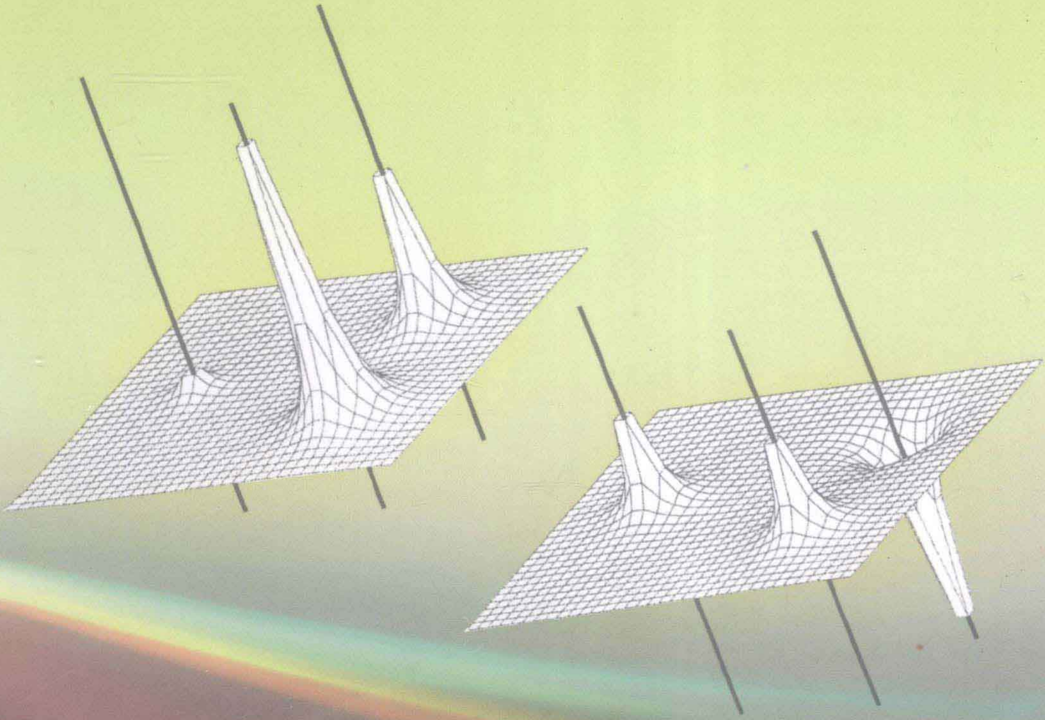
Power Definitions and the Physical Mechanism of Power Flow



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POWER DEFINITIONS AND THE PHYSICAL MECHANISM OF POWER FLOW

This book is dedicated
to Rodica, my life-long love,
and
to three great teachers of mine:
to my father Ing. Sigmund Eigeles
who taught me how to row a boat,
to Professor Constantin I. Budeanu
who opened my eyes to the beauty
of energy conversion,
and to Professor Michael S. Erlicki
who guided my first steps
in the realm of research.

Foreword

Energy policy is today a national priority. Conservation, renewable electricity sources and converting transportation from fossil fuels to electricity are major foci of activity. This is the most opportune time for someone to provide the definitive exposition of what is meant by "power" and how its various constituents are calculated and measured. Professor Alex Emanuel has done just that. This book, by gathering and clearly presenting the evolution of the increasingly complex interpretation of the V-I product, has done a great service to the engineering profession. Over time, the increased sophistication of electricity use and the introduction of solid state converters with their attendant harmonics have required that the definition and measurement of "power" be subjected to ever greater scrutiny. The resulting proposals, counterproposals and controversies evolved into a series of IEEE and DIN standards, each responding to the nascent effects of new technologies or an increased emphasis on economic accuracy. In today's restructured electricity industry, with real-time markets, the prospect of price responsive demand, and the introduction of an advanced metering infrastructure, accuracy of measurement and interpretation of power data is crucial.

