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VARIABLE SPEED CONSTANT VOLTAGE CONSTANT FREQUENCY ALTERNATOR

Annual Report

By
W. W. Granneman
P. H. Seo
C. E. Yang

July 1980

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The University of New Mexico
Albuquerque, New Mexico

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ANNUAL REPORT - JULY 1980

W. W. Granneman, PI

P. H. Seo, RA

C. E. Yang, RA

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ANNUAL REPORT

VARIABLE SPEED CONSTANT FREQUENCY CONSTANT VOLTAGE ALTERNATOR

Wayne W. Granneman, PI

Chauming E. Yang, RA

Puay H. Seo, RA

ABSTRACT

A test alternator is operated with digital control of its output frequency for variable shaft speed. Our first machine is a two-pole alternator with power removed through slip rings. The output frequency of the alternator is controlled by rotating the field by stepping through sixteen coils around the rotor. Usually four coils are active at one time. The rotating field in the stationary coils of the stator is controlled by microcircuits. The control circuits are constructed with available low-cost, low-power integrated circuits (ICs).

The test results from the first test alternator indicate the feasibility of using this type of alternator to convert available wind power directly to usable 60 hertz power.

INTRODUCTION

Our purpose has been to construct a test alternator with a microcircuit controlled rotating field, such that the output frequency will remain constant with variable shift speed. This will allow applications to wind machines. The first test alternator consists of sixteen coils spaced around a rotor. The 60 hertz AC power is removed through slip rings on the rotor. Field current is supplied through power amplifiers to sixteen coils. Normally, only four or five coils are active as a result of four or five amplifiers being switched on. The microcircuit control progressively turns on and off the power amplifiers to rotate the field, always keeping the same number of active coils.

Although the concept of rotating the electromagnetic field in variable speed machines is not new [1,2,3], our methods of generating the rotating field with digital logic circuits is. Our first test alternator was constructed by modifying an induction motor, hence cannot be expected to have a high efficiency. However, it is a good machine to test our concepts of a rotating field and digital control circuits. The machine is designed for 117 volts, 60 hertz operation. With the rotating field stationary the machine will produce 60 hertz at 3600 rpm, since under these conditions it operates as an ordinary two-pole alternator.

In the present design the rotating electromagnetic field is produced in the stator windings of the alternator and the rotor is mechanically driven at variable speed by a gasoline engine (our artificial wind propeller). Since a constant output frequency is desired the rotating electromagnetic field of the stator must be rotated in such a way that the relative speed between the stator field and the variable rotor speed must remain constant. If the rotor speed is faster than the speed required to generate 60 hertz under stationary field conditions, then the electromagnetic field of the stator must be rotated in the direction of rotation of the rotor in order to compensate for the excessive rotor speed. Conversely, if the rotor speed is slower than the 60 hertz speed the electromagnetic field of the stator must be rotated in the direction opposite to the direction of rotation of the rotor.

Our digital method of control compares a standard frequency normally 60 hertz to the output frequency of the alternator. The control circuits determine which frequency is higher and sets the direction of rotation of the rotating or circulating field. Then by measuring the difference in crossover times of the alternator output and the standard frequency, the control circuit determines how fast to rotate the rotating field. This correction can be done once every cycle of the lowest of the two frequencies.

The major effort in the first year's work has been on the frequency control. If the alternator is to parallel a main power line, phase and voltage must also be accurately controlled. Further, an automatic connect on disconnect system will be needed to accommodate wind conditions.

Digital Frequency Control System

The purpose of the digital frequency control system is to provide signals to the power amplifiers to keep four or five field coils energized in sequence to give the proper rotation of the alternator field. The digital method is to compare a standard or line frequency with the output frequency of the alternator. The control system senses by calculation the direction the rotating field needs to rotate to correct for the shaft speed, and then sets the direction of rotation of the rotating or circulating field. The positive crossover points are measured and the time difference used to gate the clock pulse train. These pulses are used to set how fast the alternator field rotates. This can be done every cycle of the lowest of the two frequencies.

Alternator Number One

The first alternator was constructed by modifying an induction motor. It serves well as a test machine, but is not highly efficient.

Figure 1 is a diagram of the alternator and associated components. The rotating machine consists of the main alternator, an auxiliary generator, shaft and couplings.

The rotor of the main alternator (Figures 2a and 2b) consists of a pair of armature coils which output the a-c power. Slip rings are provided to collect the a-c power from the armature coils.

Figure 1. Main alternator and the auxiliary generator. Auxiliary generator generates exact frequency corresponding to rotor speed.

Figure 3 illustrates the phase difference conditions the control system works with. If the rotation direction of the shaft is the same as that of the circulating field as shown in Figure 3a, then the shaft frequency, f_s is greater than 60 hertz, the line frequency, f_L . The phase difference is the time from the leading edge of f_L to the leading edge of the output frequency, f_o , which is shown as PD1 in Figure 1. If the direction of rotation of the shaft is opposite to that of the circulating field as shown in Figure 3b, then $f_s < 60$ and the phase difference is the time from the leading edge of f_o to the leading edge of f_L which is shown as PD2 in Figure 1.

