BRIDGING CIRCUITS AND FIELDS

Foundational Questions in Power Theory

Alexander I. Petroianu

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Foundational Questions in Power Theory

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This is also a moment to express my gratitude to the University of Cape Town where I have served since 1989; this is one of the oldest universities in the Southern Hemisphere. I was able to share some of the ideas on this manuscript with my colleagues and students and to use rare documents in their library related to the beginning of electricity.

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Living in Canada has given me the peace of mind necessary to continue a life with purpose.

A special 'thank you' to Luisa, my wife, love, and friend, and one of the most severe copy-editors I have ever met – she reminded me permanently of Boileau's dictum:

Ce que l'on conçoit bien s'énonce clairement,
Et les mots pour le dire arrivent aisément.[1]

With her sharp criticism and helpful suggestions, she turned my idiosyncratic and terse engineering text into a more readable manuscript. More than that, without her, I would never have finished the monograph! Thanks also to Sylvia Izzo Hunter, who helped to revise the bibliography.

[1] What is clearly thought out is clearly expressed.

As a last thought: I have written this monograph also in loving memory of my parents (Iosif and Evelyne) and of my first wife, Susanne Petroianu *née* Bock.

Preface

> ***Motto***: *To those who came before us and those who will come after us searching for the elusive meaning of electrical power.*
>
> *Dedicated to Charles (Karl) Proteus Steinmetz – with admiration and respectful dissent.*

If it is true that professors never retire, at the most they lose their faculties, then I missed the second option and, many, many years ago started to investigate (paraphrasing Riemann) the hypotheses underlying the concept of power in electrical circuits.

Starting from the mundane power plug, the search for the meaning of power followed a long, tortuous, but fascinating journey, which started from the beginning of electricity and electromagnetism and continued up to today's quantum mechanics and relativity.

No discipline can be understood without knowing its past. The monograph covers many of the historical landmark writings on electrical and electromagnetic sciences, uncovers the filiation of ideas and pays due recognition to the founding fathers' heritage.

At macro level, power engineering deals with voltage, current and power; at atomic or mesoscopic level, power engineering deals with electrons, positrons, photons and Planck's quanta; at this level physics meets metaphysics or philosophy of science.

The monograph reveals not only the many mathematical avatars of the concept of power, but also the limitations that the current state of physics imposes on us and on our understanding of the processes related to power transmission phenomena at the mesoscopic level.

This monograph is written by an engineer for his colleagues – power engineers. The mathematical formulae and expressions are kept to a minimum. However, this does not make the monograph easy reading. This is not a book that thinks for you; this is a book that should make you think about a very serious issue – power engineering as a discipline is still lacking a theory of power!

As power engineers, we are like the proverbial shoemaker whose children have no shoes. We dedicate our professional life to a scientific discipline – power engineering – without having a clear idea of what we are dealing with.

The monograph addresses this question.

Chapter 1 presents my motivation for writing the monograph, and why this subject matter is important to a large audience.

Chapter 2 gives a short historical overview of the genesis of power theory. I was lucky to stumble over a mathematical failure of Steinmetz – one of the founding fathers of electrical engineering – and, as a result, I, the author, was confronted with a paradox – not Steinmetz! How could a mathematically incorrect equation used by Steinmetz in his symbolic method give correct results? And how could it be that, for the same concept – power – we have two different mathematical descriptions (from Steinmetz and Janet)? This chapter also reveals the limitations of the existing paradigm. Power theory is only a mathematical theory: it says nothing about the physical structure of electric power and does not reveal the mechanism of power transmission.

Chapter 3 takes a position on the Czarnecki-Emanuel debate about the relevance of the Poynting Theorem for power theory and shows that this debate has historical roots in the older debate between Abraham and Minkowski about electromagnetic momentum.

Chapter 4 presents a new power paradigm that conforms to the latest developments in physics and is expressed in the language of geometric algebra. The chapter proposes both a new mathematical expression for electromagnetic power and a new physical interpretation of power.

Chapter 5 gives an overview of the many mathematical 'guises and disguises' by which the power concept has been presented in the literature.

Chapter 6 concludes that power theory is a mathematical theory only and remains unfinished from the physical point of view. I conclude that power theory is still a growing discipline. As Heaviside said, "There is no finality in a growing science."

