# Energy Processing and Smart Grid


James A. Momoh

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# *PREFACE*

**THE TRADITIONAL** electrical engineering curriculum requires a basic course in electrical machinery, which includes three-phase networks, electromagnetics, transformers, synchronous generators, induction-machine and DC-machine modeling, construction, and performances analysis.

The knowledge of these concepts does not fully prepare students to understand, analyze, and participate in the design, development, and deployment of future grids with features of micro-smart-grid functions. The skills needed include knowledge of classical machine control, real-time measurements, renewable energy resources, storage technology, inverters and converters, and power electronics for processing different energy sources to serve different load models. This book introduces energy-processing concepts and topics needed by students in electrical engineering—and those outside of electrical engineering who will work in future grid development.

The intended audience includes undergraduates and first-year graduate students in a typical engineering program. It is assumed that these students have taken network analysis and electromagnetics courses and hence these topics are only summarized. Full treatment can be found in textbooks on standard machines and electromagnetics.

The idea of this book stems from a research grant from the Department of Energy/National Science Foundation future-grid initiative to the Power System Engineering Research Center/Industry University Collaboration Research Center Research and Workforce Award. As part of this grant, the Howard University team designed research and workforce education materials to contribute to the development of a new curriculum for teaching future energy conversion that will prepare students for handling research and education modules involving future-grid development.

The workforce-education module discussed in this text is a timely assignment since the electrical engineering program at Howard University—like at other universities—is reviewing its curriculum to accommodate new topics in future grid, since there appears to be no single book to present the balance of classical-machine and new trends in energy conversion and processing. This book serves as a reference for students as well as consultants who wish to have a quick overview of machines and energy processing and their relevance to microgrid with smart-grid functions.

Basic materials have been explained with illustrative examples and pictures. In the last few years, the materials in this book have been used to teach required undergraduate courses at Howard University, and some materials were used for teaching first-year graduate students who have a minimum background in energy processing for smart grid. We recommend that any materials too basic for the reader be skipped.

Throughout the book, we tried to minimize details on classical-machine concepts to allow for understanding and working knowledge of processing energy sources in the microgrid/smart-grid environment. We urge the reader to consult advanced books for further reading on these topics.

As noted, we have added some modern topics such as renewable energy, storage technologies, inverters and converters, power electronics, metering, and control for microgrid systems. From our experience thus far, this book will help kindle students' interest in old-machine analysis and also their pursuit of new topics in design and development of smart-grid and microgrid systems.

The book is organized into nine major sections:

**(i)** Basic concepts of network analysis applied to power and electromagnetic concepts as relevant to design and understanding of electromechanical systems, which form the backbone of energy processing

**(ii)** Fundamentals of machinery functions, construction, modeling, and performance for transformers, synchronous machines, induction machines, and DC machines

**(iii)** Renewable-energy and storage-technology options for sustainability of energy needs in future grids

**(iv)** Design of inverter and converter and power electronics for energy processing from different sources to serve different loads

**(v)** Microgrid applications design, technology, and operational management

**(vi)** Review and evaluation of metering communication and control for enabling different functions for operating and managing smart-grid and microgrid systems

**(vii)** Smart-grid design, architecture, security protocols, and real-time measurements

**(viii)** Different test beds and their features with useful energy-processing technology

**(ix)** Exercises for design, testing, and evaluation of energy processing as experimental case studies; this involves a 'power game' within an energy-processing platform with OPAL RT in the loop

# ACKNOWLEDGMENTS

**I WOULD LIKE** to acknowledge the vision of the Power System Engineering Research Center (PSERC)/Industry University Collaboration Research Center (IUCRC), and Department of Energy (DOE) to encourage deployment of workforce-training materials along with research in support of design, development, and deployment of advanced tools needed for the future grid. The future grid—and its sustainability, security, efficiency, and affordability—is fundamental, and thus requires energy processing. Furthermore, electromagnetic machines, power electronics, storage, inverters/converters, tools for the design of the microgrid and smart grid are essential. Knowledge of communications, controls, and standards is essential for building the structure of the future grid. Therefore, my hope is that this book will contribute to research materials that prepare undergraduate and graduate students to prepare for research and careers in the evolving power grid and smart grid industries.

