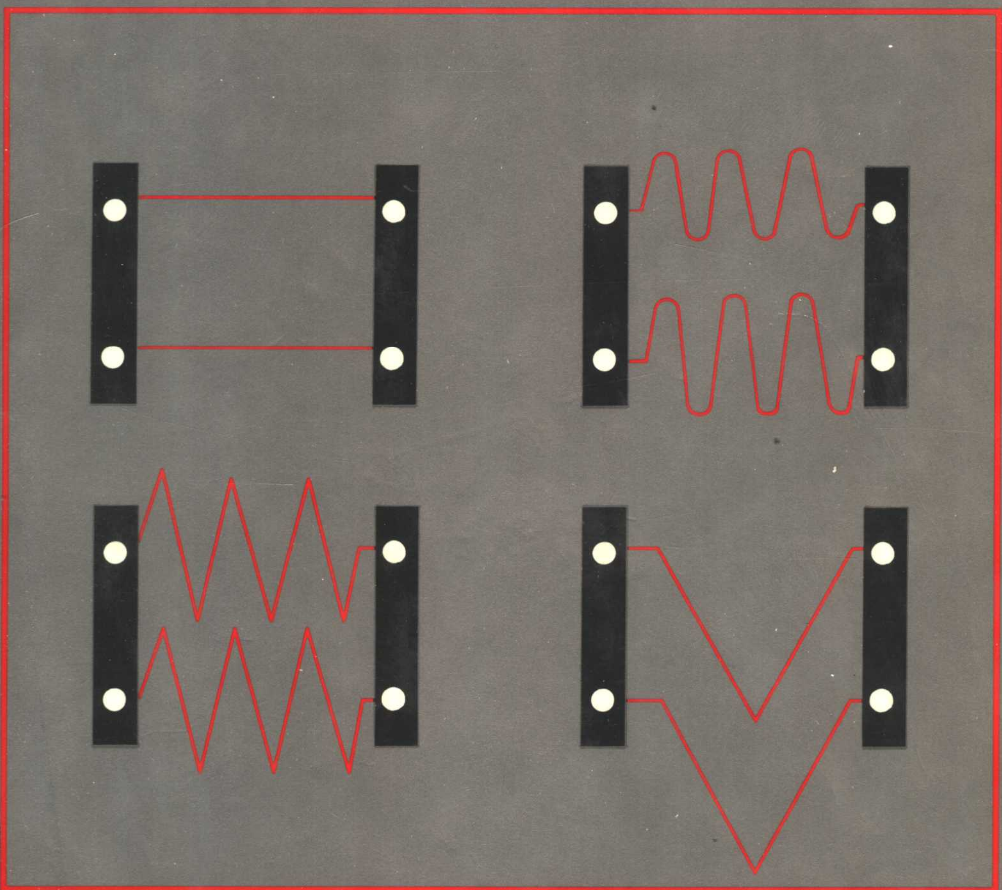
HIGH POWER SWITCHING



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Preface

Pulsed power technology is an area of rapid development propelled by potential benefits expected from thermonuclear fusion energy sources, from industrial and military applications of larger lasers, from the ever-increasing sophistication of electric power distribution (and consequently more demanding protection requirement of power lines and equipment), and from a variety of new specialized needs. This technology deals with the generation of very high power electromagnetic pulses, as distinct from the continuous production of power, and with the coupling of pulses to loads. An important segment of pulsed power technology is high power switching. This book deals with switching technology used in applications where pulser output exceeds 10^9 watts. In most cases, such output is a monopulse with current and voltage amplitudes ranging from kiloamperes and kilovolts to megamperes and megavolts. More difficult applications, which use trains or bursts of pulses to drive lasers, microwave sources, and other high power devices, have appeared recently, leading to attempts to extend high power capability to repetitively operated switches. High power switching plays a key role in advancing new technologies, such as thermonuclear energy sources in the civilian sector and technologies such as directed energy beam weapons, nuclear weapon effects simulators, and ultra-high velocity guns in the military sector. Specifically, in each of these sectors there is a need for significant improvements in closing switches and for continuing the development of new opening and repetitively operated switches that would lead to less costly and more reliable, efficient, and compact pulse power systems.

