ROTATING MACHINERY FOR USE IN PULSED POWER

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Presented at the
4th IEEE International Pulsed Power Conference
Albuquerque, New Mexico
June 6-8, 1983

Publication No. PN-84
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(Invited Paper)

Summary

In summary, for pulse times longer than one second, conventional rotating electric machines are suitable. These include commutated dc machines on the lower end of the energy scale (~ 1 MJ) and power system alternators on the upper end (hundreds of MJ). The intermediate area (tens of MJ) is not as well covered, but there are some synchronous machines in this range which might be effectively utilized in a pulsed mode. Voltages for such systems range from several hundred for the dc machines to $\sim 13{,}800$ for the power system alternators, while output currents are in the range of one to ten kiloamperes.

Subsecond pulses typically require more specialized machines. Pulses from tens to hundreds of milliseconds in duration can be supplied by homopolar generators, while submillisecond pulses are in the domain of compulsators. Although homopolar machines storing as much as 500 MJ have been built, most modern machines are in the range of 5 to 20 MJ stored at 50 to 100 V. Output currents are in the 1 to 2 MA range. Compulsators are among the newest of the rotating machines, having been invented in 1979. As a result, very few have been built, but their extremely high power outputs in the submillisecond pulse range combined with their self-switching characteristics make them extremely attractive for future development as pulsed power supplies.

Introduction

Pulsed power requirements are generally characterized by energy, voltage, current, pulse width and pulse repetition rate. If the time between pulses is many times longer than the pulse width, energy storage techniques become attractive as a means of reducing prime power requirements of the pulsed power system. This is especially true as the energy required per pulse increases.

Practical energy storage systems have been built utilizing electrostatic, magnetic, inertial, and electrochemical energy storage techniques. Table 1 compares the status of these four energy storage technologies. Rotating machines using inertial energy storage for power averaging offer an attractive combination of high energy density and current capability (ratio of source voltage to internal impedance) in addition to relatively long storage times. For applications where these parameters are of concern, rotating machines can often provide a compact, economical solution to the pulsed power problem.

Rotating electrical machine technology is typically divided into alternating current (ac) and direct current (dc) categories and although these terms have less precise meaning in pulsed mode operation, the distinction between machine configurations still holds and is used here. Conventional and specialized rotating machinery in both categories are discussed.

DC Machines

The conventional dc rotating machine is the commutated dc machine (Fig. 1a) typically used in variable speed drives with solid-state control and for extremely heavy load applications such as locomotive traction motors. A simpler, lower impedance dc machine is the homopolar machine (Fig. 1b) which has in recent years been developed specifically for pulsed power applications.

Commutated DC Machine

The commercial availability of both new and rebuilt commutated dc machines makes them potentially attractive for one-of-a-kind pulsed power installations. Also, the fact that these machines utilize wound rotors as opposed to the single-turn rotor of the homopolar generator (described in the next section) means that higher voltages are typically available from

Table 1. Present Capability of Energy Storage Systems

Storage Technique	Storage Device	Typical Module Size	Energy Density (kJ/kg)	Power Density (kW/kg)	Typical Pulse Width	Typical Module Voltage (volts)	Typical Source Impedance (ohms)	Typical Short Cir Current (kA)	Typical Storage Time (sec)
electric field	CAPACITOR	15 kJ	0.2	8000	0.1-0.5 ms	10000	0.212	50	1000
magnetic field	INDUCTOR								
	room temp.	5 MJ	1.3	324	1-5 ms	3000	0.002	1500	0.45
	cryogenic	3 MJ	3.1	1000	1-100 ms	5000	0.005	1000	1.2
	superconducting	500 kJ	2.2	50	>1 ms	10000	3142	3	10^{12}
inertial	FLYWHEEL								
	dc generator	0.8 mJ	0.32	0.3	>1 s	1800	0.0142	1	100
	homopolar generator	6 mJ	8.5	70	0.1-0.5 s	100	10^{-5}	2000	415
	alternator	185 MJ	1.3	0.7	>1 s	6900	1.12	6	3000
	compulsator	200 kJ	3.8	250	0.1-2m s	6000	0.084	71	254
electrochemical	BATTERY	5 MJ	200	0.3	1 s	12	0.02	0.5	10^8

