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IEEE Transactions on Magnetics, vol. 37 no. 1, January 2001

PR - 278

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Design and Implementation of Explosive Opening Switches in Inductive Circuits

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Abstract-- **Self-excitation in pulsed duty alternators is utilized to meet energy and power density system requirements. In the eventually fielded system, a small energy source will be pulsed into the field coil to start the excitation process. At this point, power electronics on the ac output of the generator will control the charging of the field coil and invert the field energy safely back into the rotor inertia at the end of the discharge sequence (or in the event of a fault). A static rectifier was used in the self-excitation process in the laboratory testing of a subscale prototype compulsator. Without control of this bridge, a simple cost effective method was devised to terminate the excitation process safely at the end of a generator discharge sequence or in the event of a fault. To safely dissipate the field energy an explosive opening switch in parallel with a resistive element was placed in series with the bridge output and field coil. On command, the opening switch would commutate current into the resistive element properly sized to terminate the excitation process and with sufficient thermal mass to dissipate the field coil energy. The test program for the compulsator was designed to increment the self-excitation current in small steps in the commissioning of the system. Near the end of the test program, it was observed that the opening switch was having difficulty commutating the current into the inductance of the dissipation resistor. A shunt capacitor was sized to limit the commutation voltage and allow the opening switch plasma time to extinguish before large voltage developed across the resistive element. This paper presents information on the sizing of the resistor and capacitor and test data on its performance in the compulsator self-excitation circuit. This work is important because future systems under the control of active power converters will still require a fail-safe element to dissipate field energy in the event of a control system fault.**

I. INTRODUCTION

DURING development of compulsators at The University of Texas at Austin Center for Electromechanics (UT-CEM), several machine configurations have been demonstrated [1]. The most recent machines have been air-core compulsators, compared to earlier machines that were iron-core machines. The air-core machines require much higher levels of field current to generate the output voltage needed. The relationship between field current and output voltage is linear; as field current goes up, the output voltage increases. Output voltage is what drives the intended load; it is, therefore, a primary design specification. Another configuration variable is stationary or rotating field coil. Other machine design parameters include single-shot or multi-shot machines. The basic switching concept described in this paper can be applied to many different design topologies. The basic schematic is shown in Fig. 1.

II. FIELD COIL DESIGN

To allow for several discharges, the field coil must have the thermal mass or cooling ability to allow for several charging cycles in a short period of time. The time it takes to ramp the field current up and back down is an important factor in field coil design. The overall action is what sets the thermal requirements on the field coil. In order to minimize the action in the field coil, rapid current rise is required. Rectifying the machine output voltage into the field coil is one method of achieving rapid current rise in the field coil. This is called self-excitation. Self-excitation removes energy in the form of inertia from the rotor. Due to the current levels and charging time involved, stand alone power supplies or motor drives are not practical. Utilizing self-excitation helps the project reach energy and power density goals set for the system.

All of the electrical energy from the discharge sequence is derived from the mechanical energy stored in the rotor. To achieve the desired energy delivered to the load, the energy must be derived from the rotor. After the discharge, the field coil current is inverted back into mechanical energy, speeding the rotor up. The field coil is not designed to store energy, only the rotor inertia is designed for energy storage. Future systems will have to excite in a shorter period of time to meet expected design goals, as the mass of the field coil will only be reduced.

To start the excitation process, a small seed current in the field coil is required. In laboratory testing of a subscale prototype compulsator, the initial seed current for the field coil comes from the field initiation module (FIM). A detailed pulse power schematic is shown in Fig. 2. The FIM energy storage consists of two 2,000 µF capacitors. The capacitors are charged from a high voltage power supply. The capacitors are protected from reverse voltage by a freewheel diode stack. The FIM discharge is initiated from the controller and performed by two thyristor stacks which are in series, one in each leg.

Manuscript received December 21, 1999. Funding for this effort was provided by the U.S. Army under contract DAAA21-92-C-0105. The COTR was Dr. Ed Schmidt.

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III. SWITCH DESIGN

Diodes were selected (instead of active devices, based on schedule and budget constraints) to perform the rectification duties in laboratory testing of a subscale prototype compulsator. While diodes have lower initial cost and simpler operation compared to thyristors or other devices requiring gating, they cannot perform controlled rectifying. In the laboratory system, additional switching devices (activated explosively) are required to control several parts of the discharge sequence.