The new course in energy processing and smart grid at Howard University helped meet the challenge of electrical engineering curriculum revision at the undergraduate level to reduce credit hours for graduation from 130 to 120 as in other engineering schools. It has been taught as an undergraduate junior-level course and as a first-year graduate special topic course.

Special thanks are due to several students who helped in the preparation, problem-solving, and exercises in the book. We also acknowledge the pioneering work in energy processing, machines, and smart grid and microgrid by several authors.

# FOREWORD

**INCREASINGLY, ELECTRICITY** is being produced from renewable resources—primarily solar and wind—in an effort to mitigate the consequences of global warming resulting from high concentrations of atmospheric carbon dioxide produced by burning fossil fuels. This new direction in energy production and environmental protection requires an extensive re-engineering of the existing electric grid into a computerized future grid—or a smart grid—that accommodates the special characteristics of renewable power-generating technologies. To advance grid modernization, the Power Systems Engineering Research Center (PSERC) has been conducting research with its industry partners on the technical challenges facing the electric power industry.

Keeping up with the education side of its mission, PSERC's faculty has developed software tools, courses, a virtual library, and training materials to ensure the basis of a workforce well versed in implementing the future grid. This book, *Energy Processing and Smart Grid*, developed as a part of this mission, is divided into three broad sections: energy conversion including renewables, power electronics interfaces, measurements, and controls of the microgrid and smart grid, and test beds for the smart grid.

The author, James A. Momoh, has extensive experience in power system modeling, control, planning, and operations which make him qualified to write a book addressing these topics. This book is a valuable addition to IEEE John Wiley & Sons series which addresses the development of educational tools to meet the needs of the current and future engineers that will be managing these complex cyber-physical systems as well as innovators who will bring future transformations.

The book provides a fundamental understanding of energy processing and technologies needed for building the smart grid. It covers major topics on the fundamentals of smart grid, energy conversion and power electronics, cyber security, real-time measurement, and state estimation techniques. The book is easy to use because it speaks a language that is understandable to both novices and experts. It will serve as a good reference as well as self-study guide for graduate students, research teams, and system operators.

Vijay Vittal
Ira A. Fulton Chair Professor
Director PSERC
School of Electrical, Computer and Energy Engineering
Arizona State University

CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION

The process of electric energy generation, transmission, and distribution is conducted via a large-scale central generation (CG) to meet increasing demand at industrial, commercial, and residential loads. The generation of power through central generation is done via coal-fired, fossil-fuel, hydro, and steam turbines. These resources are converted to electrical energy then processed through different technologies to meet growing load demands. Similarly, the transmission of power from generating units requires high investment, including numerous energy-processing technologies to transfer power to load centers. This is done via transformers and solid-state switching devices at very high voltages. Distribution-system networks are also significant for dispatching power at low voltage via step-down transformers to domestic consumers. Given the different direct current (DC) and alternating current (AC) load models and categories, energy-processing devices such as converters and inverters are needed especially when issues of safety, quality of power, security, and processing are important to meet different loads from various sources.

In recent years, many new distributed generation (DG) sources have been introduced with the aim of reducing losses and increasing reliability, regardless of economy of scale of CG, which can be huge when accounting for cost of transmission and reliability during failure.

DG created from solar, mini-hydro, wind, stirling engines, and fuel cells is of common interest. The debate on how to determine to what extent one should drive CG or DG is a research topic under the future grid initiative. In this paper [1], we were able to show three criteria for selecting which energy sources and processing options should be selected. The criteria included economy of scale, resilience, sustainability, and reliability. Regardless of the choice, appropriate energy processing tools and concepts are a dominant concern moving forward. It is therefore important for a book to be dedicated to addressing appropriate fundamental concepts and technologies for designing, building, and validating the performance of the future grid. That is the goal of this book.

