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COMMUTATOR DC MACHINES USED AS MECHANICAL CAPACITORS IN A SERIES RESONANT OHMIC-HEATING CIRCUIT SIMULATION

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Summary

Rotating electrical machines, and in particular commutator dc machines can serve as a high-power energy-source for testing large, pulsed magnets. This paper describes a pulsed power supply based on traction motors which will be used to test the LASL prototype 20-MJ superconducting tokamak induction coil.

Introduction

Traction motors are a class of commutator, dc electrical machine used as propulsion motors in locomotives. They are usually operated as series wound machines, i.e., machines in which the field and armature windings are connected electrically in series. In the application described here, the windings are not series connected but are separately excited. The motors have a mechanical commutator composed of carbon brushes wiping copper segments which provide direct current. Commutator flashover is a limit to the maximum values of current and voltage which the machine is capable of supplying. Kinetic energy is stored in the spinning rotor of a traction motor, and if the field current is fixed, the terminal characteristics are those of a capacitor. The fact that traction motors, as all rotating electrical machines, can behave like large capacitors makes them potentially useful in pulsed power supplies.

The particular motor discussed here, the Westinghouse Electric Company type 362 is shown in Fig. 1. These motors were manufactured in large numbers for use as drive motors in diesel electric locomotives. They are no longer manufactured by Westinghouse but exist in large numbers, and are rebuilt and exchanged or sold by various motor rewinding companies. Equivalent motors are currently manufactured by the Electromotive Division of General Motors (type D-79) and the General Electric Company (type 752).

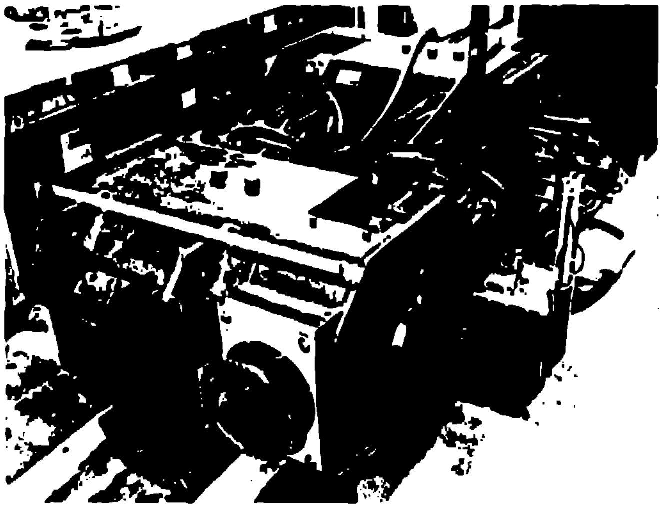

Fig. 1
Two type 362 traction motors configured for testing.

A number of characteristics make traction motors attractive for use in pulsed power supplies. Their mechanical construction is extremely robust; they are normally suspended from an axle, within a truck beneath a locomotive. They are subjected to frequent switching transients, and are used for dynamic breaking so their windings are massive and well braced. Their terminal characteristics, energy storage capacity, and available range of capacitance are reasonably well matched to many pulsed power test applications. The overriding consideration which led to the choice of a traction motor based pulsed power supply was their low cost: ~ \$3.50/pulsed kVA, when purchased as rebuilt equipment.

The characteristics of a typical type 362 traction motor are listed in Table I. Steady state characteristics were provided by industrial sources.[1,2] These values were checked and transient characteristics determined by tests performed at LASL.