The basic principal of the phase control circuit is to measure the phase difference time, PD1 or PD2, then to stop the rotation of the circulating field for a period of time which is proportional to the measured phase difference time.

The stator of the main alternator constitutes a rotating two-pole electromagnet which provides the alternator magnetic field (Figure 4). Eight pairs of coils comprise the stator field windings with one coil in each single energy location. Each coil in each pair is placed diametrically opposite to each other as shown in Figure 5; each coil is connected between the positive DC supply and a power switching transistor amplifier which is part of the alternator control circuit.

Figure 2a. Rotor and armature winding.

Figure 2b. Rotor profile

Phase Difference =
 $\uparrow f_l \sim \uparrow f_o$

Phase Difference =
 $\uparrow f_o \sim \uparrow f_l$

f_l : line frequency
 f_o : output frequency
 f_c : circulating field frequency
 f_s : shaft frequency

$$f_o = f_s - f_c$$

We hope $f_o \approx f_l$

Figure 3. Phase difference

Figure 4. Digital pattern to the switching sequence to provide two-pole rotating magnet.

Figure 5. Stator double diametric winding with switching transistors.

In Figure 5, coil a and coil a' form the pair for two opposite energy locations. When coil a is ON, it creates a two-pole magnetic field. When coil a' is ON, it creates an opposite field. Only one of the coils may be ON at one time. In the alternator stator, four consecutive coils are ON simultaneously, thus creating a stronger magnetic field.

The pattern of the switching sequence is shown in Figure 4. In operation, if the rotor rotates at an excessive speed, the pattern is sequenced in the same direction as rotor rotation to compensate for the excessive speed, and visa versa. As the pattern is sequenced in one direction, the next coil in that direction is turned ON and the last coil ON in the other direction is turned OFF. By the procedure described, a new set of four coils is ON, thus the "poles" of the alternator are rotated.

The auxiliary generator is coupled to the main shaft (Figure 1). It generates the actual mechanical rotational frequency, f_s , of the alternator. Frequency, f_s , is compared with the line frequency, f_L , in the comparing circuit and the difference frequency ($\Delta f = f_L - f_s$) is used in controlling the speed of rotation of the magnetic field. A variety of other sensors may be used for the determination of the frequency, f_s , such as a photovoltaic cell or a magnetic pick-up. However, the auxiliary generator produces a sinusoidal output which may be used with either digital or analog frequency differencing techniques.

The rated 10 horsepower gasoline engine serves as the prime mover of the alternator. In the particular application under consideration, it is used to simulate the wind which will eventually be the source of mechanical power for the generator. The engine has a flexible rpm range from about 800 to 4000 rpm. This range provides suitable simulation of varying wind conditions. The engine is connected to the alternator through standard mechanical couplings and a shaft. The mechanical coupling also includes a pony brake with a 10 inch arm and a spring scale for determining the amount of horsepower being delivered to the alternator by the engine. The determination of rpm for the calculation of brake horsepower is made using a standard tachometer.

The rotation of our circulating field is step-by-step. Each step is 22-1/2 degrees, since we use 16 coils to develop the field for the alternator.

The circulating field direction signal, V, is created by the control circuit. The multiplexer 74157, shown in Figure 6, performs as a phase difference selector. This action determines if the phase difference is PD1 or PD2.

The leading edge of the signal from 1Y will trigger flip flop 1, FF1, OR gate 1 will be enabled after the trigger. Clock 2 (125 K hertz) will go through OR gate 1 to the up count circuit. This starts the measurement of the phase difference.

The leading edge of the signal from 2Y will trigger flip flop 2, FF2, AND gate 1 will be enabled by the trigger. The output of AND gate 1 actuate the disable line, W, which stop the rotation of the circulating field. The output of AND gate 1 will also disable OR gate 1, and enable OR gate 2. Clock 2 pulse will go through OR gate 2 to the count down circuit. This will stop the count up and start the count down until the clear signal is received. After the clear signal both OR gate 1 and 2 will be disabled, but line W will be actuated to enable the circulating field to rotate again. Thus, we use the count up to measure the phase difference and the count down to create the waiting period.

Figure 7 shows the precounter. Its function is to reduce the number of input pulses. After reset AND gate 1 is enabled and AND gate 2 is disabled, pulse will then go through AND gate 1 to the counter. When the final flip flop, Q, goes high then Q goes low, AND gate 1 will be disabled and AND gate 2 will be enabled. The pulses will go directly through to the 0 line. The precounter is not used again until another reset signal is received.

The precounter is adjusted by using the variable N to give an output as shown in Figure 7a, and to prevent the situation shown in Figure 7b. The objective is to approach the zero point slowly.

