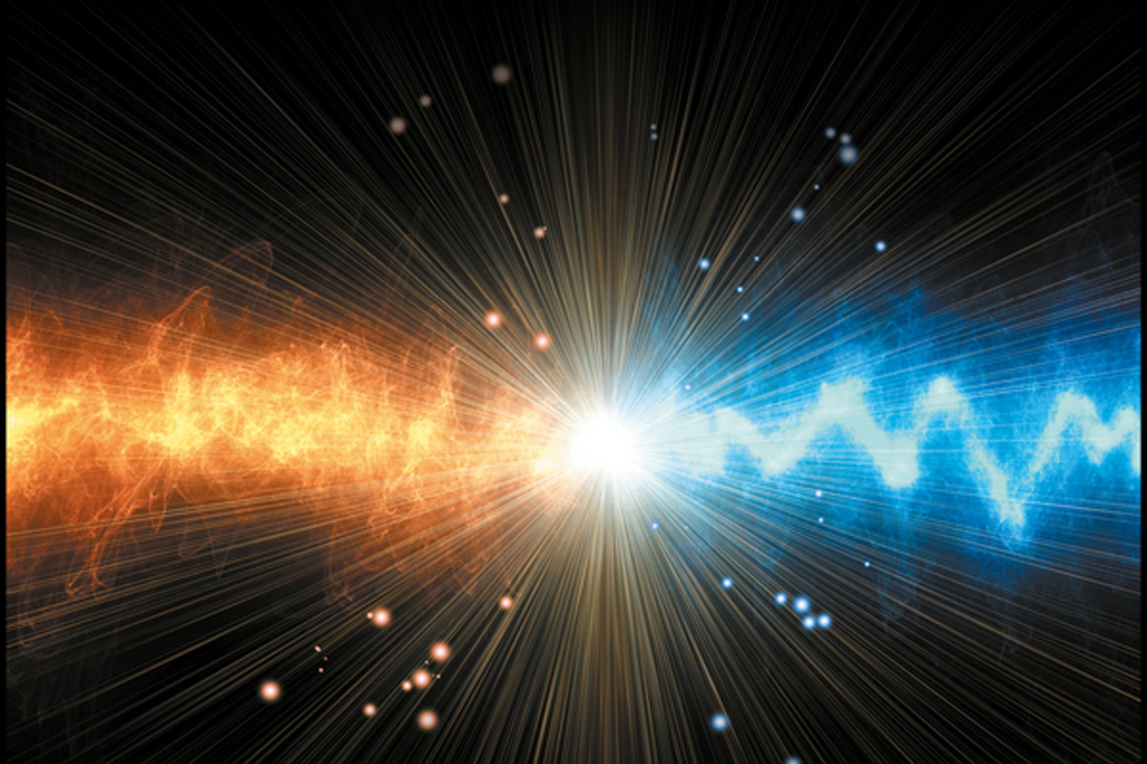
Foundations of

PULSED POWER TECHNOLOGY



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Contents

Preface

Pulsed power technology provides conditioned charging profiles for present and future applications requiring high peak power. This book is primarily concerned with providing the concepts, design information, and system techniques for optimizing this profile to the application. The field of pulsed power has been difficult to codify because each high-power application requires specific power sources. This customization, along with the innate interdisciplinary nature of the field, has inhibited comprehensive documentation. This book is meant to be useful for designers of pulsed power sources and the researchers who require them. The book will be valuable for graduate students, studying courses in pulsed power technology, plasma physics and applications, laser physics and technology, high-voltage insulation and power system engineering, measurement and diagnostics, high-power electromagnetics, particle beams, and electromagnetic interference and compatibility.