TABLE I

TYPE 362
TRACTION MOTOR CHARACTERISTICS

Parameter	Value
Maximum speed (rpm)	2500
Maximum terminal voltage (V)	800
Continuous terminal current (A)	520
Starting duty current (A)	1000
Rotor moment of inertia (Nms^2)	21.2
Armature resistance (mΩ)	19.4
Commutating field resistance (mΩ)	13.0
Series field resistance (mΩ)	12.7
Armature inductance at 20 Hz (mH)	4.8
Field inductance, dc (mH)	25.0
Field armature mutual inductance (mH)	31.4
Armature reaction mutual inductance (nHA^{-1})	189
Back iron time constant (s)	0.5
Armature coils:	
Wire size (copper) (in)	0.100 × 0.860
Turns per coil	1
Number of coils	155
Number of commutator bars	155
Number of poles	4
Winding type	Wave
Main field coil	
Wire size (copper)(in)	0.281 × 1.00
Number of turns	22
Interpole field coil	
Wire size (copper) (in)	0.144 × 1.50
Turns per coil	25

20-MJ Coil Test

A circuit for testing the 20-MJ prototype superconducting induction coil is shown in Fig. 2. Principal components are: a 60 V, 50 kA direct current reversable power supply; a superconducting coil, whose properties are listed in Table II; a discharge resistor; a bank of traction motors functioning as a large capacitor; a power supply to bring the motors up to speed; and finally, switches at each of the power supplies and between the traction motors and the coil.

TABLE II

CHARACTERISTICS OF 20-MJ COIL

Parameter	Value
Superconducting material	NbTi
Peak field (T)	7.5
Maximum current (kA)	50
Inductance (mH)	16.18
Winding type	Pancake
Number of pancakes	8
Turns/pancake	25
Coil length (cm)	135.5
Coil bore (cm)	60.0
Coil outside diameter (cm)	146.0
Loss per cycle	0.3?
Volt seconds	7

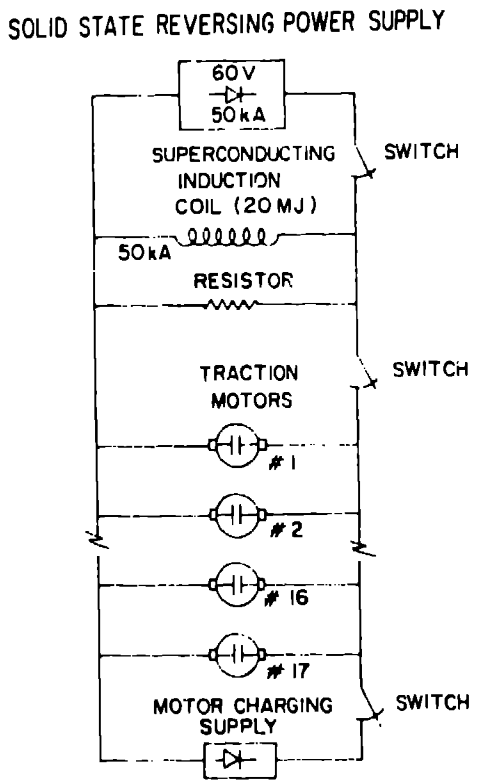

Fig. 2
Test circuit for LASL 20 MJ coil, using a traction motor bank.

The purpose of the test is to check all aspects of the coil's performance when subjected to a current pulse representative of an unassisted start-up of a tokamak. The traction motor bank will provide a high peak-power pulse for magnetic field reversal.

The current wave-form used to test the coil is shown in Fig. 3. The effect of the circuit is to charge the coil to 50 kA, reverse the current to -50 kA in one to two seconds, hold the current at -50 kA to verify that the coil has remained superconducting, and then to allow the current to decay. This waveform does not simulate the presently proposed ETF tokamak induction coil current waveform but is in fact a more severe test of the coil. By suitable alteration of the circuit, waveforms typical of an ETF tokamak or other future designs can be simulated.

A test cycle begins by charging the coil with the 50 kA power supply and charging the traction motor bank to the opposite polarity using the motor charging supply. During this phase of the cycle, the top and bottom switches in Fig. 2 are closed and the middle open. To initiate the resistive discharge phase, the top switch is opened. At this point the bottom switch is also opened and the motors allowed to coast. At the appropriate time the middle switch is closed and the current is reversed by discharging the traction motor bank. The waveform is completed by a flat top portion and a resistive discharge.