Three 74193 microcircuits are connected in series to form a 12 bit up-down counter as shown in Figure 8. This up-down counter is used to measure the time period of the phase difference via clock 2, CK2 (125 K hertz). The maximum phase difference time is 1/60 second.

Phase difference selector

Up - down count control

Figure 6

Figure 7. Precounter

Figure 8. Up - down counter

Therefore, 12 bits is enough for our counting, since $125\text{ K}/60 \approx 2\text{ K}$ bits. We use the count up to measure the phase difference time and the count down to measure the circulating field waiting time. Here the

$$\text{Phase difference} = N/125\text{ K} + \text{waiting period},$$

where N is the precounter maximum count. When the counter counts down to zero a borrow signal will clear the whole circuit.

Two symmetrical circuits for measuring the period of f_0 and f_ℓ using clock 1, CK1 are shown in Figure 9. Our explanation will be for the upper circuit, however, the lower circuit works the same way. After the reset signal, ST 41 is received, Q of flip flop 1, FF1, is low. The inputs 1 of AND gate 1, AND gate 2 and the set of flip flop 2 are all low. This sets the Q of flip flop 2 and the input 2 of AND gate 1 to a high level. When the rising edge of f_0 comes, flip flop 1 will be triggered, the high level on D will be stored on Q, so the input 1 of AND gate 1 and the input 1 of AND gate 2 will also be high. At the same time the input, the set input of flip flop 2 is inactive. The clock 1 pulses can go through the gate. The length of this pulse train depends on the length of the period of f_0 .

When the second rising edge of f_0 reaches flip flop 2, it is triggered. The low level of D will be stored on Q, so input 2 of AND gate 1 will be low. AND gate 1 is now disabled, so no pulse will pass through. At the same time input 2 Q of flip flop 2 is high so is the input 2 of AND gate 2. Both input 1 and input 2 of AND gate 2 are high. So the output of AND gate 2 and the input 1 of AND gate 3 are high. This means the circuit has counted the period of f_0 . When the f_ℓ period measuring circuit also gives a high to the input 2 of AND gate 3 the count ready signal is high. This means that both the period of f_0 and f_ℓ have been counted and the circuits are ready for the next process when it comes along.

There are two symmetrical circuits for measuring the periods of f_0 and f_ℓ as shown in Figure 10. In each part there are two 74393 circuits connected in series to form a 16 bit binary counter. When the f_ℓ clock pulses or the f_0 clock pulse arrive, the counters count

Figure 9. f_0 and f_L period measuring control circuit.

Figure 10. Frequency counter for f_L and f_0 .

their respective pulses. When the f_ℓ clock pulses or the f_0 clock pulses stop, the counters will keep their respective number until the clear signal arrives and resets the two 16 bit counters. For $f_\ell = 60$ hertz the counted number is

$$\text{Clock } 1 \times (1/2 f) = 250 \text{ K} \times (1/120) \approx 2 \text{ K} .$$

Therefore, 12 bits is enough for this number. For $f_0 = f_\ell(1 \pm 0.5)$, the clock pulses are less than 4 K, so 12 bits is enough too.

The central control circuit is shown in Figure 11. After ST 41 is active, Q of flip flop 1 is low. Therefore, Q of flip flop 2 is high. Q_a and Q_c of both the upper and lower 74194 are low. All the ST's signals are low except ST 1 and ST 41 which are high. The circuit under these conditions is ready.

Without the update speed control flip flop 1, the count ready signal will become active approximately every 1/60 second. In order to study the updating process, we control the update signal which controls the count ready signal passing from D to Q of flip flop 1. On receiving the update speed signal a high count ready signal is transmitted from D to Q of flip flop 1. Then clock 1 loads the upper 74194. Q_a of the upper 74194 goes high. The high active pulse will shift from Q_a to Q_c of the upper 74194, then to Q_a and then to Q_c of the lower 74194. A shift takes place with every 2 pulses of clock 1. The output pulse of the upper 74194 will go to ST 11 or ST 22 depending on whether DLR is high or low. After the high active pulse reaches Q_c , the ST 41 pulse will reset the whole circuit, and the control circuit is ready for an update process again.

The arithmetic logic units, ALU, and register 1 and register 2 are shown in Figure 12. To analyze their operation we will look at the basic algebra of the system. Our circulating field frequency, f_c , should be proportional to the difference between the line frequency, f_ℓ and the shaft frequency, f_s . We can measure f_ℓ directly from the power line and measure f_s optically or from a small generator on the shaft. We can use the output signal to measure both the frequency difference and the phase difference by the following calculation.

Figure 11. Central control circuit

$$f_0 = f_s - f_c .$$

Ideally,

$$f_0 = f_\ell$$

if

$$\Delta f_{0\ell} = f_\ell - f_0 = f_\ell - f_s + f_c$$

$$f_c - \Delta f_{0\ell} = f_s - f_\ell = f'_c$$

where f'_c is the new circulating frequency.