The authors have spent the bulk of their careers in government research laboratory settings in the design and construction of pulsed power technology and applications and have been heavily involved in the evolution of the field. Both authors have taught academic courses in pulsed power and recognize the deep need for a comprehensive book focused on the fundamental principles of the field. It is our deep conviction that a strong foundation in the fundamental principles – and the history of the field – will provide the future workforce with the necessary skills for emerging applications. This book, with its emphasis on engineering design and construction of pulsed power equipment, is intended for graduate students and practicing engineers with specialization in multiple disciplines, since it establishes a firm foundation in pulsed power components, systems, and measurements. Moreover, we include electromagnetic interference, compatibility, and topology concepts for the purpose of controlling noise and interference for modern designs of the pulsed power system. The book bridges the gap between a textbook for students and a monograph for research scientists. The length of the book is intended to provide in-depth insight into the theory, design, and construction of individual components of pulsed power equipment, but short enough to keep the attention anchored to overall system requirements. This book is illustrated with a large number of equations derived from fundamental concepts, figures, and solved design examples. *Foundations of Pulsed Power Science and Technology* complements the other books on the subjects of pulsed power: Gennady A. Mesyats, *Pulsed Power*, Kluwer Academic/Plenum Press, 2005; Paul W. Smith, *Transient Electronics: Pulsed Circuit Technology*, John Wiley & Sons, Inc., 2002; *JC Martin on Pulsed Power*, edited by T.H. Martin, A.H. Guenther, and M. Kristiansen, Plenum Press, 1996; S.-T. Pai and Qi Zhang, *Introduction to High Pulse Power Technology*, World Scientific, 1995; and W. James Sarjeant and R.E. Dollinger, *High Power Electronics*, TAB Books, 1989.

The entire subject of pulsed power technology is covered in 12 chapters. Each chapter contains a large number of references, to lead the researchers to greater depths in the field. This book is organized such that the Chapters 1–5 describe the "building blocks" of a pulsed power system. Chapters 6 and 7 describe considerations with examples of systems resulting from synergetic integration of individual components. The remaining five chapters describe the vital topics of electrical breakdown in insulators of interest (Chapters 8 and 9), pulsed voltage and current measurements (Chapter 10), and electromagnetic interference, compatibility, and topology for interference control (Chapters 11 and 12).

The following are the salient features of the various chapters:

- The design formulas, considerations, and examples of the widely used voltage-multiplying circuits based on the Marx generator are discussed in Chapter 1, Marx Generators and Marx-Like Circuits. A number of modified configurations of low-inductance Marx generators with capabilities for high-power delivery, fast erection with low jitter, and capability for repetitive pulse generation are discussed. Other circuits, such as the Maxwell Marx and Fitch circuit are introduced even though not widely used.
- Chapter 2, Pulse Transformers, introduces another popular means of voltage multiplication: the Tesla transformer. This chapter also includes a discussion of transmission line transformers for modifying high power pulses with minimum distortion, with its special application for impedance matching to the application device.
- Pulse forming lines, discussed in Chapter 3, receive input from a Marx generator or Tesla transformer, having capabilities to deliver gigawatts of power in a very short rise time and a flat-top. The various configurations of PFL, such as coaxial lines, striplines, Blumleins, stacked Blumleins, radial lines, helical lines, and spiral generators, are covered. The optimization of PFL design from the viewpoints of maximum charging voltage, maximum power delivery, choice of dielectric, and dielectric strength dependence on charging time are illustrated with solved design examples.
- The design considerations and performance parameters of self-triggered and externally triggered *spark gap switches* to transfer the energy to the load at

high efficiency with minimum distortion in waveform are covered in Chapter 4. A review of spark gap configurations, trigger geometries, trigger modes, and salient features of specialized spark gaps like krytrons, burst mode gaps, and radioisotope-aided gaps is included. Design examples are provided for calculation of inductive rise time, resistive rise time, and a rough estimation of number of spark channels.

