Chapter 1

Introduction

The objective of this book is to acquaint the reader with explosive driven pulsed power devices, theory and applications. This includes those devices that convert the chemical energy stored in high explosives into electrical energy and that use shock waves generated by the explosives to release the energy stored in ferromagnetic or ferroelectric materials in the form of electrical energy. The reader might well ask why one should use explosive driven pulsed power for any application, since it is inherently single shot in nature. There are really two very different answers to this question. First, explosives store the greatest amount of energy per unit mass ($4\,\mathrm{MJ/kg}$) or per unit volume ($8\,\mathrm{GJ/m^3}$) of any readily accessible energy source. In the case of high-quality solid explosives, they can convert chemical bond energy into PdV energy at a rate of $10^{10}\,\mathrm{W/cm^2}$ at its detonation front. If this energy is converted into pulses of electrical energy having the proper characteristics, then very compact, lightweight, high power sources may be developed. The requirements of a particular load to be energised is a critical consideration in selecting an explosive pulsed power system. Second, C. Max Fowler often listed four criteria for using explosive driven pulsed power. These criteria are requirements for (1) portability, (2) compactness, (3) a very large quantity of electrical energy and (4) a need for a limited number of events or tests that do not justify the investment in a conventional pulsed power system. In this chapter, a brief introduction to pulsed power and, in particular, to explosive pulsed power devices, is presented.

1.1 What is Pulsed Power?

Pulsed power are those processes by which stored energy is subsequently released or delivered very rapidly to a load. A mechanical variant of pulsed power is a bull whip. Energy is stored in the angular momentum of the whip as it is rotated, only to be delivered to the tip of the whip in the form of a ‘crack’ as the tip snaps. An electrical variant of pulsed power is the Marx generator. Electrical energy is slowly stored in a capacitive medium and then delivered to a load as a single short pulse or as a train of short pulses with a controllable repetition rate. For the purposes of this book, pulsed power systems can be categorised as being one of two types: explosive driven and non-explosive driven. A detailed description of non-explosive pulsed power technologies is given in [1–3], but there is no single book that addresses all the explosive driven pulsed power technologies. This work intends to do just that.

Non-explosive pulsed power is the generation of short, intense pulses of electrical energy through a process called *pulse compression*. Pulse compression is the process of taking energy from a low voltage, long pulse system and compressing this energy in time and space, increasing both voltage and current, with an accompanying decrease in pulse duration [4]. The development of high voltage pulsed power systems was started in the early 1960s by J.C. Martin at the Atomic Weapons Research Establishment in England [5]. The objective of his research was to develop a technique for using a Marx generator to pulse charge a transmission line to produce short (10–100 ns), high power electrical pulses for X-ray machines, which were needed to resolve fast explosive events. A Marx generator is a specialised capacitor bank that is charged in parallel and subsequently discharged in series. This process enables the production of very high voltages (˜1 MV) from a relatively low voltage source (40–100 kV). Since then, progress in developing non-explosive pulsed power technologies has been rapid and work still continues in many laboratories around the world today.

As pointed out by Sarjeant and Dollinger [6], there are two main types of energy storage used in non-explosive pulsed power systems: mechanical and electrical. In the case of mechanical energy storage, energy is stored in the rotary motion of a machine such as a flywheel homopolar DC generator or a pulse compensated alternator. This energy can be represented mathematically by the expression $W_r = I_0\omega^2/2$, where I_0 is the moment of inertia of the rotating component and ω is its angular velocity. In the case of electrical energy storage, the energy is stored either electrostatically or magnetostatically. In the case of electrostatic storage, energy is typically stored in capacitors, which is mathematically represented by the formula $CV^2/2$, where C is capacitance with units of farads (F) and V is voltage with units of volts (V). In the case of magnetostatic storage, energy is typically stored in inductors, which is mathematically represented by the formula $LI^2/2$, where L is inductance with units of henries (H) and I is current with units of amperes (A). While all these energy storage systems can store very large amounts of energy, none of them can match the energy storage per unit volume or mass of explosives.

