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CYCLOCONVERTER ON THE ALL-ELECTRIC AIRPLANE

Robert C. Webb
General Electric Company
Binghampton, New York 13902

This paper discusses the application of a cycloconverter to a permanent-magnet generator. Recent developments, advanced concepts, and advanced technology systems will be covered. Recent developments include permanent magnets, permanent-magnet motors and generators, and power semiconductors.

Figure 1 compares the coercive force as a function of induction for three magnets. In the 1970's a revolutionary breakthrough was made in magnet development that allowed them to be applied to high-power motors and generators.

When the permanent magnet is used in a high-power generator, the control permanent-magnet generator and exciter can be removed, as shown in figure 2. The generator is significantly simplified and its efficiency increased. Figure 3 compares two 60-kVA-rated generator rotors of comparable speed range. A current wire-wound system and a permanent-magnet system are essentially equal in weight, but the advances in magnet technology indicate that the energy product will increase. This will allow the use of smaller magnets; it will minimize the containment, and it will increase speed. The result will be a lighter weight motor or generator. Current rotor technology is based on blocks of permanent-magnet material made into disks or wheels as shown in figure 4. (It will probably not change much.) This allows some flexibility in changing ratings by changing the number of wheels or disks.

For the last 15 years of cycloconverter work variously rated generators have used stud-mounted silicon-controlled rectifiers (SCR) (shown in fig. 5) mounted on a heat plate. This is a fairly common technology, but it has created a cooling penalty. The bases on all of these SCR's were hot and also had to be electrically isolated. Conducting the heat through the electrical isolation is difficult and inefficient.

On the left of figure 6 is an SCR power module that GE developed, built, and tested under a program sponsored by the Wright Patterson Aeropropulsion Laboratory. We took the C158 SCR and put it in a module with a dry interface. Typically, dry interfaces tend to create a problem because of the differential expansion rates. Therefore we used structured copper in a hermetically sealed case and beryllium; so the base of the unit is electrically isolated but has an excellent thermal path as judged by existing technology. On the right in figure 6 is an SCR developed in the last few years. Until very recently transistors with sufficient power range in an individual device were not readily available to apply in power conditioning for aircraft electrical systems. The device is a 450-V, 200-A device.

GE has spent some time working on package development. Figure 7 shows a very small package - about an 1-1/2 in. long and 1/2 in. wide - containing a 450-V, 200-A device. This package has the same type of construction as the power module shown in the previous figure, and it provides the same benefits.

GE's advanced concepts for future aircraft electrical systems are shown in figure 8. The generator could be either integrated with the engine or mounted on the accessory gearbox. We expect that military aircraft generators would be more likely to be integrated and commercial aircraft generators more likely to be accessory gearbox mounted. We have shown an unconditioned, or wild, frequency and voltage bus to be used for distribution and for some loads such as electric deicing. However, conditioned power (115 V, three phase, 400 Hz) will probably always be required and could be provided with either a cycloconverter or a dc link. Direct-current loads could be provided from the wild frequency and voltage bus through transformer rectifier supplies. Some of the larger loads such as actuators, fuel pumps, and environmental control systems (ECS) could be driven by electric motors. We expect that they would use permanent-magnet motors with a cycloconverter or dc link for speed control. In selecting either cycloconverters or dc link, an ac distribution system would seem to favor the cycloconverter and a dc distribution system would favor the dc link.

Figure 9 shows the installation of an integral starter-generator on the TF-34 engine. The study that developed this installation was limited to existing engines. Although the results were quite reasonable, they probably could have been even better had a new engine design been used. If an engine is to be equipped with an integral starter-generator, the best approach would be to design the engine and the starter-generator together.

Three GE programs touched on briefly are the 60-kVA variable-speed, constant-frequency VSCF starter-generator program, which is ongoing; the 150-kVA VSCF starter-generator program, which has been completed, and the 140-hp PM brushless motor, which has been developed. The Wright Patterson Aeropropulsion Laboratory is sponsoring a program to take the permanent-magnet technology developed by GE and flight test it on two A-10's over a 1-year period (fig. 10). This is the next step in the evolution of a permanent-magnet starter-generator system on an airplane. The large housing on the right end of the generator contains a gearbox to match the generator speed to a starter pad on the engine. The actual generator is quite small. The package to the right of the generator contains the cycloconverter which controls the generator during its use as a starter and also allows the two generators to be paralleled. The cycloconverter package is not a final flight design.

Figure 11 is an artist's rendering of a cross section of the 60-kVA permanent-magnet generator. It is a high-speed design with a dry-cavity construction. This eliminates the problem of oil getting into the air gap and of trying to design effective bore seals and slingers. This construction does require that the stator end turns depend on conduction for cooling. We used a contained oil system for cooling, which is similar to the cooling systems on other types of generators.

The cycloconverter has the inherent capability of bidirectional power flow (fig. 12). Thus combining it with a permanent-magnet generator that does not have an exitation problem at standstill results in the ideal system for an ac starter-generator. Only a minimal change in the cycloconverter is required for rotor position sensing during standstill. The change in system weight is insignificant. There is approximately a 7-percent system part-count increase and only a 4-percent decrease in reliability.

Figure 13 shows drag torque plotted against input drive shaft speed for the TF-34 engine. It also shows the starter-generator output torque. When GE originally started this program, it was planned to have a 60-kVA system to go on the A-10. The A-10 has a 30/40-kVA system. It was originally conceived that it would require 60 kVA to start the engine. With some of the circuit and system improvements we have been able to employ, the TF-34 can be started at 40 to 45 kVA. Now let me present some differences between the permanent-magnet system and an air-start system. An air-start system has a high impact torque and a real decaying curve, so that at high speeds there would be minimal torque. The electric starter-generator concept gives a much higher torque at high speed. From lightoff to idle the starter-generator is faster than the air starter, but from initial rollover to lightoff the reverse is true. For the TF-34 engine the electric starter-generator was a couple of seconds faster than the air starter.