Professor Emanuel promises an "in-depth understanding of the very physical mechanism that governs energy flow," and he delivers. He starts with the fundamental field description of power represented by Poynting's vector, then carefully and logically transitions to lumped physical systems, adding complexity until we arrive at all the components of "power" that constitute the V-I products of three phase, four-wire, unbalanced systems with non-sinusoidal currents and voltages. During the entire journey he builds upon the contributions of Budeanu, Fryze, Depenbrock and Czarnecki, pioneers in attempting to provide a rational interpretation of the result of multiplying current by voltage. And the comparisons he draws among the results of their proposed methods and that of the recent IEEE 1459-2010 standard is most interesting.

Few engineers are as well qualified as Professor Emanuel to undertake the writing of this monumental work. He has dedicated his entire professional life to the study of energy related problems, and has been a leading authority and educator in the field of power systems. It is clear that writing this book has been a labor of love, and we fellow electrical engineers owe Professor Emanuel a debt of gratitude for the fruit of this labor.

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Preface

These days the implementation of an "Advanced Metering Infrastructure" will be determined by the technology that enables the manufacturing of "Smart Meters." The quest for the smart meter is an integral part of a revolutionary movement, the big impetus for the Smart Grid and energy management. When the flow and the use of electric energy is monitored by means of smart meters, the energy provider receives, via real-time data acquisition, information that enables the remote control of customer loads, the ability to adjust demand response, asset management, variable pricing programs, and many more capabilities that improve the energy transmission efficiency by reducing the power losses and by leveling the load curves. Smart meters also benefit customers by increasing the reliability of supply as well as the ability to monitor the use and cost of energy. This technology will stimulate much needed behavioral changes that will lead to a significant decrease in energy use.

The metering instrumentation is designed to conform to the mathematical definition of the electric quantity monitored; however, the definition on which such smart meters' design is based must be true to the law of physics and provide information that enables the accurate determination of energy flow rate and quality, optimum power dispatching, and efficient maintenance planning.

The meters in use today, even some of the most modern electronic meters, are designed and built following a tradition rooted in the 1930s and 1940s. It is well known that meters that measure energy (kWh) and active power (kW) provide accurate measurements also under nonsinusoidal or unbalanced conditions; nevertheless, meters dedicated to apparent power (kVA) and nonactive power (kvar) measurements are prone to significant errors when the current and voltage waveforms are distorted. The main reason for such uncertainties stems from the inadequate power definitions that dictate the conceptual design of such instrumentation. Evidently this situation led to the search for a practical solution. The progress toward universally accepted definitions is slow and hindered by economic factors tied to an existing infrastructure of large proportions. A lively debate over the apparent power definition and its resolution started a century ago and has not yet reached a conclusion. I am an active participant in this ongoing debate and have witnessed how, in the last decades, a vigorous "technological soul searching" has produced two significant standards:

1. The IEEE Std. 1459–2010, Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions.
2. The DIN 40110-2: 2002–11, Quantities Used in Alternating Current Theory–Part 2: Multiconductor circuits (Polyphase Circuits).

Both standards provide improved power definitions that have been scrutinized and approved by large groups of experts and have triggered a multitude of engineering papers. This book has its main origin with the IEEE Std. 1459–2010. Many users of this document complained about its "tough reading" and asked for support documentation. Another important motivation for the production of this book stems from my desire to make a small contribution toward the acceptance and proliferation of smart meters. The major goals of this book are as follows:

1. To provide a clear understanding of the physical mechanism that governs the electric energy flow under different conditions: single- and three-phase, sinusoidal and nonsinusoidal, balanced, and unbalanced systems,
2. To be able to propose and advocate for recently developed power definitions that are not mathematical artifacts, but expressions that help correctly describe the actual effects and interactions between the energy sources, loads, equipment, and environment. Such definitions must be based on the solid understanding of the physical characteristics of the different components of energy,
3. To explain, discuss, and recommend power definitions that played a significant historical role in paving the road for the two standards,
4. To compare the two standards.

This book consists of eight chapters. The first explains electric energy flow. It introduces the concept of power as the rate of flow of energy and emphasizes the fact that electric energy is carried by an electromagnetic wave characterized by the power density (W/m^2) that is a function of time and space. Such electromagnetic waves travel (slide) along the conductors and contain a host of components. The main tool, used through the entire book, for recognizing the characteristics that help separate the actual elementary components of energy, is the Poynting vector. It is shown, with the help of a set of solved problems, that some components are active and carry unidirectional energy from sources to the loads, and other components oscillate between the loads and the sources and do not contribute to the net transfer of energy, but cause additional power loss in the conductors that connect loads and sources. This key chapter concludes that the Poynting vector is an excellent tool for the visualization of the power flow distribution in space and time; most importantly, it helps to reveal the correct energy and power components that ultimately are reflected in the ways the apparent power is resolved, thus leading to power definitions that are true to Nature's laws.