Initially, *explosively driven pulsed power*, or simply *explosive pulsed power*, was generally defined as the conversion of the chemical energy stored in high explosives into electrical energy. This conversion has usually been accomplished by propelling a conductive medium with the explosive. In turn, this medium is used to compress or do work on a magnetic field. More recently, explosive pulsed power has been generalised to include any use of explosives to produce an electrical pulse. For example, the explosive may be used to induce a shock that initiates the release of energy stored in ferromagnetic, ferroelectric or superconducting materials. It is important to note that these latter examples do not convert the explosive energy into electrical energy in the usual sense. The energy is already stored in the ferromagnetic or ferroelectric materials. In the case of the superconducting system, the pre-stored energy is in the form of a magnetic field supported by the current in a superconductor.

The development of explosive pulsed power was started by W.B. Garn, C.M. Fowler and their colleagues [7] at Los Alamos National Laboratory in the United States and, independently, by A.D. Sahkarov, A.I. Pavlovskii, V.D. Chernyshev, R.Z. Lyudaev and others [8] at the All-Russian Institute of Experimental Physics (VNIIEF), also known as Arzamas-16, in the Soviet Union in the early 1950s. The objective of this research was to support the nuclear weapon programs in the respective countries. In particular, E. Teller and J. Willig in the United States and A.D. Sahkarov in the Soviet Union proposed using magnetic flux compression generators in place of fission bombs to achieve fusion in the hydrogen bomb. Throughout the intervening period to the present, this research has continued in a cyclic manner to support a variety of weapon programs, including the development of directed energy weapons, electromagnetic launchers and so on. However, only recently has there been a systematic investigation of the physics of explosive pulsed power sources by a consortium of universities and by a few companies in the United States in an attempt to improve the performance of explosive pulsed power generators. While nearly all of the findings in these recent studies were known to researchers at the various national laboratories and are considered to be rules of thumb in good design practice, the completion of these studies has provided a fundamental understanding of many cause and effect issues.

Both types of pulsed power systems have their advantages and disadvantages. For example, explosive pulsed power systems generate the highest electrical powers and currents and have the smallest mass and size, but they also generally destroy themselves and, quite usually, the load they are driving. Thus, they are single shot in nature. Non-explosive pulsed power systems are usually not self-destructive and can be repetitively pulsed, but they tend to be massive, large in size and fairly expensive. The advantages and disadvantages of both types of system must be closely examined when selecting the proper pulsed power source for a particular application. In this book, attention is focused on explosive pulsed power sources, since there has been recent progress in our understanding of their performance limitations and how to negate them and since laboratories in several countries are currently developing these power sources for specific applications.

1.2 Pulsed Power Parameters

No matter what method — i.e. explosive or non-explosive driven — is used to generate the electrical pulses produced by pulsed power systems, these pulses all have common characteristics. They include power level, energy content and pulse shape — i.e. rise time, pulse width, fall or decay time and flatness of the top of the pulse.

The electrical power generated by pulsed power systems typically ranges from kilowatts (kW) to terawatts (TW). The energy content of the pulses ranges from a joule (J) to megajoules (MJ), depending on the type and size of the pulsed power source used. Presently, the highest power and energy that have been achieved in a single pulse are a few hundred terawatts and 100 MJ respectively. The corresponding voltages and currents that have been achieved range from 10 kV to 50 MV and from 1 kA to >100 MA respectively [3].