Alexander I. Petroianu

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CHAPTER 1

Introduction

1. The Subject Matter: Why Does it Matter?

The subject of the monograph is *power* in electrical circuits and transmission networks. The author examines the many mathematical representations of the electrical power concept.

Electrical power is the subject of power theory, which is an important discipline in electrical engineering. No discipline can be successfully investigated without knowing its history; for this reason, the monograph reflects the development of the power concept in its historical context. The development of power theory is tightly connected with the history of science and developments of two important schools of thought: Continental Electrodynamics and Faraday-Maxwell Electromagnetism.

Power phenomena occur over a broad spatial and temporal range. At their smallest scale, they approach Planck's quanta, and at their largest scale, their velocity approaches the speed of light. At these limits, physics meets metaphysics. The conceptual problems of power theory overlap the fundamental problems in the philosophy of science.

1.1 Author's Motivation

As a student, the author did not understand *why*, in direct current (DC) circuits, electrical magnitudes are represented as real numbers, whereas in alternating current (AC) circuits electrical magnitudes are represented as vectors, phasors, and complex numbers.

As an engineer involved in power system operation and control, the author focused on large-scale computer applications such as power flow and state estimation; this did not leave too much time for thinking about the meaning of the terms active or reactive power. However, he had a nagging feeling that double-frequency power components oscillating between source and load contradicted the principle of least action.

As a teacher, the author had difficulty explaining to students how a "crawling" electron (with speed through the conductor of approximately 10^{-4} m/s) enables an almost instantaneous transfer of energy, over long distances, from generator to load (the velocity of energy transfer is near to the velocity of light in vacuum, approximately 3×10^5 m/s).

In the context of electromagnetic theory, students are taught, on the basis of Poynting's theorem, that energy flows from outside the wires into the wires. But when studying circuit theory, they are taught, on the basis of Kirchhoff's law, that currents of electrons carrying power flow through the wires. Teaching the same concepts (e.g., power flow, energy flow) in completely different ways is inconsistent and confusing to the students.

Teaching something that the teacher himself does not understand reminds us of Faust (Goethe, 1790), who frustrated with his inability to understand the world, turns to magic:

Dass ich nicht mehr mit saurem Schweiss
Zu sagen brauche, was ich nicht weiss.
So that no more with bitter sweat
I need to talk of what I don't know yet

(translation by George Madison Priest) http://userhome.brooklyn.cuny.edu/anthro/jbeatty/COURSES/German/german1.2/faust.html

As academic fields, circuit theory and electromagnetism are closely related; however, they are separated by a huge gap with regard to their mathematical formalism and physical interpretation of the same fundamental concepts: power and energy. In other words, each of these disciplines is taught in "splendid isolation."

At the end of a long career in power engineering, the author realized that he is not alone in being far from understanding the question: *what is electrical power?* Even an eminent physicist like Feynman confessed that he did not understand what energy is.

Satisfying the author's curiosity and his frustration with old vexing problems perhaps justifies writing this monograph. However, this is not an argument for you, the reader, to read it. Here are the arguments showing that the question "*what is power?*" should bother you as well.

1.2 Reader's Motivation

For more than a century, the power industry has successfully generated, transmitted, and distributed huge quantities of power over long distances. The question that could be asked is, if it works and nothing is broken, what should we worry about, and why? The answer is that we have two types of power engineering knowledge: procedural and conceptual. This monograph deals only with conceptual knowledge. Its scope is not to change or improve how we calculate load flow or state estimation, but rather to understand what we are calculating: what physical and mathematical entities we are dealing with. The goal is to gain insight rather than simply to follow Leibniz's exhortation "calculemus" (let us calculate).

1.3 What is Electrical Power?

This is a simple, obvious question for everybody using power. Sometimes, the most obvious and simple questions are the most difficult ones.

It took the author 14 years to ponder this question and more than four years to write down an answer to the following questions: What is electrical power? How much do we understand what we know, where the limits of our knowledge are, how to represent the concept of power mathematically, and how to interpret it physically?

Contrary to opinions such as: "The concepts and definitions of electric power for sinusoidal AC systems are well established and accepted worldwide" (Akagi et al., 2007:19), there are still numerous open questions related to power theory.

Emanuel (2010:xiii) complains about the "inadequate power definitions" and states that "a lively debate over the apparent power definition and its resolution started a century ago and has not yet reached a conclusion."