Commutator dc Machines as Capacitors

A commutator dc machine whose shaft is not connected to an energy absorbing or producing device external to the machine can be made to function as a capacitor in an electric circuit. This can be shown quite simply using the classical equations which represent the operation of an unsaturated dc machine.

The terminal voltage of an open circuited, unsaturated, commutator dc machine is proportional to the speed of rotation and the field current:

$$e_a = M_{fa}\omega I_f \qquad (1)$$

where M_{fa} is the mutual inductance between the field and armature windings as listed in Table I. The other variables are defined in Fig. 4.

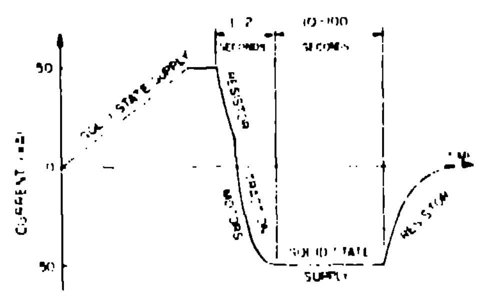

Fig. 3
Current waveform for 20 MJ coil test.

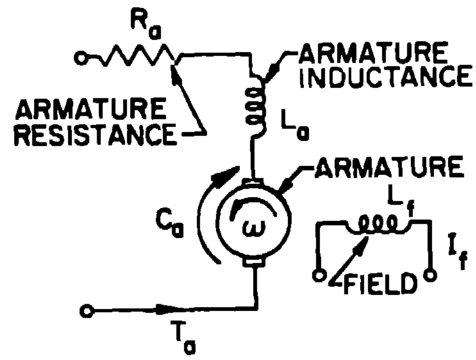

Fig. 4
Equivalent circuit of traction motor.

Torque produced by the interaction of the field and armature currents causes an acceleration of the rotor:

$$J \frac{d\omega}{dt} = M_{fa} i_a I_f \qquad (2)$$

where J is the polar mass moment of inertia of the rotor plus flywheel. These equations can be combined to eliminate ω noting that M_{fa} and I_f are constants:

$$i_a = \frac{J}{(M_{fa} I_f)^2} \frac{de_a}{dt} \qquad (3)$$

Equation (3) has the form of the terminal relationship of a capacitor where:

$$C = \frac{J}{(M_{fa} I_f)^2} \qquad (4)$$

While the mutual inductance is fixed by choice of a particular machine, the moment of inertia can be augmented by addition of a flywheel and the field current can be decreased from its rated value to zero. It appears from Eq. (4) that a wide range of values of capacitance are available by using field control. In fact the variation is limited to about an order of magnitude by the effects of remanence, saturation, and armature reaction. Equation (3), while idealized and simplistic still demonstrates the basic relationship and reason for using commutator dc machines in pulsed power supplies.

Transient Tests

A series of tests have been performed on two type 362 traction motors to measure their characteristics and find the limits of their operation. A circuit similar to that shown in Fig. 2 was employed during the test. Two traction motors constituted the electromechanical capacitor, and a previously tested 540 kJ superconducting coil was used as the inductor.[3,4]

A series of tests were performed to determine the range of validity of Eq. (4). Three effects limit the usefulness of this simple relationship: remanence, saturation, and armature reaction. These effects can be accounted for by recasting Eq. (4) in terms of the terminal voltage per unit speed as a function of a reduced field current which is yet to be defined:

$$C = \frac{J}{[K(I_{fe})]^2} \qquad (5)$$

The function K is the open circuit voltage per unit rotational speed and accounts for remanence and saturation. The reduced field current I_{fe} is the actual field current adjusted for the effects of armature reaction.