The second chapter deals with the single-phase system with sinusoidal waveforms. While introducing new definitions, such as the intrinsic power, this chapter presents a needed introduction and review of basic power definitions. Ample space is dedicated to the notion of apparent power, proving that it is a defined (convention) quantity that governs the equipment size, equipment losses, and the equipment aging and life-span. The power factor concept is presented in detail. A major section in this chapter is occupied by the discussions about the power oscillations between load and source, about the quantification of reactive and nonactive powers. It is shown that reactive power does not have to be produced by inductive or capacitive loads, but can also be caused by any energy converter that has the ability to store and return energy. It is also proved that the Poynting vector provides an excellent vehicle to help the reader familiarize with the separation and grouping of different active and nonactive instantaneous power components, their mathematical symbolism, and physical interpretation.

Chapter 3 explains the single-phase systems with nonsinusoidal waveforms. It starts by analyzing linear loads exposed to nonsinusoidal excitation and gradually advances to basic nonlinear loads, ultimately addressing a general case that provides the foundation needed to understand and critically compare different methods recommended for the apparent power resolution. This chapter emphasizes the need for the separation of the fundamental (50/60 Hz) active and reactive powers from the remaining apparent power components; this being an important IEEE Std. 1459–2010 contribution. Significant considerations are given to harmonics generation and injection mechanism, and how this phenomenon affects the power flow and the power definitions. It is shown how a certain amount of the fundamental power supplied to a nonlinear load is converted by nonlinear loads in a set of higher frequency components (harmonics) which, in turn, are injected into the power system. Flow charts that describe the flow path of different instantaneous power components are explained and used to demonstrate that the flow of instantaneous powers replicate the flow of Poynting vector components, thus providing the essential background for a correct decision when one needs to sort and define the apparent power components.

Chapter 4 is meant to provide the foundation needed for understanding approaches to power definitions, features, and limitations. The content is focused on apparent power resolutions as advocated by the researchers who directly, or indirectly, influenced the outcome of the two standards. They are:

C. I. Budeanu (1927)

S. Fryze (1932)

F. Buchholz (1950)

M. Depenbrock (1960)

L. S. Czarnecki (1984)

The author (1995)

The different methods are evaluated and compared by means of numerical examples. The transition to three-phase systems starts in Chapter 5. The scope is limited to sinusoidal balanced and unbalanced conditions. The key concept of Buchholz-Goodhue effective apparent power, the pivotal quantity of IEEE Std. 1459–2010, is introduced. Plenty of space is dedicated to the presentation of Fryze-Buchholz-Depenbrock (the FBD) method, which is the backbone of DIN 40110–2. The issue of power factor is discussed in detail. Ample explanations help prove the vector apparent power–the most popular apparent power definition–as being deficient. The mechanism of negative- and zero-sequence power generation is explained. A set of numerical examples allow the comparison of the definitions promoted by the DIN and the IEEE standard. It is concluded that for practical conditions, encountered in actual power systems, the two standards, while having different outcomes as concerns the zero-sequence voltage, yield very close results.

The sixth chapter deals with the most general case, the three-phase system with nonsinusoidal and unbalanced conditions. The literature abounds with studies of such conditions, promoting definitions that complete or contradict each other. This chapter presents only the most popular power definitions, i.e., those in use by instrumentation manufacturers in response to the request of electric utilities, or recommended by the two major standards. A central issue is debated: the IEEE Std. 1459–2010 considers that, ideally, a well compensated three-phase load must operate with positive-sequence currents and zero reactive power (unless the load is used as a power conditioner). DIN 40110–2 is different: it requires for unity power factor currents with waveforms that are replicas of the line–to an artificial neutral point voltage, (the actual neutral line is treated as the fourth phase). This means that traces of zero- and negative-sequence currents remain after the compensation. It is also explained that if all the loads supplied by a substation are compensated using either one of the two methods described in the two standards, the final results will be identical: perfect, pristine, positive-sequence sinusoidal currents with the respective symmetrical sinusoidal voltages.