In addition to power and energy, the shape of the pulse is also an important parameter since the input requirements of the load often require certain pulse shapes to operate properly. The parameters that determine the shape of the pulse are depicted in Fig. 1.1. Typically, the overall duration of high power pulses lies between a few nanoseconds to a few tens of microseconds. The rise time of the pulse from a pulsed power system, which is defined to be the time it takes the voltage to rise from 10 to 90% of its peak value typically ranges from a few nanoseconds to a few microseconds. The fall time is similarly defined and typically ranges from a few nanoseconds

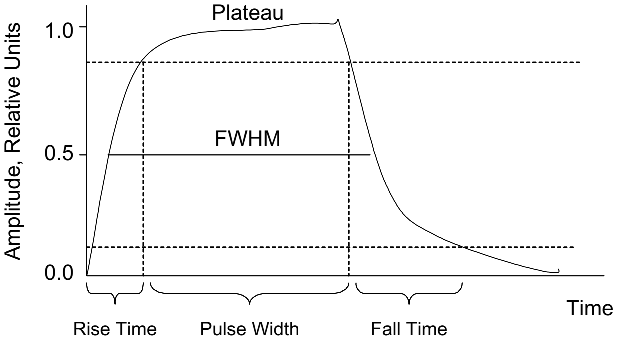

Fig. 1.1 Pulse shape parameters.

to a few microseconds. The pulse length or duration is often taken to be the Full Width of the pulse at Half its Maximum amplitude (Full Width Half Max, FWHM) or, in some cases, the width of the pulse at 90% of its peak amplitude. The flatness of the plateau of the pulse is usually another important parameter when driving certain types of loads, such as high power microwave tubes like virtual cathode oscillators (VIRCATORs) or magnetically insulated line oscillators (MILOs).

The particular pulse characteristics required to optimally power a given load will dictate which type of pulsed power is best suited to drive that load and what power conditioning is needed. In a low-energy example, if high peak voltage is required, the explosive driven ferroelectric generator would be the best choice as the power supply. If high peak current is required, then the explosive driven ferromagnetic generator would be the better choice here.

1.3 Explosive Power Sources

There are five basic types of explosive pulsed power systems. Of these, the one that is the most developed and that generates the highest electrical powers (kilowatts to gigawatts) and currents (kiloamperes to megaamperes) is the magnetic flux compression generator (FCG) [9]. These generators were first developed in the early 1950s. Likewise, the other types of explosive generators have also been investigated since the 1950s, but they have not received the attention, until recently, dedicated to the FCG. A brief description of each major type of explosive pulsed power source is given in this section.

The operation of three of the generators (FCG, explosive magnetohydrodynamic generator (EMHDG) and moving magnet generator (MMG)) is based on a moving conducing medium interacting with a magnetic field or vice versa. The ferroelectric generator (FEG) and ferromagnetic generator (FMG) are based on phase transitions, i.e. polarised-to-depolarised and magnetised-to-demagnetised states respectively. A variant of the FCG that utilises both a phase transition and a moving conductor in a magnetic field is the semiconductor or solid state FCG, generally referred to as a Shock Wave Source (SWS). Unlike classical FCGs, where compression takes place in air or in a gas such as SF_6, the compression in the semiconductor generator takes place in a solid crystal, such as CsI, or a powder, such as oxidised aluminium. Shock pressures cause the dielectric to transition into a metallic state. The resulting moving conducting shock front takes the place of the metal armature in the conventional FCG. One potential advantage of this approach is that liner instabilities observed in classical FCGs may not occur. However, this optimism should be tempered with the knowledge that there has been little development of the SWS at the very high magnetic fields associated with conventional FCGs. Another variant of the FCG is the superconducting generator, which is also based on a phase transition. In this case, the transition is from a superconducting to a non-superconducting state, where this moving transition forms the armature of the generator.

In summary, there are two general classes of explosive pulsed power generators: *field interaction* generators, which include the FCG, EMHDG, and MMG, and *phase transition* generators, include the FEG and FMG.

