RF Power for Industrial Applications

Louis E. Frenzel, Jr.

RF POWER FOR INDUSTRIAL APPLICATIONS

Louis E. Frenzel Jr.
Austin Community College, Texas

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PREFACE

Whenever you see the term *radiofrequency* (RF), it generally refers to high-frequency radio communications equipment. The term wireless is also very popular today, and *wireless* is RF. Although RF equipment is primarily devoted to some type of electronic communications, however, there is another entire category of RF equipment used for noncommunications industrial applications. Some examples are RF power used to generate plasmas in semiconductor manufacturing equipment, RF power used in industrial heating, and RF power used in magnetic resonance imaging (MRI) machines and in other medical equipment. Although many books have been written about RF power in communications applications, few, if any, have been written about the use of RF power in industrial applications—thus, this book. The concepts, equipment, and techniques presented in this text emphasize industrial applications but are also applicable to most radio communications equipment.

This book has three primary target audiences:

1. Engineers and technicians in industry who install, operate, maintain, service, and repair RF power-generating equipment. This book can be used for personal continuing education or as an on-the-job reference.
2. Students of RF power in community colleges and universities teaching a course in RF power. This book is intended as the primary text for a one-semester, 2- to 4-hour course. An accompanying lab and activities manual (ISBN 0-13-096576-6) is available for courses offering a laboratory segment. For this audience, the book meets all the workforce competencies established by the National Science Foundation–funded Maricopa Advanced Technology Education Center (MATEC) for semiconductor manufacturing technology.
3. Engineers and technicians who seek formal continuing education in company training programs, industrial training courses, or seminars and workshops. This book provides a base on which more company- or equipment-specific courses can be developed.

Although this is a relatively complete text on RF power generation, applications, and servicing, it does assume that you have some prerequisite knowledge. If you are a student, the book assumes that you have completed courses in DC and AC circuits, semiconductor device fundamentals, basic electronic circuits such as amplifiers, power supplies, and oscillators, and basic test and measurement techniques.

If you are a technician or engineer working in industry, this text assumes that you have prior knowledge of electronic fundamentals and circuits similar to those covered in the college courses mentioned above.

ORGANIZATION OF THE TEXT

Chapter 1 surveys the primary applications for RF power in industry. This chapter also includes a section outlining the Federal Communications Commission rules and regulations regarding the use of RF power in industry. Power levels, interference, and frequency assignments are spelled out.

Chapter 2 introduces the primary signal source used in RF generators and crystal oscillators. Operation and typical configurations of frequency synthesizers, both phase-locked loop and direct digital synthesis, are discussed.

Chapter 3 covers RF power amplifiers. Circuits include class A linears, push-pull class AB and B linears, class C amplifiers, and class D and E switching amplifiers. Related impedance-matching and power divider-combiner circuits are included.

Chapter 4 continues the coverage of power amplifiers with discussions of special amplifier types, including vacuum tube amplifiers, feed-forward amplifiers, and amplifiers for UHF and microwave frequencies.

Chapter 5 deals with impedance-matching circuits. These π, T, and L networks using inductors and capacitors are widely used to provide impedance matching between RF power amplifier stages and loads. Transformers and baluns are also covered. A key discussion in this chapter is the use of such networks in matching high-power amplifier output to the unique loads used in industrial applications.

Transmission lines are the subject of Chapter 6, with a focus on coaxial cable. Smith charts are covered in Chapter 7. Despite its age (about 65 years as this is written), the Smith chart is still widely used for transmission line and circuit design and impedance matching, and you will learn how to use it.

Chapter 8 covers RF power measurement and control. Circuits for measuring forward and reflected power, phase-magnitude, and standing wave ratio are discussed. Control circuits used in automatically varying the power of an RF generator are also covered.

Chapter 9 covers the troubleshooting, maintenance, and repair of RF generators and related equipment. Common test equipment and their applications are discussed. Troubleshooting techniques are illustrated using typical industrial commercial RF power generators, and safety issues and procedures are presented. The problems with EMI-RFI are considered and solutions are reviewed.

Chapter 10 introduces the most common applications of RF power in industry. Examples included are plasma generation in semiconductor manufacturing, industrial heating, and medical electronics such as magnetic resonance imaging (MRI).