The A-10 program will have both engines dedicated to the 60-kVA system, but the air-starter system will be left on as a backup. The auxiliary power unit (APU) will serve as a backup for electric power in case something goes wrong with the generators because these are not flight test airplanes. They are tactical airplanes that will be used in their common training mission. The configuration is shown in figure 14.

In 1981 we conducted an A-10 engine start test at the Air Guard open-air test facility in Syracuse, New York. We have done numerous laboratory tests where we simulate the engine drag-torque curve. We have tested it with equivalent generators on a ground power cart, but we still did not know what would happen in the flight test program. The Air Guard test was a way of minimizing risks and finding out how well the system works. We used the standard Air Force ground power cart, A/M32A-60, on an actual TF-34 engine. The test setup is shown in figures 15 and 16.

We did three motorings before turning on the fuel and ignition to find out how the system worked. Each time the system performed as had been anticipated; then we did a total of three starts. I was initially concerned that the start times were so high. It turned out that the engine had a dead set of ignitors and it was taking 11 to 12 sec for the fuel to ignite. The start times were still 2 to 3 sec faster than with the air starter.

In February 1982, we set up and ran a test at GE Lynn, where the TF-34 is manufactured. We worked out an arrangement to do starting and generating as part of their component improvement test (CIT) on a new turbine section (fig. 17). A diagram of the Lynn engine test cell is shown in figure 18. We mounteda generator on the engine. The converter was on the catwalk above the engine. We wired the start switch and the disconnect switch into the engine control console and fabricated a load bank with 30 kVA and a 0.7 power factor. The choice of 30 kVA was based only on the availability of resistors and inductors to make that load bank.

Figure 16 shows AMT-IIIR, a factory test cycle used for accelerated life testing. During this cycle the throttle goes from maximum to minimum power nine times. This is followed by a slow deceleration, a return to idle, and a 5-min shutdown. Then the cycle is repeated. We thought - based on our laboratory tests - that we could run the motoring in a continuous mode. The present air-starter system has an overheating problem if run continuously. There is sufficient oil circulation in the idle position to cool the generator. The cycloconverter is a fan-cooled device: whenever it operates in the start mode, the fans are on. Thus there was no limitation on cooling and we could use extended motoring.

In a typical CIT program with the air-starter system, four or five failures occur during accelerated testing. We performed 434 electrical starts and operated the converter for 432 hours with no failures and no unsuccessful starts. The system operated so smoothly that we were able to leave after the first week and a half and allow the regular test personnel to conduct the remainder of the testing.

Figure 20 shows the 150-kVA VSCF starter-generator system. On the basis of the drag-torque data available for the E^3 engine, this starter-generator could provide acceptable start times for that engine. The E^3 engine is very difficult to start because of its high cycle pressure ratio. The 150-kVA starter-generator was built as a potential starter for the F-101 engine used on the B-1 bomber. Figure 21 shows the cycloconverter used with the 150-kVA starter-generator. The package is a laboratory design and therefore is larger than a flight system would be.

We applied this technology to a brushless, high-speed, permanent-magnet motor, shown in figure 22. The motor, which was designed for a torpedo propulsion program, won the 1981 IR-100 award. The motor produced 5 hp/lb for a 0.2-lb/hp specific weight. The 504 power transistor was controlled off a battery, so it employed essentially the dc-link approach.

The trend is toward more electrical loads on airplanes. The electrical systems on the airplanes in inventory today are not of sufficient size to start many of these engines. On most new airplanes -- particularly the new military airplanes -- it appears that the electrical load will exceed the starting load. Permanent magnets will continue to be a real consideration. Energy products are indicated to be rising. The only unfortunate factor there is that all of the significant research in magnets is being done in Japan and the Peoples Republic of China. Very little significant work is being done in the United States in my opinion. Large brushless motors will take on a more and more active role in fuel pumps, environmental control systems, other pumps, and actuators. The future of hybrid electric power generating systems is not clear cut. Evolution of a generator integral with the engine will remain peculiar to military aircraft.

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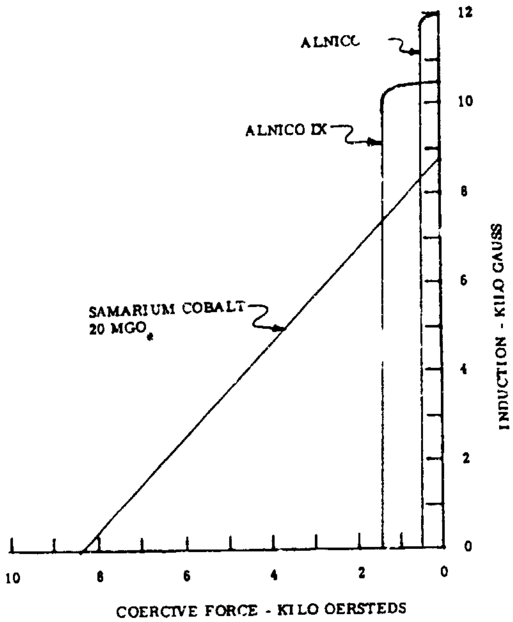

Figure 1. - Comparison of magnets.

