperature, in turn, sets the maximum generator rating. Thus, there is better generator utilization and efficiency with a higher repetition rate and lower energy per pulse.

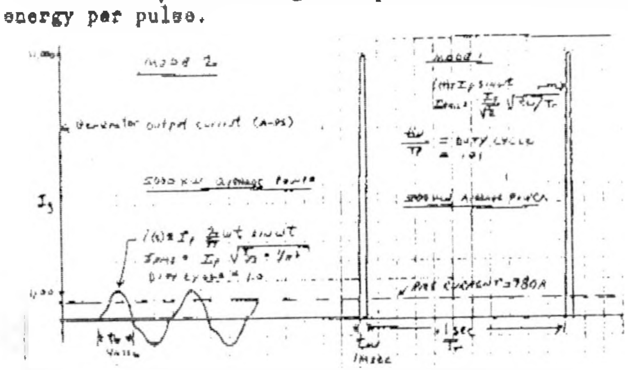

Fig. 3. Profiles of the generator output current during Modes 1 and 2 type operation.

General Arrangement

Figure 4 shows the complete generator set. The drive-motor is rated at 1000 hp (horsepower) and is a 2-pole squirrel-cage induction motor. To prevent the drive-motor from receiving the impact force produced by short circuits, a flexible coupling was used between the generator and drive-motor shafts.

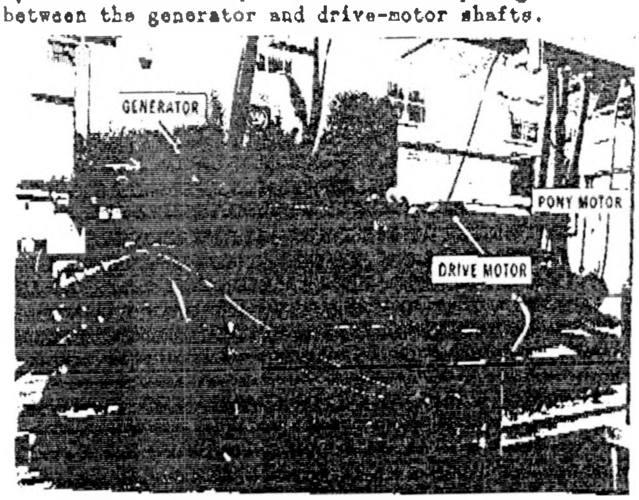

Fig. 4. General view of the pulsed ac generator and drive motor set-up at Sandia National Labs.

The generator is brought up to full speed in two minutes by a small pony motor run by a variable speed variable frequency drive. The pony motor is connected to the other end of the drive-motor shaft. Once the generator is up to speed, the pony motor is shut down and the main drive-motor is energized. Excitation can now be applied to the generator field winding initiating a train of pulses to the network. No warm-up period is required.

Figure 5 shows a typical system block diagram of the generator and its auxiliaries. Collector and brush rigging for the dc field current are located at the opposite end of the generator shaft. Other systems include the bearing lubrication system and various auxiliary motor starters and breakers.

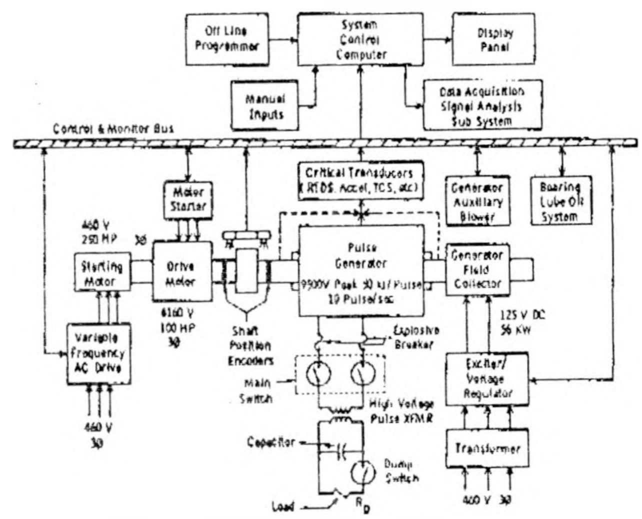

Fig. 5. System block diagram of pulsed ac generator power supply (Mode 1 operation).

Electrical Design

The main parameters of ac generators designed for pulse duty are the terminal voltage, internal inductance, and electrical frequency. They are set by the system requirements as explained earlier and, in turn, set the physical size of the machine along with consideration of temperature and mechanical stresses.

