DEVELOPMENT OF INDUCTIVE STORAGE FOR GENERATION OF HIGH VOLTAGE PULSES

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ABSTRACT

Traditionally, the generation of very high power electromagnetic pulses, applied to the production of intense relativistic beams, dense hot plasmas and other transient phenomena has depended on the capacitive energy storage. Growing needs for increased energy capability of the generators has led to studies[1] and proposals[2] to demonstrate the feasibility of using magnetic storage systems with high voltage, power-multiplying stages as means of satisfying these needs. Most recent progress in the development of the elements for such high power systems is presented. Examples demonstrating the integration of inductive storage and high voltage technologies, to achieve high power output are considered.

I. Introduction

The principles governing the generation of pulsed high voltage output using magnetic storage as a primary source of energy have been described in many publications.* Some of these propose to use inductive storage for generation of pulses with energy ranging up to 1 MJ, utilizing capacitors in the final stage to achieve power output of the order of 0.1 TW.

Recently, advances have been made in the development of inductive storage components and systems, including the inertial-inductive systems, indicating that magnetic storage can be exploited for the generation of high power, large energy, pulses. The advances in the component development for megavolt operating range as well as the progress in the development of pulse systems is discussed. The opening (current interrupting) switches are emphasized because of their critical role in the generation of high power. Switches, as well as other components, are discussed mainly in terms of the limitations arising from the system aspects as they are understood at this time.

* A survey of methods of energy storage for pulsed power applications has been presented by Nasar and Woodson[3]. Their survey includes an extensive list of references.

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Traditionally, the generation of very high power electromagnetic pulses, applied to the production of intense relativistic beams, dense hot plasmas and other transient phenomena has depended on the capacitive energy storage. Growing needs for increased energy capaoility of the generators has led to studies1 and proposals2 to demonstrate the feasibility of using magnetic storage systems with high voltage, power-multiplying stages as means of satisf'ying these needs. Most recent progress in the development of the elements for such high power systems is presented. Examples demonstrating the integration of inductive storage and high voltage technologies, to achieve high power output are considered.

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II. Principles of High Power Generation

Inductive storage of energy requires a source of current, I, which provides an energy of $(1/2)LI^2$ in the inductor of inductance L. The choice of L and I values depends on the system requirements, such as pulse length and voltage level. In applications where pulse energy must exceed 1 MJ level, rotational machinery[4] or magnetic compression[5] can serve as a source of current, typically ranging from tens of kiloamperes to megamperes. An example of an inductive storage system used for charging of a capacitive load, C_L, is shown in Fig. 1. Initially the current is provided by a homopolar generator, represented as a large capacity C_o. The circuit is completed through an inductor L_o and through the fuse (opening switch) represented as a variable resistance R(t). Initially low resistance of the fuse is made to increase by some

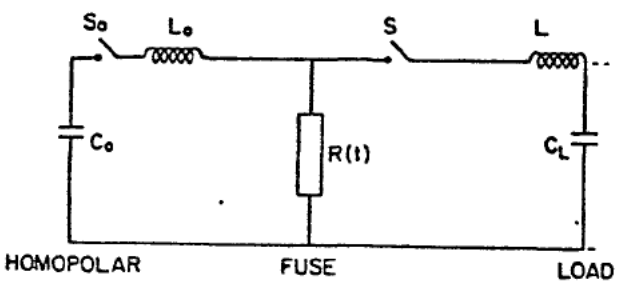

Fig. 1. Inductive storage system charging a capacitive load.

means to a large value, interrupting the flow of current. For sufficiently large values of C_o, the voltage, V, that develops across the fuse is L_o (dI/dt). Because the inductive voltage must be supported by the resistive drop in order to realize the maximum voltage gain over that initially across C_o, the fuse resistance must reach, in time ΔT, a value $R > L_o/\Delta T$. After closing the switch S, an additional condition on the value of R(t) is imposed by the inductive-capacitive load chosen in the example of Fig. 1. This constraint on R is summarized in Fig. 2 which shows the effect of the value of R and of the circuit parameters of Fig. 1 (for the case when $C_o \gg C_L$ and $L_o \gg L$) on the efficiency of energy transfer and on the voltage that can be developed across C_L. The relationships given in Fig. 2 are useful for estimating energy transport in those types of high power generators where low inductance capacitors or transmission pulse lines are used. Although these relations were derived for step-function changes in resistance, they are quite accurate for more realistic cases. For example, the data points in Fig. 2 are calculated values based on accurately modeled resistance of an exploding foil fuse.[6]

It is not likely that a single circuit breaker or fuse can provide sufficiently large change in resistance to satisfy the needs of inductive storage system designers. It is for this reason that simple circuits such as the one shown in Fig. 1, has evolved in two directions. Use of more than one loop with an effective arrangement which puts several fuses in series has been tested.[1] A more promising approach is being employed in large systems where several current interruptors (circuit breakers and fuses) are staged in parallel.[7] Significant

