Description of

High Frequency Magnetic Link Brushless Excitation System for Synchronous Machine.

By Alex Faveluke, Oregon State University
09/20/95

Principles of Conventional Synchronous Machines

Synchronous electrical machines are used as generators and motors in many applications. Synchronous machines operate on the principle of Faraday's Law. Faraday's law states that a voltage is induced around a path if this path encloses a changing magnetic field. In the operation of most synchronous machines, magnetic flux is created by passing current through a "field winding" that electromagnetically creates two or more "poles" on the machine "rotor." Magnetic flux emanates from these poles. This rotor is rotated within a "stator" which holds coils of wire called the "stator winding" or "AC winding." When the rotor is turned the direction and amount of flux at any fixed location changes. The stator winding coils, being fixed, encircle changing flux, and by Faraday's law, electrical voltage is magnetically induced in these coils. AC power may be taken from these coils. In practical machines, iron is used to help focus and increase the amount of magnetic flux to useful levels.

Function of Brushes in Conventional Synchronous Machines

Small synchronous electrical machines today rely on sliding electrical contacts between brushes on the stator and slip rings on the rotor to transmit power to the rotor field windings.

Problems Created by the Use of Brushes

This brush and slip ring electrical contact is undesirable for many reasons. First, brushes wear down and must be replaced periodically on machines in medium to continuous duty use, causing down time and maintenance expense. The brush/slip ring contact is prone to contamination; grease, oil, or dust can cause the contact to fail, causing loss of power. The sliding electrical contact often sparks, rendering these machines unfit for service in explosive or hazardous environments.

Description of Invention

The High Frequency Magnetic Link Brushless Excitation System provides a way to transmit power to synchronous machine rotor field windings without using any sliding electrical contacts. The invention consists of a high frequency switching power converter and a small transformer, wound in a commercially available ferrite part called a "pot core." One half of the

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pot core is attached to the stator, and does not rotate, while the other half is attached to the rotor and rotates with the machine shaft. The halves are centered and aligned with each other on a non-magnetic shaft (the prototype uses Delrin * ,) and separated by a thin disc of Teflon * or other non-conductive plain bearing material (see Figure 1.) The "primary winding" is the power input winding to the transformer and is wound in the stator attached pot core half. The "secondary winding" is the power output winding and is wound in the rotor attached pot core half. The power converter changes electricity from a direct current source (such as a battery) to high frequency alternating electrical current suitable for input into the transformer primary winding. A rectifier circuit is mounted on the rotor, and converts the high frequency electrical power from the transformer secondary winding into DC electrical current which flows in the rotor mounted field winding. The only means of energy transfer to the rotor is by the alternating magnetic field in this transformer, this is why the system uses no brushes or slip rings. Generator regulation is readily availiable by pulse width modulating the high frequency alternating current to the transformer primary.
(See Figure 2 for electrical overview.)

<u>Brushless Systems in Use Today</u>

There are several alternatives available to a conventional brush fed field synchronous machine.

First, wherever possible, induction machines are used. Induction machines operate by inducing currents in short circuited rotor windings or heavy bars. Induction machines are especially suitable for use as motors. As generators, they must be connected to an existing outside alternating current system to create power, and the shaft must be driven past a certain speed, depending on the outside system.

Rotor mounted permanent magnets are used to create the field in some synchronous machines. This is the technique used in small, high performance motors called "brushless DC servomotors." Permanent magnet machines can be used for generator systems, but have the serious disadvantage of a non-controllable field. This means that the output voltage is dependant on the shaft speed, and there is no way to regulate the output voltage in a machine that must run at different speeds (such as an automobile alternator or a generator for use with wind applications.)

The Brushless Doubly Fed Machine being worked on here at Oregon State University is somewhat of a cross between an induction and a synchronous machine. In it there is an auxiliary stator winding called the "control winding" that is fed with a variable frequency power converter. Control of the Brushless Doubly Fed Machine requires relation of the main power winding electrical frequency, the control winding frequency and the shaft speed.

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All power to the rotor field is magnetically coupled to the control and power stator windings.

Large synchronous machines often use a "brushless exciter system" that is based around an auxiliary generator mounted on the machine shaft. The field for this auxiliary generator is created from stationary poles with DC windings. The current from the armature winding of this auxiliary generator is rectified by a shaft mounted diode bridge and is passed to the field windings of the main machine. The output voltage of the main machine is controlled by changing the amount of current in the auxiliary generator field poles, thus changing its output voltage and how much current it delivers to the main machine field.

How the High Frequency Magnetic Link Brushless Excitation System Differs From the Above Brushless Solutions

Induction Machine:

This High Frequency Magnetic Link Brushless Excitation System concerns excitation for synchronous machines. The field power is transmitted to the rotor magnetically, but it is done in an auxiliary, high frequency, axial mounted transformer. In an induction machine, the field is set up by the stator currents generating flux, which induces current directly into the field coils or bars. In the invention, the field is independently controlled from the main power winding. This makes it much more suitable as a generator because the main power winding does not have to be connected to a pre-existing alternating current system to generate power.

Permanent Magnet Machine:

The invention allows control over the level of field magnetization. The invention drives a conventional synchronous machine with an electrical winding to supply adjustable field magnetization. Permanent Magnet Machines have a fixed field excitation.

Brushless Doubly Fed Machine:

The invention uses an auxiliary, axial mounted transformer with high frequency currents. The energy transmission through this transformer is not dependant on the shaft speed of the machine. The invention is basically a direct drop-in replacement for the conventional synchronous machine slip rings and brushes system. The Brushless Doubly Fed Machine does not contain an axial mounted transformer; all power is induced to the rotor from stator mounted windings. The Brushless Doubly Fed Machine must have a frequency controlled inverter to drive the control

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winding. There is no need for accurate frequency and timing control in the High Frequency Magnetic Link system.

Large Generator Brushless Exciter Systems

The invention uses an axial mounted transformer with high frequency currents. The brushless exciter systems in present use an auxiliary generator, with stationary, stator mounted field poles. These systems are designed for operation at a set speed as the excitation is dependant on shaft speed. The invention gives complete control over the field current over the full speed range of the machine.

Construction Of The Prototype

This system was prototyped and tested using a modified automotive alternator. This alternator was a rebuilt machine sold as a replacement part for a 1976 Dodge truck with a 318 cubic inch engine.

The stator circuits and windings were not modified. The stator circuit of this alternator consists of a three phase winding and a three phase diode bridge. The rotor field coil and the rotor pole structure were also left unmodified. (See Figure 2.)

The stator mounted brushes were removed. The rotor mounted slip ring assembly was also completely removed. Two Schottky diodes were glued to the rotor fan using an epoxy resin based glue. (See Photograph 6.)

A hole was cut in the axial back of the case of the bearing running on the back end of the main shaft to pass the pot core mounting shaft and connecting wires.

A 1/4" diameter hole was drilled axially in the back of the alternator shaft to attach the pot core mounting shaft. This was done on a drill press, using the existing small hole in the shaft as the starting center. (See Photographs 6 and 5.)