I strongly recommend the accompanying lab and activities manual for this book. It contains material not included in the text and many hands-on activities useful in reinforcing the text material. It contains student chapter exams, activities such as Internet searches and web accesses, and various hardware lab exercises. The lab experiments can be implemented with the low-cost equipment recommended. Also included are selected Multisim (Electronics Workbench) simulations that provide further reinforcement of critical concepts. The appendices contain manufacturer resources and other useful references.

Finally, if you are teaching a course on RF in college or industry, you should look into the supplementary teaching modules developed by the Maricopa Advanced Technology Education Center (www.matec.org). Their RF Modules 104 through 109 include PowerPoint presentations, student activities, and student assessments, which are an excellent supplement to this text and to the lab and activities manual.

I hope you will find this book useful. Let me know how I can improve it for you.

ACKNOWLEDGMENTS

Writing a book is a tough job. This is my seventeenth book and, frankly, it does not get any easier. But, I had help and I would like to acknowledge it here.

First, I dedicate this book to my editor, Charles Stewart. Not only did he encourage me to write it but he also provided the ongoing support and motivation I needed to get through it. There literally were times when I thought I would never finish, but Charles never gave up on me. Thanks for your faith in me and your patience.

There were also many from industry who supplied valuable information. Companies such as Applied Materials, Advanced Energy Industries Inc., Bird Technologies, and Intel Corporation were helpful. I particularly thank Tom Lane of the ENI RF Power division of MKS Instruments for supplying photos. My special appreciation goes to Gil Yetter and Mike Pendley of the RF lab at International Sematech in Austin, who were always available to me and answered all my stupid questions with clarity and patience. Thanks, guys.

Thanks also to Joe Koenig, president of Interactive Image Technologies, Ltd., and his support guru, Luis Alves, who helped me learn and use Electronics Workbench and Multisim. I was not convinced at first that simulations would help, but they did, and they make an excellent supplement to the book.

I also want to thank the administration, faculty, and staff at Austin Community College, where I was Professor and department head. Special appreciation goes to Provost Dr. Tyra Duncan Hall, who hired me, and to Dean of Advanced Technologies, Mike Midgley, who provided the opportunity to run the department and teach RF. Further thanks to Hector Aguilar, Alberto Quinonez, and Venancio Ybarra, who were a great help in the lab with real RF tools.

Finally, to my dear wife, Joan Ree, I say thanks for your patience with me throughout this project. I know we missed a great deal of beach time because of this book, but now that it is finished, we can do some serious catching up.

I appreciate the valuable feedback from the following reviewers: Thomas D. Edwards, Carteret Community College, California; Bill Hessmiller, Editors & Training Associates; K. R. Kirkendall, Montana State University; Costas Vassiliadis, Ohio University; and Richard L. Windley, ECPI College of Tecnology, Virginia.

Best wishes to you all.

Lou Frenzel

CONTENTS

1

INTRODUCTION TO RADIO FREQUENCY POWER

LEARNING OBJECTIVES

When you complete this chapter, you will be able to:

1. Define radio frequency (RF) power as it applies to industrial applications.
2. State the RF frequency range.
3. Draw a general block diagram of a typical industrial RF power generator system, name each major component, and explain briefly what each does.
4. Name three common industrial RF power applications.
5. List the most common frequencies used in industrial RF power applications.
6. State the Federal Communications Commission (FCC) publication number in which RF power regulations are defined.

WHAT IS RF POWER?

RF power as the term is used in this text is high-power alternating current at a frequency defined to be a radio frequency. The basic RF power signal is a sine wave whose frequency can be anywhere between 9 kHz and 300 GHz. Radio signals in this frequency range are usually generated by a transmitter and applied to an antenna, where they are converted into the electromagnetic field that is a radio signal. In industrial applications, the alternating current (AC) signal is applied to a load that will produce some useful output, such as the generation of a plasma or the heating of an object.