- Chapter 5 describes a variety of *opening switches* that are a critical component of inductive energy storage systems. An exhaustive coverage of opening switches, their configurations, and performance are discussed at length. The subject covered in this chapter is taken largely from the NRC Report "Opening Switches in Pulsed Power Systems," Rep.TR-GD-007, by P.H. Ron & R.P. Gupta.
- Chapter 6 on multigigawatt pulsed power systems describes advanced systems with capabilities to deliver single or repetitive pulses at very high peak power levels. The major system categories are cascaded capacitor storage, cascaded inductor storage, magnetic pulse compression schemes, inductive cavity cells, and induction linacs. Some well-known machines comprised of fast Marx generators, fast pulse forming lines, and multichannel spark gaps are discussed at greater length, because of their historical importance and the relevance to the evolution of modern-day pulsed power systems.
- In Chapter 7, Energy Storage in Capacitor Banks, the theoretical, practical, and safety aspects involved in the design and construction of high current or energy storage capacitor banks are discussed. Capacitor banks are used for the delivery of large energy in the microsecond regime. The capacitor bank discharges have wide ranging applications in plasma heating, high magnetic field generation, and electromagnetic propulsion.
- Chapter 8, Electrical Breakdown in Gases, gives basic concepts of the kinetic theory of gases and ionization. The early experiments of Paschen and Townsend are described as well as insight into the fundamental mechanisms of electrical breakdown of gases. Pseudospark discharge and corona phenomena are also introduced. The techniques of optimum utilization of insulation by providing intermediate electrodes into electrically weak cylindrical and spherical geometries are discussed at depth. Practical hints are given for deriving maximum benefit out of SF_6 gas and its mixtures with other gases.
- Chapter 9 deals with the properties of electrical insulation and electrical breakdown in solids, liquids, and vacuum. The breakdown mechanisms in the above dielectrics and practical techniques to be adopted for enhancing insulation performance are discussed. The important topics of partial discharges and electrical trees, which govern long-term performance of solid dielectrics, behavior of liquids for PFL insulation, and vacuum in application

devices, and the theory of surface flashover and some mitigation techniques are described.

- The concepts and techniques for *pulsed voltage and current measurements*, which necessarily involves the accurate scaling down of parameters without distortion of pulse shape, are discussed at great depth in Chapter 10. The electro-optical and optoelectronic techniques, which possess high immunity to intense EMI, are introduced.
- The topic of Chapter 11 electromagnetic interference and compatibility, is important because of the intense radiated electromagnetic fields generated by the operation of the pulsed power system. This radiation may damage equipment or cause inaccurate measurements or even operation because of extraneous ground loops. After discussing the theory of fundamental mechanisms of capacitive coupling, inductive coupling, common impedance coupling, and radiative coupling responsible for electromagnetic interference, the practical methods of incorporating protection techniques such as shielded cables, power line and signal line filters, isolation transformers, effective earthing, and shielded enclosures are discussed at length.
- Techniques required for high frequencies are introduced in Chapter 12, EM Topology for Interference Control. Multiple, nested shields in complicated geometric shapes may be incorporated to enable the safe and reliable operation of electronic systems from high interfering levels in harsh environments. To maintain high shield integrity in the presence of numerous shield surface discontinuities requires specialized techniques in the various protection zones and high standards of connections between the penetrating devices and shield.

Jane Lehr
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About the Authors

Jane Lehr received the Bachelor of Engineering degree from Stevens Institute of Technology and the Ph.D. degree in Electrical Engineering from New York University in 1996 under the supervision of Professor Erich Kunhardt. Dr. Lehr joined the University of New Mexico's Electrical and Computer Engineering faculty in 2013 after spending 12 years at Sandia National Laboratories in the Pulsed Power Sciences Center. She served 5 years at the Air Force Research Laboratory's Directed Energy Directorate studying ultra-wideband high-power electromagnetics and repetitive pulsed power where she was awarded the USAF-wide Basic Research Award in 2001. Dr. Lehr's research interests are in all aspects of high-power electromagnetics, pulsed power, high-voltage engineering, and the physics and application of electrical breakdown in vacuum, gases, and liquids. Dr. Lehr is a Fellow of the IEEE.