This 3600-rpm rotating-field synchronous generator is a single-phase, four-pole design based on a horizontal cylindrical rotor. See Table II for the generator design parameters.

The speed was set at 3600 rpm so that a standard induction motor could be used to drive the alternator directly, thus eliminating the need for a gear box.

The principal function of a pulsed ac generator is to deliver a large surge of power in a short period of time. This demands a machine designed for very low reactance and relatively long time constants. The subtransient reactance is the generator reactance which corresponds to and limits the initial short circuit current. The usual range of the subtransient reactance of power producing or conventional generators is approximately 10 to 25%, where 100% equals the ratio of rated phase voltage to rated phase current. Pulsed ac generators require a reactance an order of magnitude less than this. Therefore, a pulsed generator requires special proportions and provisions to obtain the specified low reactance.

To obtain the minimum reactance it was necessary to use a high air gap flux density and to minimize the permeance of the leakage flux paths.[2][3] To accomplish the latter, the width of the leakage flux path was minimized by using an air gap stator winding and a full damper winding on the surface of the rotor separated by a small clearance gap. The minimum size of the gap was dictated by ventilation pressure drop considerations.

Table II — Pulsed AC Generator Design Parameters

• Electrical	
• Voltage	9800 Volts Peak
• Subtransient Inductance	125 µH
• Frequency	120 Hz
• Field Voltage	125
• Field Current	400
• Air Gap Flux Density	70 Kilolines/in^2
• Ventilation	
• Cooling Scheme	All air with external blower
• Ambient Temp.	32°C
• Elevation	6500 ft.
• Construction	
• Stator Winding	Single Phase Concentric
• Speed	3600 RPM
• No. of Poles	4
• Rotor	26" dia. x 38" long
• WR^2 Rotor	5600 lb-ft^2
• Service Life	10^{11} Pulses

The Stator

The stator (see Figures 6 and 7) is constructed from electrical steel laminations like a conventional stator, but the teeth are reduced to tiny vestiges that do not carry flux and are only half the height of the stator coil. This permits a single layer air gap winding that is supported in the peripheral direction by the vestigial teeth. The core is rigidly attached to the frame which in turn is bolted to the foundation. The core clamping plates and winding support struts are made of nonmagnetic steel to minimize stray losses and heating. For this same reason the laminations at the ends of the core are slit at their inner diameter.

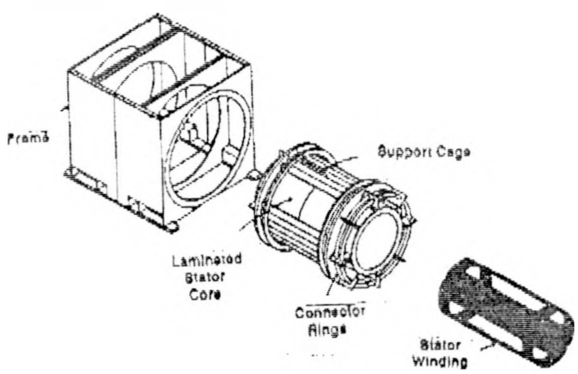

Fig. 6. Pulsed ac generator stator assembly.

The four stator coils are concentrically wound from finely stranded Litz wire cable insulated for 7 kV (rms) to ground with mica-based insulation and are electrically connected in series. The entire stator structure was subjected to two vacuum-pressure impregnation (VPI) processes with epoxy resin to complete the insulation system and also produce a solid structure.

The Rotor

The generator rotor body consists of a single piece steel alloy forging. Slots are cut in the rotor body to accommodate the field winding, slot wedges and damper bars, as illustrated in Figure 8. Additional shallow slots are located in the pole faces to accommodate damper bars. Nonmagnetic retaining rings are mounted on the rotor body with heavy shrink fits. They provide the main support for the end windings against centrifugal force.