The open circuit voltage per unit rotational speed can be obtained from the open circuit saturation curve, Fig. 5, by dividing the voltage at 2500 rpm by 261.8 s^{-1}. Note that Eq. (1) is valid to about 1.2 kV

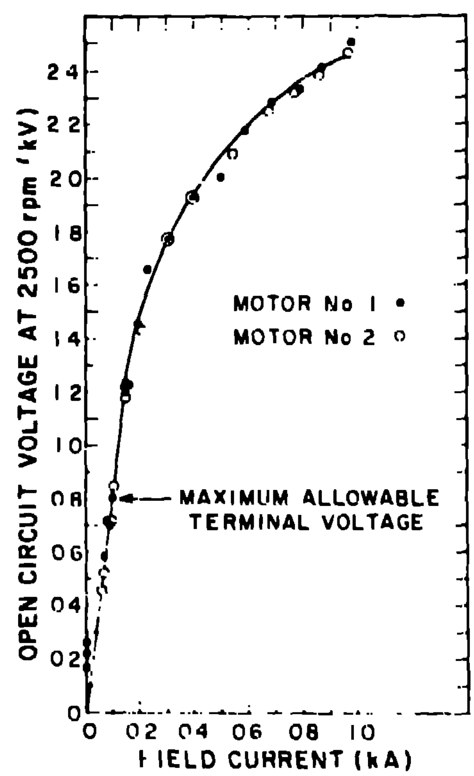

Fig. 5
Open circuit saturation curve for type 362 traction motor.

on this figure. Remanence, the flux which remains when the field current is set to zero, is illustrated by the three experimental points which lie on the voltage axis. Remanence is a hysteresis effect and so is a function of the prior history of the machine. Because of this effect, the terminal voltage does not go to zero with the field current but remains at about 200 V. Hence the maximum value of attainable capacitance is limited.

The open circuit saturation curve flattens out as field current is increased as a result of saturation of portions of the iron magnetic circuit. This limits the smallest value of capacitance which can be obtained.

As its name implies, the open circuit saturation curves applies to a machine whose terminals are open circuited. If armature current flows, this relationship is altered. For armature currents up to the rated value, the alteration is slight. When currents in excess of this value flow, the magnetic field produced by the armature current begins to increase the magnetic field in some portions of the field poles and decrease it in others. Field distortion lowers the terminal voltage. The effect is nonlinear and not amenable to calculation. Accepted practice is to generate a family of curves such as the curve of Fig. 5 with armature current as a parameter. The generation of saturation curves under load requires specialized equipment, and the results may not apply to transient conditions so an alternative approach to the problem was devised.

It was assumed that the open circuit saturation curve could be applied to all operating conditions if the field current were replaced by some suitable function of the field and armature currents. Experimental evidence indicates that a suitable function could be defined:

$$I_{fe} = I_f - a i_a^2 \qquad (6)$$

$$0 \le i_a \le 2.5 \text{ kA}$$

$$I_{fe} = I_f - b \qquad (7)$$

$$i_a > 2.5 \text{ kA}$$

where the values of a and b are 6×10^{-6} A^{-1} and 44 A respectively. In Eqs. (6) and (7) i_a is the peak armature current reached during the first cycle. Equations (6) and (7) have not been defined for steady-state operation, nevertheless they appear to predict performance in close agreement with the scant data in the literature.[5]

The line marked "theory" on Fig. 6 represents a prediction of the capacitance of one type 362 traction motor plotted as a function of reduced field current. This line was drawn from the open circuit saturation curve, the known value of J and Eq. (5). The experimental points represent the result of a number of oscillatory tests using a circuit similar to that of Fig. 2. The data was obtained by measuring the period of oscillation and is plotted against the reduced field current defined in Eqs. (6) and (7). Armature currents reached during these tests ranged from a few hundred to 5 kA. This scheme allows