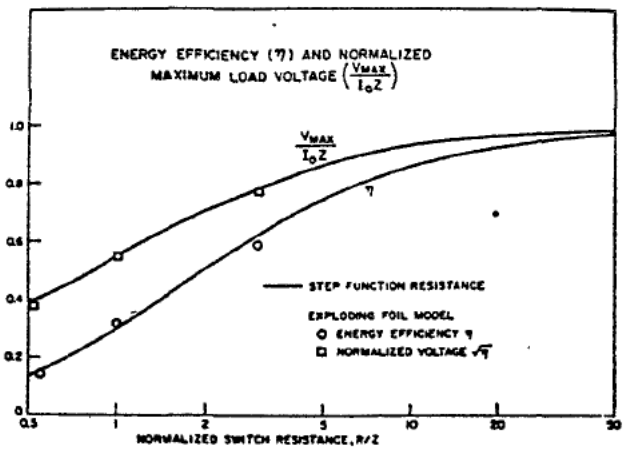

Fig. 2. Efficiency $\eta = L_0 I^2/C_L V^2$ and load voltage for the circuit of Fig. 1.

implication associated with the latter approach is that, in simple circuits derived from that shown in Fig. 1 all switches must be capable to withstand the voltage developed by the switch in the final stage and the total parallel resistance must be consistent with relationships in Fig. 2. To overcome partly these problems, use of transformers has been proposed[2] and used.[8]

III. Current Interruption

Current interrupting switches can be divided in two groups. In the first group are those switches which depend on the mechanical disruption of conductors, such as separation of electrodes (circuit breakers) and cutting of conductors (using explosives). Because at high power operation an arc is formed in the growing electrode gap, some means of extinguishing the arc is always employed. The most frequently employed methods depend on the extinction of the arc by cooling through the contact with the mass of cold fluid or with the walls. Another method employs, sometimes in combination with cooling, auxiliary circuits for reducing the arc current to near zero level for sufficiently long time to allow the interelectrode gap to recover to the point of being able to hold off the full voltage across the switch. One of the most important advantages of circuit breakers and exploding switches is the ability of command firing. This allows the switch to carry current without any energy dissipation for unlimited time, unlike the fuses discussed below.

In the second group are those switches that interrupt the flow of current by depending on the increase of resistivity either through heating or use of magnetic and/or electric fields. The most important switches in this group are the exploding wires or foils (fuses). The amount of heating energy necessary to interrupt the current, for a given fuse material and surrounding medium, increases as the length of time to explosion increases.[9] For this reason, there are two main functions that fuses normally perform in power amplifying inductive storage systems. First, they are used as auxiliary elements that direct the current away from circuit breakers and exploding opening

switches during the critical time when the latter are not ready to sustain the applied high voltage. Their second function is to provide very rapid voltage build up across the load, made possible by much more rapid resistance increase than can be provided by mechanical switching.

The disadvantages associated with the circuit breaker used in the inductive storage systems are the relatively low hold-off voltage and slow recovery rates. To overcome this difficulty and to retain the 5-10 msec opening time, that is typical of conventional circuit-breakers used in the electric power transmission, a fast breaker (with opening time of about 1 msec) is being developed at NRL to be used in a manner similar to that being investigated by ITE-Imperial, Inc.[10] Using the fast circuit breaker in series with the conventional slower unit and synchronizing the opening of the former with extinction of current in the conventional unit would permit the fast breaker to open without arc generation. Thus, the interruption of the current by the slower breaker can occur under the condition of low voltage across the electrodes (using, if necessary, an auxiliary parallel fuse). The high voltage hold-off capability is then insured by designing the "open" configuration of the fast breaker to conform with the high voltage requirements of the system. In the ITE-Imperial investigation a vacuum bottle in series with the circuit breaker is used. The NRL approach will use a fast breaker with an explosively driven opening of electrodes with the high pressure SF_6 providing the 0.5 to 1.0 MV insulation.

Another recent development that promises to have an important impact on the development of high power inductive storage systems is an explosive current interruptor.[11] Although operating on a principle similar to that of a circuit breaker, 100 μsec opening times have been achieved.

The limitations of various extent that are encountered when fuses are used in the induction storage systems arise from the need to dissipate energy in the switch from low restrike voltage and from difficulties in reaching high values of the final switch resistance. To overcome the first problem, command switches that do not dissipate significant energy while in "closed" position are used to carry the current generated in the primary stages of the storage system. Depending on the type of the command switch used, the risetime of the current transferred to the fuse can range from 5 msec (for conventional circuit breakers) to 100 μsec (for explosive switch). The reduced time during which the current flows in the fuse reduces the amount of energy that must be deposited in order to interrupt the current.[9] Such current transfer by staging the opening switches has been recently demonstrated in a 150 kJ experiment.[7] To increase the final fuse resistance and restrike voltage, tamping and chemical reactions have been employed recently very successfully.[6] The improvement of the efficiency of energy transport in charging of capacitors or pulse lines due to the increase in resistance (by a factor greater than 4 over the standard values reported in the literature)is evident from Fig. 2. The significance of the increased restrike voltage (by a factor greater than 3 for charging time of 200 μsec, over the values summarized by Braunsberger,

et al[9]) together with increased final resistance lies in lowering the energy required to open a switch to a given design voltage by an amount approximately proportional to the reduction in the switch length, as well as in reducing parasitic inductance of the switch.

IV. Inductive Storage Systems

The advances in primary storage systems (rotational, and magnetic compression devices), in opening switches (circuit breakers and fuses) and in the development of such interface elements as transformers, peaking capacitors and pulse transmission lines has led to implementation of inductive storage for production of high power pulses. At present, submegajoule output pulses at power level near 10^{11} W have been achieved.[8] These advances together with the growth of the high voltage technology, as for example applied to the design of large pulser systems[12], will lead to the development of the inductive storage systems for applications that require very large energy and power output such as inertial fusion research.

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