Two 1/8" diameter holes were drilled on either side of the centered 1/4" diameter hole. Holes were drilled radially in the shaft to meet these and form passages for the transformer secondary wiring. (See Photograph 6.)

The transformer windings were wound first around half a standard bobbin mounted on a bolt held in a vice. While thus wound, they were saturated in catalyzed (mixed, hardening) epoxy resin. While the resin was firm but not brittle, they were separated from the bobbin and bolt, and fit to the ferrite core halves. This assembly was then filled with catalyzed epoxy resin and clamped gently with wax paper, cardboard and a smooth metal plate

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to ensure the windings did not protrude beyond the face of the core halves. After the epoxy had hardened, the core faces were cut down a small amount with a progression of fine sand papers to remove any unwanted build up of the epoxy. On the primary core, the winding is 20 turns of 17 strands #35, with center tap. On the secondary core, the winding is 40 turns of 8 strands #35. The stranding was to improve high frequency performance, and will probably not be necessary.

To make the pot core mounting shaft, a section of 1/4" diameter Delrin rod was chucked into a drill press and cut down with a file to fit the transformer halves center holes. The section which the primary rotates about was cut down for a slip fit to the pot core center hole, while the section on to which the secondary is pressed was left a few thousandths larger. A washer shaped disk was cut from .011" thick Teflon sheet to form a separator between the two transformer core halves. (See Photograph 4.)

Three mounting holes were drilled and tapped for a #4-40 screw in the back of the alternator frame. These were to mount the three stand-offs that support the spring attachment assembly. (See Photograph 3 for spring attachment location.)

The transformer halves were fitted to the pot core mounting shaft. The secondary half was hooked to wires running to the field winding and rectifier bridge. The connections to these wires were secured with epoxy resin between the secondary core half and the alternator frame. (See Photograph 4.)

The spring attachment assembly was made from a small triangular piece of .065" thick aluminum plate. Three 1/8" inch holes were drilled to fit #4-40 screws for attachment to the stand offs projecting from the alternator frame. A 1/4" x 20 threaded hole was drilled and tapped in the center of this plate, into which was screwed a 1/4 x 20 screw. A small bushing cut from Delrin rod was cut to closely fit the steel spring that was used to gently hold the core halves together. An additional small bushing was pressed over one of the standoffs to loosely key into the primary transformer half unused wire outlet to prevent rotation. (See Photograph 3. Rotational restriction bushing is not visible. See Figure 5 for axial view of pot core half, and location of "retainer rod" to restrict rotational movement.)

The power converter/regulator was built on to a small piece of prototyping "pad per hole" board. This was firmly mounted to a small heat sink, which was screwed to the alternator frame. Wires were run to the transformer and to the alternator ground (frame) and power connections. (See Figure 3.)

For operational testing the machine was bolted into a test rig and coupled by a V-belt to a DC motor as a drive. A 12 volt battery is connected, with a current meter in series and a volt meter across the terminals. The machine has been run up around

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2500 RPM. In the prototype, voltage output was set to 13.9-14V, which was demonstrated holding constant with fluctuation of shaft speed. (See Photograph 1.)

Alternative Methods of Construction

In mass production, the spring mounting supporting the primary side transformer half would be die cast into the machine housing. Shafts could be made in an automatic screw machine, and separator discs could be punched from sheet stock. It would also be interesting to explore the possibility of just Teflon coating the bearing face of one of the pot core halves.

For a larger, more powerful machine, a small ball or roller bearing may be used instead of the plastic positioning shaft and thrust washer combination. This bearing would have to provide both radial and thrust positioning, but would only have to support a very light load. It would turn about a small brass or bronze shaft pressed into the machine main shaft. (See Figures 5 and 6.)

Advantages Over Present Practice

The main advantage offered by the invention over present practice is the elimination of brushes and slip rings with the preservation of conventional brushed synchronous machine features such as voltage regulation and ease of power generation. The elimination of brushes will allow use of the controllable field machine in previously "off limit" areas such as explosive or dirty environments, and in applications where brush service and replacement is prohibitively costly. Another potential advantage comes from the fact that because a transformer is used, the availiable voltage for the field coil is not limited to the system voltage. This may allow machine designers to build more efficient or cheaper machines by optimization of the field voltage. In addition, this excitation system may cost less to manufacture than the conventional brush and slip ring system. All the alignment critical machine work is done axially to the shaft, and can be accomplished by one inexpensive shaft press fit to a hole that is already partially drilled in the present version of most machines.

* Note: Delrin and Teflon are trademarks of DuPont.

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Potential Manufacturers

Kohler Power Systems (generator manufacturer)
Kohler, WI, 53044

Marathon Electric (motor, generator, and drive manufacturer)
PO Box 8003
Wausau, WI 54402-8003

Baylor Generator/Motor Group (brushless generators)
Sugar Land, TX 77478

General Electric (generators, motors, and controls)
3135 Easton TPKE
Fairfield, CT 06431

GM AC-Delco (automotive electronics)
3031 W. Grand Blvd.
Detroit, MI 48202

Electric Power Conditioning (may be interested in building a wind generator)
1895 NW 9th
Corvallis, OR 97330

Sure Power Industries (automotive/truck electronics)
10189 SW Avery
Tualatin, OR 97006

Zman Magnetics (custom transformers and magnetic components)
1600 NW 167th Place
Beaverton, OR 97006

There are hundreds of companies building generators and power systems. Any one of these could possibly be interested in manufacturing or using the brushless excitation system in their machines.

Commercial possibilities include the use of the system in wind power systems, emergency generators, marine generators, submerged generators, high performance motors, generators and alternators for explosive environments (such as needed in fire trucks or mining equipment,) automobile and truck alternators, as well as many other applications.

Price range depends on the method of implementation. The electronics for the prototype system (an alternator) cost around $13 retail, which is also about the retail price for a conventional regulator that is replaced by the system. I have not looked at cost issues beyond this. I believe that in some systems the market would be willing to pay a premium to gain the benefits of brushless excitation.

Quantity depends on the application. A small wind system for battery charging might draw orders of a couple thousand a year. If the large automobile manufacturing companies decide to use this system, they could eventually be building millions.

Introduction to Figures

All figures are photocopies from my notebook, with the exception of the circuit schematic. I have a hand drawn version of this schematic on page 49 of my notebook, dated 09/11/95.

All photographs are of the proof-of-concept prototype system first demonstrated 09/11/95. These photographs were taken on 09/18/95 and received and annotated on 09/19/95. The prototype was disassembled in the process of taking the pictures. I reassembled the system to demonstrate its operation for Dr. Alan Wallace on 09/19/95.

Figure 1: Copy of notebook page 32. This is a basic drawing showing the arrangement of the transformer.

Figure 2: Copy of notebook page 48. This is a good basic explanation of the electrical operation of the system. On the bottom of this page are some inconsequential notes to myself about an air hose for the lab.

Figure 3: Schematic of control and power electronic circuit. A full description of the LM3525 can be found in National Semiconductor's 1989 General Purpose Linear Devices Databook. I can supply a photocopy of the pertinent information.