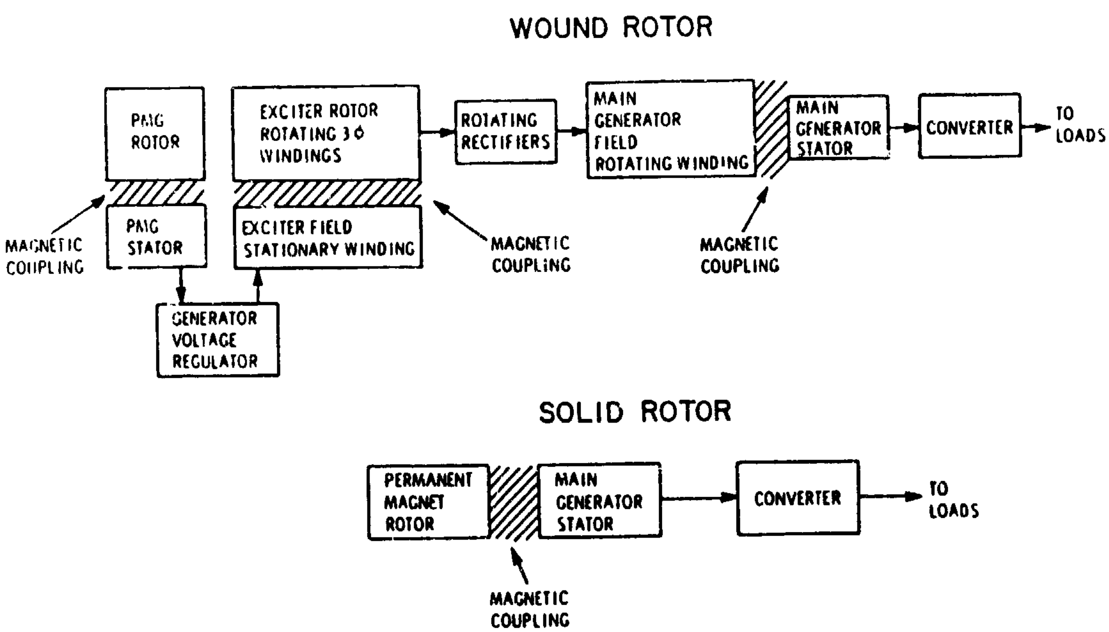

Figure 2. - Comparison of wound and permanent-magnet (solid) VSCF systems.

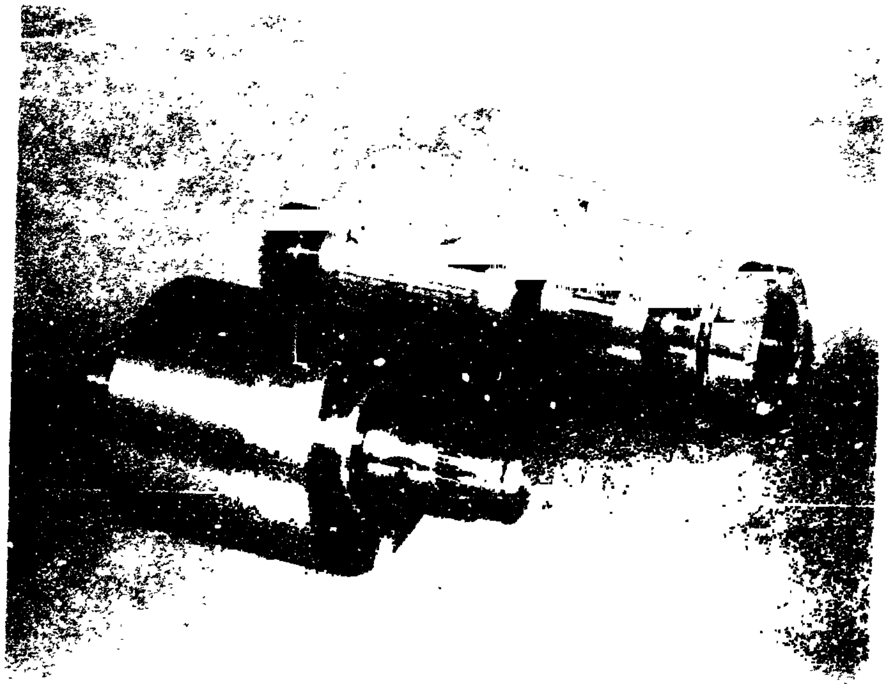

Figure 3. - 60-kVA generator rotors.

Figure 4. - Disk of permanent-magnet material.

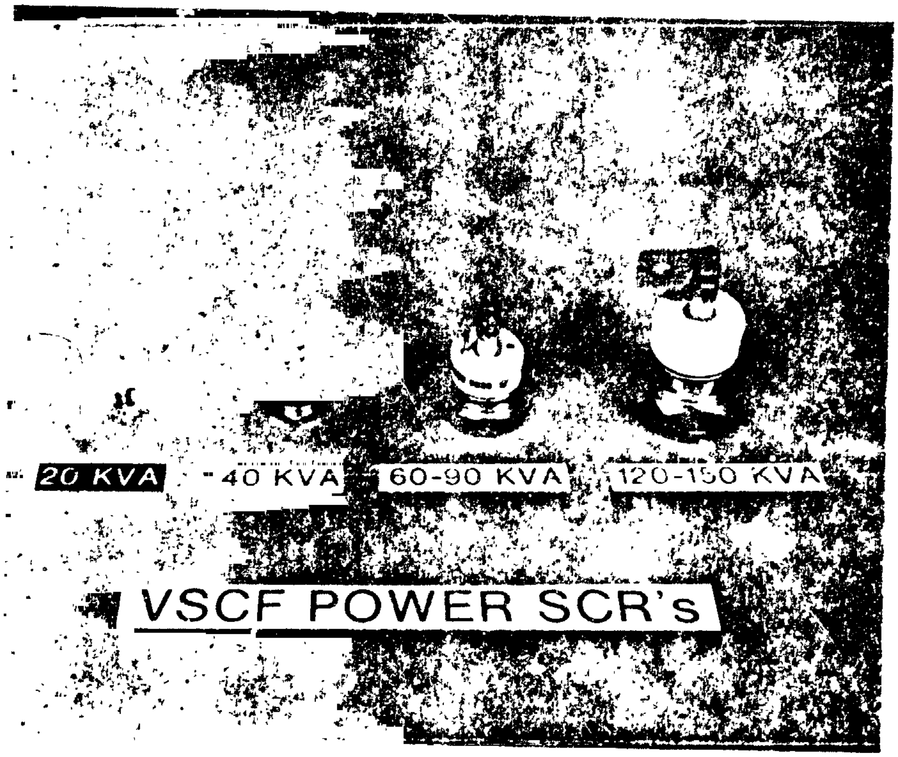

Figure 5. - Stud-mounted silicon-controlled rectifiers.