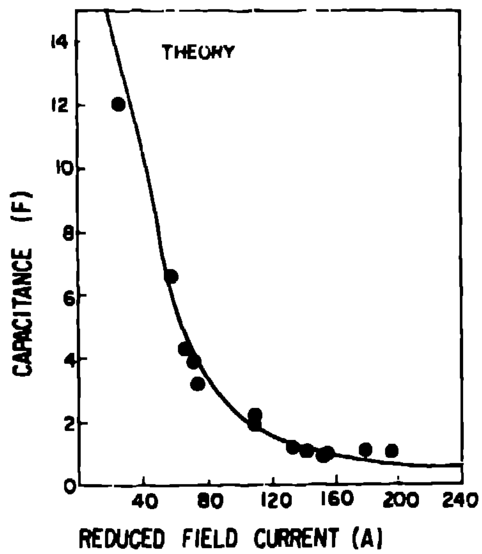

Fig. 6
Capacitance of one type 362 motor as a function of reduced field current.

prediction of the capacitance of a traction motor with sufficient accuracy for design of the 20 MJ test facility.

The last significant circuit parameter which was determined by this series of experiments was the internal inductance of the armature circuit. This parameter (L_a) was measured as a function of field current and is shown in Fig. 7. The measurement was made at 20 Hz and zero armature current. As the field current is increased the armature inductance decreases as a result of saturation of the iron magnetic circuit. The effect of armature current on this inductance is measured by comparing the armature current following a switching transient with the initial coil current. The energy loss during the switching transient is chiefly determined by the armature inductance. The relationship between the armature and coil current i_c is:

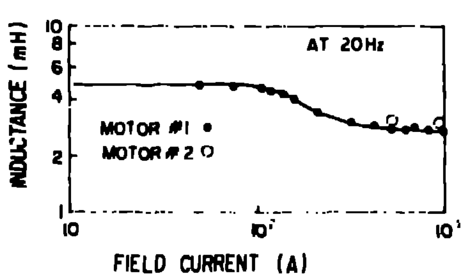

Fig. 7
Armature inductance of one type 362 motor as a function of field current, measured by inductance bridge at 20 Hz.

$$i_a = i_c \left[\frac{1}{1 + 2L_a/L_c}\right]^{1/2} \qquad (8)$$

where L_c is the coil inductance. In deriving Eq. (8) the arc voltage of the switch is assumed to be a constant. In many tests the coil and armature inductances were comparable and the current reduction predicted by Eq. (8) was significant. Figure 8 is a comparison of observed and predicted values of armature current based on Eq. (8) and Fig. 7. The evident agreement is a strong indication that the armature inductance is a function of the field current alone.

While tests were run to 5 kA, it was found that severe arcing at the commutator occurred above 3 kA. This is undoubtedly the consequence of saturation of the interpoles which prevents completion of commutation while the commutator segment is under the brush. The range of sparkless commutation may be extended by the use of a more resistive brush but this has not yet been confirmed experimentally.

Conclusion

Traction motors have been operated in parallel to form a power supply with the same characteristics as a capacitor bank. The maximum current per machine without damage to the commutator is 3 kA. A simple scheme for characterizing the machines has been formulated and verified by test. On this basis it is concluded that a number of traction motors can be combined to form a large pulsed power supply.

Acknowledgments

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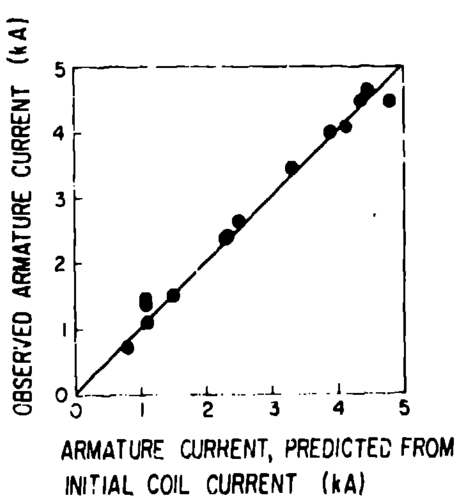

Fig. 8
Comparison of observed and predicted maximum armature current.

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