Figure 4: Copy of notebook page 35. This is a conceptual drawing of the transformer centered around a shaft pressed into the main machine shaft. This provides an easy and cheap method for axial transformer alignment and mounting and was implemented in the prototype system.

Figure 5: Copy of notebook page 41. This is a drawing of how a large machine may use an auxiliary bearing to line up the transformer. It also shows one possible method of constructing this system as a "bolt on" modification to an existing synchronous machine.

Figure 6: Copy of notebook page 51. It shows an alternate method of attaching the primary pot core half to an auxiliary bearing. Also notes the problem of axial location, which is solvable but does create a few additional steps in manufacturing. One possible method of accurately locating these pot core halves axially on the shaft would be to machine the mounting shaft to have a step in the diameter for the bearing and for the secondary pot core half.

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FIGURE 1

CONCEPTUAL DRAWING

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THIS IS BASICALLY A COPY OF A DRAWING FROM 6/15/95. I HAVE THE ORIGINAL DRAWING IN MY FILES UNDER "BRUSHLESS SYNCRO"

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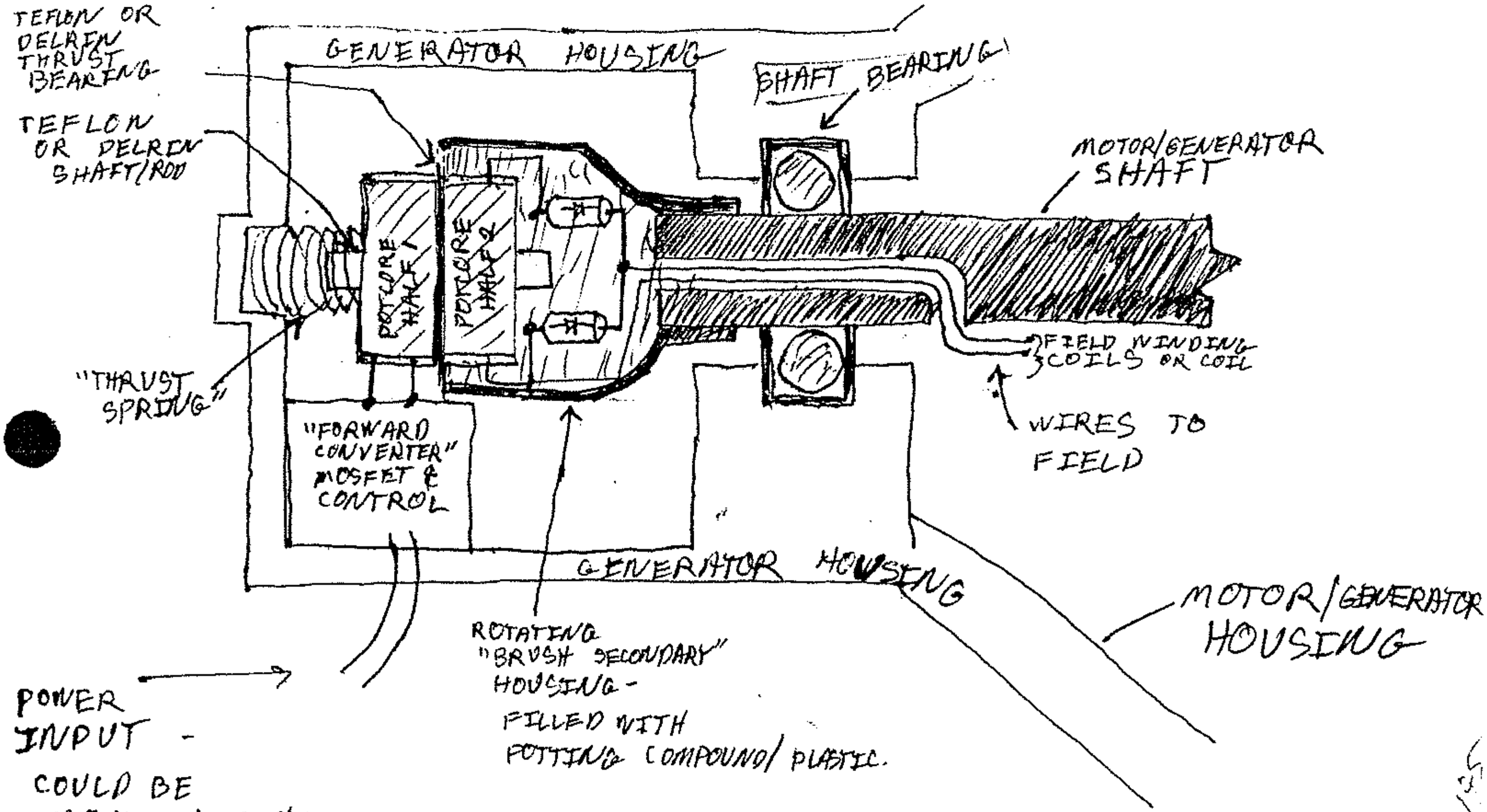
REPLACES CONVENTIONAL BRUSHES/SLIPRINGS WITH HIGH FREQUENCY MAGNETIC LINK USING FERRITE "POT CORE" TRANSFORMER AND DIODES ON THE ROTOR

ABSTRACT? TITLE?

(HERE GOES WITH AN "IN PEN" DRAWING ATTEMPT



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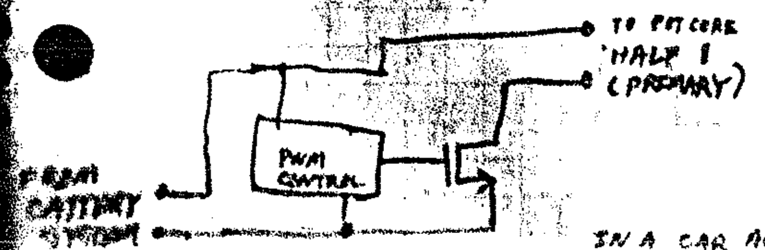
"FORWARD CONVERTER" - TAKES ELECTRICAL POWER IN FROM BATTERY, CONVERTS TO HIGH FREQUENCY SQUARE WAVE OF VARIABLE DUTY CYCLE (PWM)



THE DESIGN OF THIS WILL BE DEPENDANT ON THE POWER RATING OF THE FIELD WINDING, AND THE BATTERY SYSTEM CHARACTERISTICS.