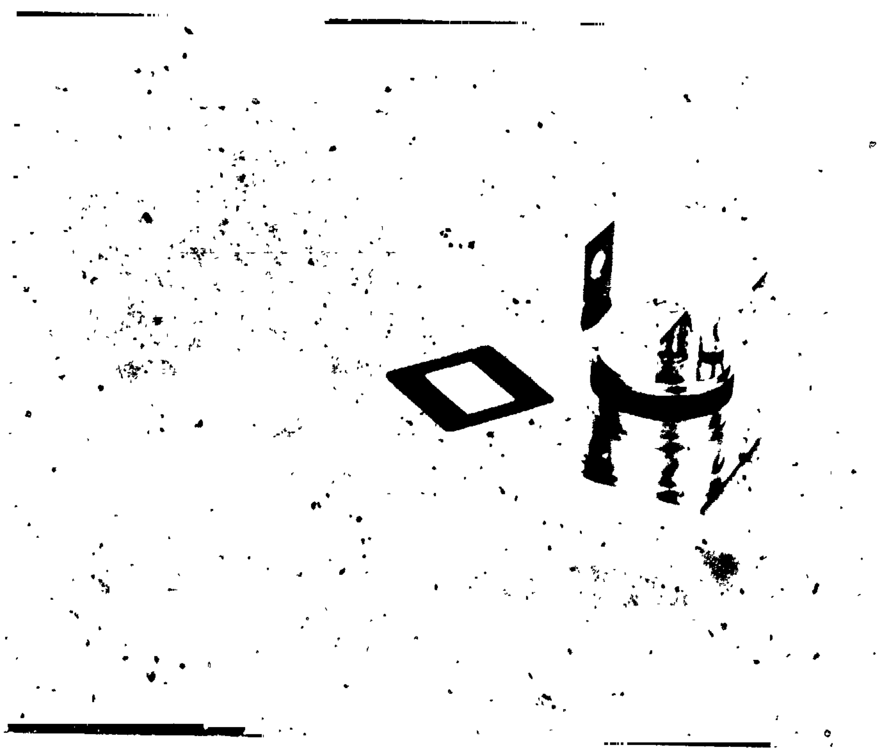

Figure 6. - Two GE SCR power modules.

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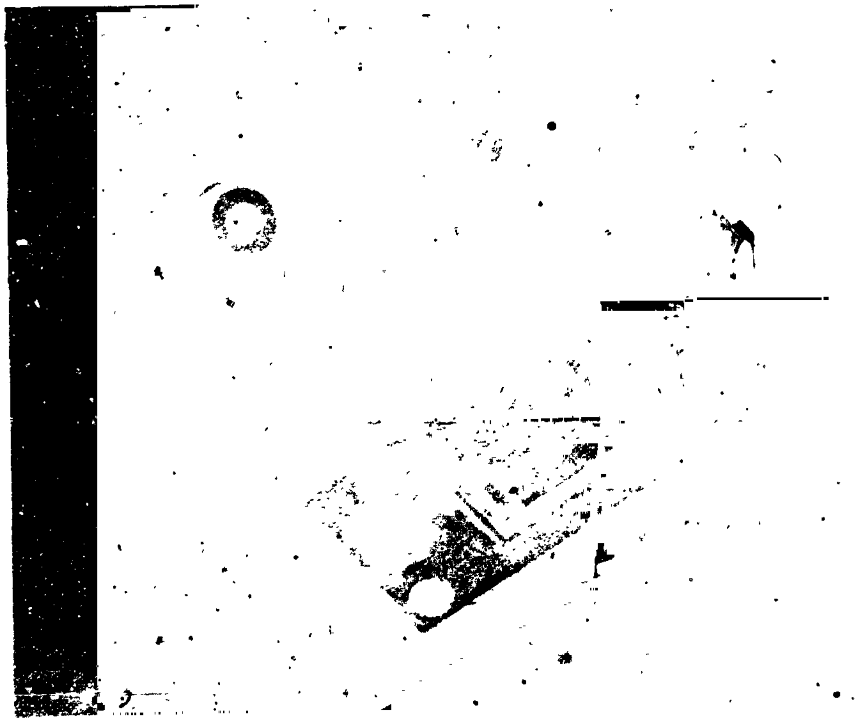

Figure 7. - Small transistor package.