This book is intended to serve as a source of information on existing types of high power switches, and on new switching concepts currently being developed or those that are in speculative stages. The book consists of two major chapter groups in addition to the introductory chapters and Appendix. One group (Chapters 3 through 6) deals with closing switches, and the other group (Chapters 7 through 10) deals with opening switches and includes a discussion of repetitively operated switches. Typical switch applications are illustrated where appropriate. The first two chapters consist of a tutorial discussion of general switching principles and of circuits employing high power switches. The discussion is limited to idealized circuits to allow the reader to relate switch performance to that of the entire pulser without being burdened with the intricacies of other considerations. The last chapter conveys peripheral information related to electromagnetic noise problems and considers the important safety aspects of switch operation. The book includes basic physical principles, engineering data, and scaling laws that permit the reader to assess both the applicability of a given switch in specific areas of interest and the risks versus potential pay-off associated with future development of given switch types or pulser systems. The chapters contain many references to sources for additional information.

In concept, *High Power Switching* is a reference surveying many types of switches and discussing their operating principles and performance. In numerous instances, examples of applications have been provided to demonstrate their potential, as well as to emphasize the interdependence of the switches, the pulser system, and the load. The field of high power switches continues to develop as new applications of pulsed power arise and new concepts emerge to overcome the older technological bounds. Therefore, throughout the book, potential new directions for development are highlighted.

At this time (1987), no convenient, accessible monograph is available that surveys both closing and opening switches. Some valuable material on closing switches has been collected in such works as those of V. S. Komelkov[1] and T. Burkes[2], which are limited, not easily accessible editions. *Pulse Power Notes Series*[3] should be noted by those interested in switches as well as in other components of high power pulsed sources. None of the published compendia includes an extensive exposition of opening switch concepts and technology; limited discussion of opening switches appears in publications such as Mesyats[4]. Relevant material on both types of switches is available in books dealing with pulse power generation and application. Some texts deal with specialized applications of switches, for example, *Current Interruption in High Voltage Networks*[5], edited by K. Ragaller, dealing with electric power line circuit-breakers. And, of course, there are published proceedings of many conferences, workshops and special-issue periodical journals. These however, are not widely available and usually take for granted the specialized technical background of its audience. This book attempts to remedy, in part, this situation and devotes the entire second group of chapters to opening switch technology, including its most recent embodiments. Both one-shot switches that are destroyed as a result of the opening action and those that can be reused are described.

The author and his colleagues at the Naval Research Laboratory were key

contributors to the development of some of the switches discussed in this volume. These colleagues have generously provided some written material for Chapters 5, 8 and 9. Other switch types have been developed elsewhere, and in many cases, illustrations and performance data have been included in this book with permission of several publishers, for which I am very grateful.

I am also very grateful to several colleagues, known experts in pulse power technology, for critical reviews of the various chapters in the book. I would like to thank R. E. Pechacek for consultation regarding the material in Chapter 3 and for the review by D. Hinshelwood that raised significant points subsequently incorporated into Chapter 4. In reviewing Chapter 5, J. D. Shipman wrote in his comments to me that "it would have been very nice to have had material such as this available when we started out." This comment was extremely encouraging and helpful in my perserverance with the manuscript. R. A. Miller provided an invaluable critique of Chapter 6, as well as some material for this chapter. R. Dethlefsen reviewed Chapter 7 from the viewpoint of an expert on electrical power switchgear. W. H. Lupton's knowledge of exploding wires and fuses led to many discussions in preparation of Chapter 8. R. J. Commisso supplied very useful material and discussion for Chapter 9 and R. J. Meger ably reviewed this chapter. Finally, P. J. Turchi provided the critique and made suggestions for improving Chapter 10. The overall review of the book and the continuing encouragement with this project by Prof. W. J. Sargeant of the State University of New York at Buffalo is greatly appreciated.

I am also greatful to various persons within the Naval Research Laboratory as well as outside for programmatic support. Dr. G. Cooperstein, Dr. S. L. Ossakow, and Dr. T. Coffey are thanked for their support and their enthusiasm for the various pulse power science and technology programs at the Naval Research Laboratory. This support has resulted in many switch developments discussed in this book. Dr. T. Coffey is especially to be thanked for his early recognition of pulse power technology as the key to advances in many fields of national interest and his active support of these programs. Mr. P. Haas and Mr. J. Farber of the Defense Nuclear Agency were the primary supporters of the pulse power programs both at the Naval Research Laboratory and elsewhere over many years. These individuals and many others in various laboratories and institutions had the foresight to allow many of the concepts in switching to come to fruition and those results are reported here. I feel especially indebted to J. C. Martin of the Atomic Weapons Research Establishment in Great Britian for his early perspective on switching technology that stimulated much of the high power switch development reported here. This book draws on the work of

many other individuals and their contributions are reflected through the references. Personal contacts with many of them were invaluable in the preparation of the manuscript for *High Power Switching.*