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IN A CAR ALTERNATOR SYSTEM, THE "FORWARD CONVERTER" WILL ADJUST ITS OUTPUT TO HOLD THE BATTERY SYSTEM

FIGURE 2

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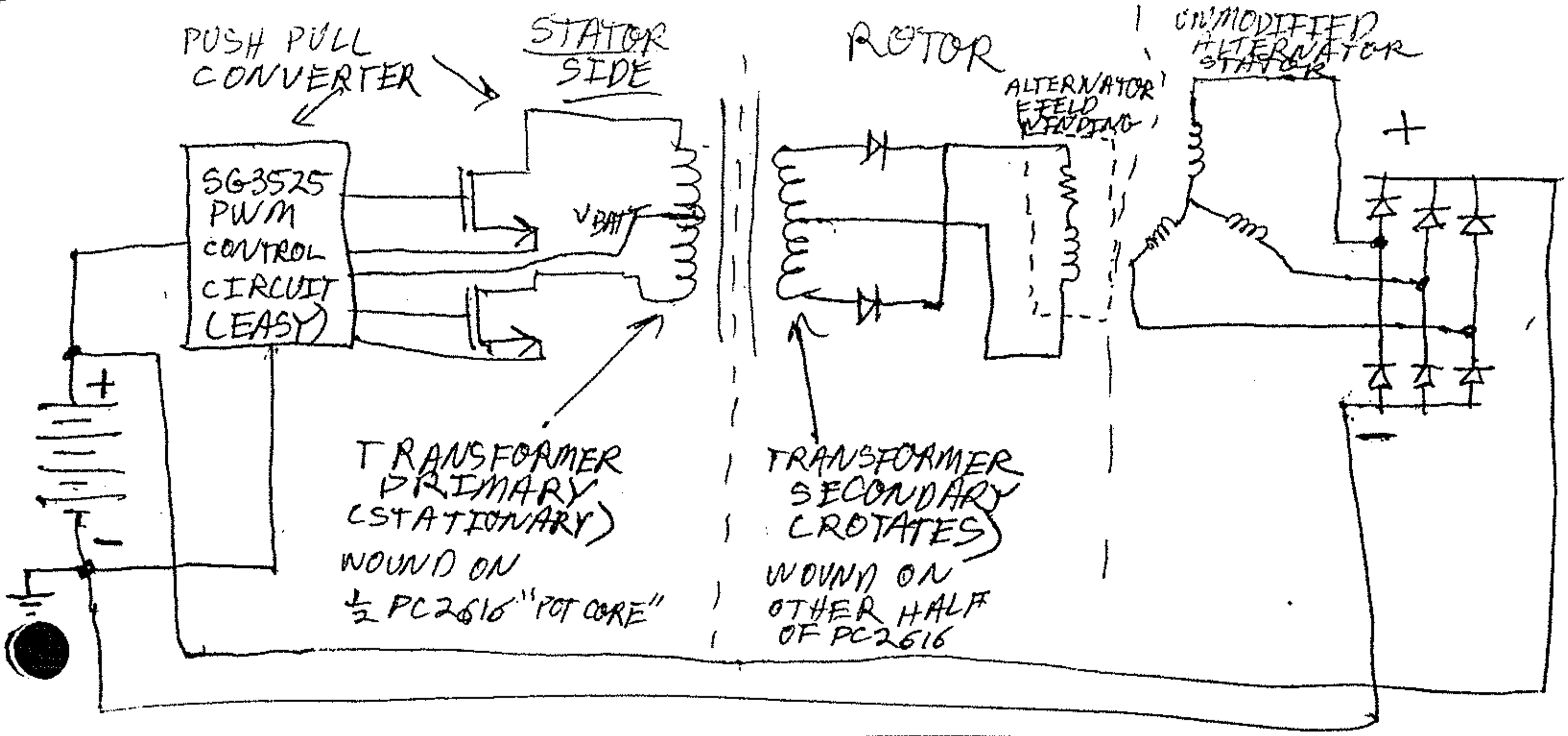
HAD THIS ON THE BLKBOARD FOR THE DEMO

HIGH FREQUENCY MAGNETIC LINK EXCITATION PROOF OF CONCEPT SYSTEM



CHALK BOARD PICTURE TO HELP EXPLAIN SYSTEM

AIR HOSE FOR "PRIME MOVER" COOLER

3/8" ID TUBE - FROM OUTLET TO "SEPARATOR" — 65 FEET

9/16" ID TUBE FROM SEPARATOR* TO MOTOR (6')

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* SEPARATOR - JUST A 2 OR 3L POP BOTTLE TO SEPARATE OUT CONDENSED WATER -

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FIGURE 3 [illegible] 09/20/95

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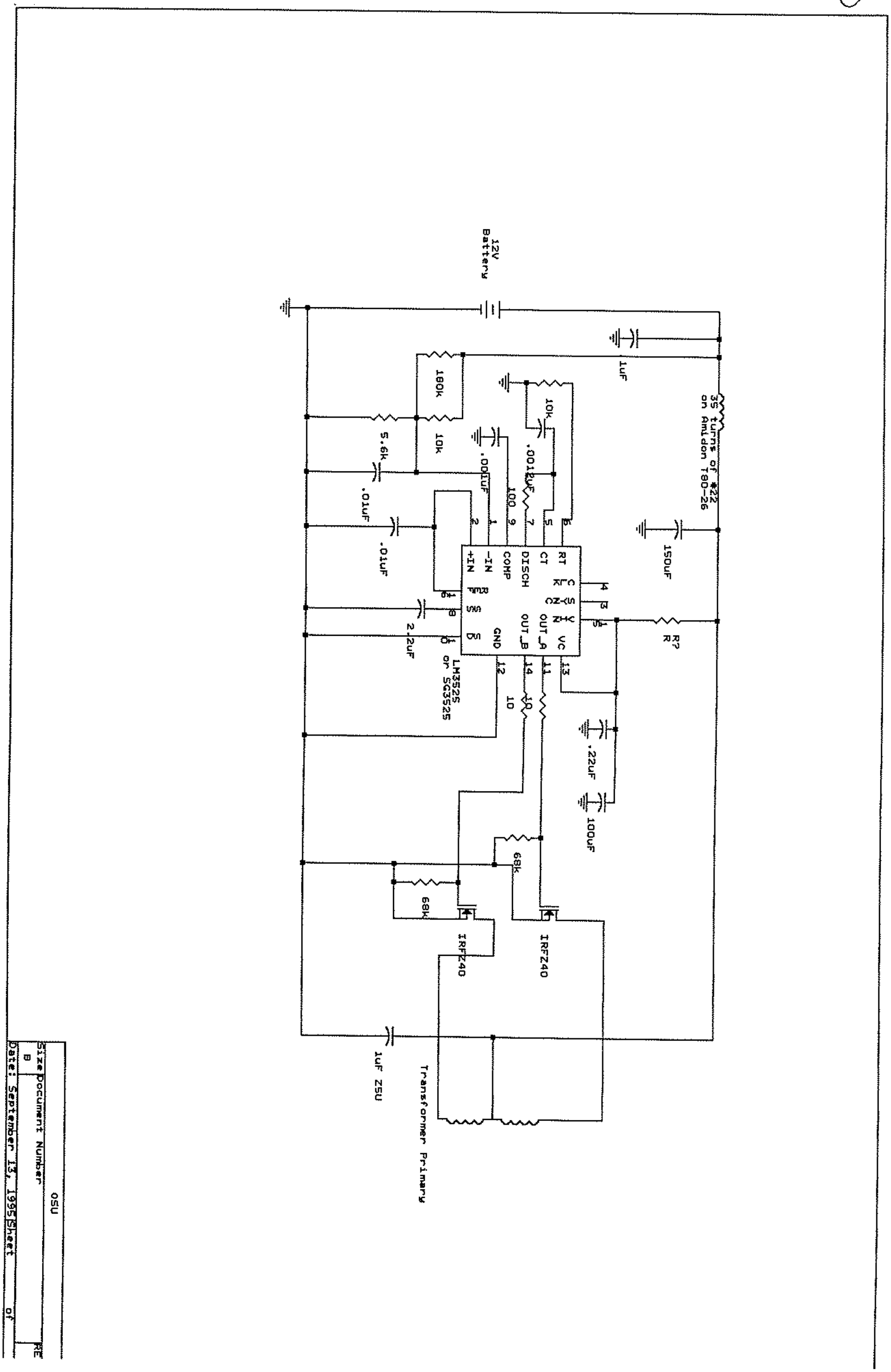