In this book, we propose to provide an integrated foundational knowledge that harnesses the role of energy conversion machines and devices with some new topics

*Energy Processing and Smart Grid*, First Edition. James A. Momoh

for energy generation, transmission, distribution, delivery, and consumption. First, it is relevant to provide the working definition of *microgrid*.

The microgrid involves a stand-alone or grid-connected system to:

- match generation with load
- serve as a reserve margin
- help stabilize the power system
- increase reliability and affordability
- reduce the impact of threats on the bulk power system

In contrast, the smart grid is a two-way digital system with active participation of customers within the grid that includes renewable energy resources (RER) with the aim of sustainability and allows reasonable penetration levels and interoperability [2]. It possesses self-healing capabilities; cyber security; and real-time, design-based functions such as reconfiguration, demand-side management (DSM), demand response, and power quality.

We present eight points in this book to support control communications and energy processing for the smart grid. They are the basis of the seventeen chapters, categorized as follows:

1. A basic review of network (circuit) analysis and electromagnetics is provided. This includes discussion on the fundamental concepts of three-phase analysis of AC sources to different load configurations. The text assumes the sources are AC that can be converted to DC or AC/DC or DC/AC using inverters and converters, as discussed in Chapter 12. A set of hand-calculation exercises is presented although software tools such as NEPLAN [3], Electrical Transient and Analysis Program (ETAP) [4], and Personal Computer Simulation Program with Integrated Circuit Emphasis (PSPICE) [5] can also be used. Balanced or unbalanced conditions can also be analyzed using symmetrical components.
2. Electromagnetic concepts are introduced by providing the unified theory of Maxwell's equations and their applications for understanding machinery concepts, including transformers, synchronous and induction machines, and DC machines. The unified theories of Faraday, Lenz, and Ampère are given to illustrate the concept of electromagnetic computation. Equivalent analogous forms of magnetic circuits in electric circuits are given for magnetic circuits with rectangular and toroidal shapes with and without air gaps for different ferromagnetic materials.
3. Fundamental understanding of machines is discussed. This includes the conversion process and the role of Maxwell's equations. The construction and model of the machines using electrical network equivalents are given using short-circuit and open-circuit analyses for determining the equivalent parameters [6]. The power flow in each machine—accounting for conversion, electrical, mechanical, and stray losses—is given. Following this, the text provides a guide for computing efficiency of the power input relative to the output power

received. In addition, voltage regulation and control strategies to achieve optimum energy processing are discussed.

4. Fundamental knowledge of storage and renewable resources is important for development of future grids where sustainability and mobile power are needed. Storage is safe, inexpensive, and the reason for interest in the design of future environmentally friendly grids. The text provides a working model, description, size, and metrics of different resources and storage technologies. Software packages are recommended for studying the impact of RER for reliability and cost–benefit analysis for stand-alone distribution system topologies for the future grid.
5. Efficient technology to handle processing energy from one state or form to another includes inverters and converters, which provide AC/DC, DC/DC, or DC/AC conversion from a given resource to given loads. To minimize poor power quality, different electronic devices and filters are used. The text provides a fundamental knowledge of power electronics to allow the reader appropriate choices of electronic devices for energy processing.
6. In designing the operation and management of the smart grid and microgrids, real-time processing of energy and information is essential. We present an overview of real-time data such as voltage, current, power, and frequency, which measure the status of the grid via smart meters and phasor measurement units (PMUs). The formulations and specifications of the devices and their use in communication and control schemes are given. Work in areas of real-time voltage-stability management, power quality, frequency control, voltage/volt-ampere reactive (var), reconfiguration, and several other grid functions are included in the proposed exercises.
7. We provide a description for understanding the smart grid and microgrid, including functionality, architecture, and the test bed. The chapters integrating the concept of microgrids in this text are an evolving process. Research work and laboratory exercises are important activities for general electrical installations.
8. Finally, the design of microgrid systems with smart grid functions is described.

Our research involving the design and construction of a microgrid test bed consisting of solar power, super capacitors, batteries, metering devices, converters and inverters, and a real-time simulator is ongoing at Howard University. The introduction of the OPAL-RT real-time digital simulator (RTDS) to the array of research and educational equipment at the Center for Energy Systems and Control (CESaC) at Howard University is allowing us to develop functions such as power quality, voltage stability, voltage/var, DSM, and restoration.