The question naturally arises as to why RF power is used in some applications rather than high-powered direct current (DC) or readily available 60-Hz AC. RF power is used because the high-frequency nature of the sine wave provides some benefits that DC and 60-Hz AC do not. For example, RF produces faster, more efficient heating in some applications or permits a plasma to exist under conditions not possible with DC or lower frequency AC power. Specific reasons for using RF power are explained later in Chapter 10.

THE RF POWER GENERATOR

The system used to create the high-power RF signal is generically known as the RF generator. In radio (wireless) applications, of course, the RF generator is called the transmitter. But, in industrial applications, the term *RF generator*, *RF power supply*, or *RF signal* source is used. RF generators are straightforward in their design because they use well-proven, highly developed, and standard electronic components and circuits. There are also many manufacturers of commercial RF power generators. (See Appendix A.)

Figure 1–1 shows a general block diagram of an RF power generator. A crystal oscillator initially generates the RF signal. Crystal oscillators are used to ensure that the signal operates on the assigned frequency designated by the FCC and maintains that frequency within the specified tolerance limits. Where multiple frequencies are required, several crystal oscillators are switched in to change the frequency of operation.

In some special applications, the frequency of the oscillator must be changed. Small changes in frequency can be facilitated in any oscillator by including a variable capacitor in series or parallel with the crystal in the oscillator. Alternately, a frequency synthesizer using a phase-locked loop (PLL) may be used to generate the signal. Direct digital synthesis (DDS) is used in some of the newer signal-generating circuits.

The small signal from the crystal oscillator or synthesizer is then amplified by one or more low-power buffer amplifier stages. These are typically class A power amplifiers that boost the signal power with minimum distortion and buffer the oscillator from load changes that may affect the frequency of operation.

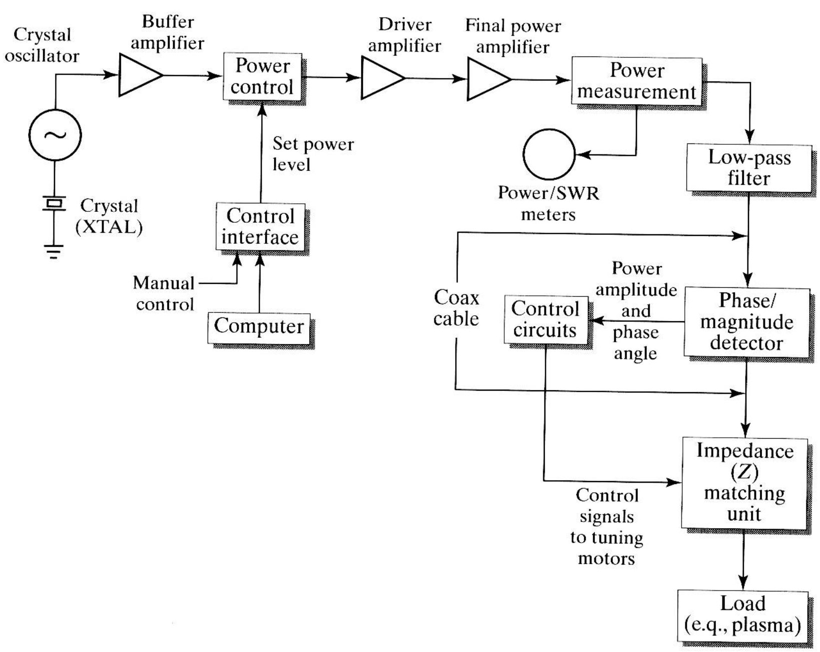


FIGURE 1–1
Block diagram of a common RF generator.

Following the buffer in the signal chain is a circuit that permits the power level to be set and controlled. Like a volume control in a stereo amplifier, this circuit may be as simple as a pot or some more complex circuit whose signal attenuation is controlled by a signal from a manual source or a control computer. Exact power output settings are critical to most RF processes.

Next, driver amplifiers boost the signal level up to several watts of power. From there, larger, more sophisticated power amplifiers are used. Virtually all amplifier circuits in an RF generator are made with discrete component circuits rather than integrated circuits (ICs) because of the higher power these circuits generate.