The rotor supports two windings with rather different characteristics, the field winding and the damper winding. The former is similar to a conventional field winding. The damper winding or bars are dovetailed into the tops of the slots and also into the pole faces. They are shaped so that

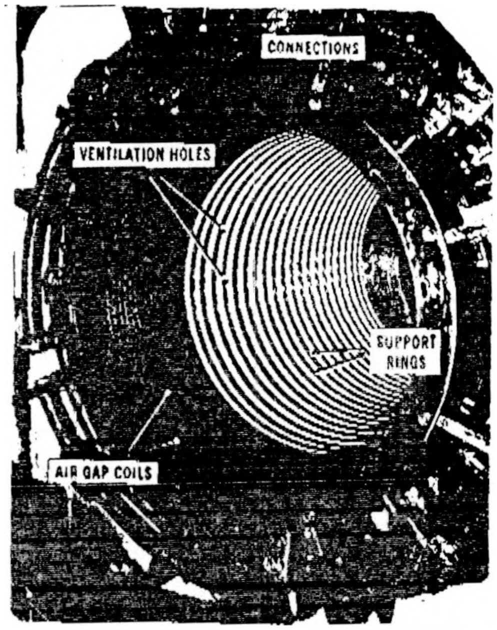

Fig. 7. End view of pulsed ac generator air gap winding arrangement.

they extend past the tops of the slots and spread out over the surface of the rotor forming an almost continuous covering. The retaining rings are also slotted to accept the dampers which cover both the rotor body and the retaining rings. The completed rotor looks like a copper cylinder with very narrow slits which are the gaps between the damper bars (see Figure 9). The dampers over the retaining ring area are short circuited by a laser welding operation.

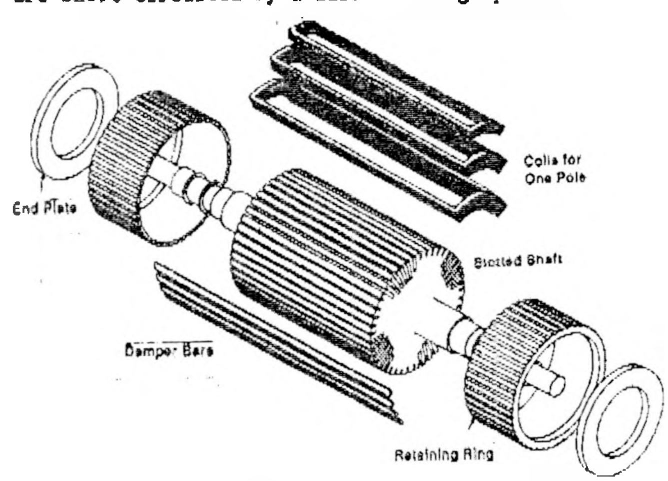

Fig. 8. Pulsed ac generator rotor assembly.

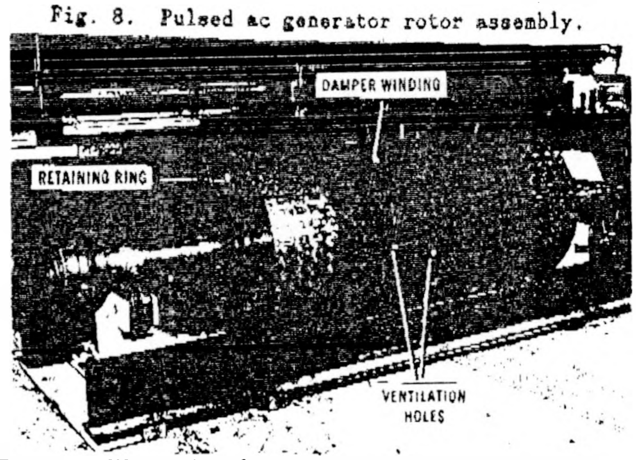

Fig. 9. View of pulsed ac generator rotor showing damper winding construction.

Cooling Method

The generator is air cooled to allow continuous duty operation. The use of air as the cooling medium greatly simplifies the unit construction.

Since it is possible to run the generator at various speeds, it is not possible to entirely incorporate adequate self-ventilating features into the rotor. Thus, pumping pressure is provided by both the centrifugal head of the rotor and an external fan which draws air into the ends of the machine and out the center. The fan discharges the air to the outside, thus no coolers are required. The stator core and coils are cooled by air flowing through radial ventilation ducts located in each of the laminated core packs. Cooling of the rotor coils is accomplished by cold air flowing through axial ventilation paths in the bottom of the rotor coil slots and then radially through vent slots in the rotor winding conductors and damper bars.