1.3.1 *Flux Compression Generators*

There are several different types of FCGs, depending primarily on their geometrical shape — that is, the shape of their conducting components. In this introduction, attention is focused on the helical FCG (Fig. 1.2), which is further discussed in Chapter 6. The other types of FCG will be discussed in Chapter 5. Helical FCG consist of an outer coil or solenoid, called a *stator*, and an inner coaxial explosive-filled tube, known as a *liner* or *armature*. For an FCG to operate, a magnetic field must be present between the armature and stator. Thus, a seed source of energy is required, either in the form of a current source or an externally imposed magnetic

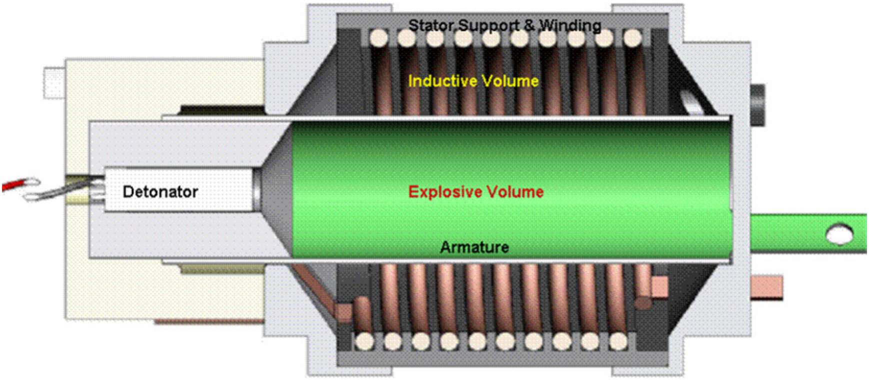

Fig. 1.2 Helical flux compression generator.

field. Given the appropriate conditions for the seed magnetic field, the high explosive in the armature is typically initiated at one end. The detonation releases chemical energy, which causes the armature to expand and form a propagating cone of conducting material that forces the magnetic field down the length of the generator by continually shorting turns of the stator, thus compressing the magnetic field. Initially, the expansion of the armature causes it to make contact with the input block of the FCG, which causes the armature and stator to short together, forming a magnetic flux trap within the annular region between the stator and armature and the FCGs associated load. The armature then propagates outwards along a *glide plane* that must support this shorting action without losing contact between the conductor connected to the stator and the armature. The term ‘glide plane’ is a misnomer in the sense that the armature does not glide along anything in its outward expansion. Rather, this is an input surface that is tapered appropriately to control the collision of the armature in such a way to avoid ‘tent pegging’ the input glide plane or tearing the armature. The explosive process converts the chemical energy of the explosive into the mechanical energy of the armature. In turn, the armature kinetic energy is converted into electrical energy, which is delivered to the load, by performing work against the magnetic field.

1.3.2 *Explosive Magnetohydrodynamic Generators*

The *explosive magnetohydrodynamic generator* (EMHDG) (Fig. 1.3) consists of an explosive charge, magnets, electrodes and output circuit. When

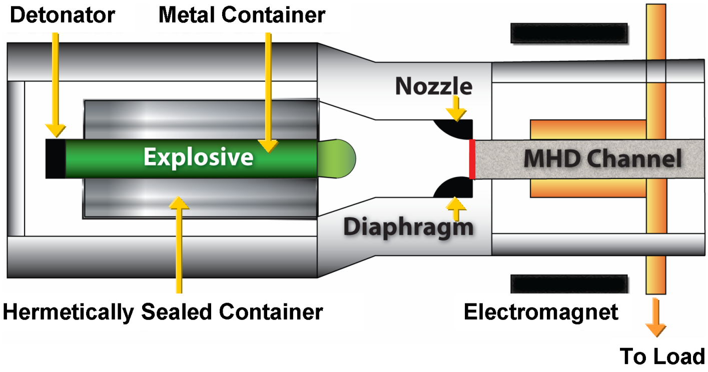

Fig. 1.3 Explosive driven magnetohydrodynamic generator.

