

## INDUCTIVE STORAGE - PROSPECTS FOR HIGH POWER GENERATION

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Abstract

Recent progress in the development of key elements of high power inductive storage systems makes it possible to generate high power pulses using energy storage systems (other than explosive generators) that include single-pulse inductive systems, hybrids (inductor/pulse line<sup>1</sup> and inductive devices for steepening of the capacitor output<sup>2</sup>) as well as inductive systems for generation of high power pulse trains.

Prospects for further development of opening switches and storage systems suggest potential near-term payoff. Improvements based on such developments can be expected to impact system efficiency, compactness and operational convenience.

Introduction

Magnetic storage of energy for applications, requiring large amounts of energy, is preferable to capacitive storage because of its characteristically high energy density, some  $10^2$  to  $10^3$  times higher than electrostatic energy storage. S. A. Nasar and H. H. Woodson<sup>3</sup> have surveyed the methods of energy storage for pulse power applications, concluding in 1975 that inductive storage has great potential, but that it has not been used extensively in the past. Specifically, the problem of opening switches is indicated, with the prediction that high current, high voltage opening switches will evolve from power circuit breaker technology.

This paper discusses the status of opening switches and their relation to development of large inductive storage systems designed for loads requiring high power input, and for systems with specialized output, such as pulse trains with short pulse-to-pulse separation. Prospective development of one new type of opening switch, a plasma switch, is also discussed to illustrate further possibilities for improved performance of these systems, including repetitive capabilities.

Opening Switches

The requirements imposed on the opening switches in inductive storage systems, i.e. high resistance of the opened state, high inductive electric field, high restrike voltage with the attendant rapid recovery rate and fast opening time were discussed in Ref. 4 in relation to the circuit parameters. It can be seen from the analysis of the energy transport from the inductor,  $L_0$ , to the load that the above switch characteristics strongly influence the pulser's efficiency. This is because the efficiency of transfer from one switching stage to a succeeding one (as is necessary to do in systems with large power amplification factors<sup>4</sup>) is given by

$$\frac{W}{W_0} = \left[ 1 + \frac{R}{R_0} + \frac{L}{L_0} \right]^{-1},$$

where  $W/W_0$  is the ratio of energy transferred to the next stage (characterized by resistance,  $R$ , and inductance  $L$ ) to the stored energy<sup>5</sup>. The magnitude of the effect can be estimated from  $W/W_0$  by noting that the inductance  $L$  of the next stage is always

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approximately proportional to the inductive or restrike electric field. In high power systems using several opening switch stages small improvements in the value of these parameters improves the transfer efficiency substantially. In addition to the circuit efficiency, the transfer time, determined by such constraints as the recovery rate must also be short, so that non-recoverable energy losses, such as vaporization energy in the case of fuses, represents acceptably small portion of  $W_0$ .

Figure 1 maps a variety of opening switches in terms of their dependance of the restrike field (noting that it is that field rather than the inductive electric field that usually dominates the switch length) on the recovery time,  $T_R$ , needed to achieve the corresponding magnitude of the field. By normalizing  $T_R$  to the time,  $T_0$ , i.e., to the time that the switch conducts before interrupting the current,

the switches are seen to fall into two categories. Those designed to perform with (nearly) unlimited conduction time are plotted using values of  $T_0$  of the specific experiments which provide the above restrike field data.  $T_0$ , of course, cannot be shorter than the electrode separation time. In these cases, the electrodes can conduct over much longer time. The lower shaded region corresponds to switches operating with  $T_0$  longer than used in published experiments. It, thus, delineates the parameter space accessible to the inductive storage designer. The second category of switches are those with limited conduction time. Such limits arise from a constraint specific to a given type of switch. Opening switch controlled by an external electron beam is an example of the limit on the conduction time arising from the constraints on generation of the electron beams. For reference, Figure 1 also shows the hold-off voltage of closing switches, emphasizing the typically higher electric field available for the pulser design.