The high-power amplifier stage, or final amplifier as it is called, is usually a class AB or B push-pull amplifier using either bipolar or MOS field effect transistors. Some generators use class C amplifiers. The newer generators use the more efficient class D, E, or F switching amplifiers. Output power levels typically range from about 100 watts to 10,000 watts. In some cases, multiple amplifiers with drivers are used. For very high power output (2000 watts or more), a vacuum tube amplifier stage may be used.

The output of the power amplifier is fed to a power measurement circuit. A sample of the RF power sent to the load is taken so that both forward and reflected power as well as standing wave ratio (SWR) can be accurately measured. The power measurement is displayed on the front panel meter. The generator signal is then usually filtered in a low-pass filter to remove harmonics and spurious signals that may have been developed in the final amplifier stage.

The signal is then sent to a phase/magnitude detector that measures both the amplitude and phase angle of the signal sent to the impedance matching unit. DC signals proportional to the power amplitude and phase shift determine if the load is resistive or complex, meaning a combination of resistive and reactive.

The output signal is then fed to an impedance (*Z*) matching unit. This usually contains an L network that matches the output impedance of the generator to the unique load. Most RF generators are designed for a 50-ohm resistive load. However, in practice, the load is rarely ever at that value. Most loads are a complex impedance consisting of both resistive and reactive components that change during operation.

To ensure a constant output level and maximum power transfer, the impedance matching unit makes the load look like 50 ohms resistive to the generator. The inductors and capacitors in the impedance matching network may be manually adjusted or may be controlled by servomotors in a special feedback control system.

The control system portion of the generator takes the phase/magnitude signals and processes them into control signals for operating motors that tune the inductors and capacitors. In most industrial applications, the load changes over time. Therefore, the impedance matching unit must be periodically or in some cases continually adjusted to ensure maximum power transfer. An electronic servo feedback system is used for this purpose.

Figure 1–2 shows a typical commercial RF generator. This fully solid state generator is capable of supplying up to 1250 watts for a 50-ohm load. Note the front panel meter that displays both forward and reflected power to the load and the manual power adjust knob.

Figure 1–3 shows two commercial impedance matching networks. The impedance matching network is typically a separate physical unit mounted as close to the load as possible. The output from the generator is connected to the matching unit by a coaxial cable. The photo shows the coaxial cable input connectors from the generator as well as the protrusions that connect the matching unit to the load. Later chapters will discuss generators, matching units, and coaxial cable in more detail.

FIGURE 1–2
A RF generator commonly used in semiconductor manufacturing equipment. Courtesy MKS Instruments/ENI.

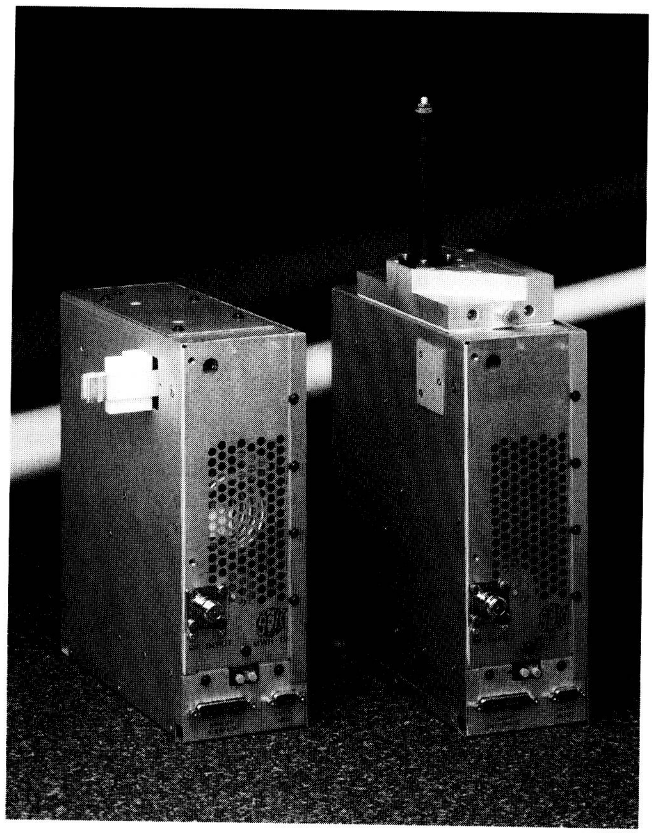


FIGURE 1–3
RF impedance matching units that are built into semiconductor manufacturing equipment. Courtesy MKS Instruments/ENI.