Czarnecki (1997:360) states that "interpretation of power phenomena of circuits with nonsinusoidal voltages and currents remained unclear and controversial."

Küpfmüller et al., in their book Theoretische Elektrotechnik: Eine Einführung (2013:44), state that there is no consistent mathematical representation of the AC calculation from Steinmetz and Kennelly.

The mathematical analysis of Steinmetz's symbolic method (Someda, 2006) reveals that his definition of active power as an inner product of two vectors is different from the definition of power as the product of two complex numbers. The difficulty of matching the two expressions resides in the fact that vector space and complex space are not isomorphic spaces.

Atabekov (1965) considers complex power to be a phasor quantity, which can be represented graphically in a complex space, whereas Faria (2008:260) emphasizes that "complex power is not a phasor."

The author tends to agree with Kennelly (1910:1265), one of the founding fathers of electrical engineering, who stated more than one hundred years ago that "the algebra and geometry of vector alternating current technology...are, at present, in a state of great and unnecessary confusion....[which] has existed for more than twenty years and is not confined to any one country or language."

These examples (and there are many more) show that the mathematical and physical foundations of the power concept are in need of revision.

In an anecdote associated with Faraday and electricity, it is said that when Gladstone, the British prime minister, asked Faraday what use his discovery of electromagnetism might have, Faraday replied: "Someday you will be able to tax it." (Cohen, 1987: 177-182). To the reader's putative question about the worth of reading this monograph, the author's answer is that perhaps in reading it, you might understand what are you taxed for.

The question "What is electrical power?" is a matter of interest for students, practitioners, and specialists in electrical and power engineering, electrodynamics, electromagnetism, signal theory, physics, and applied mathematics.

2. Foundational Issues Related to the Concept of Electrical Power

2.1 Ontological Point of View

The author examines the physical meaning of entities such as voltage, current, and active, reactive, and apparent power, as well as how these entities are reflected in classical electromagnetic theory, or more specifically, how these entities are related to force, energy, and momentum.

2.2 Epistemological Point of View

The author examines the different mathematical formalisms (real algebra, complex algebra, trigonometric algebra, vector and tensor calculus, geometric algebra, etc.) used to represent physical entities in circuit theory and in electromagnetism.

The concept of electrical power is not antecedent-free; it is related to the concept of force. The monograph shows that the Blakesley-Ferraris expression for electrical power derives from the Amperian concept of force. The author stresses the important contribution of the Continental Electrodynamics school (Coulomb, Ampère, Poisson, Gauss, Riemann, Grassmann, Neumann C. and Neumann F., Weber and Poincaré) to the development of the expression for power: $p = vi$.

In Germany, one of the strongest supporters of the Faraday-Maxwell electrodynamic theory was August Föppl, whose book was cited by Steinmetz (as well as by Einstein). Föppl influenced Steinmetz's approach to power theory in two ways: 1) by introducing vectors as geometric representations of electrical magnitudes and 2) by his skeptical attitude toward the physical reality of voltage and current.

In recent years, there was a heated debate between Czarnecki and Emanuel related to the relationship between the Poynting vector and the expression of electrical power. For this reason, the author investigated the large body of literature related to electromagnetism (Faraday, Maxwell, Heaviside, Hertz, Lorentz, Lorenz) and electrodynamics (Ampère, Gauss, Weber, Neumann, Poincaré).

As a result of developments in physics (such as the Aharonov-Bohm effect, gauge theory, and the Yang-Mills experiment), electromagnetic theory is still being re-evaluated, and alternative theories have been proposed by writers such as Liènard-Wiechert, Wheeler-Feynman, Born-Infeld, and Hartenstein. However, the schism between quantum theory (Dirac, Heisenberg, and Schrödinger) and relativity (Einstein) remains; this is the reason why electromagnetic theory remains an unfinished theory as well. Because of the existing "crisis" in physics, many fundamental concepts (including the concepts of energy and power) are still under debate.

3. Contributions of this Monograph to Power Theory

3.1 Reappraisal and Reformulation of Steinmetz's Symbolic Method

The author demonstrates that Steinmetz was "wrongly right": his expressions for active and reactive power are correct, although his mathematical "proof" is false. Against his conviction, Steinmetz did not use complex algebra or vector calculus. He rediscovered Grassmann-Clifford Geometric Algebra. Unfortunately, he fooled not only himself, but many, many generations of electrical engineers who used geometric algebra thinking that they were using complex algebra and vector calculus.