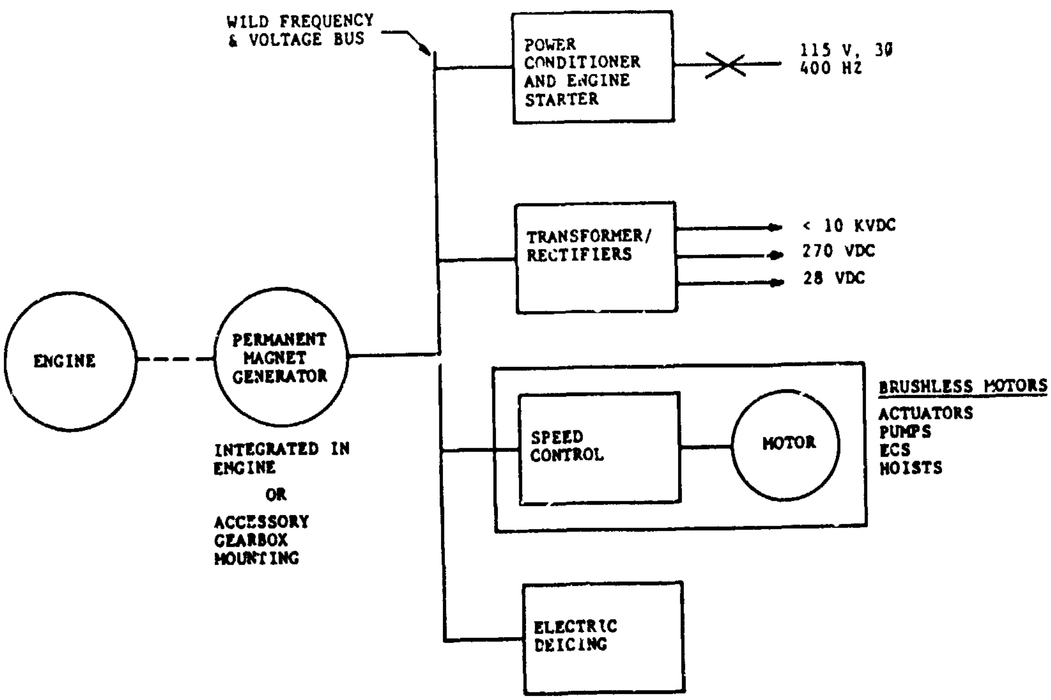

Figure 8. - Future aircraft electrical systems - GE concept.

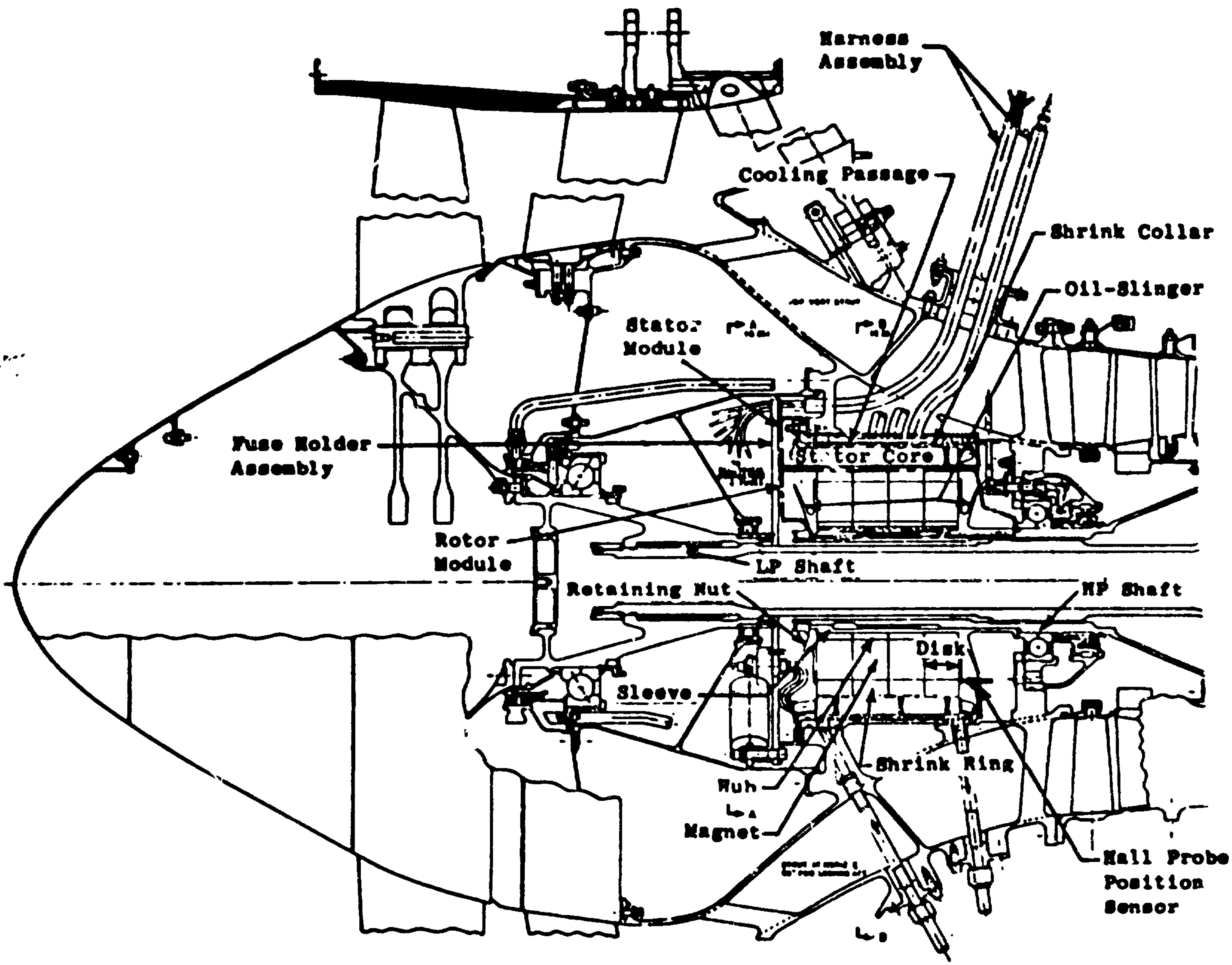

Figure 9. - High-pressure-shaft-mounted, permanent-magnet integral engine starter-generator for TF-34 engine.