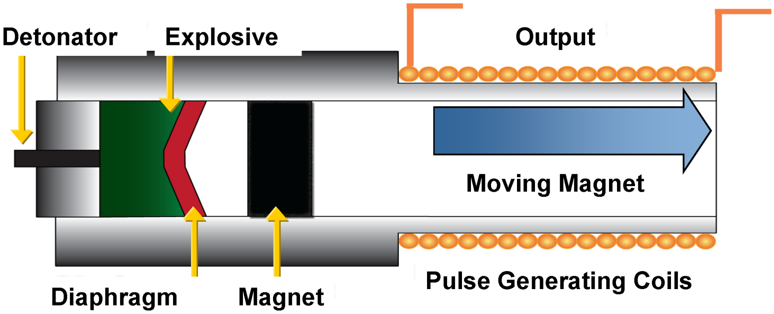

Fig. 1.4 Explosive driven moving magnet generator.

specially seeded explosives are detonated, the explosive products retain sufficient ionisation that their flow between electrodes, immersed in an external magnetic field, induces Hall currents. In other words, the magnetic field causes a charge separation in the plasma as it flows between the electrodes. Positive charge accumulates on one electrode and the negative charge on the other. The accumulated charge then flows through the output circuit to a load. Since these generators are thoroughly discussed in Refs. 1.10 and 1.11, they will not be further discussed in this book.

1.3.3 *Moving Magnet Generators*

The explosive driven version of the *moving magnet generator* (MMG) (Fig. 1.4) consists of an explosive charge, magnet, solenoid and output circuit and is discussed in Chapter 13. When the explosive is detonated, the shock wave it produces propels the magnet through the solenoid. The changing magnetic flux inside the solenoid induces a current in the coil, which is delivered to a load. An alternative version of this generator is the so-called Pro-FLUX system. In this case, the coil is first energised, just as in the instance of a conventional helical FCG. The conducting projectile is then fired into the magnetic field, forcing it to perform work on the field. This, in turn, amplifies the initial current in the exterior coil.

1.3.4 *Ferroelectric Generators*

The *ferroelectric generator* (FEG) (Fig. 1.5) is also sometimes called a *piezoelectric generator* (PEG), though this is not entirely correct, since the ferroelectric process is a nonlinear process, while the piezoelectric process is a linear process. The difference between the two types of generator will be discussed in Chapters 9–12.

The FEG consists of an explosive charge, ferroelectric element, end plates and output circuit, and is discussed in Chapters 9–12. When the explosive is detonated, a shock wave is generated that propagates into the ferroelectric element. The shock wave depolarises the ferroelectric element and the charge that has accumulated on the polarised element's end plates is released to an output circuit and delivered to a load. Thus, the energy delivered to the load in this instance is strictly the energy that was initially stored within the polarised ferroelectric material.

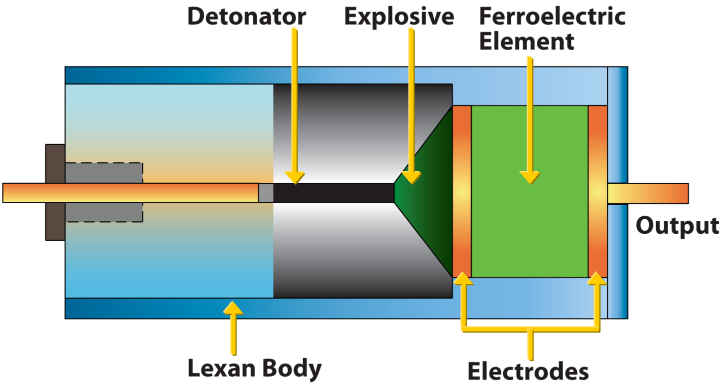

Fig. 1.5 Ferroelectric generator.

