AN ELECTRICAL GENERATOR WITH A VARIABLE SPEED INPUT - CONSTANT FREQUENCY OUTPUT

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ABSTRACT

A new type of rotary energy conversion device for obtaining a desired constant frequency output independent of the speed of the prime-mover has been developed and tested, using the technique of field modulation and solid-state alternator output processing. This paper describes a 10-kilowatt prototype field modulated frequency down converter system designed, built, and successfully tested at Oklahoma State University. Experimentally obtained performance characteristics are presented and discussed.

PRINCIPLE OF OPERATION

A conventional three-phase synchronous machine of basic frequency f_r will have induced voltages of frequencies $(f_r + f_m)$ and $(f_r - f_m)$ when excited with an alternating current of frequency f_m; $f_r > f_m$. When such three-phase voltages are individually full wave rectified and their outputs tied in parallel, an output voltage containing the following components results:

(1) dc component
(2) Ripple of frequency $6 f_r$
(3) Full-wave rectified sine wave at the frequency f_m;

$$V|\sin \omega_m t| \text{ where } \omega_m = 2\pi f_m$$

The dc component is, in general, proportional to the reciprocal of the modulation frequency ratio m, where $m = f_r/f_m$. For values of m greater than 10, this component becomes negligibly small. The resulting full-wave rectified sine wave can be converted to a sine wave voltage at the modulating frequency f_m by using a suitable switching circuit employing controlled rectifiers.

DESCRIPTION

Figure 1 shows a simplified schematic of the frequency down converter system. It is built around a high-speed high-reactance high-frequency three-phase alternator. Both rotor and stator are laminated to minimize the iron losses. The six stator leads are brought out and three full-wave bridges are connected as shown, one across each of the phases. The outputs of the bridges are tied in parallel across the load through a silicon controlled rectifier switching system. Tuning capacitors C are connected across each of the stator windings to decrease the excitation requirements (both watts and vars) at the rotor terminals. The main switching process is accomplished by the four controlled rectifiers, SCR1 through SCR4. The commutating circuit consisting of L_2 and C_2 and the controlled rectifiers SCR 5 and SCR 6 aid in this switching process, especially when the load is not purely resistive. In addition to filtering, capacitance C_3 enables the handling of lagging power factor loads by the system.

The field is excited by an ac power source of frequency f_m. Since this frequency fixes the output frequency, care must be exercised in the design of this part of the system. In case the system is required to be completely self starting, an inverter dc source combination must be used to excite the field. The dc power might come from an exciter alternator-rectifier unit mounted on the same shaft as the main generator.

The 10-kilowatt 220-volt single-phase 60-hertz prototype designed and built has 16 poles and runs at around 7000 rpm. This corresponds to a frequency f_r of about 930 hertz. For a modulating frequency of 60 hertz, m is between 15 and 16. The dc component associated with this value of m is essentially negligible and causes no problem in the switching action of the SCR circuitry. The rotor diameter is 6 inches and active iron length is 2.5 inches. Overall dimensions of the generator are a diameter of 9.75 inches and a length of 7.75 inches. The electronics associated with the system can be arranged compactly. A photograph of the 10-kilowatt prototype system is shown in figure 2.

PERFORMANCE RESULTS

The efficiency of the generator for three values of stator tuning capacitors is shown in figure 3 plotted against output power. Figure 4 shows the rotor input power for three values of C. Stator tuning capacitors significantly improve the performance of the system.

The desirability of rotor tuning is brought out in figure 5. Rotor tuning reduces the volt-ampere capacity required of the excitation source.

The voltage regulation of the frequency down converter is improved by the variation of the effective rotor reactance with output power (see fig. 6). Figure 7 shows the variation of the output voltage from rated output rated voltage conditions as the output power is decreased. It can be seen that with $C=5\mu F$, the output voltage stays essentially constant down to about 40 percent of rated load. Smaller values of C do not result in this desirable characteristic. It is possible to exploit this property by properly choosing C to obtain nearly constant output voltage from low-load to full-load conditions.