Reference [1] includes a detailed description of compulsator auxiliary operation. For the sake of brevity, however, several auxiliary systems and operations are omitted from the following description of the basic operation sequence of the prototype machine.

The compulsator rotor is brought up to speed using a hydraulic motoring system. Once the rotor is at the desired test speed, the electrical discharge sequence is initiated. After all the auxiliary systems are in the proper state, the FIM is discharged into the field coil. Fig. 3a shows the field current. This initial field current produces magnetic flux, and a corresponding voltage is generated on the armature windings as an output voltage. The output voltage is full wave rectified back into the field coil. Although this process starts at a low level, the field current and output voltage build up exponentially. During this process, rotor mechanical energy is converted into electrical energy. The hydraulic motoring system is allowed to freewheel during the discharge sequence; therefore, the rotor is not being actively driven.

After the field coil current and resulting output voltage is at the desired level, the test load is connected across the output terminals. The load current is switched in and then out again after the prescribed amount of cycle time. Fig. 3b shows the load current and individual phase currents. All of this electrical discharge cycle happens in a very short period of time. After the discharge, the field explosive opening switch (FEOS) (fig. 4) is activated to halt the field coil current. The simplified schematic of the FIM is shown in fig. 5. After the field current is stopped, the rotor is brought to a stop using the hydraulic motoring system.

The subscale prototype system is equipped with mechanical switches that are operated using explosives. These switches are a simple and cost effective way to test the compulsator in a laboratory. This type of switch is what completes the load circuit, called an explosive closing switch (ECS). Another type of explosive switch used in the subscale system is the explosive opening switch (EOS). The EOS is utilized in two basic configurations: flat plate conductors and coaxial cylindrical conductors. Both of the EOS configurations open the circuit to change or stop the current flow.

The field coil EOS is a flat plate conductor style switch designed to terminate the excitation process. The field EOS is in series with the full wave bridge and the field coil. All of the EOSs in the pulse power circuit (except the field EOS which has a dump resistor connected in parallel with the EOS) are set up to open a circuit current. The resistor is designed to dissipate the field energy safely. The dump resistor is shown in Fig. 6. The goal of the dump resistor is to control the applied voltage across the field coil when the switch is activated. The resistor is a stainless steel serpentine matrix with measured impedance of 12 μH and 0.23 Ω. The resistor active length is 12 in. wide by 28 in. tall with 24 serpentines on each plate. There are a total of 10 plates with serpentines, with insulators between each plate. This construction allows for removable jumper bars to lower and adjust the resistance, if desired.

A new flat plate EOS was designed that would connect to the dump resistor with a minimum of inductance. The minimum inductance connection helps the switch commutate the field current into the resistor. In Fig. 7, the resistor is the tall part on the left; the flat plate EOS is next to the resistor, and has the detonating cord installed in the picture. The white plastic polyethylene is used as an insulator. The entire field coil circuit was optimized for lowest inductance, to allow for the quickest charging time and the lowest losses.

IV. SWITCH TEST RESULTS

The normal sequence of switch operation is as follows. The control system sends a fire command to a fireset module at the proper time. This module has been charged to several kV. When the module receives a fire command, it discharges a high voltage and high current pulse into the detonator. The detonator in turn ignites the detonating cord. The detonating cord tears open seven gaps in the aluminum plate to stop the flow of current in the field circuit. The detonating cord is installed into stress riser gaps that are machined into the flat plate. The stress risers are machined to a thickness that the 15 grain per foot detonating cord can easily open. With the resistor bus bar connection in parallel with the switch element, the current is now forced to commutate into the resistor. A drawing of the aluminium plate and support parts of the FEOS is shown in Fig. 8. Several papers have been published that describe the EOS operation in detail, including reference [2].

The compulsator testing program started at a low rotor speed and a low field coil current, and progressed upward. As the field coil approached half the rated current, it was noticed that the voltage collected across the FEOS was not reaching the expected magnitudes. The voltage was not a smooth curve; it became very erratic, smoothing out towards the end of the field current decay (fig. 9).