If

$$\Delta f_{0\ell} \rightarrow 0$$

then

$$f_c = f'_c .$$

We can obtain the new circulating, f'_c , from the old circulating field frequency, f_c , and the frequency difference, $\Delta f_{\ell 0}$.

The 74157 circuit on the left side of Figure 8 is used to control the functions of the arithmetic logic unit, ALU. There are four steps to calculate f'_c , all controlled by the central control circuit in Figure 7.

The steps of the ALU are:

Step 1 $F = \overline{f_\ell - f_0} = \overline{\Delta f_{\ell 0}} \quad A - B$ (F is the output of ALU's)

Step 2 if $DIR = 1$, $F = \overline{(\overline{\Delta f_{\ell 0}} + 1 + f_c)} = \overline{f'_c} \quad A + B + 1$

if $DIR = 0$, $F = \overline{(\overline{\Delta f_{\ell 0}} + f_c)} = \overline{f'_c} \quad A - B$

Step 3 if bit 16(MSB) of $\overline{f'_c}$ is 0, $DIR = 0$

if bit 16(MSB) of $\overline{f_C^T}$ is 1, $DIR = 1$, $F = \overline{\overline{f_C^T}} = f_C'$

Step 4 Reg 1 $\rightarrow$ Reg 2

In Step 1 a Q_a pulse of the upper 74194 goes to line ST 11 and line ST 1 which will create the following functions:

- (a) The output of the 74194 is 0100 (S_0, S_1, S_2, S_3) so the ALU's perform A-B.
- (b) All 74158's select group A inputs, i.e., f_0 and f_ℓ so the output of the ALU's is $\overline{f_\ell - f_0} = \overline{\Delta f_{\ell 0}}$.
- (c) Register 1 latches $\overline{\Delta f_{\ell 0}}$ at the end of the ST 11 pulse, so $\overline{\Delta f_{\ell 0}}$ is stored in register 1.

In Step 2 a Q_b of the upper 74194 goes to the ST 11 or ST 22 line depending on whether D2R is 0 or 1. If D2R is 0 the pulse on ST 11 will start the following functions:

- (a) The ALU's will perform A-B.
- (b) The 74158 selectors will select the group B inputs, so that the outputs of the ALU's is

$$\overline{\text{Reg 1} - \text{Reg 2}} = \overline{\overline{\Delta f_{\ell 0}} - f_C} = \overline{f_C^T}$$

- (c) Register 1 latches $\overline{f_C^T}$ at the end of the ST 11 pulse.
- If D2R is 1, a ST 22 pulse will create the following functions:
- (a) The ALU's perform $A + B + 1$.
 - (b) The 74158 selectors select group B inputs so that the output of the ALU's is

$$\overline{\text{Reg 1} + \text{Reg 2}} = \overline{\overline{\Delta f_{\ell 0}} + f_C + 1} = \overline{f_C^T}$$

- (c) Register 1 latches $\overline{f_C^T}$ at the end of ST 22.

In Step 3 a Q_a pulse of the lower 7194 goes to ST 3 which latches MSB of Reg 1 to DIR. If MSB of Reg 1 is 1, the following functions will be performed:

- (a) If $ST\ 32 = 1$ then $DIR = 1$ for all ALU's. The output of 74158 is 11.11 and the ALU's perform A.
- (b) If all 74158 selectors select group B inputs then the outputs of the ALU's is

$$\overline{\text{Reg 1}} = \overline{f'_C} = f'_C$$

(c) Reg 1 latches f'_C until the end of the pulse on ST 31.

In Step 4 a Q_b of the lower 74194 goes to ST 41 and ST 42 which will create the following functions:

- (a) The new f_C , f'_C , in Reg 1 is stored in Reg 2.
- (b) As f_L and f_O are cleared the period measuring counter resets the control circuit and the center control circuit is reset.

The circulating frequency f_C is converted from digits to pulses in pulse converter. The shift speed of the shift register depends on these pulses. The direction of shift depends on D2R. The 16 output signals from the shift register control our circulating frequency to the power amplifiers. The amplifiers in turn control the coil current through the 16 stator coils.

Design Procedure

In our preliminary design the rotor will contain the rotating field. We plan to reduce the field winding groups from 16 to 8. For this machine we want to maintain the flexibility in the machine design, so we can utilize either 8 or 16 groups. This will allow either 16 or 32 steps per rotation.

Determination of D and L

Figure 13

The ratio of pole arc to pole pitch is assumed to be 0.56.

A pole of circular section or approximately of square section gives an economical field winding design

b = pole arc in meters,

τ = pole pitch in meters,

ℓ_p = length of pole in meters.