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CHAPTER 2

# ELECTRIC NETWORK ANALYSIS IN ENERGY PROCESSING AND SMART GRID

## 2.1 INTRODUCTION

In modern AC electric power systems (Figure 2.1), power is generated, transmitted, and distributed as balanced, three-phase AC. The three-phase system was independently invented by Galileo Ferraris, Mikhail Dolivo-Dobrovolsky, Jonas Wenström, and Nikola Tesla in the 1880s and is the most widely used means of transferring power through power grids. The three-phase system has the advantage of economy over the single-phase system because more power can be transmitted with significant cost savings in conductors per unit line length. The three-phase system may be configured as three-wire star, four-wire star, or three-wire delta system.

Because of advances in electronics, the future electric power system is headed in the direction of microgrids and smart grids. In anticipation of demands, researchers and students need to be equipped with relevant knowledge on the emerging trends in this area. This chapter introduces the fundamentals of electric power systems and the basic computational tools needed for the design and analysis of the future-generation power system.

## 2.2 COMPLEX POWER CONCEPTS

In electrical power systems, we are mainly concerned with flow in the electrical circuit, such as Voltage (V), Frequency (f), Current (I), and Power (P). To treat sinusoidal, steady-state behavior of an electric current, some further definitions are necessary.

Let

$$v(t) = V_m Cos(\omega t + \theta) \tag{2.1}$$

and

$$i(t) = I_m Cos\ (\omega t + \theta - \varphi) \tag{2.2}$$

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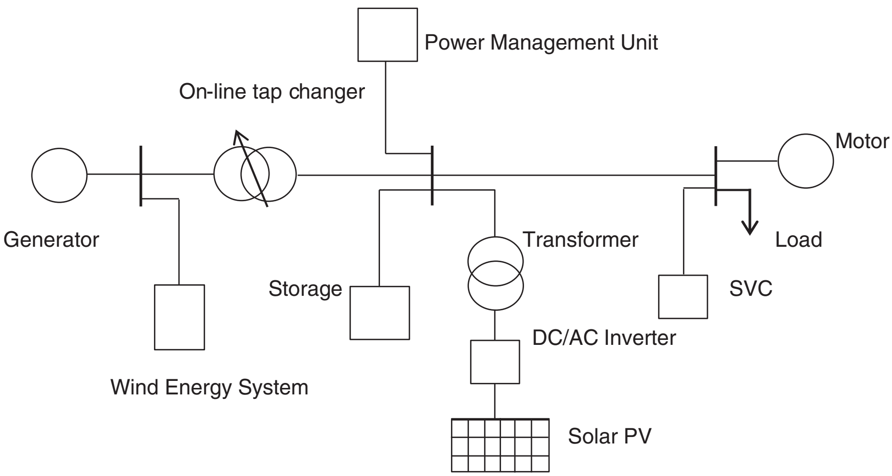


Figure 2.1 Simplified single-line diagram schematics of a modern electric power system.

and

$$Z = Z\angle\psi \tag{2.3}$$

where

$$I_m = \frac{V_m}{Z}. \tag{2.4}$$

In polar form,

$$V = V_m e^{j\varphi} = V_m\angle\varphi \tag{2.5}$$

or

$$V(t) = Re\left(Ve^{j\omega t}\right). \tag{2.6}$$

It is important to recall the following trigonometric identities:

$$Cos\alpha Cos\beta = \frac{1}{2}\left[Cos\,(\alpha-\beta) + Cos\,(\alpha+\beta)\right] \tag{2.7}$$

$$Sin\,(\omega t+\alpha) = Cos\left(\omega t - \frac{\pi}{2}\right). \tag{2.8}$$

For a voltage signal represented in terms of root mean square (rms) value:

$$V(t) = 100\sqrt{2}Cos\left(\omega t + 30^\circ\right)\,Volts \tag{2.9}$$

$$V = 100\angle 30^\circ$$

$$i(t) = 10\sqrt{2}Sin\left(\omega t + 30^\circ\right)A \tag{2.10}$$

$$i(t) = 10\sqrt{2}Cos\left(\omega t + 30^\circ - \frac{\pi}{2}\right)A \tag{2.11}$$

$$i(t) = 10\sqrt{2}Cos\left(\omega t - 60^\circ\right)A. \tag{2.12}$$

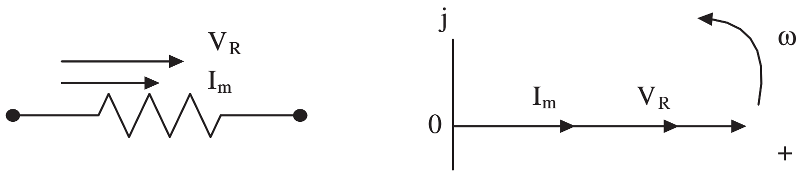


Figure 2.2 Phasor diagram of a purely resistive circuit.

For impedance, if the circuit is purely resistive, inductive, or capacitive, there will be difference in current and angle phase shift.

### 2.2.1 Purely Resistive Circuit

In a purely resistive circuit, Figure 2.2, the current is in phase with voltage:

$$V_R = RI_m. \tag{2.13}$$

### 2.2.2 Purely Inductive Circuit

Current lags behind $V$ by 90° as seen in Figure 2.3:

$$V_L = j\omega LI_m. \tag{2.14}$$

### 2.2.3 Purely Capacitive Circuit

In a purely capacitive circuit Figure 2.4, current leads voltage by 90°:

$$V_c = \frac{I_m}{j\omega C} \tag{2.15}$$

### 2.2.4 Instantaneous Power

The instantaneous power is given by:

$$P(t) = \frac{V_m I_m}{2}\left[Cos\varphi + Cos\left(2\omega t - \varphi\right)\right] \tag{2.16}$$

$$P_m = \frac{V_m I_m}{2} Cos\varphi \tag{2.17}$$

$$V_m = \sqrt{2} V_{Rms} \tag{2.18}$$

$$P_{av} = V_{Rms} V_{Rms} Cos\varphi \tag{2.19}$$

where $Cos\varphi$ is the power factor.


Figure 2.3 Phasor diagram of purely inductive circuit.

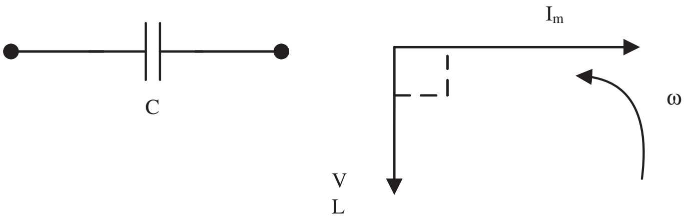


Figure 2.4 Phasor diagram of a purely capacitive circuit.

### 2.2.5 Power Factor

The power factor of a system is defined as:

$$Cos\varphi = \frac{Active\ Power}{Apparent\ Power} = \frac{P\ (KW)}{S\ (KVA)} \tag{2.20}$$

where $P = VICos\varphi$ and $Q = VISin\varphi$.

$Q$ is the reactive power measured in kilo-var (kvar).

### 2.2.6 Complex Power

The apparent power S is then:

$$S = VI \tag{2.21}$$

$$I = I\angle\varphi, \tag{2.22}$$

and

$$I^* = I\angle - \varphi \tag{2.23}$$

$$S = VI^*. \tag{2.24}$$

If the load impedance is Z, then,

$$S = ZII^* = Z|I|^2. \tag{2.25}$$

In terms of load admittance,

$$S = VY^*I^* \tag{2.26}$$

$$= Y^*|V|^2. \tag{2.27}$$

## 2.3 REVIEW OF AC-CIRCUIT ANALYSIS USING PHASOR DIAGRAMS

Consider the AC circuit of Figure 2.5. The load, operating at a voltage $V_L$, draws a current $I_L$ from the source whose voltage is $V_s$, through resistance $R$ and inductive reactance $jX$.