After careful examination, it was determined that the switch was not commutating the current into the resistor. The problem was the inductance of the dump resistor. The inductance was causing the voltage to build up rapidly, not allowing the arc to extinguish. The voltage across the switch is the IR voltage plus the L(dI/dt) component. Using the inductance of 12 μH and an opening time of 80 μs yields an L (dI/dt) component somewhat lower than the IR voltage. The combined effect is beyond the switch capability in a plasma environment. Several methods of reducing the voltage across the switch were investigated.

The method selected was adding a snubber or shunt capacitor across the switch. The shunt capacitor would limit the initial voltage rise across the switch. When the commutation voltage is limited in this way, the opening switch plasma has time to extinguish before the voltage builds to the resistive value. The basic formula is I = C(dV/dt). The capacitor was sized to absorb energy for about 40 µs at peak field coil current. The capacitor selected is 480 µF.

The capacitor was installed with minimal cable inductance. Also, a safety discharge and grounding resistors were added. Several tests were performed that show the switch to be operating without arcing. After the capacitor was tested, the field current in the system has more than doubled with no other problems. Fig. 10 presents the same data as Fig. 9, with the commutation capacitor installed and at a greatly expanded time base to record the initial voltage rise at commutation. The effect of the L(dI/dt) part is greatly reduced on the switch voltage. Fig. 10 also shows the current that flows into the capacitor as the switch opens.

The explosive activated switch may be replaced in future-generation systems; however, a fail-safe element is still desirable even in a system that utilizes active power converters. The inductance can be managed to limit voltage developed using a capacitor, as shown in this paper. In the event of converter failure, the system will require a method to dissipate the field coil energy if it can not be inverted back into rotor inertia. This might be accomplished using an active converter circuit or other switching methods, but must be included.

V. CONCLUSION

The subscale prototype machine and pulse power circuit has proven to be a reliable test bed. The FEOS has never had a fault, through many tests. With the addition of the shunt capacitor across the FEOS, the transient voltage has proved to be manageable. In the event of a converter failure, the ability to dissipate the field energy is an important element to have in a system. For future systems, a tested example now exists.

VI. REFERENCES

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[2] R.L. Sledge and J.H. Hahne, "Experimental data on high power explosive opening and closing switches at CEM-UT," presented at Seventh IEEE Pulsed Power Conference, June 11-14, 1989.

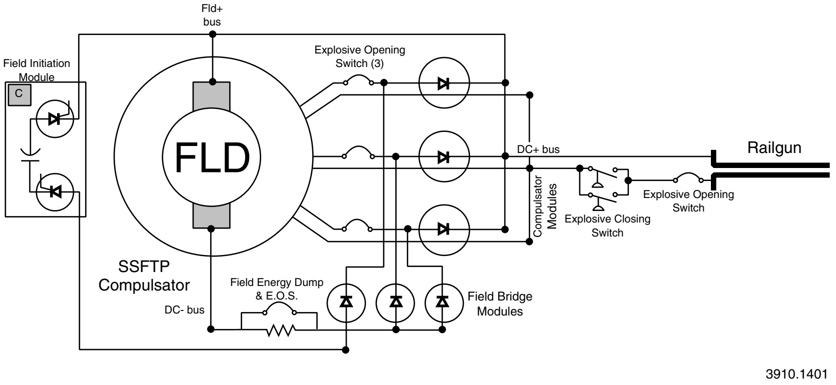


Fig. 1. Basic switching schematic.