If $\frac{\ell_p}{b} \approx 1$, $\ell_p \approx b$,

$$\tau = \frac{\pi D}{p}$$

The armature length L is usually made about 10 percent greater than pole length, ℓ_p , so that

$$L = 1.1 \ell_p = 1.1 b.$$

Assuming $\frac{b}{\tau} = 0.56$, $b = 0.56 \tau$

$$L = 1.1 * 0.56 * \tau = 1.1 * 0.56 * \frac{\pi D}{p} = 1.94 \frac{D}{p}.$$

Suppose we know the output coefficient design factor is given as

$$D^2 L = \frac{1}{C_o} * \frac{KW}{N}$$

Then

$$D^2 L = 1.94 * \frac{D^3}{p}$$

$$D^3 = \frac{D^2 L p}{1.94}$$

$$D = \sqrt[3]{\left(\frac{D^2 L p}{1.94}\right)} = 0.802 \sqrt[3]{D^2 L p}$$

From this and curve available, allow us to determine

$$\begin{aligned} D_s (\text{stator dia.}) &= 6.339 \text{ in.} & L_s (\text{stator length}) &= 6.15 \text{ in.} \\ &= 0.161 \text{ m} & &= 0.1562 \text{ m} \end{aligned}$$

Also using $l_g = 0.2 + 20_s \sqrt{0.97}$, (l_g = air gap length)

$$= 0.517 \text{ mm}$$

$$\equiv 0.02 \text{ in.}$$

Figure 14

For a two-pole single-phase generator the voltage generated in every turn of the armature is given by

$$e = BLV * 10^{-8} \text{ volts/turn .}$$

If the armature has N_a turns/phase then the voltage/phase is given by, i.e., $E = 117\sqrt{2}$,

$$E = N_a BLV * 10^{-8} \text{ volt .}$$

From the above diagram we have

$$\begin{aligned} v &= \left(\frac{R_{so} + R_{si}}{2} \right) \omega \\ &= 2\pi * 60 (3.68) \\ &= 1387.74 . \end{aligned}$$

Here we have,

$$NaB = \frac{117\sqrt{2} * 10^8}{1387.74 * 6.15 \text{ in.}}$$

$$NaB \equiv 1938.731 \text{ K line/inches .}$$

If

$$B \equiv 25 \text{ K line/in.}^2 \text{ (from table)}$$

$$\equiv 0.385/\text{m}^2 ,$$

then the specific magnetic loading is

$$B = \frac{2p \phi_m}{\pi DL} \text{ webers/m}^2$$

$$\phi_m = \frac{0.385 * \pi * 0.161 * 0.159}{4} \equiv 7.741 * 10^{-3} \text{ wb .}$$

The number of turns per phase (armature winding)

$$\begin{aligned} T_{ph} &= \frac{V}{4.44 * Kw * f * \phi_m} \\ &\equiv \frac{117\sqrt{2}}{4.44 * 60 * 7.741 * 10^{-3}} \\ &\equiv 80.240 . \end{aligned}$$

So if we choose $Na = T_{ph} = 90$

$$B \equiv \frac{1938.731}{90} = 21.54 \text{ K line/in.}^2$$

Pole Pieces

To maintain the constant voltage output, we need to have flux density $B = 21.54 \text{ K line/in.}^2$.

For good design, say we consider core loss and fringing effect, it is good to approximate

$$B = 32.468 \text{ K line/in.}^2$$

Since we assumed that the magnetic reluctances are primarily due to the air gap, ℓ_g , the flux density can be obtained from

$$B = \frac{N_p I}{\ell_g} \mu_0 .$$

Using $B = 32.47 \text{ K line/in.}^2$, the total ampere-turn of the pole pair is

$$\begin{aligned} N_p I &\equiv \frac{B \ell_g}{\mu_0} \\ &\equiv \frac{32.47 * 10^3 * 10^{-8} \text{ weber/in.}^2 * 0.02 \text{ in.}}{4\pi * 2.54 * 10^{-9}} \\ &\equiv 203.440 . \end{aligned}$$

For good design, we can make it as

$$N_p I \equiv 250 \text{ amp-turns} .$$

Now consider the rotor to have 32 slots. So we can have 16 coils to cover a single layer. We also want to consider parallel two coils to form a group. If we use four groups to form the pole pair then,

$$\begin{aligned} \therefore 4 * 2 N_{\text{coil}} I &= 250 \\ N_{\text{coil}} I &\equiv 31.25 . \end{aligned}$$

If we assume the current in each coil carries one ampere. We have 32 turns for each coil. This design can be changed to optimize the inductance of the coil.

Since we are using the M19 lamination for the machine stator and rotor, we know that the information data of the sectional area of rotor $\equiv 116.2 \text{ mm}^2$.

Taking into consideration for insulation, we allow area for

$$\begin{aligned}
 \text{wire in slot} &\equiv 0.75 * 116.2 \text{ mm}^2 \\
 &\equiv 87.15 \text{ mm}^2 \\
 &\equiv 0.135 \text{ in.}^2
 \end{aligned}$$

$$\therefore \text{wire size} = \frac{0.135}{32} = 4.218 * 10^{-3} \text{ sq in.}^2$$

Choose AWG #14 wire, gives 0.003122 r/ft at 80°C for AWG #14.