3.2 Reappraisal of Janet's Heuristic Expression $S = \dot{V} I^*$

The author through geometrical reasoning demonstrates that Janet's rule ensures the invariance of two geometric areas, one representing active power and the other, reactive power. The author demonstrates that Janet was also right, only he did not know *why!*

3.3 Demonstration of the Mathematical Isomorphism between Steinmetz's Power Expression and Poynting's Expression for Energy Flow

The author demonstrates the mathematical isomorphism between Steinmetz's power expression and Poynting's expression for energy flow. In a similar way, it is shown (as many other authors have shown before) that Janet's expression is mathematically isomorphic with Poynting's expression for energy flow.

What differentiates this monograph from previous contributions (as reflected in the Czarnecki-Emanuel debate) is the fact that it contradicts the ontological interpretation of all the other authors. Behind a formal mathematical isomorphism (the epistemological aspect) hides a fundamental ontological contradiction. The author rejects, on the basis of physical interpretation, the relevance of the Poynting vector for power transfer in electrical circuits. A mathematical proof does not automatically represent a physical truth. The author rejects the idea that power comes from the exterior electromagnetic field and compensates for the Joule losses. The author rejects the idea that electrical networks are merely passive antennas. The interaction between the electromagnetic field and the electrical charges of the conductor are more complex than Poynting's interpretation. Power transfer between generator (sources) and the load (sinks) involve both electromagnetic waves and electrically charged particles of the conductor. This monograph offers a hypothesis of helicoidal-like power transfer (a combination of linear and rotational momentum).

3.4 Reactive Power is as much Power as Active Power

The author considers that there is only *one* power: *active* power is a tautology, and *reactive* power is a contradiction in terms (an oxymoron, or at least a misnomer). Reactive power is as much power as active power. One could be considered as derived from potential energy, and the other, from kinetic energy. *Reactive* power is in fact a momentum and a condition *sine qua non* (something absolutely indispensable or essential) for the transfer of potential energy (or power). The "struggle" for reactive power compensation is an ill-posed problem. We need momentum (linear in DC circuits and linear plus rotational in AC circuits) in order to move/transport/transfer energy from generators to the consumers. Momentum represents the mechanism for power transfer in both DC and AC circuits; for this reason, is incorrect to link the concept of *reactive* power with only the AC circuits.

3.5 Apparent Power does have Physical Meaning

Authors in the majority of power engineering publications consider that apparent power has no physical meaning: the KVA (kilovolt ampere) is just a "design" magnitude useful to calculate the dimensions of electrical machines, transformers, and apparatuses.

The author contradicts this opinion. Apparent power is equivalent to Lorentz's force in classical electromagnetic theory. The author gives a new interpretation of the power expression:

$$S = VI = V \cdot I + V \wedge \mathrm{I}$$

This expression represents (in the mathematical formalism of geometric algebra) the equality between an external force and the sum of electromagnetic energy and momentum (in a closed power system).

3.6 Criticism of the Interpretation of Double-frequency Terms

The monograph criticizes the interpretation of the double-frequency terms that appear as result of multiplying voltage by current in their trigonometric representations; the majority of textbooks interpret these terms as *oscillations* of power between generators and loads, or as power (active and reactive) surging back and forth, with no net energy transfer. The author challenges this interpretation, which contradicts the principle of least action and resembles a kind of (energetic) perpetuum mobile within the power network.

3.7 Validity of the Instantaneous Power Concept

The author questions the validity of the *instantaneous power* concept. The idea of instantaneous power obtained as a measurement of instantaneous voltage and instantaneous current contradicts Heisenberg's uncertainty principle in quantum mechanics.

3.8 Physical Interpretation of Voltage and Current as Inseparable Entities

The author questions the physical interpretation of voltage and current as separate or separable entities. The author interprets voltage and current as two mathematical representations or faces of the same physical entity: *electromagnetic power*.

3.9 Issues Related to Load Flow and State Estimation

The author raises some issues related to load flow and state estimation. These analytical tools were developed within the framework of "classical" power theory. Classical power theory, likewise classical electromagnetism, considers the *scalar electric potential* but does not consider the existence of the *vector electromagnetic potential*. It also ignores the delayed and action-at-a-distance (aaad) electromagnetic effects. The development of quantum mechanics and mathematics proves the need to re-assess the existing analytical tools currently in use for power system analysis, operation and control.