CONCLUDING REMARKS

The field modulated generator system (FMGS) described in this paper has several advantages and potential applications. Since the output frequency is independent of the prime-mover speed, variable speed prime movers such as the ones available in aircrafts or unregulated high-speed turbines and wind energy devices can be used to drive the generator.

In addition to being smaller in size and weight, it has inherently better regulation and independence from rotor inertia effects. The principle of operation appears to be applicable to systems of any size. The efficiency of the system is similar to those of conventional systems of equivalent rating. Whereas a conventional synchronous machine operating in parallel with bus bars can receive or deliver power (motor or generator) to the supply, FMGS can operate only as a generator because the bridge rectifiers will prevent any power flow from the bus bars to the generator. The behavior of the FMGS operating in parallel with an existing power system under normal and fault conditions is yet to be completely explored. The results obtained from the prototype are promising, and further development, testing, and design optimization are underway.

DISCUSSION

Q: Do you have any idea what the dollars per kilowatt would be on, say, a 1-megawatt unit?
A: Again, you play the game the way everyone else here has played the game; that is, if you want to build a million of them, the price will be quite low. We've made a fairly careful analysis of it, and if you built a lot of them in reasonable sizes, about a hundred dollars per kilowatt is our projection. We are also standing ready to sell you some, up to the 60- to 100-kilowatt level, at a very much inflated price over that unless you want to order four of five hundred thousand of them.

Q: What is the working rpm of that generator?
A: The generator that we showed operates at 7000 rpm. It would operate successfully at any speed from, we think, around 1200 to 10,000 rpm. A 5 or 6 to 1 speed range is not inconceivable. We built it to operate at 7000 rpm because that was the nature of the prime mover in the pulley arrangement we had to begin with. We could, of course, design it to operate from, say, 500 to 5000 rpm. You take your choice as to what the speed range is. You propeller people tell us what the speed range should be and what gearing should be, and we will easily accommodate 5 to 10 to 1 speed variations, we think, with no particular problem. This particular machine's most spectacular characteristic is obtained if you run it at its rated load condition, and then if you simply turn off the power to the prime mover you will find the 60-hertz sineusoid absolutely stable until there is no prime mover turning at all. You will find, of course, that its amplitude varies.

Q: That is a brushless generator?
A: It is not a brushless generator at present. We built it to handle

brushes because we figured we could make it much lighter that way. We checked with various people about brushes, and we found that in terms of trying to get a constant frequency output for variable frequency input brushes would be the least of your problems. We think we can make it without brushes, and we are proceeding in that particular direction now.

Q: Can you synchronize this on a single powerline and match your modulate with a power angle, or with the power output ahead of that?

A: We've done that, yes. You see the thing is that the frequency can be obtained directly from the powerline, as your particular discussion indicated, and then the problem is no problem at all. The only thing that you can't do with this particular machine is pump power from the powerline into it, which we consider an overwhelming asset, and that is the reason we designed it that way.

Q: Can you contrast your generator with a Precise Power Corporation's generator?

A: No, because we don't have complete information on the Precise Power Corporation's variable speed generator. We are interested in getting that information, and we will give them free access to all of ours and hope that they would reciprocate.

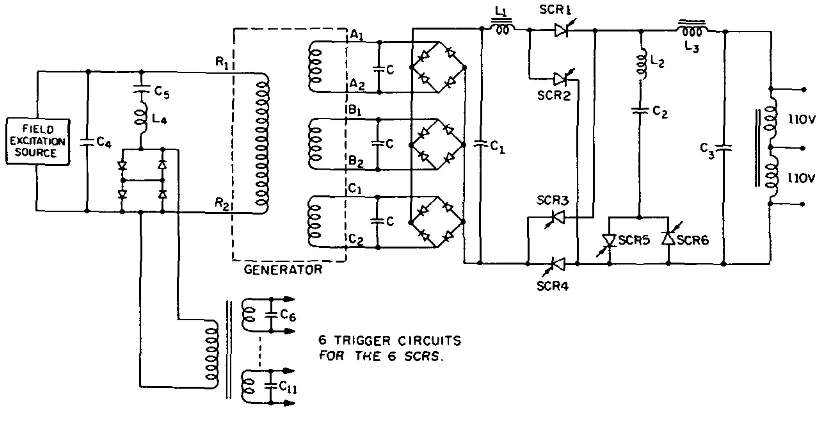

Figure 1. Simplified schematic of the field modulated generator system developed at Oklahoma State University, Stillwater.