Similarly, the sectional area of stator slots = 244.3 mm^2

$$\begin{aligned}
 \therefore \text{allowable area for wire in slot} &= 0.75 * 244.3 \text{ mm}^2 \\
 &= 183.23 \text{ mm}^2 \\
 &\equiv 0.284 \text{ in.}^2
 \end{aligned}$$

$$\text{No. of conductor/phase} = 90 * 2$$

$$\text{No. of conductors/phase/slot} = \frac{90 * 2}{6} = 30$$

$$\text{Wire size} = \frac{0.284}{30} = 9.47 * 10^{-3} \text{ in.}^2$$

Choose AWG #10; 0.001235 r/ft at 80°C.

Approximate consideration of efficiency

- (a) Stator copper losses $W_a = 3 I_a^2 R_a$
- (b) Field winding copper loss $W_f = I_f^2 R_f$
- (c) Iron losses of the core materials $W_i = W_h + W_e$
- (d) Mechanical losses W_m (bearing, friction and windage)
- (e) Stray load losses $W_c \rightarrow$ by virtue of the eddy current effect in the copper conductors due to the varying fluxes in the system

Computation

$$(a) \text{ Full load current } I_a = \frac{10,000}{117 * 3} = 28.49 \text{ A}$$

Suppose we choose AWG #10

$$\begin{aligned}
 \text{Mean length of coil} &\equiv 12.68 + 2 * 1.25 \text{ (7.36 in.)} \\
 &= 31.08 \text{ in.}
 \end{aligned}$$

$$\begin{aligned}
 \text{Total length of wire/phase} &\equiv 90 * 31.08 \text{ in.} \\
 &= 2797.20
 \end{aligned}$$

$$R_a \equiv 0.001235 \text{ ohm/ft} * \frac{2797.20}{12}$$

$$\equiv 0.2879 \text{ r}$$

$$W_a = 3 * I_a^2 R_a$$

$$= 3 * (28.49)^2 * 0.2879$$

$$= 701.00 \text{ watts}$$

- (b) Since we had presumed each coil carries one ampere. On the contrary, we want to allow for maximum losses in the field winding. Let us suppose we allow 2 ampere in each coil to maintain a sufficient ampere turn for the field coils. But in one group there are two coils, thus a group carries 4 amperes. Hence, we need to supply 16 amperes to the field poles which consist of 4 groups.

$$\text{Mean length of wire} = 11.132 + 2 * 1.25 (5.35)$$

$$\equiv 24.22 \text{ in.}$$

$$\text{Total length for a coil} \equiv 32 * 24.22$$

$$\equiv 775.04 \text{ in.}$$

$$\text{Resistance/coil} \equiv \frac{775.04}{12} * 0.003122$$

$$\equiv 0.202$$

$$\text{Resistance for field poles, } R_f \equiv 1.82 \text{ r}$$

$$W_f = J_f^2 * R_f$$

$$= 16^2 * 1.82 \equiv 465.92 \text{ watts}$$

- (c) Iron loss $W_i \equiv W_h + W_e$

$$W_h = K_h B^{1.6} f \text{ watts/kgm.}$$

Assume the material is ordinary dynamo steel, $K_h \equiv 0.065$

$$W_h \equiv 0.065 * (0.42)^{1.6} * 60$$

$$\equiv 0.97 \text{ watts/kgm}$$

$$W_e \equiv k_e B^2 f^2 t^2 \text{ watts/kgm}$$

$$K_e = 1750. \text{ for ordinary sheet steel}$$

$$t \equiv \text{thickness of lamination} \equiv \left(\frac{0.5}{10^3}\right) \text{ m}$$

$$W_e = 1750 * (0.42)^2 * (60)^2 \left(\frac{0.5}{10^3}\right)^2$$

$$\equiv 0.279 \text{ watts/kgm}$$

$$\text{Vol. of core material} \equiv \pi * D * A \text{ (sectional area)}$$

$$\equiv \pi * 0.161 * 0.015$$

$$\equiv 0.0078$$

Assuming density of material is $D = 7.8 \text{ gm/cm}$

$$\text{Wt of armature core} \equiv \frac{7.8 * 10^6}{10^3} * 0.0078$$

$$\equiv 60.6 \text{ kgm}$$

$$\text{Total iron loss } W_i = (0.97 + 0.279) * 35.53$$

$$\equiv 75.72 \text{ watts}$$

(d) Mechanical losses

$$W_b = K_b f_b P_b A_b V_e \text{ watts}$$

$$K_b = 981 * 10^{-5}$$

$$f_b = 0.25$$

$$P_b = 150 \text{ gm/cm}^2$$

$$V_c = \text{velo. metr/sec} \rightarrow 9.58 \text{ m/sec}$$

$$A_b = \text{total area of contact of all brushes}$$

$$\equiv 16 * (\pi * 2 \text{ in.} * 1/4 \text{ in.}) * 2.54^2 \equiv 162.15 \text{ sq. cm}^2$$