The seventh chapter presents a newer, nonactive power, the randomness power. In situations when the monitored load is randomly time varying and power measurements are taken over a relatively large total observation time, the observation time is divided into small subintervals. The measurement taken for each subinterval is characterized by its own set of active and nonactive powers, stored for every subinterval. It is proved that the equivalent values for active and nonactive powers, measured over the total observation time, are the mean values of the active powers measured for each subinterval. This feature, however, does not apply to the measurements of apparent power, and it is necessary to include a randomness power in the resolution of apparent power, even when we deal with purely resistive loads. This new quantity gains in significance when the monitored loads are arc furnaces, welders, elevators, or any type of aleatory loads.

The last chapter includes eight appendices. The presented material is meant to help clarify heavier mathematical aspects, learn more about the Poynting vector applications, and find useful information that reveals the beauty of electromagnetic fields theory and the usefulness of Poynting vector in visualizing the energy flow. The reader interested in more rigorous mathematical demonstrations finds application of Lagrange multipliers to the computation of maximum active power. Another appendix deals with the computation of the allocated power loss to a monitored load connected in a network with a multitude of loads. Such information is crucial for the apparent power definition. The final appendix lists the readings of varmeters in the presence of distorted voltages and current waveforms.

I want to express my gratitude to Mrs. Catherine Emmerton, who coached my first steps in the complex world of LaTeX. Special appreciation goes to Prof. David Cyganski and Mr. Robert Brown for taking time from their busy schedule and bailing me out every time when “my PC was getting in trouble.” Their friendship and camaraderie helped me to overcome some difficult moments during the preparation of the manuscript. It is my pleasant duty to acknowledge the diligent work of Dr. Grazia Todeschini, who was the first person to read the completed manuscript, flag typos and technical errors, and suggest improvements. A special thank you is extended to the team at Wiley including Simone Taylor, Nicky Skinner, Laura Bell and Clarissa Lim for their support in publishing this book. I would also like to thank Jane Utting for copyediting the book and also to Shalini Sharma at Aptara for typesetting the book. I am also indebted to many of my students who studied this material with me and inspired me by asking tough questions. Finally, my deepest appreciation goes to my beloved WPI, and to my colleagues who create and maintain an environment conducive to creativity and true camaraderie.

It is my sincere hope that this book will inspire and motivate the engineers and scientists that will design and build the new generation of smart meters to conform with the recommendations of the IEEE Std. 1459–2010 or the DIN 40110–2, and to continue the quest for more correct and practical apparent power definitions, symbolic mathematical expressions that will be embraced by all the electrical engineers living and working on all four corners of our Earth.

Alexander Eigeles Emanuel
Southborough, Massachusetts
January 2010

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Electric Energy Flow: Physical Mechanisms

> Through valuation only is there value; and without valuation the nut of existence would be hollow. Hear it, ye creating ones!
>
> —Fr. Nietzsche, *Thus Spake Zarathustra*

There are two schools of thought that help students visualize the flow of electric energy from source to load and grasp the basic relations among voltage, current, power, and energy. The first, and seemingly the simplest, explanation relies on the flow of electric charges represented in Fig. 1.1. We imagine a cylindrical conductor with a cross-sectional area A and length ℓ, containing uniformly distributed charged particles that carry a total electric charge q. The volume charge density is

$$\rho_v = \frac{q}{A\ell} \quad (\mathrm{C/m^3}) \tag{1.1}$$

When a voltage v is applied between the ends of the conductive cylinder, a uniform electric field

$$E = \frac{v}{\ell} \quad (\mathrm{V/m}) \tag{1.2}$$

is created within the conductor. The vector of this field is oriented parallel with the conductor. The interaction between the charged particles and the field E is causing their motion along the conductor. The force developed on the charged particles found within a thin slice of thickness dx, that holds the charge $dq = \rho_v A dx$ is $dF = E dq$. The total force applied on the entire charge held by the cylinder is

$$F = qE = A\ell\rho_v E = A\rho_v v \quad (\mathrm{N}) \tag{1.3}$$

Once this system reaches steady-state the voltage source will pump continuously a constant flow of charge in a closed loop. One may picture this flow as the effect of a mechanical pressure