FIGURE 4

CONSIDERATIONS–

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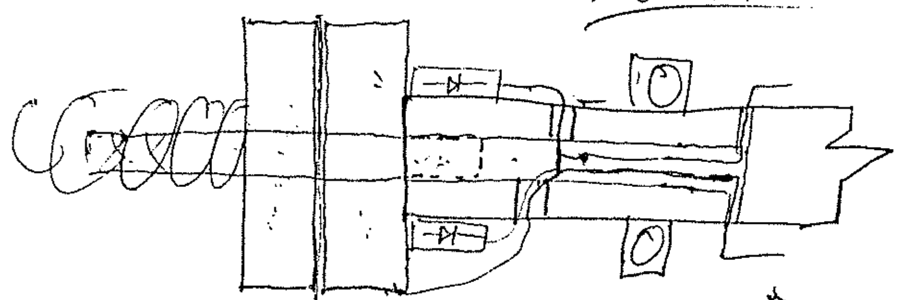
MUST BE CENTERED AROUND SHAFT R AXIS – OTHERWIZE THE "SPING MOUNT" WILL HAVE TO COMPENSATE FOR TOO MUCH WOBBLE

NO PROBLEM



BAD PICTURE

THIS HALF MUSN'T START TURNING AND TWIST UP ITS LEAD WIRES

BASICALLY, THE POTCORE MOUNTING SHAFT IS FIT TO THE MAIN SHAFT. – PRESS FIT?

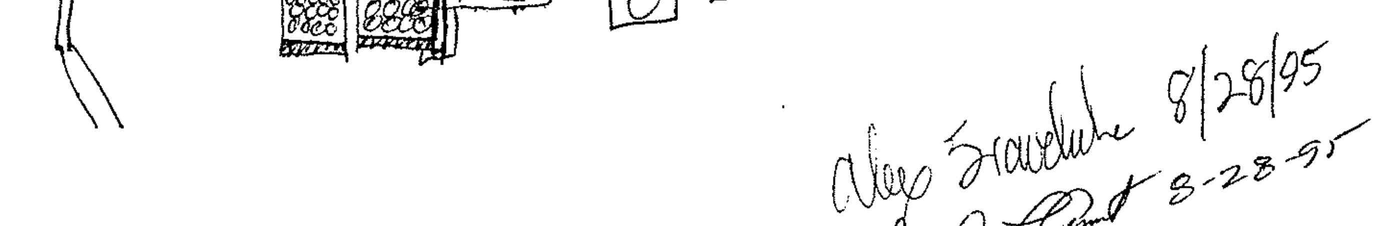


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FIGURE 5

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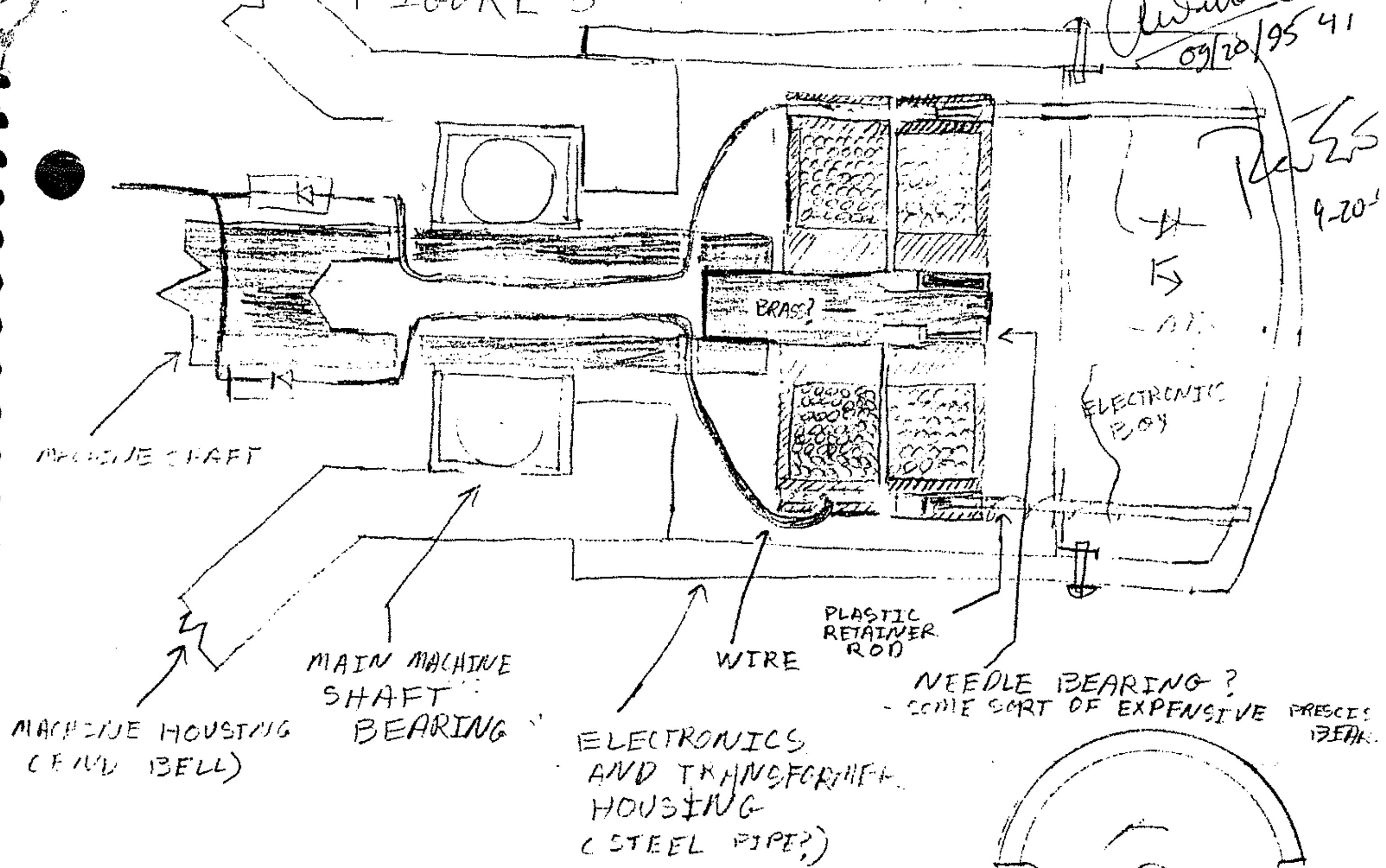