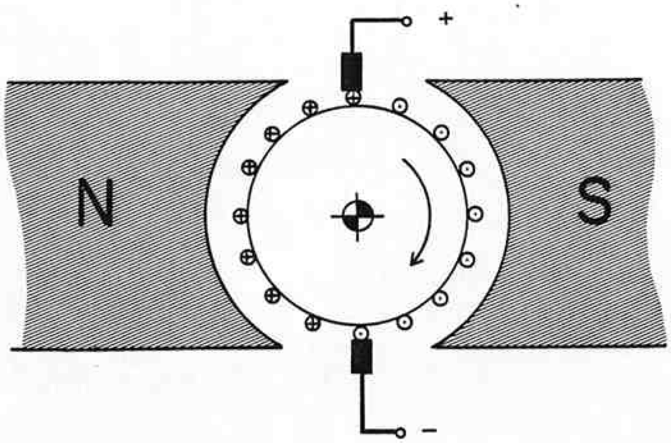

Fig. 1a. Commutated dc machine

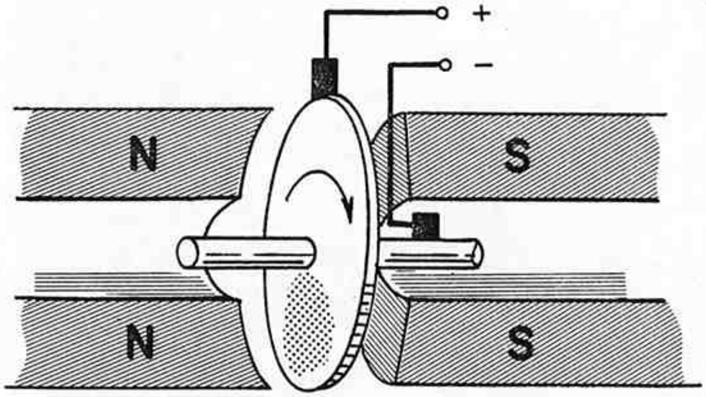

Fig. 1b. Homopolar machine

the commutated machines. Most of the difficulties of pulsed operation of commutated dc machines center around the performance of the commutator itself. The function of the commutator is to reverse the direction of current in the rotor windings as they pass from under one stator pole to another. In order to accomplish this change in current direction, the brush/-commutator system must develop a voltage drop equal to the product of the time rate of change of current (dI/dt) and the inductance of the current loop. This establishes a limit on acceptable levels of dI/dt which may be expressed as the product of current and rotor speed. A typical value for a modern, well designed commutated dc machine with commutating poles and compensating windings is 2×10^6 A-rpm.[1]

The commutator is also the source of another limitation on machine performance. The spacing between commutator bars in combination with brush surface speed limits and the presence of ionized air and/or carbon dust limits the voltage which can be generated between bars. A practical limit is 30-40 V/bar,[2] which limits most large commutated dc machines to 1-2 kV terminal voltage. Wound rotor construction limits these machines to rotor surface speeds below 150 m/s for most applications.

Homopolar Machine

The homopolar machine, since it is the only dc rotating machine without a commutator, effectively avoids most of the problems associated with the commutated dc machine. In the homopolar machine, the entire monolithic rotor acts as the armature conductor, resulting in extremely low internal impedance (<10 μΩ). This at least partially offsets the inherently low terminal voltage of the homopolar machine. Normal machines using room-temperature copper-wound field coils and ferromagnetic rotor and stator materials usually develop voltages in the range of 50 to 100 V per rotor, while the use of superconducting excitation and nonferromagnetic rotors can raise this value by a factor of 2 to 4.

The low internal impedance and rugged construction of the homopolar machine allows it to operate at very high currents (1 to 2 MA). For machines with ferromagnetic rotors, typical short circuit current rise times on the order of 20 ms are realizable, while the machines with nonferromagnetic rotors can reduce this value by two orders of magnitude. Sliding contact technology presently limits homopolar rotor surface speeds to between 220 and 250 m/s.

AC Machines

The conventional ac machine, the synchronous machine or alternator, is by far the most highly developed of the rotating machines because of its use in central plant generating stations. It combines the high voltage capability of the wound armature with greatly simplified current collection. A recent development, the compensated pulsed alternator or compulsator, is essentially an alternator with reduced internal impedance, which is more suitable for fast pulse (1 ms) generation.

Synchronous Machine

In its simplest form the synchronous machine consists of a winding rotated in a magnetic field (Fig. 2a), but in most large machines the armature winding which generates the output power is stationary while the field winding rotates (Fig. 2b). This arrangement eliminates the need to pass the high output power of the generator through sliding contacts.

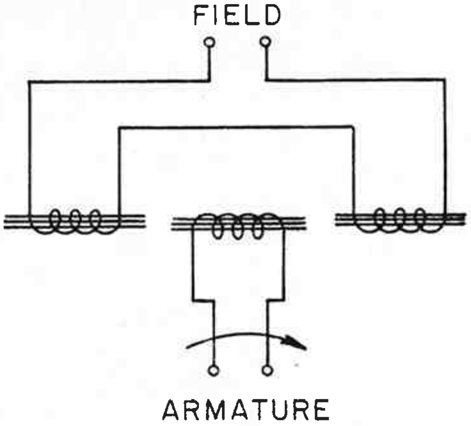

Fig. 2a. Simple synchronous machine

Although most modern power system alternators operate in the 10 to 15-kV output voltage range, successful machines have been built operating in the 30 to 40-kV range. However, most power system alternators are designed to have a fairly high internal inductance[3] (~1 to 2 mΩ) in order to limit their peak (fault) current and consequently their pulsed power output capability.

Conventional alternators have been used in the pulsed mode to drive resistive loads (arcs) with alternating currents,[4] but they are typically used in conjunction with rectifiers to produce an extended dc pulse.[5] Pulse durations of one to a few seconds are normal during which generator frequency is usually reduced from ~90 Hz to ~60 Hz. Field control is often utilized to maintain constant output voltage during the pulse.