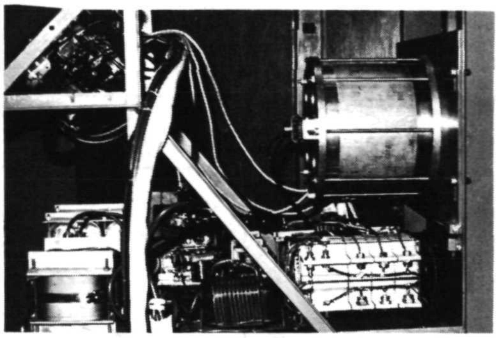

Figure 2. Photograph of the 10 kw generator prototype and the associated electronics (prime-mover not shown).

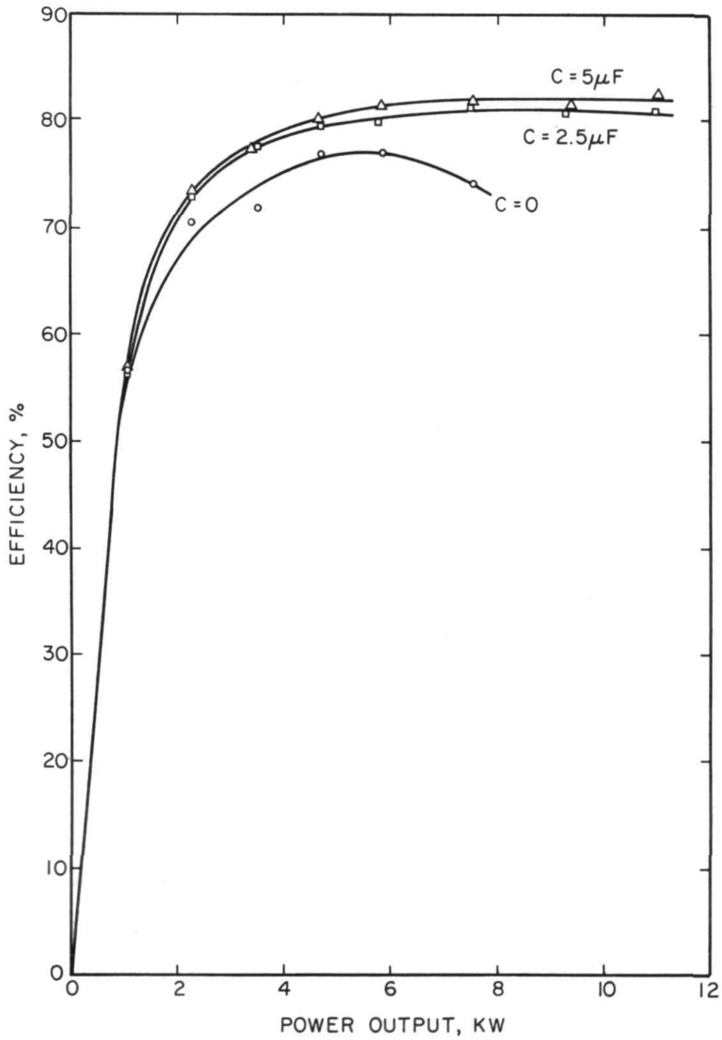

Figure 3. Efficiency versus output characteristic.