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Contents

1
Introduction

SWITCHES IN TECHNOLOGY

Growth of electric power distribution networks in the first part of the twentieth century stimulated the improvement of network switching, as well as the development of switches required to operate electrical equipment at ever increasing power. It became necessary to develop the technology not only for switchgear to control power distribution, but also for protection against abnormally high power surges, which became imperative in order to protect expensive equipment tied to power lines and to assure that electric power service would be restored in the shortest possible time. While the early electric power networks required protection at low power levels, the post-World War II period witnessed the development of power grids with currents above 100 kA and transmission voltages of 1 MV level[1]. This required switchgear to handle power levels much higher than 10^9 W. Such technology became a base for the development of switches for applications employing single pulses of current. In this book, circuit breakers, used for electric power transmission and their derivatives, developed for pulse power applications, are discussed in Chapter 7. Because of the widespread use and economic importance of switchgear for power distribution and protection, many detailed treatises dealing with the underlying principles, design criteria and applications have been published, for example, Ref. 2. The need for much higher power switches became evident, as their application in various experimental facilities to drive particle accelerators, intense magnetic field generators, and high power radio transmitters was established. P.L. Kapitsa in the early 1920's used the mechanical energy of an electrical generator rotor to produce short circuit current as a means of inducing 50-tesla magnetic fields[3], which for that time were considered extremely high. Such experiments led to the evolution of more sophisticated power generation as well as of switching techniques required for transferring power pulses to the load. One of the first generators specifically constructed for pulsed applications in high energy particle accelerators (synchrotrons) was a large homopolar generator. It was integrated with the new switching design and, tested at a current level of nearly 3 MA at 100 V output[4].

In the second half of the twentieth century, attempts to exploit new concepts for generating electric power based on nuclear fusion in plasmas confined by strong magnetic fields have been initiated. This has led to development of a new class of closing and opening switches capable of extremely fast switching times. To explore the feasibility of controlled thermonuclear burn for electric power generation, it has become necessary to utilize much higher currents than those produced previously and to reach peak current values in times much shorter than could be provided by rotating machinery or batteries. The shift in switch capability toward higher currents and to shorter pulse times becomes, in time, a foundation of the newly developing pulse power technology, leading to investigations of a large variety of very high power switches capable of handling powers approaching levels higher than 10^{12} W. An example of such a switch is described in Chapter 6 (and shown in Fig. 6-7). It combines the design features of low power switches with techniques of mitigating the strong mechanical forces arising in high power switching. Some switching methods, nevertheless, have proved to be difficult to extend to higher powers. One type of switch, the thyratron[5], could not be adapted to handle power at 10^9 W level and therefore, is not included in the content of this book, even though it is included in other reviews which contain some discussion of pulse power switching[5, 6]. The shift in switch parameters to higher currents was recognized by V.S. Komelkov, who then proceeded to publish in 1970 a significant comprehensive survey of the pulsed high current technology[3], discussing its two major elements—the power sources, such as capacitor banks and inductors, and high power switches.

The broadening of thermonuclear fusion concepts to include attempts for production of electric power using inertially confined plasmas[7] heated by very intense lasers, electron, or ion beams made high power, low inductance switching even more critical to the development of an inexhaustible supply of electric power. Rapid pulsing of input power to heat inertially confined plasmas as well as to provide power sources for various other application placed another requirement on switching technology: repetitive operation at very high power levels[8]. This aspect of switch design, the capability to switch repetitively, is discussed throughout this book, with special attention devoted to it in Chapters 4 and 9.

Technology areas other than those already mentioned continue to stimulate development of high power switches. Intense lasers and charged particle beam generators require power sources with output of 10^9 to 10^{12} W and even a higher power regime[9]. Simulation of x-ray and electromagnetic pulses from nuclear weapons also exploits sources in this regime. Simulator sources and their characteristics are listed, for example, in Table 1.1 of Ref. 10. Invariably, the design of high power sources ends up with some part of the system utilizing spark gap switches. This type of switch is most commonly used in high power systems. A large section of this book is, therefore, devoted to various spark gap designs. Gaps with gas, liquid and solid insulation between the electrodes are described in Chapters 3, 5, and 6, respectively. Further applications, such as propulsion of projectiles by strong magnetic fields[11] (e.g., to simulate collisions of meteorites with spacecraft or to produce super-high pressure pulses) constitute other examples of the high power switches, which must handle very large currents in the millions of amperes.

The phenomenon of switching is not limited to man-made devices—it also appears in nature. Lightning discharge represents, in terms of scale, the largest closing switch. It is used by nature to discharge the electrified earth-cloud parallel plate "capacitor" system. Figure 1-1 is a photograph of the natural "switching" occuring in the Albuquerque, New Mexico, area[12].