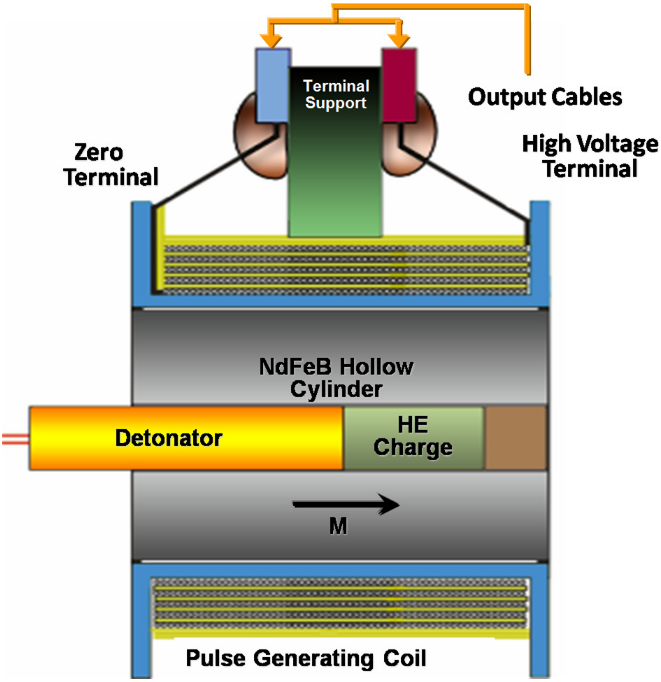

Fig. 1.6 Ferromagnetic Generator.

1.3.5 *Ferromagnetic Generators*

The *ferromagnetic generator* (FMG) (Fig. 1.6) consists of an explosive charge, a permanent magnet within a solenoid and output circuit, and is discussed in Chapters 7 and 8. When the explosive charge is detonated, a shock wave is generated that propagates into the magnet material. The shock wave demagnetises the permanent magnet material. This changing magnetic field within the coil induces a current in the solenoid coil, which is delivered to the load.

1.4 Book Outline

Explosive pulsed power generators have been around since the early 1950s. They have been used in a number of applications. For example, FCGs have been used to drive high-power lasers [12], high-energy density plasma systems, high-power microwave and ultra-wide band sources [13], electromagnetic launchers [14], detonator arrays [15] and particle accelerators [16]. The FEG and FMG have been used as seed sources for FCGs and to charge capacitor banks. In this book, we will discuss the design, construction and testing of four of the five types of explosive generators along with some of their applications.

To make this a self-contained book, the basic principles of electromagnetic theory and electric circuits are presented in Chapter 2. Similarly, the basic principles of shock waves, high explosives, detonation trains and explosive interactions with materials are presented in Chapter 3. Since the operation of explosive pulsed power generators requires both mechanical and electrical measurements, methods for making detonic and electrical measurements will be presented in Chapter 4. As the electrical output parameters of explosive pulsed power sources are not usually electrically matched to those of the load, power conditioning is usually required. Since each type of generator has its own unique set of output characteristics, power conditioning for one will be discussed in their respective chapters. Flux compression generators are consider in Chapters 5 and 6. In Chapter 5, all the known versions of FCGs are discussed, while Chapter 6 focuses on one specific type of generator — i.e. the helical FCG, since it is the most widely used of all the FCGs. In Chapter 7, an introduction to magnetic circuits is presented, followed by a detailed discussion of FMGs in Chapter 8. Even though ferroelectric generators have been around since the mid-1950s, not much is known about them outside of a small community of specialists. Therefore, four chapters are devoted to FEGs. Chapter 9 is an introduction to ferroelectric materials, Chapter 10 looks at the phase transitions that occur in ferroelectric materials, Chapter 11 provides a historical review of shock studies involving ferroelectric materials, and Chapter 12 is an in-depth look at FEGs. Chapter 13 is devoted to MMGs. Finally, several examples of how explosive pulsed power generators were used with specific loads are presented in Chapter 14.

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