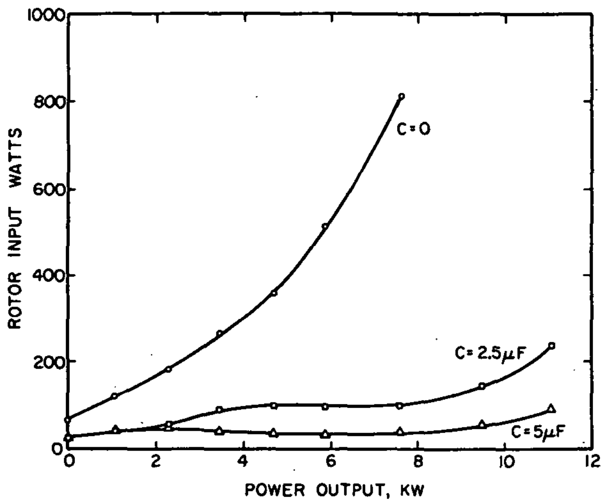

Figure 4. Variation of the rotor input power with output.

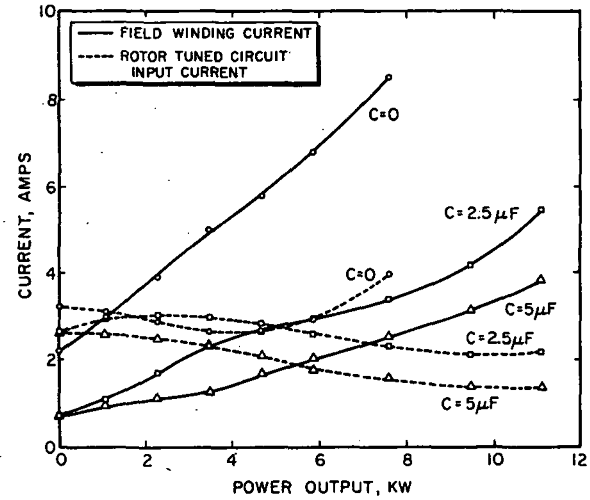

Figure 5. Variation of field winding and rotor circuit input currents with output.

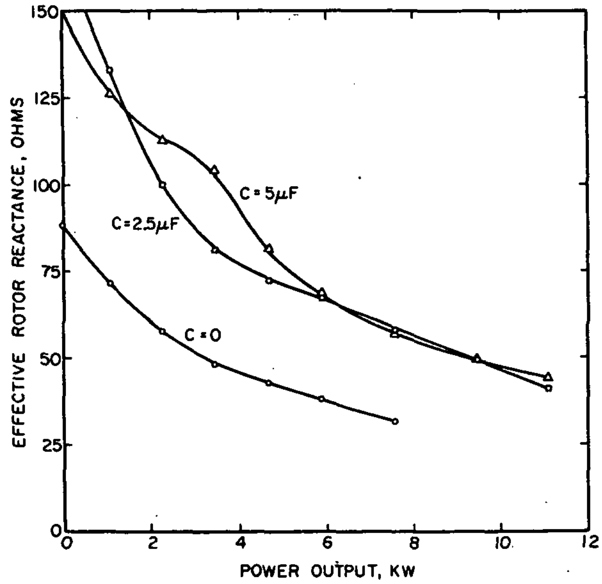

Figure 6. Plot of effective rotor winding reactance for different values of C and output.

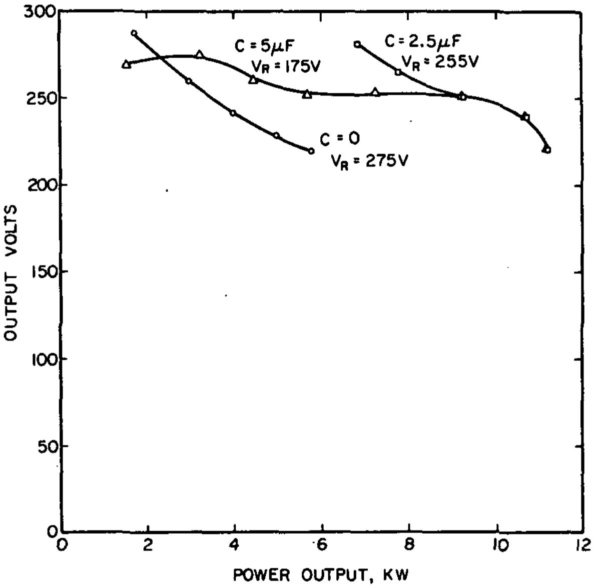

Figure 7. Voltage regulation characteristic of the 10 kw prototype.