In the span of three decades, high power switching has become a distinct field of applied physics. As the use of switches has proliferated with the growth of new applications, the literature describing the physics and technology of high power switching has accordingly grown in volume. The most comprehensive list of references related to the pulse power technology, and within it to switching, is the annotated and indexed bibliography edited by

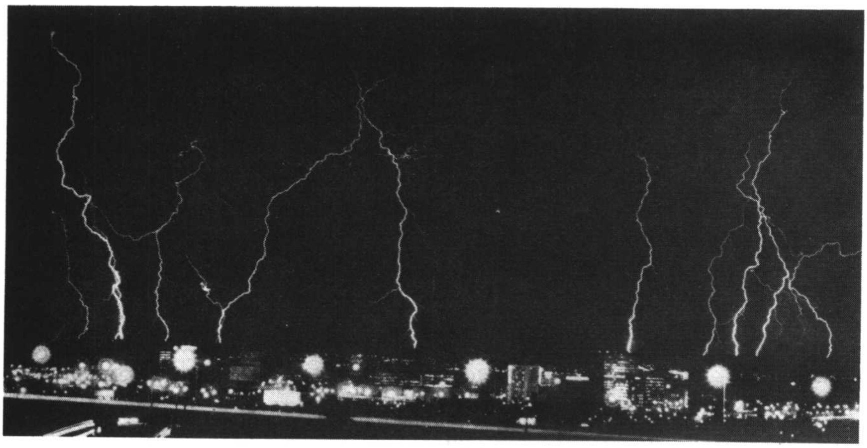

Fig. 1-1. Thunderstorm over Alburquerque, NM, depicts the switching of the electrostatic energy stored between the clouds and the ground.[12] Albuquerque Journal Photo by Brian Walski.

J. Bernesderfer et al.[13] It contains about 2500 full bibliographic citations, original sources, availability, key words and abstracts. Through the use of these indexes—subject matter, personal author and corporate author, with world coverage—the bibliography becomes an indispensable tool for the designer of high power switching and for the developer of pulsed power systems.

CHARACTERIZATION OF SWITCHES

Diverse applications of high power switches requires many types of switches with a broad range of characteristics. These characteristics can be grouped into those relating to electrical capabilities of the switch and those relating to its physical, operational, and other features. The succeeding chapters generally follow this division. Switch voltage characteristics are

- Hold-off, or stand-off voltage.
- Voltage drop across the switch impedance (during conduction).
- Rate of rise or drop of voltage across the switch for opening and closing switches, repetitively.
- Prefire or switching below nominal switch hold-off voltage.
- Trigger voltage, or secondary voltage pulse necessary to initiate switching.

In addition to voltage characteristics, there are several characteristics of switches related to the current conducted by the switch. These are

- Maximum current that can pass through the switch without damage.
- Maximum charge (or the time integral of current) that can pass through the switch without damage.
- Rate of rise of current allowed by the switch impedance.

The product of the current through the switch and hold-off voltage, even though not necessarily occurring at the same time, provides the customary definition of power of the pulse that the switch handles. This definition of *power* handled by the switch is used in this book. The definition applies to closing switches (with the voltage taken to be that before switching and the current peak occuring after the voltage across the switch collapses) and to opening switches (where the current is that during conduction before the opening of the switch, and the voltage appears subsequent to the current drop in the switch).

The *energy* handled by the switch is defined more rigorously, as the time integral of the product of current and voltage during switching, i.e., while the current and voltage of the switch are changing due to switching action. This time interval and other characteristic intervals are

- Time of current conduction through the switch.
- Time of voltage hold-off.
- Opening time.
- Closing time.
- Switching delay, or the interval between trigger signal and switch closing or opening.
- Jitter time, or the deviation from nominal switching delay time.
- Recovery time, or time required by the switch to become ready for next operation.
- Repetition rate (with the maximum rate being the inverse of the recovery rate).

Obviously not all the factors listed above are of consequence to each switch operation. Depending on the switch application, some of the following characteristics can also be significant and frequently dominate the choice of switches or determine their design:

- Lifetime, or the number of switching operations before failure.
- Reliability.
- Maintainability.
- Fault modes, or ways in which the switch fails.
- Ease of installation.
- Weight and volume.
- Cost.