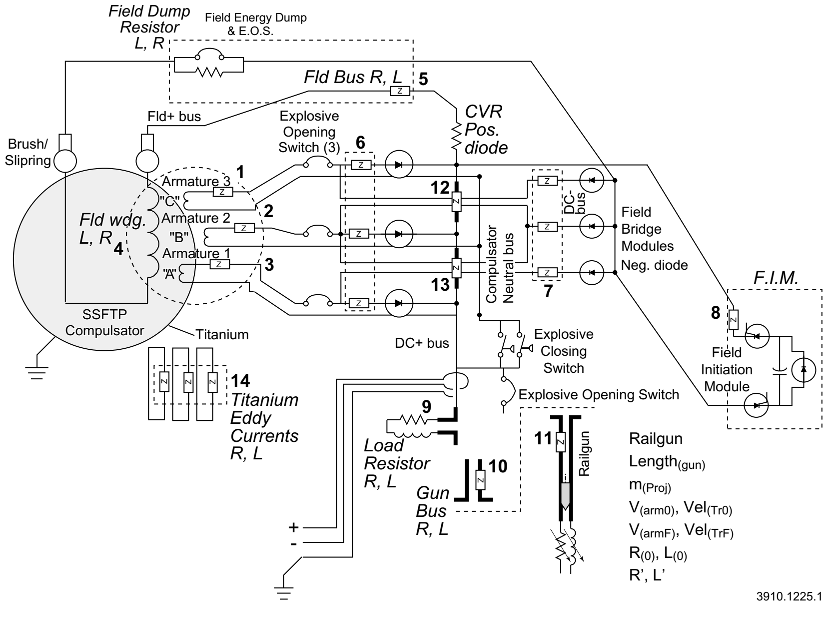
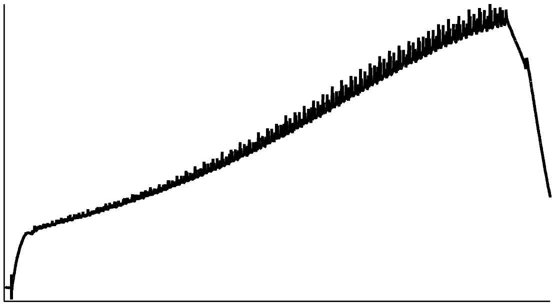
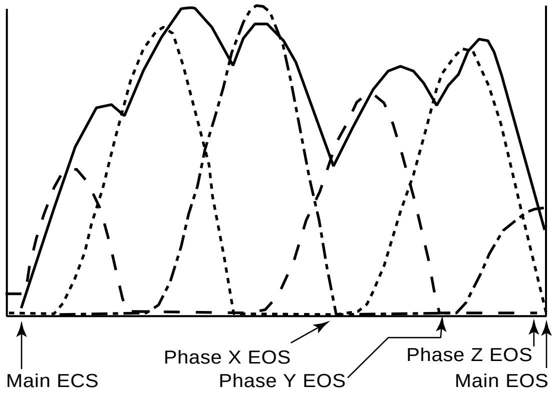


Fig. 2. Detailed pulse power schematic.