$$W_b = 981 * 10^{-5} * 0.25 * 150 * 9.58 * 162.15$$

$$\equiv 571.24 \text{ watts}$$

(e) Allow 50 watts for stray losses

$$\text{Efficiency} \equiv \frac{\text{output}}{\text{output} + \text{losses}}$$

$$\approx \frac{5000}{5000 + \text{losses}}$$

$$\approx 84.3\%$$

In considering eight group coils instead of sixteen group coils field excitation, the power transistors circuitry has to be remodified. Our concept is to have each coil group in the following switching system. The principle operation is when signal A from buffer amplifier will give the coil polarity as shown in Figure 15. Whereas for signal B it will reverse the polarity.

In Figure 16 is the circuit diagram. Only when transistors ECG 5507 and ECG 283 receive the signal from the pattern generator then it will turn on. In turn, transistors ECG 252 and ECG 181 are turned on. Thus, maintaining a potential across the coil.

Preliminary Theoretical Consideration for the Alternator Number 2

Let us analyse the switching effect of the field coils. On assumption that we only have four coils for the field, the switching pulse waveform is

Figure 17. Switching pulse

Figure 15. Switching Block Diagram

Figure 16. Switching circuit

Figure 18 Switching circuit

From the above figure, we can use fourier series to represent $V(\alpha)$ as

$$V(\alpha) = B_0 + \sum_{h=1}^{h=\infty} A_n \sin n \alpha + \sum_{n=1}^{n=\infty} B_n \cos n \alpha ,$$

$$B_0 = \frac{1}{2\pi} \int_0^{2\pi} V(\alpha) d\alpha = \frac{1}{2\pi} \left\{ \int_0^{\pi/2} V_s d\alpha - \int_{\pi}^{3\pi/2} V_s d\alpha \right\} = 0$$

$$A_n = \frac{2}{2\pi} \int_0^{2\pi} V(\alpha) \sin n \alpha d\alpha$$

$$= \frac{1}{\pi} \left[\int_0^{\pi/2} V_s \sin n \alpha d\alpha - \int_{\pi}^{3\pi/2} V_s \sin n \alpha d\alpha \right]$$

$$= \frac{V_s}{\pi} \left[\left. \frac{-\cos n \alpha}{n} \right|_0^{\pi/2} - \left\{ \left. \frac{-\cos n \alpha}{n} \right|_{\pi}^{3\pi/2} \right\} \right]$$

$$n \neq 0, n = 1, 2 = \frac{V_s}{\pi} \left[\frac{1}{n} - \left(\frac{\cos n \pi}{n} \right) \right]$$

$$\left. \begin{aligned} A_n &= \frac{2V_s}{\pi n} & n &= \text{odd} \\ &= 0 & n &= \text{even} \end{aligned} \right\}$$

Similarly,

$$B_n = \frac{V_s}{\pi} \left[\int_0^{\pi/2} \cos n \alpha \, d\alpha - \int_{\pi}^{3\pi/2} \cos n \alpha \, d\alpha \right]$$

$$= \frac{V_s}{\pi} \left[\left. \frac{\sin n \alpha}{n} \right|_0^{\pi/2} - \left\{ \left. \frac{\sin n \alpha}{n} \right|_{\pi}^{3\pi/2} \right\} \right]$$

$$= \frac{V_s}{\pi} \left[\frac{1}{n} - \frac{\sin \frac{3\pi n}{2}}{n} \right]$$

$$B_n = 0 \quad n = \text{even}$$

$$= \frac{2V_s}{n\pi} \quad n = 1, 5, 9, 13$$

$$= \frac{-2V_s}{n\pi} \quad n = 3, 7, 11, 15$$

Thus, we can represent $V(\alpha)$

$$V(\alpha) = \sum_{n=\text{odd}}^{\infty} \frac{2V_s}{\pi n} \sin n \alpha + \sum_{\substack{\text{odd} \\ n=1,5,9}}^{\infty} \frac{2V_s}{n\pi} \cos n \pi + \sum_{\substack{\text{odd} \\ n=3,7,11}}^{\infty} \frac{-2V_s}{n\pi} \cos \pi n$$

Similarly, for each of the four coils in the field can be written for displacement of $22\frac{1}{2}^\circ$ from the adjacent coil.

A computer program can be used to analyze the resultant waveform. Further study can be done regarding the variation of V_s with switching frequency Δf .

If we consider the inductances, self-inductances can be defined as flux linkages per ampere. Whereas, mutual inductance refers to the flux produced by one current and linking the other circuit. Thus, both the stator inductance (say, L_1) and the rotor inductance (L_2) can be seen to be a function of θ . They have maximum values at $\theta = 0$ or $\theta = 180^\circ$, and minimum values at $\theta = \pm 90^\circ$.

In Figure 19(a), when $\theta = 0$, the mutual inductance has its maximum value but, at $\theta = 180^\circ$, the lines of flux produced by one current

link the other winding "from the other side"; in other words, the sign of M is reversed.