Other characteristics also become important in those circumstances where large energy transfer through the switch occurs. Explosive forces arising from rapid deposition of electrical energy due to ohmic losses in the switch, or from large magnetic currents passing through the switch also require attention. For example, special methods for moderating such forces in opening switches are discussed in some detail. In other circumstances, switch operation influences the design of the circuit served by such switches, as in the case of spark gaps for shaping power flow in large pulse lines, where the pulse line and the switch form an integral component. The interaction between the circuit and the switch is emphasized in discussion of liquid dielectric spark gaps in Chapter 6, i.e., in those power systems where the high dielectric constant of the liquid insulator significantly reduces the electromagnetic wave transit time with resultant shrinking of the system dimensions.

Many of the switch characteristics described above are assigned symbols for rigorous discussion of the physical phenomena, for prescribing the circuit parameters and for characterizing the switch performance. The symbols for more common quantities such as current, voltage, resistance and the intrinsic quantities, such as resistivity or density, are the same throughout the book. The symbols for more special characteristics, such as time characteristics or dimensions, relating to given switch or associated with the specific circuit, are defined in each chapter for the specific cases.

The units are mks in most cases. In a few instances, other units, specifically indicated, are used to maintain the simplicity of commonly used formulae.

PHYSICAL PROCESSES

High power switch technology employs a wide spectrum of physical principles and engineering practices. Although most of the phenomena associated with switching are well understood, there are also areas which are poorly understood and require further studies. To supplement the lack of understanding there has accumulated a large body of empirical data and scaling laws for relatively narrow operating regimes to help the switch designer make appropriate choices for optimizing pulse power systems. Some of the newer types of switches, such as those discussed in Chapter 10, which use phase transitions in solids to change the bulk resistivity by many orders of magnitude have potential for development of very practical devices once the physics determining the material behavior is fully understood and the technology of forming materials with suitable properties is mastered.

The dominant physical phenomena which govern the switch performance are determined first and foremost by the dielectric used as the insulator in the switch. The dielectric between the switch electrodes can be a solid material, liquid, or gas at high, atmospheric, or very low pressure. Ionized gases at low pressures (plasmas) also are employed in switches, with the use of magnetic fields to turn off conduction, rendering such plasmas as effective insulators with hold-off fields of several MV/cm. The closing switch action in solids, liquids, and gases—formation of a discharge—can be initiated by a variety of means, including self-breakdown or triggering. The opening switch can interrupt the current flow with a large variety of methods which in one way or another manage to change resistance of the switch from the initial low value to a final high value.

The most significant characteristics governing the performance of the opening switches are the insulation properties, transition rate from insulation (i.e., high resistivity) to conduction and vice versa, and current density at which such transition can occur reversibly. The most significant factor in determining the switching range is the nature of conduction in the switch. Both types of switches can be divided into two groups, according to the type of conduction which they employ during the conduction phase. One type of switch employs channel conduction, associated with highly localized flow of current and produces high energy density; the resulting heating leads to formation of ionized gas or plasma. Volume conduction, where the current to be switched is made to flow over a large cross-sectional area, prevents formation of very high energy density, leading to more controllable transition from one resistance state to another state. Chapters 3, 4, 5, 6, 7, and 8 deal mainly with switches utilizing channel discharges. Chapters 9 and 10 describe switches based on volume conduction.

The high energy density of channel discharge switches also leads to significant pressures and explosive forces. This requires that switch structural integrity must be considered. Volume discharge switches greatly reduce or eliminate the problems caused by strong mechanical impulses and therefore are attractive for high power switch designs. However, because the price for volume conduction may be high, in terms of switch complexity, its practicality or reliability (for example, complex ionization sources may be needed to assure volume conduction), volume discharge switches are not used frequently; thus, much effort has been devoted to finding methods to reduce or redistribute the impulse (for example, by subdividing the discharge into multiple channels). The pressure impulses generated by the channel discharges further complicate the design of some switches, because it becomes necessary to consider the resulting dynamic phenomena, such as shocks, since they can alter significantly the insulating properties of the regions subjected to the electric stress by the potential applied across the switch.

Less encompassing, but nevertheless important phenomena in many switches are those associated with electrode surface physics and with various predischarge effects. Surface control in low pressure switches is the main factor in determining reliable switch performance. Electrode erosion and deposition of the products resulting from the switching action determines the subsequent switch performance and plays a very important role in determining switch lifetime.

The performance of switches is also related to circuits in which they are employed. High power switches are typically employed in circuits containing energy storage elements. The characteristics of such elements determine the current through the switch, voltage across the switch and their duration, as well as mechanical characteristics. Chapter 2 discusses basic circuits with energy storage elements used as current or voltage sources and the role of switches in transforming the stored energy into an appropriate pulse shape and its subsequent transfer to the load.

In high power applications, these circuits are relatively uncomplicated,