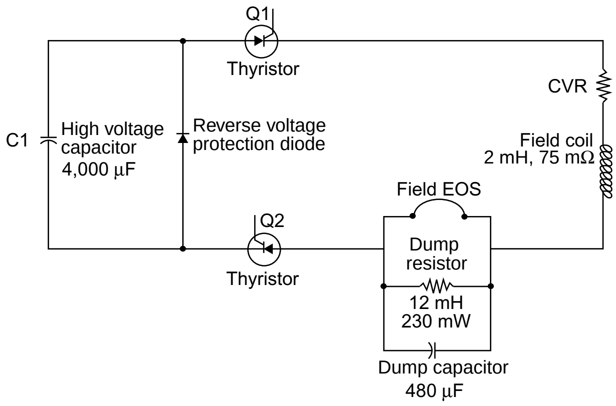
(a) field current



b) Load and phase currents

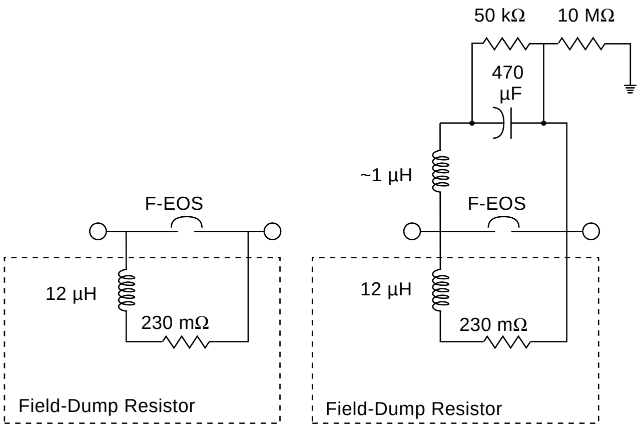
3910.1402

Fig. 3. Compulsator test data



3910.1403

Fig. 5. Simple field coil/FIM/FEOS circuit



3910.0981

Fig. 4. Field dump resestor

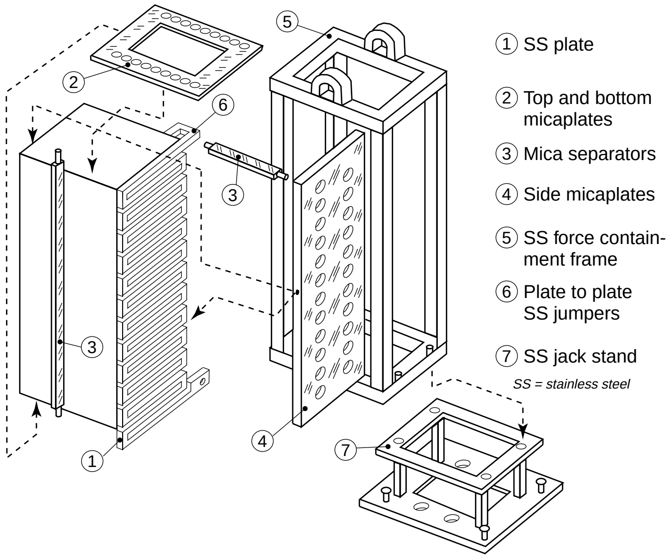


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Fig 6. Dump resistor

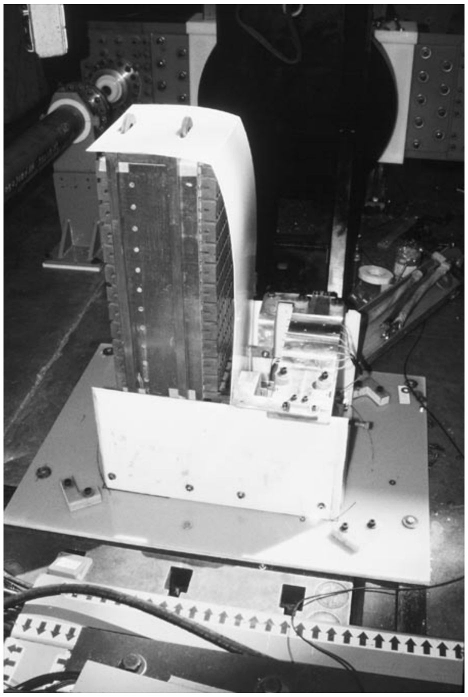

Fig. 7. Field explosive operating switch (photograph).

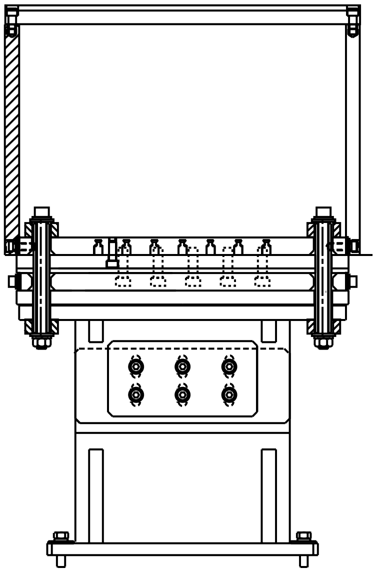

Fig. 8. Field explosive operating switch (schematic).

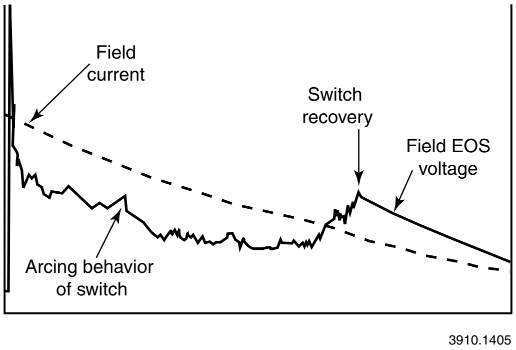

Fig. 9. FEOS voltage with restriking.

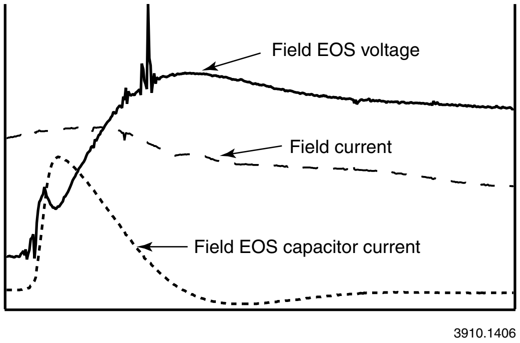

Fig. 10. FEOS voltage without restriking, with an expanded time base.