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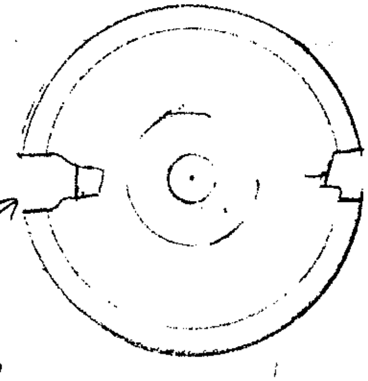
THE POTCORE
BEARING
MUST RESIST
END PLAY



Alex Savelchuk
09/11/95
(DREW THIS SOME TIME
LAST WEEK)

9-11-95

09/18/95 – AM WORKING ON OFFICIAL INVENTION DISCLOSURE FORM.

FIGURE 6

Alex [signature] 09/20/95

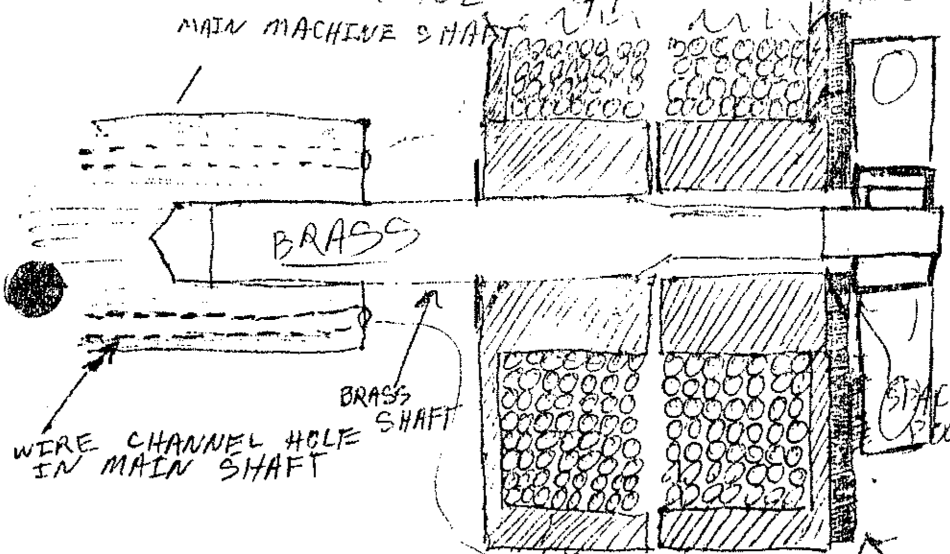
[signature] 09/20/95

DISSASEMBLED MACHINE TODAY TO TAKE BLACK & WHITE PHOTOS OF ~~ENTIRE~~ ALL MODIFICATIONS MADE TO DODGE ALTERNATOR.

[signature] 9-20-95

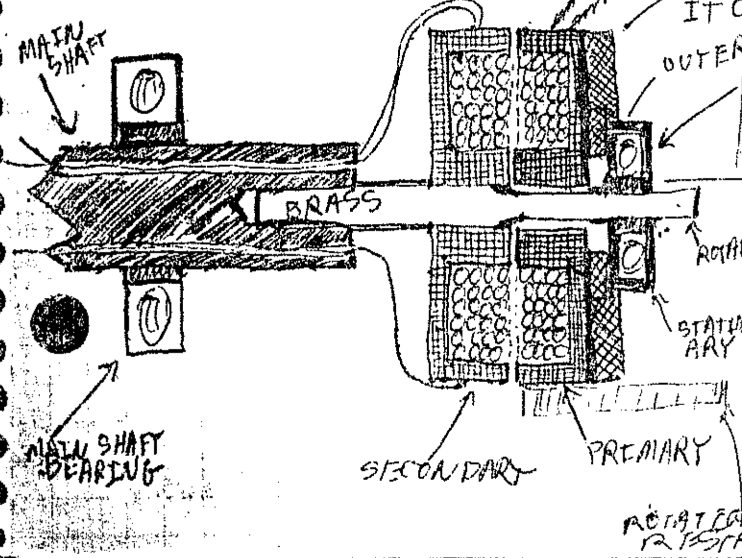
WILL ATTEMPT TO PUT BACK TOGETHER FOR WALLACE. HE'S GOING TO STOP BY TOMARROW

HERES PROBABLY A BETTER WAY TO ATTACH BEARING IN GENERAL IDEA ON PAGE 41 OF THIS NOTEBOOK.



BAD DRAWING!

TRY AGAIN



THIS PLASTIC BETTER HAVE LOW THERMAL COEFF. EXPANSION. IT COULD BE BRASS...

OUTER RACE ATTACHED TO PHENOLIC/THERMOPLASTIC DISC

POT CORE BEARING! MUST HAVE VERY LOW END PLAY

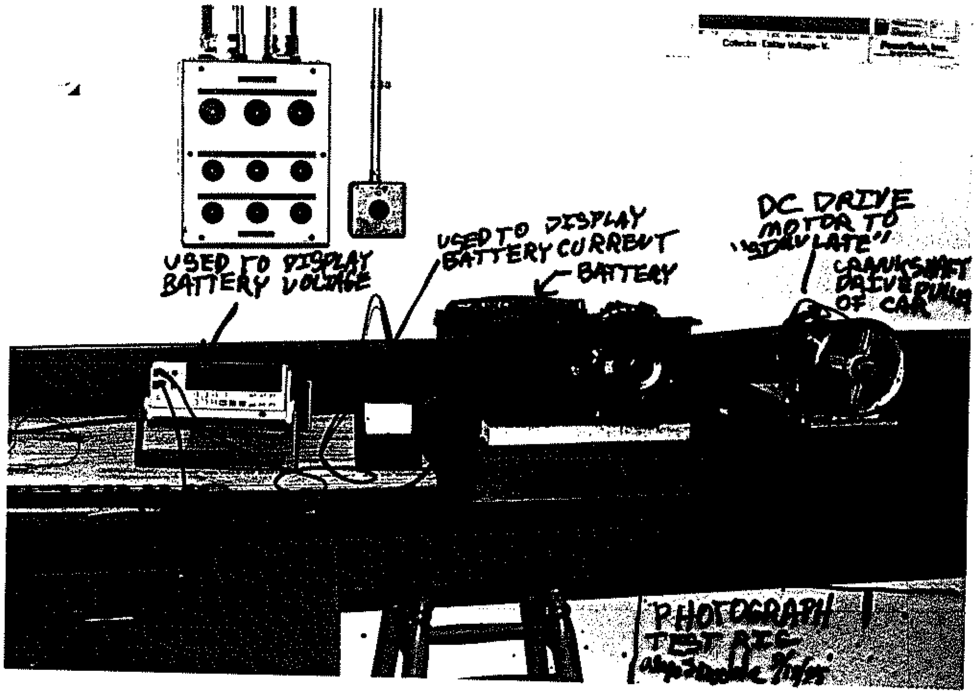
INNER RACE PRESS FIT TO POTCORE SHAFT.