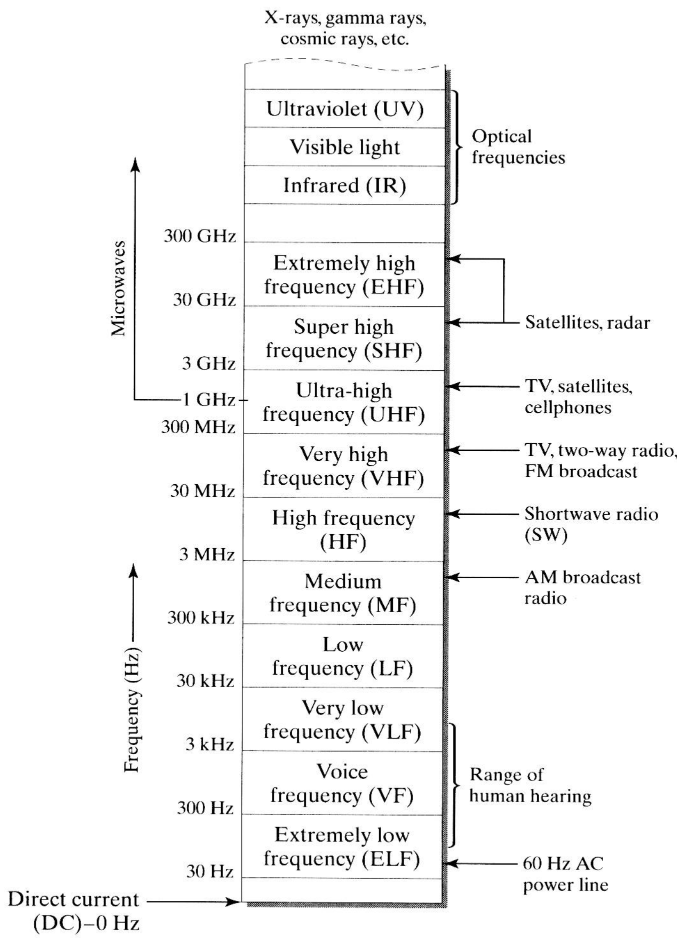
FREQUENCY OF OPERATION

The frequency of operation of an industrial RF generator is determined by the application as well as by the rules and regulations set by the FCC. The FCC regulates any device that generates signals in the radio frequency spectrum.

The electromagnetic frequency spectrum is illustrated in Figure 1–4. This shows the range of frequencies in which electrical and magnetic fields combine to form radio waves in free space. Note that this range is divided up into bands of frequencies in decades of frequency. Each band or range is given a name, such as high frequency (HF). A brief list of some of the services that use each range is given. Frequencies above 1 to 300 GHz are referred to as microwaves.

If the RF device is used for radio communications of any type, its frequency of operation as well as its power level, modulation, and other characteristics are specifically determined by the FCC. The FCC also regulates any industrial RF-generating device, even though it is not designed for radiating wireless communications signals. The reason for this is that any generator of high-power RF has the potential to interfere with radio signals because of

FIGURE 1–4
The electromagnetic frequency spectrum.



unintended radiation of harmonics or other spurious signals. The FCC regulations specify frequency of operation and maximum radiation levels so that interference does not occur in the various communications services.

These regulations are spelled out in the code of Federal Regulations (FR), Section 47, Subpart 18, which concerns the industrial, scientific, and medical (ISM) portions of the spectrum. The FCC defines frequencies, power levels, and radiation levels so as to prevent harmful radio frequency interference (RFI) or electromagnetic interference (EMI) to authorized communications services.

The FCC defines RF energy as any signal within the range from 9 kHz to 300 GHz. This is an enormous range and you will find that most ISM applications occupy only a few standard frequencies. The industrial, scientific, and medical equipment regulations apply to equipment designed to generate RF energy for any industrial, scientific, medical, domestic, or other noncommunications application. Most of these applications involve heating, ionization of gases, mechanical vibrations, or the acceleration of charged particles.