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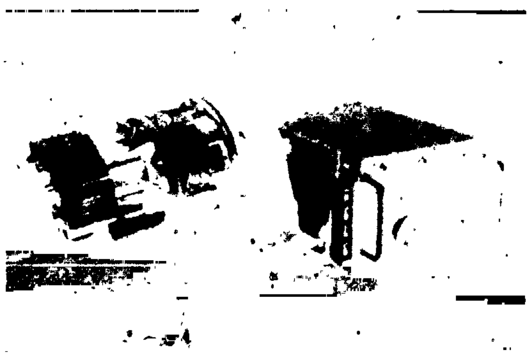

SYSTEM DESCRIPTION

- POWER — 60 KVA, 115 VOLT, 3 PHASE, 400 HZ, .75 TO .95 PF
- STARTER — 65 LB.-FT. MIN. (LIGHT OFF)
- GENERATOR SPEED — 15 TO 30 K RPM

SYSTEM FEATURES

- PERMANENT MAGNET ($SmCo_5$) SOLID ROTOR
- COMBINED STARTER AND GENERATOR SYSTEM
- GENERATE IN PARALLEL OR ISOLATED
- HIGH START AND GENERATE EFFICIENCY

Figure 10. - 60-kVA VSCF starter-generator.

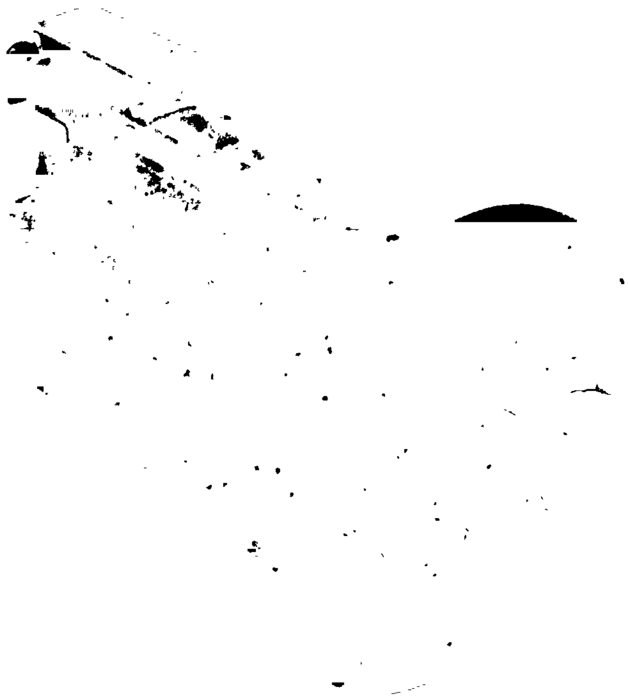

Figure 11. - Cross section of 60-kVA starter-generator.

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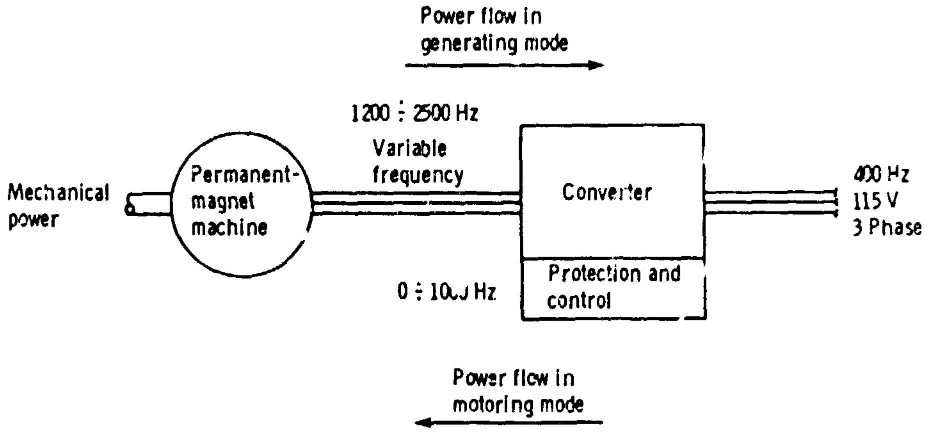

Figure 12. - Permanent-magnet VSCF system concept - bidirectional power flow.

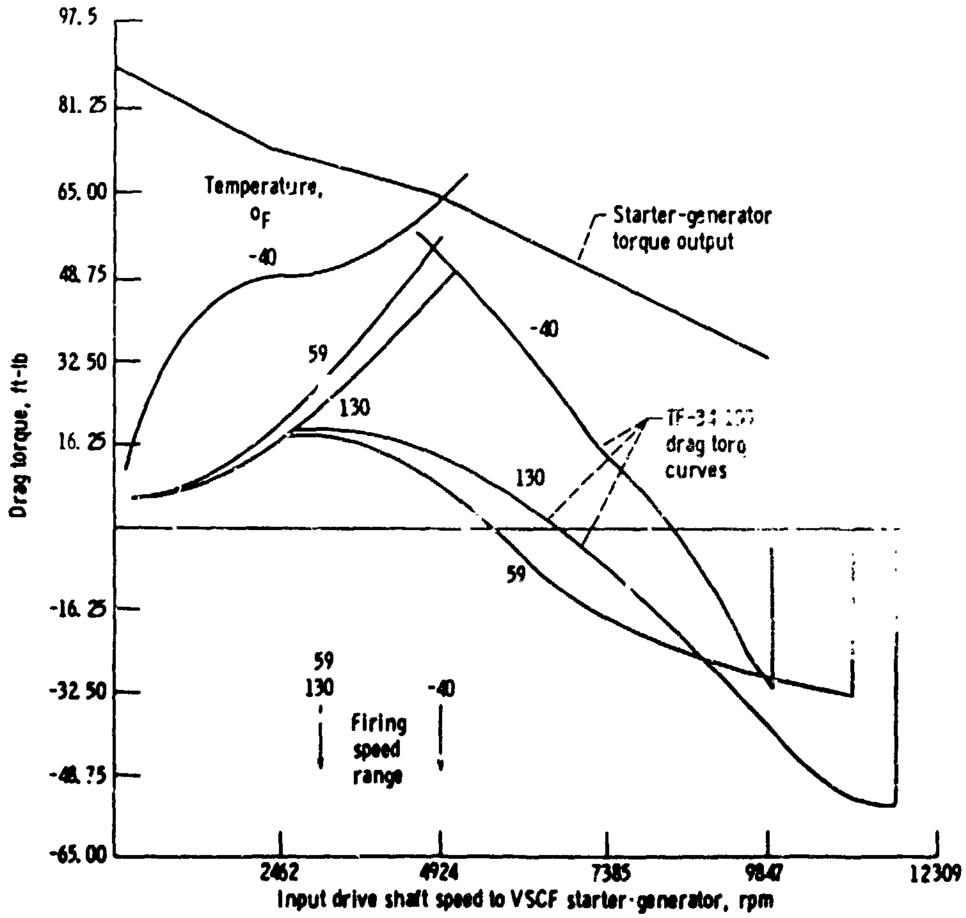

Figure 13. - 60-kVA starter-generator output torque. Starter-generator cutout speed: minimum, 9350 rpm; maximum, 9850 rpm.