Dr. Lehr served as President of the IEEE Nuclear and Plasma Sciences Society in 2007 and 2008. She has served the Society in a number of roles since then and currently serves as the Chair of the NPS Society Fellow Evaluation Committee. She has served on the Administrative Committees for both the Nuclear and Plasma Science and the IEEE Dielectric and Electrical Insulation Societies. She has served as an Associate Editor of the *IEEE Transactions on Dielectrics and Electrical Insulation*, Guest Editor of the *IEEE Transactions on Plasma Science*, and on the IEEE Technical Activities Board Publications Committee. Dr. Lehr received the IEEE Shea Distinguished Member Award in 2015 and the IEEE Region 6 Award for Leadership in 2001. She was named an Outstanding Woman of New Mexico and has been inducted into the New Mexico Hall of Fame for her technical accomplishments and volunteer activities serving her local community.

Pralhad Ron was born in 1939 in Dharwad, Karnataka, India. He obtained his Bachelor of Engineering degree from Pune Engineering College, India, in 1961. He was the winner of the Homi Bhabha Award for top performance in electronics engineering. He joined the Bhabha Atomic Research Centre

(BARC) in 1962. He obtained the M. Sc. (Engg.) degree from the University of Manchester, UK, in 1969 and a Ph.D. from the Indian Institute of Science, Bangalore, India, in 1984.

At BARC, Dr. Ron specialized in the design and development of high-voltage equipment for carrying out applications, such as (a) electron beam processing for melting and welding in vacuum., (b) industrial electron beams for radiation processing in atmosphere, (c) pulsed power technology for production of nanosecond multigigawattt electron beams, flash X-rays, and EMP testing, (d) pulsed high magnetic fields for magnetization, demagnetization, and magnetoforming, and (e) electromagnetic interference simulation and protection technology. Dr. Ron led a team of engineers, who successfully carried out garter spring repositioning in the nuclear power reactors at Narora and Kakrapar. Under his leadership, electron beam processing plants based on Cockcroft-Walton multipliers and RF Linacs were successfully developed for industrial applications.

Dr. Ron served as Head of the Accelerator and Pulsed Power Division of BARC from 1992–2001. He was a visiting scientist at Queen Mary College, London, UK in 1970 working on electrical breakdown and at the National Research Council in Ottawa, Canada in 1985 and McGill University, Montreal, Canada, in 1987 working on pulsed power technology. He taught a graduate course in pulsed power technology from 1996 to 2000 at the Devi Ahilya University in Indore, India. Dr. Ron was the Steering Committee Chairman of the Electron Beam Centre in Kharghar, New Bombay, to carry out radiation processing of polymers. He was Chair of the Atomic Energy Regulatory Board's Design Safety Review Committee for the construction of particle accelerators in India. He was Chairman of the Engineering Design Committee for the conversion of BARC's 5.5 MV van de Graff generator into a 7 MV folded tandem ion accelerator. He was a member of the following councils for the Department of Atomic Energy: (a) Trombay Council at BARC, (b) CAT Council, Center for Advanced Technology, Indore, Madhya Pradesh, India, and (c) Cyclotron Council, at Variable Energy Cyclotron Centre, Calcutta, West Bengal, India.

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Introduction

Pulsed power technology is an area of interest to physicists and engineers in fields requiring high voltages and large currents. Modern pulsed power runs the gamut from its historical roots in flash radiography, X-ray generation, and the simulation of weapons effects, such as nuclear electromagnetic pulse (EMP), to packaged pulsed power for directed energy weapons and biological and medical applications. New applications and techniques continue to emerge.