AXIAL LOCATION OF PRIMARY BEARING AND SECONDARY PRESS FIT IS CRITICAL

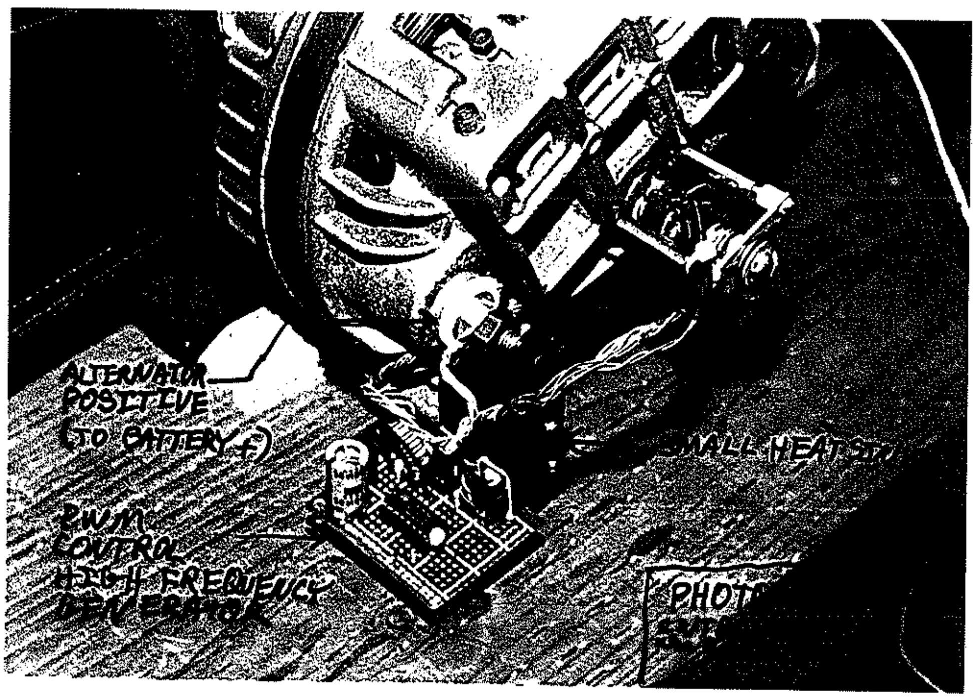
I LIKE THE PLASTIC THRUST WASHER.

Alex [signature] 09/1

Photograph 1: The test rig, showing mounting of alternator and drive motor. Also visible is the battery and the meters used to monitor and display the system voltage and current flow of the system while in operation. Not shown is a piece of 1/2" thick plywood that was secured to the front of the mounting as a cover for the V-belt and pulleys.



Photograph 2: Shows high frequency power supply and attachment to alternator. Electrically, the circuit simply is connected to the main power terminal and the ground.



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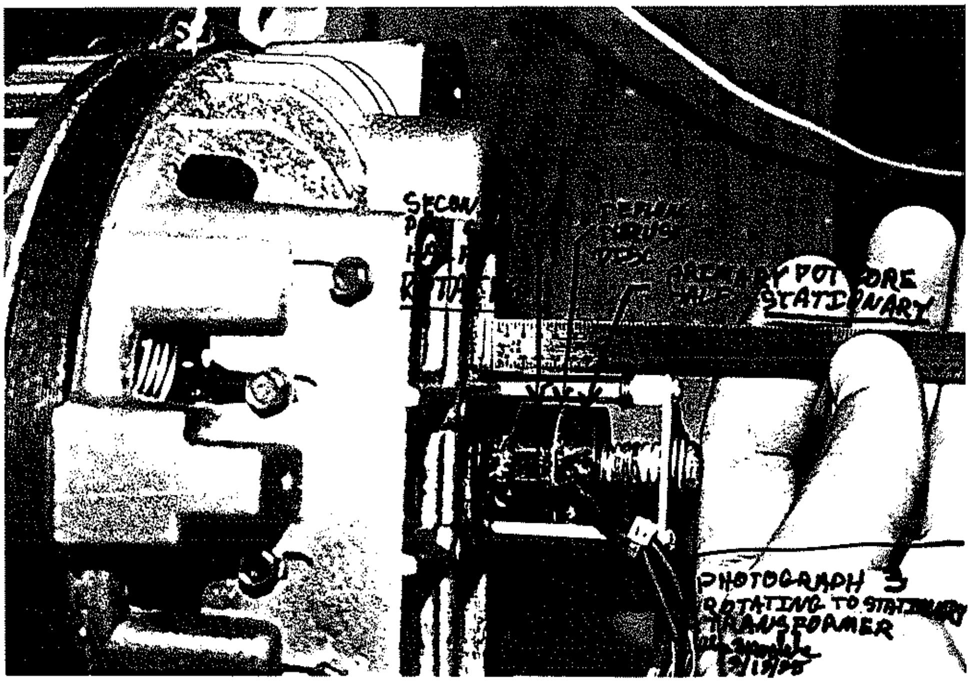
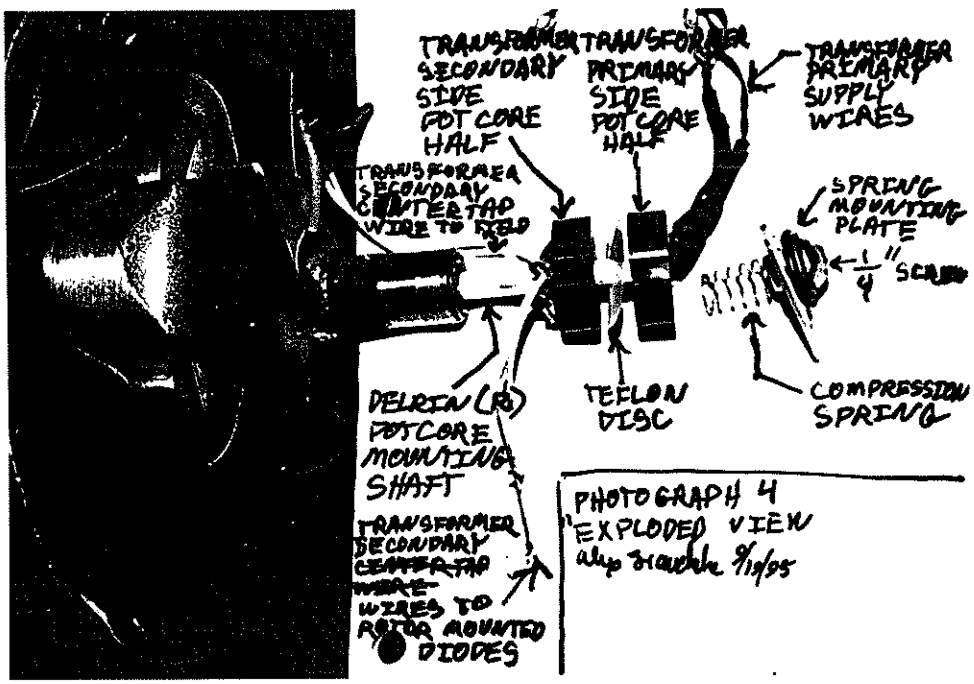
Photograph 3: A close look at the transformer and thrust spring assembly. Not visible is the bushing around a stand off that slips into the primary side pot core wiring outlet slot to prevent rotation. A good view of the pot core wiring outlet slot is in photograph 4.