The largest category is industrial, where RF energy is used to heat some object or material. Another industrial application is ultrasonics, where RF energy is used to drive an electromechanical transducer to produce ultrasonic mechanical vibrations. These are used for chemical and medical applications.

Medical applications are another ISM area. They include diathermy equipment, magnetic resonance imaging (MRI), CT (computer tomography) scanners, and other medical equipment, including ultrasound. Another large application area is semiconductor manufacturing equipment. RF is widely used in etching, sputtering, and chemical vapor deposition and in other semiconductor manufacturing processes.

ISM Frequencies

The FCC actually indicates that you may use any radio frequency above 9 kHz as long as the radiation is at a sufficiently low level to prevent interference to any communications equipment operating near the designated frequency. However, there are bands of frequencies where it is strictly prohibited to operate RF ISM equipment. These frequencies are listed in Table 1–1. All these frequencies are used in some type of aircraft or marine safety, search, or rescue application.

Further, specific frequencies have been set aside strictly for ISM applications. These frequencies are not used by any radio communications services. These assigned frequencies and the frequency tolerances are given in Table 1–2.

Observe in Table 1–2 that the first four frequencies are harmonically related ($6.78 \times 2 = 13.56$, $13.36 \times 2 = 27.12$, $13.56 \times 3 = 40.68$ MHz) This relationship takes into consideration the fact that high-power RF systems generate harmonics that are also radi-

TABLE 1–1
Prohibited Frequency Bands (Sec. 18.303)

490–510 kHz
2170–2194 kHz
8354–8374 kHz
121.4–121.6 MHz
156.7–156.9 MHz
242.8–243.2 MHz

TABLE 1–2
Approved ISM Operating Frequencies

6.78 MHz	±15 kHz
13.56 MHz	±7 kHz
27.12 MHz	±163 kHz
40.68 MHz	±20 kHz
915 MHz	±13 MHz
2450 MHz (2.45 GHz)	±50 MHz
5.8 GHz	±75 MHz
24.125 GHz	±125 MHz
61.25 GHz	±250 MHz
122.5 GHz	±500 MHz
245 GHz	±1 GHz

Note: Remember, 1 GHz = 1000 MHz.

ated. The undesired harmonics will be radiated on frequencies assigned to ISM applications and, therefore, will not interfere with radio communications. The most widely used ISM frequency is 2.45 GHz. This is the operating frequency of the millions of microwave ovens in use throughout the world. The second most widely used ISM frequency is 13.56 MHz. It is the preferred frequency in many semiconductor manufacturing tools such as etchers and chemical vapor deposition machines. Other common frequencies used in semiconductor manufacturing equipment are 2 MHz, as well as 27.12 and 40.68 MHz. Magnetic resonance imaging (MRI) machines used in medical diagnosis use frequencies in the 60- to 65-MHz range.

The operating frequency tolerances in Table 1–2 are given in frequency, but sometimes you will see tolerance expressed as a percentage of the operating frequency. For example, the tolerance at 2.45 GHz is 50 MHz. In terms of percentage, the tolerance is

$$(50/2450) \times 100 = 0.020408 \times 100 = 2.0408\%$$

(actually $\pm 2.0408\%$).

In practice, most RF generators operate on the designated ISM frequencies recommended by the FCC. However, this does not prevent a manufacturer from using another frequency as long as radiation interference to nearby equipment is below the limits specified by the FCC.

Radiation Limits

The ISM equipment may radiate RF energy only on the frequency and over the tolerance band specified in Table 1–2. Any radiation outside of those designated bands must meet a maximum FCC field strength level. The field strength is a measure of the radio signal as picked up by a piece of test equipment known as a field strength meter. The field strength meter is a small radio receiver with an antenna and a calibrated output that measures the radiated signal in units of microvolts per meter (μV/m). The radiation limits for the most common types of ISM equipment are given in Table 1–3. The equipment refers to the type of industrial or medical equipment. Frequency refers to the actual frequency of operation, ISM frequencies or not. RF power gives the typical operating output power range of the equipment. Field strength is the measurement of the signal received at the distance specified in the last column in meters.

Field strength meters and the related measurements are covered in Chapter 9.