Pulsed power has traditionally been described as the gradual accumulation of energy over a relatively long timescale and the subsequent compression into pulses of high instantaneous power for delivery in the required form to a load. This process is illustrated in Figure I.1, and is discussed in Chapter 3. Depending on the application, the slow accumulation of energy may be over minutes, such as for charging large capacitive energy store, or milliseconds for systems operating in a repetitive burst mode. The fast discharge is usually less than tens of microseconds but may be measured in tens of picoseconds.

Pulsed power generally falls within the following range of parameters:

Energy per pulse	1–10^7 J
Peak power	10^6–10^{14} W
Peak voltage	10^3–10^7 V
Peak current	10^3–10^8 A
Pulse width	10^{-10}–10^{-5} s

This explanation, however, does not capture the two key elements of the field: the exploitation of the time dependence of electrical breakdown on insulating materials and the specifics of the load requirements.

The observation that electrical breakdown of insulators – be it gas, liquid, or solid – occurs at higher electric fields at shorter pulse durations was well known before the “birth” of pulsed power in the United Kingdom in the late 1950s. Definitive work on electrical discharges in gases and the mechanisms leading to electrical breakdown was performed in the first half of the twentieth century, starting with Townsend's experiments on current growth in low-pressure gases and its relation to ionization. The invention of the Marx generator, patented in 1923, allowed the generation of substantially higher voltages with shorter pulse durations than previously available. The streamer mechanism of electrical breakdown of gases was proposed in the 1940s and seminal work was performed by Loeb, Meek, Craggs, and Raether. At the same time, Llewellyn-Jones and Davies, as well as Raether, continued to advance the understanding of the Townsend breakdown mechanism. The focus, however, was on physics and scant attention was paid to the increased breakdown strength of insulators upon application of pulses of short duration. Even in the very thorough, modern text, *Gas Discharge Physics* by Yu. Raizer [1], the time dependence of electrical breakdown is rarely mentioned.

The integral nature of the time dependence of electrical breakdown to pulsed power is illustrated in an anecdote relayed by Goodman [2] and Martin [3]. The Atomic Weapons Research Establishment (AWRE) in the United Kingdom had acquired a used electron accelerator that was being used to radiograph explosive events. The radiographs were somewhat blurred and a better resolution was needed. The conventional option was to increase the accelerator beam current by three orders of magnitude – an enormously expensive option. Martin proposed an alternative concept of a high-voltage (~6 MV), high-current (~50 kA) accelerator lasting for 30–50 ns exploiting the time dependence of electrical breakdown. The second option was chosen on the basis of cost, and, with its success, pulsed power was born. Martin and his colleagues went on to develop a number of high peak power devices, and, along the way, an empirical relation for the time dependence of insulator breakdown that had the general form:

$$F \cdot t^a \cdot A^b = k$$

where F is the average electrical breakdown field, t is the charge time, A is the area, and a, b, and k are constants that depend on the insulating material. These empirical relations allowed electrical breakdown to be predicted and therefore exploited, and are discussed in detail in Chapter 3. The scaling relation clearly shows that higher breakdown electric fields are attained with shorter charge and discharge times. Thus, using the pulse compression scheme illustrated in Figure I.1 permits the generation of high peak power. An in-depth history of these early developments can be found in the article by Smith [4]. Much of the material presented here is derived from work done in the United States and the United Kingdom. Pulsed power was independently and simultaneously developed in the former Soviet Union and is well documented by Mesyats in the English translation of his incredibly detailed book *Pulsed Power* [5].

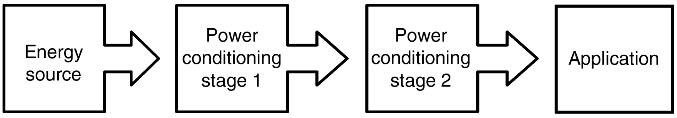

Figure I.1 Pulsed power may be represented schematically as a series of power conditioning stages that increases the peak power while decreasing the pulse width. This technique is known as pulse compression.