Photograph 4: An exploded view of the transformer assembly. Not shown is the machine frame and main shaft bearing, which are located between the secondary pot core and the main shaft. All wiring is disconnected in this photograph.



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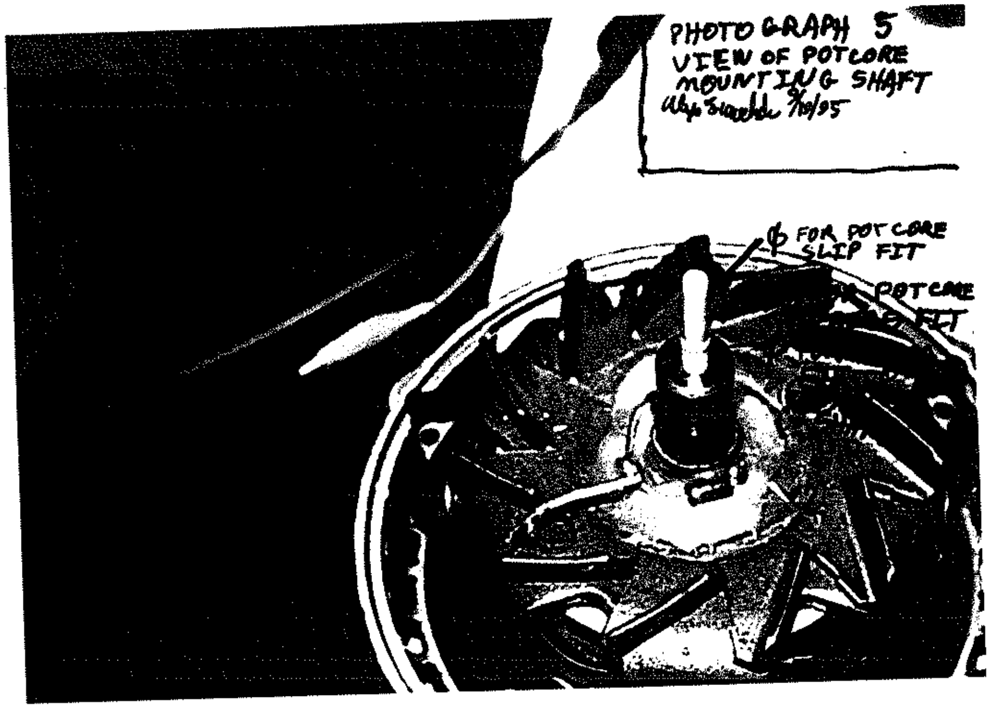
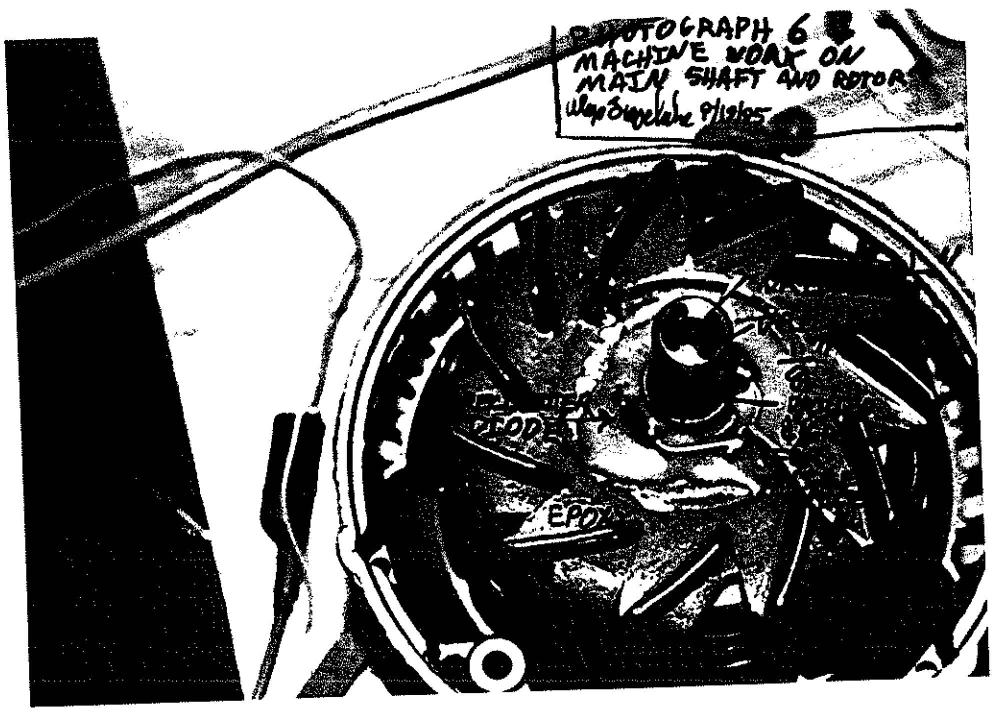
Photograph 5: A view of the pot core mounting shaft.



Photograph 6: Showing drilling on main shaft. All this work was done on a small drill press. The center hole was located by a small hole already existing in the back of the shaft. The two smaller holes are passages for the wire to run through. In a production version, there would almost certainly only be one hole for both the transformer mounting and the wiring. This photograph also shows the rectifier diodes and their attachment to the machine rotor. In a production version, these diodes may be located directly under the secondary transformer half for simpler manufacturing and use of less wire.



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OFFICE OF
TECHNOLOGY TRANSFER

OREGON
STATE
UNIVERSITY

312 Administrative Services
Corvallis, Oregon
97331-2140

541-737-0672
FAX 541-737-3093

January 25, 1996

Alex Faveluke
180 D SE Viewmont Ave
Corvallis, OR 97333

RE: Invention Disclosure OSU 95-23
HIGH FREQUENCY MAGNETIC LINK BRUSHLESS
EXCITATION SYSTEM FOR SYNCHRONUS MACHINE

Dear Alex:

You have discussed with Steve Adamson the results of his patent search concerning this invention.

Based on the results of the patent search which shows that there are patented technology that are similar to your invention and that the possibility of receiving meaningful patent protection is unlikely, the University had decided not to proceed further with your invention.

Since you are a student and University resources have not been utilized in this invention, you do not have an obligation to assign the invention to the University.

Thank you for submitting your invention.

Sincerely,

William W. Hostetler, Director
Technology Transfer