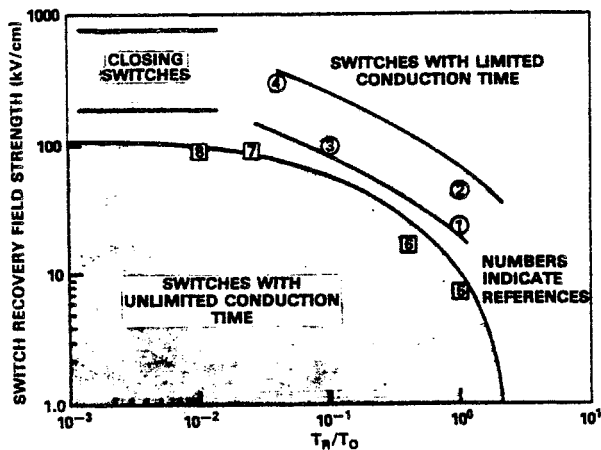


Fig. 1. Parameter space outlining the performance of opening switches. The following switches are mapped: 1-foil fuses, 2-crossed field switch<sup>6</sup>, 3-plasma switch with its prospective development described in this article, and electron-beam controlled high pressure gas switch discussed in ref.7, 4-erosion switch<sup>8</sup>, 5-magnetically operated mechanical breaker<sup>9</sup>, 6-explosively driven switch<sup>10</sup>, 7-SF<sub>6</sub> circuit breaker<sup>11</sup>, 8-vacuum breaker<sup>12</sup>.

The ability of switches, with unlimited conduction and operating at high current levels, to open in a time about 100 times shorter than that of conventional circuit breaker<sup>9,10</sup> has recently provided a necessary technology for developing inductive storage pulsers based on rotational energy storage with typical slow rise time.

Figure 2 is a schematic of a plasma switch\* with a potential to combine fast opening and recovery times and high hold-off electric field. It is based on use of dense plasma flow (at  $10^7$  and  $10^8$  cm/s) generated by external plasma gun<sup>13</sup>. When the plasma is in the region between the electrodes, conduction of high current is possible. As the plasma exits the electrode gap, interruption of current ensues. Appropriate commutating circuit can be expected to provide very fast voltage recovery associated with that of vacuum breaker using mechanical separation of electrodes<sup>12</sup>. Promising performance of this switch, as well as that using high pressure gas

\*Concept of the switch by P. J. Turchi,  
U. S. Patent Application (1979)

with electron beam controlled conduction<sup>7</sup>, must await experimental evaluation to assess their use in efficient storage systems.

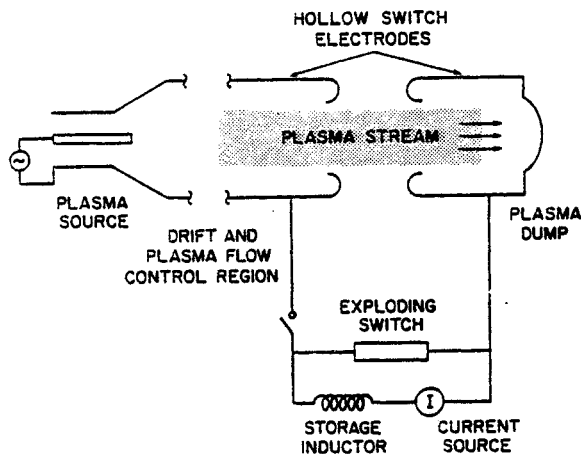


Fig. 2. Schematic configuration of plasma switch.

### Conclusions

The development of the opening switch technology has now progressed sufficiently to a point that efficient inductive storage modules with output power exceeding  $10^{11}$  Watts can be built<sup>14</sup>. Derivatives of such systems producing pulse train output at  $10^{10}$  Watt with pulse-to-pulse separation equivalent of  $10^5$  Hz have been demonstrated<sup>15</sup>. As a result of this progress, large storage systems can be designed for use with inertial current sources that are necessary for low cost designs.

The major obstacle to wider use of the large inductive storage is the necessity to replace switches after each opening action. This suggests that the development of the opening switches that can be operated many times, in analogy to circuit-breakers used in transmission of the electric power, will be emphasized in the future. The new switches will, likely, evolve from combining desirable features of several switch types and lead to system designs superceding in all respects the capabilities of present capacitive pulsers.

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