Pulsed power technology, simply stated, is the technique and equipment required to adapt the power characteristics of the prime power source to the electrical requirements of the load. Pulsed power in the context of power conditioning captures the quintessence since significant efforts must be made to optimize and specify the power demand. In the preface to the Pulsed Power Monograph series [6–8], Magne (Kris) Kristiansen and Art Guenther describe pulsed power as "special power conditioning for specific applications." This statement captures both the inextricable link between pulsed power and the application and their uniqueness. In applications requiring high peak power, pulsed power is a low-cost power conditioning technique. Electrical efficiency is increased by delivering the power in a specific optimal form – the "art" of pulsed power. Pulsed power provides unique solutions to certain physics applications.

Based on the above, the following succinct description of pulsed power is proposed:

> Pulsed power is a special power conditioning technique that transforms the characteristics of the prime energy source to the electrical requirements of the load. Energy from a primary source is accumulated over a relatively long time scale and compressed into pulses of high instantaneous power. Several stages may be needed to fully exploit the time dependence of breakdown of insulating materials to deliver energy with the required time dependence and amplitude for the application. The resulting peak power delivered to the load has a large ratio of instantaneous-to-average power.

Recognizing pulsed power as special power conditioning, the breadth of applications and the wide variety of implementation imply an overwhelming amount of knowledge is needed to participate. Certainly, this is true in part, but a large user-facility or a high-performance system is rarely designed by a single engineer. Our premise in choosing material for this book is that a strong foundation in fundamental principles – using realized systems as examples – provides a better perspective for the wide number of applications a pulsed power engineer should expect to encounter over a career. In modern times, it is rare that a pulsed power engineer spends an entire career on a single application. In general, an in-depth treatise on applications is avoided to highlight this and instead the focus is on the foundations of pulsed power technology on which most systems are built. Many of the references in this book are old, which is a reflection of fundamental nature of this book, but modern references are included where appropriate.

While traditional applications of pulsed power are still relevant and continue to incorporate advances in technology, a host of new applications with very different operational requirements are emerging. For this reason, we chose to avoid application-driven pulsed power and focus on the fundamentals to provide a strong technical foundation for the next generation, as well as to document the many innovations achieved thus far. It is our belief that once the basics are mastered, they can be combined in any number of ways to create the specified output. The dimensional scale of the equipment may be vastly different but a focus on the fundamentals allows the similarities to be seen. For example, the Marx bank was invented almost a century ago, but continues to play an integral part in many systems. The basic Marx architecture is very versatile: It has been used with solid-state switches to produce a few hundred volts and is used exclusively to produce tens of megavolts, and it stores energy ranging from joules to kilojoules. It is the basis for trigger generators as well as lightning simulators. Marx generators are used exclusively as the energy storage stage of multigigawatt pulsed power systems and voltages over 18 MV have been produced [9]. However, the fundamental circuit architecture used to produce a 10 J per pulse, 200 kV peak voltage Marx generator that is only 15 cm long [10] is also configured into a bank of Marx generators that yields 5 MV, requires a robust mechanical support, and powers a current source. While is it obvious that the application of these two voltage sources are vastly different, their basic operation is the same.

Sources of Information

The dissemination of information related to pulsed power has been a low priority for much of its history and this may be attributed not only to its initial rapid growth but also to its initial use for military applications. Thus, much of the early progress was preserved primarily in reports and internal memoranda and passed informally throughout the community. Copies of these early reports are increasingly difficult to find, with the exception of Carl Baum's Note Series. The Note Series was started in early 1964 by R.E. Partridge, a technical staff member at Los Alamos National Laboratory, to document the rapid progress in the simulation of the nuclear-generated effects. The Note Series recorded both simulation technology (largely pulsed power) and measurement techniques. The Note Series quickly passed into the care of Carl Baum and now stands at over 2000 documents, most of which are available electronically (The Note