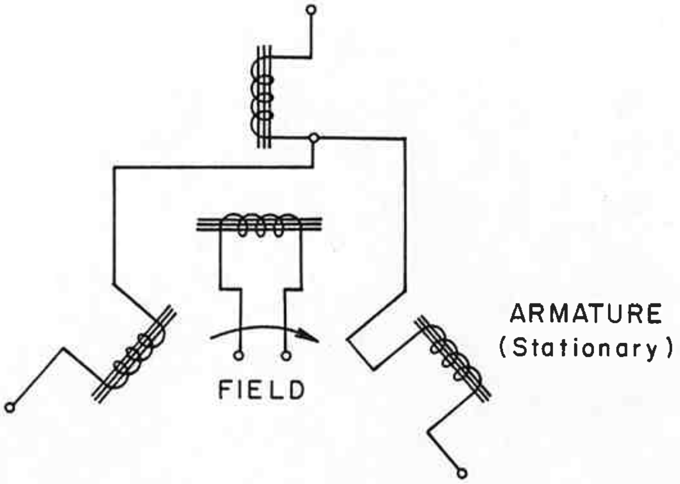

Fig. 2b. Conventional power system alternator

Compulsator

The compulsator differs from the conventional synchronous machine in that it has an additional stationary winding in series with the rotating armature winding (Fig. 2c).[6] The function of this additional winding is to compensate the internal inductance of the machine at one point in the cycle (usually at peak voltage) through the principle of flux compression. Figure 3 shows the relationship between voltage, inductance, and output current for a typical compulsator design. Both the rotating and stationary windings are of the "air-gap" type, adhesive bonded to the smooth surface of the laminated steel rotor and stator through the ground plane insulation, rather than fitting into slots as in conventional machines. The air-gap winding reduces the leakage inductance of the winding and at the same time reduces the gap between the rotating and stationary windings at the point of minimum inductance. However, the adhesive joint inherent in this air gap winding is the source of one of the primary performance limitations of the compulsator. The shear strength of the joint under combined loading limits the peak deceleration torque which the windings can apply to the rotor inertia. This combined with the operating speed limit imposed by wound rotor construction results in a peak power limit of around 3 to 4 GW/m^2 of rotor surface area. Although only a few have been built, compulsators appear to work best in the range of 6 to 15 kV and typical inductance variations which can be achieved range from 25:1 to 200:1. Pulse times (FWHM) in the range from 300 μs to 2 ms appear to be realizable.

Since the compulsator only slows down a small fraction during a pulse, as opposed to stopping as the homopolar generator does, it is inherently bulkier than the homopolar machine for the same energy per pulse. Typical speed variation per pulse for the compulsator is from 5 to 20 percent. On the other hand, this smaller speed variation makes the compulsator easier to drive with most prime movers and its natural "self-switching" due to the cyclical inductance variation make it more suitable for burst or continuous operation in the repetitive-pulse mode.

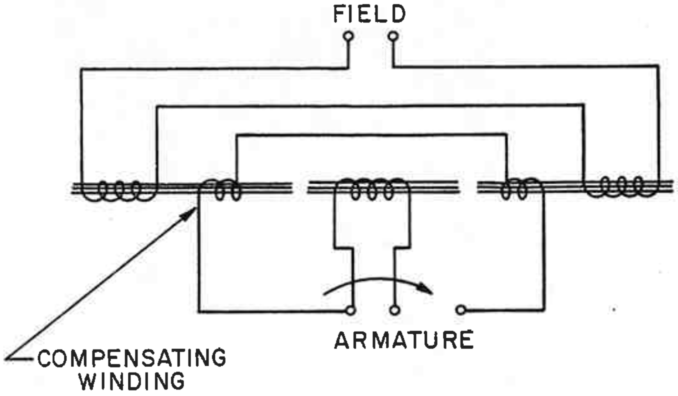

Fig. 2c. Compulsator

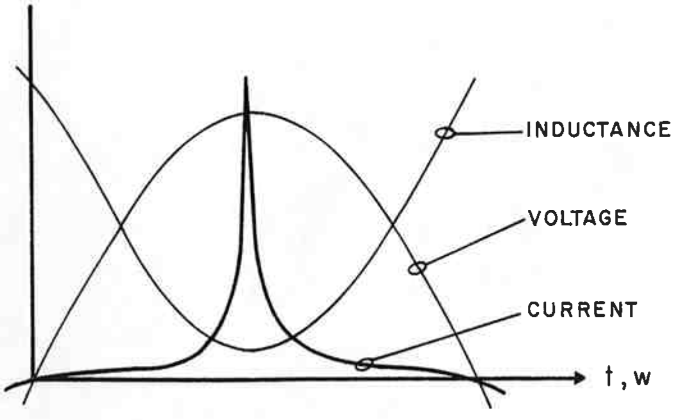

Fig. 3. Compulsator output characteristics

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