Figure 19(b) shows that, for $\theta = 90^\circ$, the flux produced by the rotor current does not link the stator winding at all and vice versa, i.e., $M = 0$.

Figure 19. Flux produced by rotor current.

In Figure 20 is a sketch of the inductances as a function of θ . For our machine, with nonsalient poles on both stator and rotor, the self-inductances are constant. Whereas the mutual inductance is still a function of θ .

Consequently, the self-inductance for each phase of armature winding is

Figure 20. Inductances as a function of θ .

$$M_{af} = M \cos \omega_s t$$

$$M_{bf} = M \cos(\omega_s t - 120^\circ)$$

$$M_{cf} = M \cos(\omega_s t + 120^\circ)$$

Perhaps we can simulate the resultant field by the individual coils as

- (a) Calculate the field produced by a single coil carrying a direct current, and resolve it into a series of harmonic components.
- (b) Replace the direct current by an alternating one, causing all the harmonic components of the field to pulsate sinusoidally.
- (c) Resolve each pulsating harmonic component into two equal, constant, oppositely-revolving fields.
- (d) Add vectorially the similar harmonic fields produced by the adjacent series-connected coils in the same phase.
- (e) Add vectorially the separate harmonic fields produced by the different phases.

Later with the element parameters appropriated we can model the equivalent circuit as in Figure 21.

Figure 21. Equivalent circuit

Laboratory Results

The alternator tests which have been completed include the following:

1. Determination of machine characteristics in various configurations.
2. Static (non-rotating field) testing of the alternator in various configurations. Also static efficiency test.
3. Verification of the concept that a digitally controlled notational field can compensate for variable speeds of mechanical rotation.
4. Dynamic tests:
 - (a) Variation of rotor speeds (rpm), the output maintaining at 60 hertz.
 - (b) Indicating machine is like induction type.

Laboratory tests were conducted to determine the input-output characteristics of the prototype in configuration using 1,2,...,7 field coil sets. Table 1 summarizes the results of the tests at the designed field current of one ampere per coil set.

The alternator was initially designed to produce 117 volts (rms) at 60 hertz using four field coil sets with a total field current of four amperes. The prototype in design configuration produce 120 volts (rms). However, the waveform produced in the five coil sets configuration is better than any other configuration.

Table 1

I-0 Characteristics at One Ampere Field Current per Coil Set

	Field Coil Set Configuration (No. of Coils)						
	1	2	3	4	5	6	7
Total Field Current (amps, dc)	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Field Voltage (volts, dc)	0.64	0.65	0.63	0.64	0.63	0.67	0.66
Open Circuit/Output Current (amps, ac)	36	68	95	120	140	142	145
Short Circuit/Output Current (amps, ac)	0.5	0.95	1.23	1.53	1.79	1.96	2.10
Input Impedance (ohms)	0.64	0.32	0.21	0.16	0.13	0.11	0.11
Output Impedance (ohms)	72.0	71.6	77.2	78.4	78.2	72.4	69.05

Tests were conducted in the static or non-rotating field condition to determine the efficiency and load capacity of the alternator for this first prototype, the average efficiency for the static case was determined to be 47 percent. The load capacity of the alternator was approximately 1.5 kW in the static case.

Manually dynamic tests of the machine was executed to verify that a digitally controlled rotational field can control the output frequency of the alternator. Then by varying the rotor speeds and with control to maintain at 60 hertz the efficiencies test on each variation speeds were executed. The experiment indicates that at higher rotor speed (i.e., higher mechanical input) give greater efficiency. Results show that a difference of 135 percent efficiency is obtained from 2700 to 4000 rpm. Also, different combinations of performance have indicated a 6-coil set will give the optimum output.

An experiment is the comparison of efficiencies at 50 hertz output for varying rotor frequencies below and above 50 hertz. Then

compare it with the stator field at stationary and rotor speed at 50 hertz. The results are tabulated below.

Indicating the machine is acting like induction type. There is a slip loss when running with the controlled rotational field.

<u>Rotor frequency</u>	<u>Efficiency</u>
43.4	39.05
50.0	46.65
57.14	37.4

This characteristic may change with the change in torque angle of the alternator. The frequency control can change this angle.

The results from the bench tests of the logic control circuit indicate that the circuit works as described under the previous heading, Digital Frequency Control System. It was found that it was necessary to slow down this system on start up to prevent some instability in the alternator-frequency control system combination. This problem appears to be solved, and tests on the combined systems are continuing.

References

1. U.S. Patent No. 3,454,864, July 8, 1969, J. F. Roesel, Jr., "Electric Power Generator for Generating Power of a Predetermined Frequency, Magnitude, and Wave Form."
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3. U.S. Patent No. 3,483,463, Dec. 9, 1969, O. J. Smith, "System and Method for Alternating Current Machines and Apparatus Therefore."