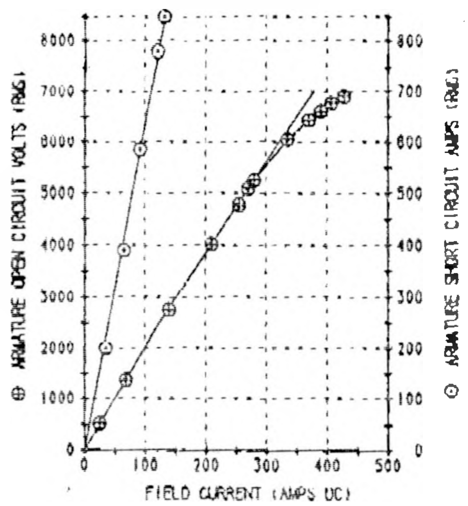

Fig. 10. Generator open end short circuit saturation curves.

Field Testing

The completed machine was subjected to a series of electrical tests. Test results were used to verify the design calculations and to provide practical data to adjust system parameters. The test data includes maximum capability, electrical and magnetic performance, temperature rise data, and losses.

Open- and short-circuit saturation curves are shown in Figure 10. To test the thermal performance of the generator, the system was initially run at open circuit (rated voltage and zero armature current) and steady state short-circuit (zero voltage and rated rms armature current) conditions for about five hours each, allowing all temperatures to stabilize. Steady-state temperature data is given in Table III. The generator was designed to operate with Class B temperatures, 180°C total temperature in a 40°C ambient. The heat runs confirmed the maximum rated rms current (field and armature) for both Modes 1 and 2 operation. A summary of the generator losses is given in Table IV. The generator is more efficient in the Mode 2 operation since power is being delivered to the load continuously.

The generator system was tested under load as the base power supply and first stage of the pulse forming network of the RHEPP module at a continuous power output of 600 kW. The output is limited by the size of the drive motor (1000 hp). As of 11/90, over 9 x 10^6 pulses at 10 kV and 240 Hz have been delivered with no problems. Figure 11 illustrates actual system waveforms.

Table III — Pulsed AC Generator Steady State Temperature Data

Component	Temperature in °C	
	Open Circuit 9.5 kV Peak 0 Amp 400 Field Amps	Short Circuit 780 Amp RMS 0 Volts 120 Field Amps
• Ambient Temperature	30	32
• Generator Bearing Housing:		
• Drive End	42	42
• Collector End	43	43
• Cooling Air		
• Generator Discharge	62	58
• Rotor Discharge	70.5	59
• Stator Winding		
• Main Body	102	108
• End Turns	53	154
• Connecting Rings	-	49.5
• Series Connections	-	42.5
• Rotor Winding (Average)	80	49
• Stator Core		
• End Pack	94	83
• Center Pack	65	61
• Bracing Struts	42	41

Table IV — Summary of Generator Losses and Efficiency for Modes 1 and 2 Operation

Component	Mode 1 500 kW	Mode 2 5000 kW	BNL RHEPP Module
Bearings	9	9	9
Stator Copper	22.5	22.5	.8
Stray	5	5	2.3
Stator Iron	27.2	27.2	12.3
Rotor Damper Winding	29.4	23.4	10.8
Windage	30.8	30.8	30.8
Rotor Field Copper	37.4	37.4	14
Total Losses	161	155	80
Efficiency, %	75.6	97	88

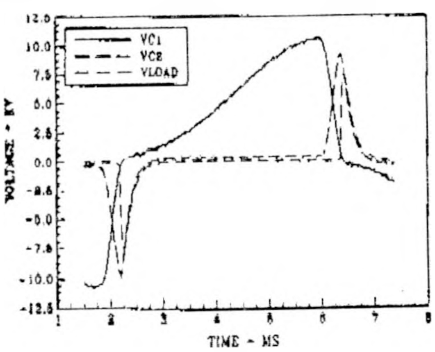

Fig. 11. Actual system waveforms of the pulsed ac generator output as part of RHEPP module.

Summary

A pulsed ac generator has been constructed, installed, tested, and proved serviceable for its specified duty. Many novel features were incorporated to enable this machine to perform successfully in various pulse forming networks. This type of continuous duty system has met its main goal, that is, to be a rugged, reliable and versatile power source to support research and development in pulse forming devices and network operation.

References

[1] H. C. Harjes, et al., "The Repetitive High Energy Pulsed Power Module," Proceedings of the 19th Power Modulator Symposium, June 26-28, 1990, San Diego, CA.

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