4. Research Methodology

Power theory, as a sub-discipline of electrical engineering, is at the crossroads of Physics and Mathematics; it is also tightly interconnected and influenced by other disciplines, such as circuit theory, electrodynamics and electromagnetism, signal theory, electrical machines and power electronics, quantum theory, relativity, algebra, and geometry.

For this reason, the author adopted a multidisciplinary approach in his investigation of the foundational concepts related to electrical power.

This approach required a broad knowledge of both the literature on many topics and the development of these topics over time. As a result, the author sometimes trespasses into the domain of the history of electrodynamics and electromagnetism. The monograph also deals with epistemological and ontological topics pertaining to the philosophy of science that, although beyond the scope of a strictly technical investigation, are highly relevant for a proper understanding of the power concept.

5. Literature and References

The author examined a large body of primary and secondary literature pertaining to the evolution of the power concept. Special attention has been given to the heritage left by the founding fathers of electricity, electrodynamics, and electromagnetism. The author tried to determine the filiation of ideas and the interconnectedness of electrical engineering, electromagnetism, physics, and mathematics with regard to concepts of power, force, energy and momentum.

The author also consulted the following databases: EBSCO Academic Search, Archives-Ouvertes, ArXiv.org e-Print Archive, Compendex, DART-Europe E-Theses, Eidgenössische Technische Hochschule (ETH) Library (Zürich), Elibrary.RU (Russia), École Polytechnique de l'Université de Lausanne (EPFL) Theses, Gallica Digital Library, Google Scholar, Hathi Trust Digital Library, Göttinger Digitalisierungszentrum (GDZ), IEEE Xplore® Digital Library, Inspec, JSTOR, Knovel, MathSciNet, Project Gutenberg, ProQuest Dissertations & Theses, ScienceDirect, Scopus (Elsevier), SPIE Digital Library, Springer Link, Technische Informationsbibliothek (TIB) – German National Library of Science and Technology.

The research for this monograph required access to books, archives, and online resources. The author has been fortunate to belong to the University of Cape Town, one of the oldest in the Southern Hemisphere (unfortunately destroyed in a devastating fire). Its archives contain a treasure trove of telegraph and electricity journals from the early nineteenth century.

He also greatly benefited from his affiliation to the University of Calgary; its library is one of the most modern in North America with regard to online access to books, publications, and databases in engineering, physics, and mathematics.

6. Style

Since the monograph is focused on the conceptual aspects of the power theory, mathematical formalism is kept at a minimum. However, readers need a basic knowledge of algebra (real-, complex-, trigonometric algebra) and geometry (vector calculus and geometric algebra).

7. Structure

In Chapter 1, the author presents his motivation for writing the monograph, and why this subject matter is important to a large audience.

Chapter 2 gives a short historical overview of the genesis of power theory. The author was "lucky" to stumble over a mathematical failure of Steinmetz – one of the founding fathers of electrical engineering – and, as a result, he was confronted with a paradox. How could a mathematically incorrect operation (Steinmetz's symbolic method) give correct results? And how could it be that, for the same concept – power – we have two different mathematical descriptions (from Steinmetz and Janet)? This chapter also reveals the limitations of the existing paradigm. Power theory is only a mathematical theory: it says nothing about the physical structure of electric power and does not reveal the mechanism of power transmission.

In Chapter 3, the author takes a position on the Czarnecki-Emanuel debate about the relevance of the Poynting Theorem for power theory and shows that this debate has historical roots in the older debate between Abraham and Minkowski about electromagnetic momentum.

In Chapter 4, the author presents a new power theory paradigm that conforms to the latest developments in physics; this paradigm is formulated in the mathematical language of geometric algebra. The chapter proposes both a new mathematical expression for electromagnetic power and a new physical interpretation of power.

Chapter 5 gives an overview of the many mathematical "guises and disguises" by which the power concept has been presented in the literature.

Chapter 6 concludes that power theory is a mathematical theory only and remains unfinished from the physical point of view. The author concludes that power theory is still a growing discipline. As Heaviside said, "there is no finality in a growing science."

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