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Figure 14. - 60-kVA starter-generator installed in A-10 airplane.

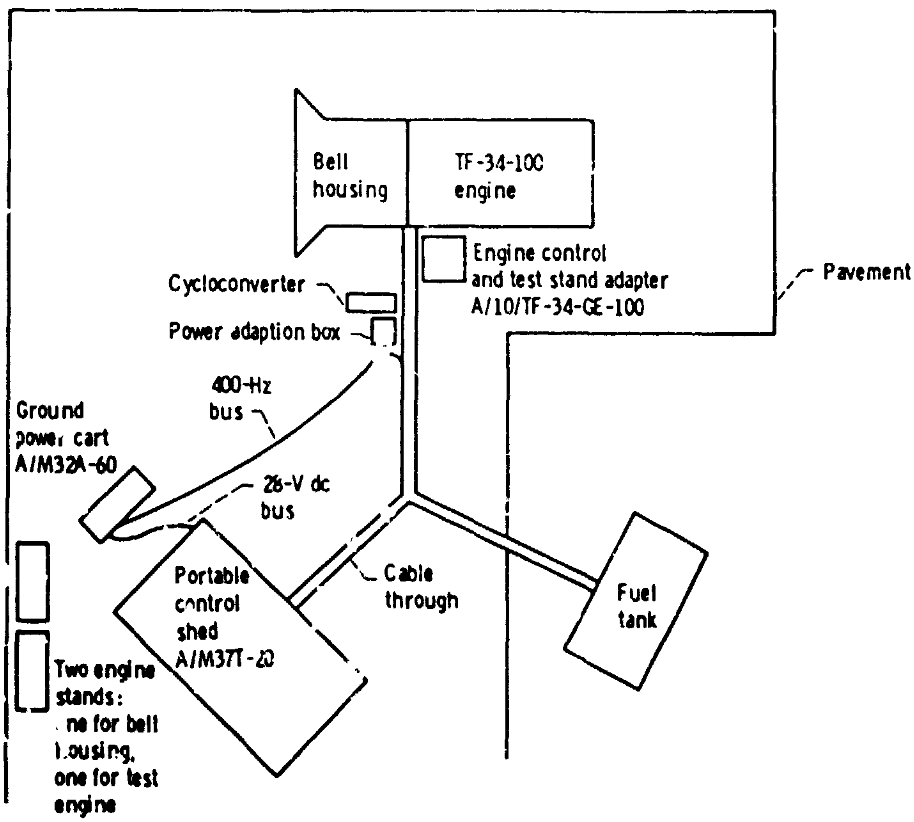

Figure 15. - Syracuse engine test cell.

Figure 16. - Syracuse open-air test facility.

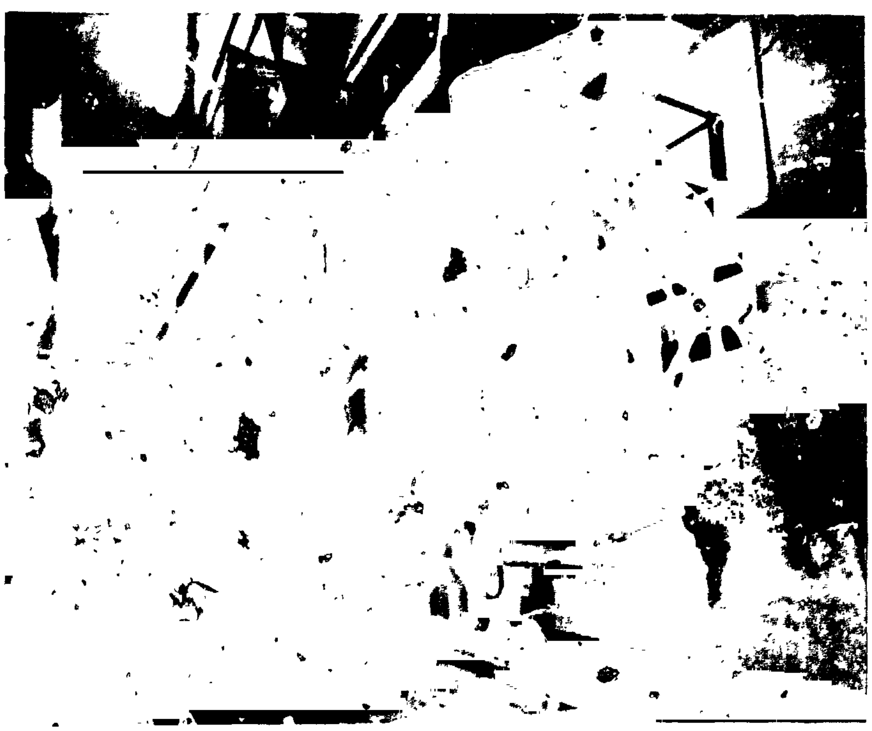

Figure 17. - Lynn test facility.