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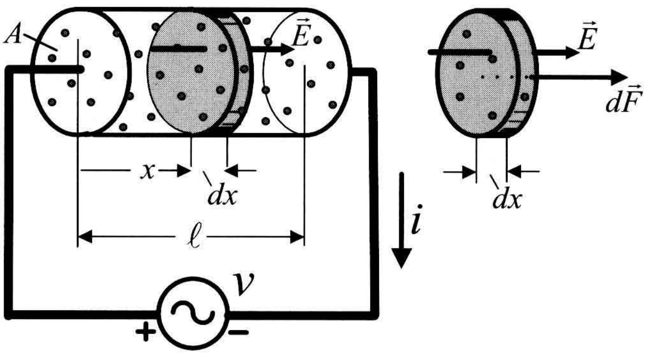

Figure 1.1 Flow of uniformly distributed charges in a homogeneous conductor.

$F/A = \ell\rho_v E = \rho_v v$. This model leads us straight to the notion of work or energy. To slide the total charge q a distance dx, consequent to the application of the force F, it is tantamount with doing the work

$$dw = Fdx = A\rho_v v dx \quad \text{(J)} \tag{1.4}$$

It may be assumed that the charged particles move with an average drift velocity $u = dx/dt$, proportional to the magnitude of the electric field, thus

$$u = KE \quad \text{(m/s)} \tag{1.5}$$

where the constant K is known as the mobility of the particles, (m^2/Vs). The elementary work dw is proportional to the drift velocity u. This fact becomes evident when (1.4) is written in the form

$$dw = A\rho_v v \frac{dx}{dt} dt = A\rho_v v u dt \tag{1.6}$$

The drift velocity $u = dx/dt$ is also hidden in the electric current expression

$$i = \frac{dq}{dt} = \frac{\rho_v A dx}{dt} = \rho_v A u \quad \text{(A)} \tag{1.7}$$

Substitution of (1.7) in (1.6) gives

$$dw = vidt \tag{1.8}$$

During a time interval $t = t_2 - t_1$ the voltage source will generate the total energy

$$w = \int_{t_1}^{t_2} vidt \quad \text{(J or Ws)} \tag{1.9}$$

The rate of flow of the electric energy at a particular time is the electric power

$$p = \frac{dw}{dt} = vi \quad \text{(W)} \tag{1.10}$$

From (1.7) and (1.5) we also obtain a simple deduction of Ohm's law. The current

$$i = \rho_v AKE = \frac{\rho_v KA}{\ell} E\ell = \frac{v}{R} \tag{1.11}$$

where

$$R = \frac{\ell}{\kappa A} \tag{1.12}$$

is the resistance of the conductor of length ℓ and cross-sectional area A, and $\kappa = \rho_v K$ is the specific conductivity of the observed conductive medium, $(\Omega\text{m})^{-1}$.

Finally, equations (1.10) and (1.11) lead to the well known expressions of electric power

$$p = Ri^2 = \frac{v^2}{R} = vi \tag{1.13}$$

The above explanation of power and energy flow appears in some introductory textbooks of physics and is favored by electrical engineers that deal with low frequency equipment. A major drawback of this rudimentary model becomes apparent when we try to explain situations where the energy is stored in, or transferred through, dielectrics immersed in alternating electromagnetic fields, Fig. 1.2.

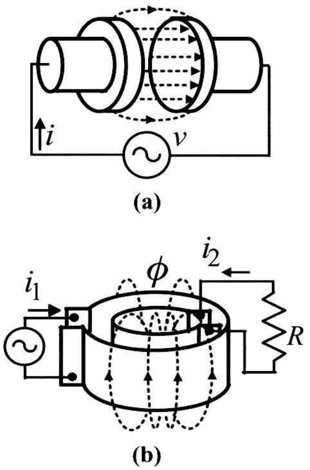

Figure 1.2 Examples where the Energy is Transferred via Dielectric Material: (a) Capacitor. (b) Magnetic Coupling.