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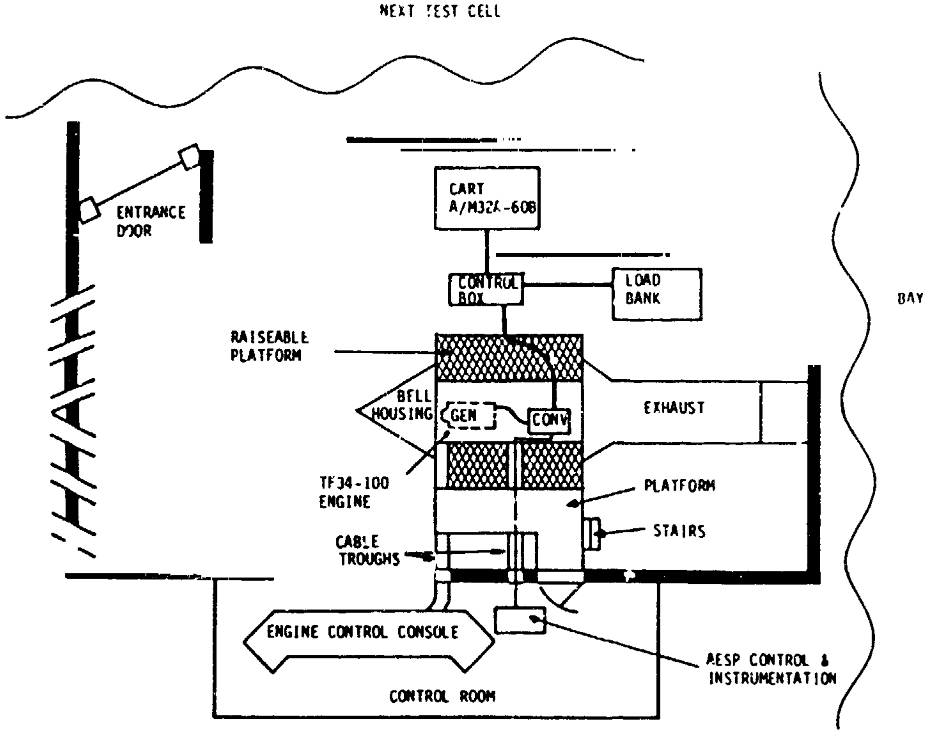

Figure 18. - Diagram of Lynn engine test cell.

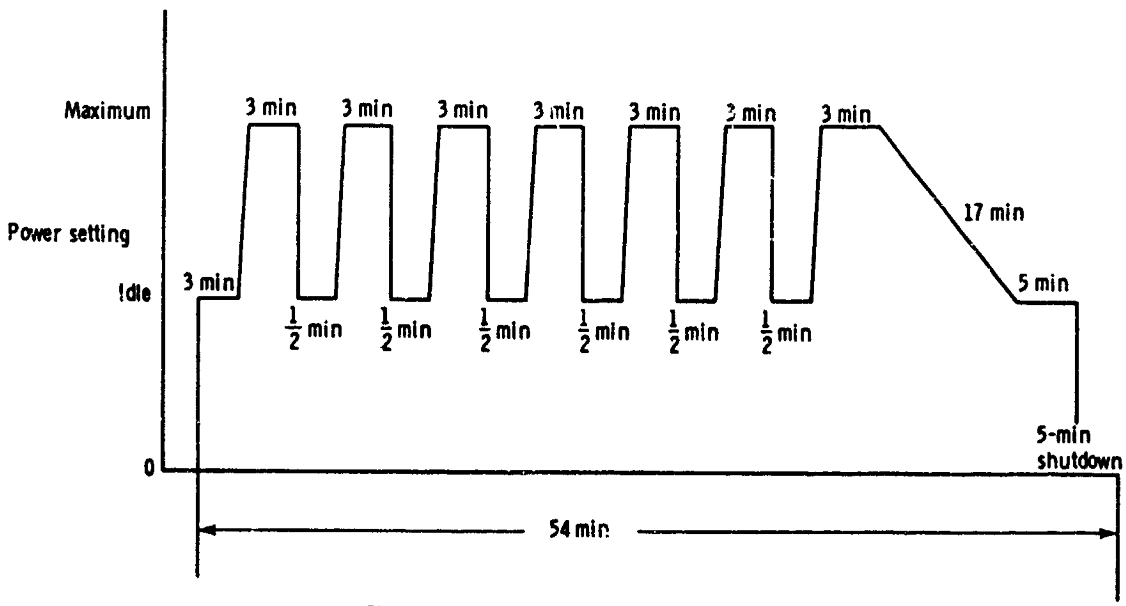

Figure 19. - TF-34-100 proposed AMT III R factory test cycle.

C-3

Figure 20. - 150-kVA VSCF starter-generator.

Figure 21. - Cycloconverter for 150-kVA starter-generator.

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Description	
Horsepower	141
Speed	20 K RPM
Weight	31 lbs
Rotor Dia.	3.8 inches
Stack	2.8 inches

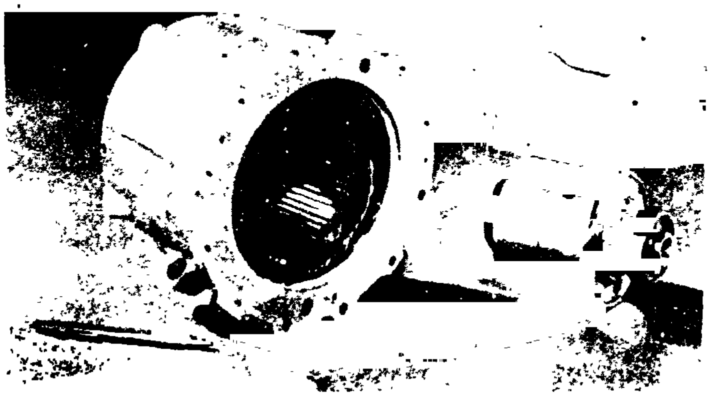

Figure 22. - Brushless, high-speed permanent-magnet motor.