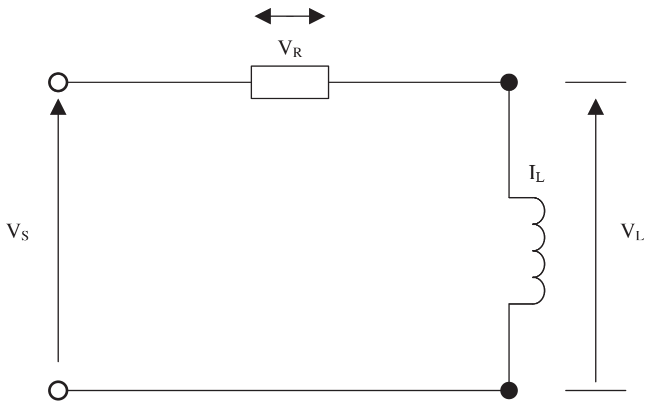

Figure 2.5 AC circuit analysis with phasor diagram.

By Kirchhoff's voltage rule:

$$V_s = V_L + V_R \tag{2.28}$$
$$V_s = V_L + IR \tag{2.29}$$

where

$$Z = (R + jX) \tag{2.30}$$
$$Z = |Z| \angle\theta. \tag{2.31}$$

If the load is operated at power factor $Cos\varphi$ and voltage $V_L$ then

$$V_L = |V_L| \angle 0° \tag{2.32}$$
$$I_L = |I| \angle\varphi. \tag{2.33}$$

Then Equation 2.29 may be rewritten as:

$$V_s = |V_L| \angle 0° + (|I| \angle\varphi)(|Z| \angle\theta) \tag{2.34}$$
$$V_s = |V_L| \angle 0° + |I|\,|Z| \angle\varphi + \theta. \tag{2.35}$$

A phasor diagram Figure 2.6 may be constructed based on Equation 2.35 from which the source voltage $V_s$ may be determined.

## 2.4 POLYPHASE SYSTEMS

One of the methods of transmitting and distributing AC electric power is by means of polyphase systems. This is a system with three or more energized AC currents

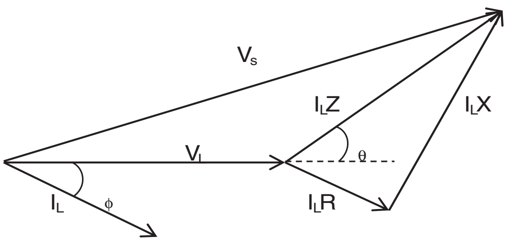


Figure 2.6 Phasor relationships of power system quantities.

carrying conductors with a phase deviation between them. For a balanced n-phase system, the phase difference is given by:

$$\emptyset_d = \frac{2\pi}{n}\ degrees. \tag{2.36}$$

For two-, three- … six-phase systems, voltages will be out of phase by 90°, 120°, … 60°, respectively.

Polyphase systems are particularly useful for transmitting power as more power can be transmitted than when a single phase is used.

### 2.4.1 Three-Phase Circuits

Power generation, transmission, and distribution are usually connected in a type of polyphase system for heavy utilization of AC electric power. These types of connections provide economic advantages as well as system stability and capacity control. Both voltage and currents are sinusoidal waveforms equal in magnitude, but are displaced from one another by 120° in time phase. Stator windings are connected in three-phase through a ground wire, leading to four wires. The center of the four wires (Figure 2.7) leads to a Y-connected system, where each is referred to as a phase and the fourth conductor is called the *neutral wire*, which has four-wire balanced connection.

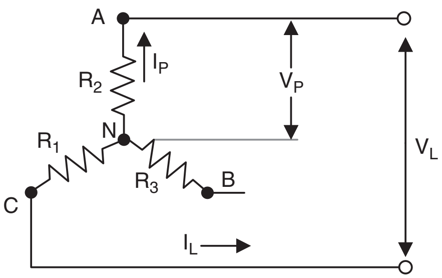


Figure 2.7 Equivalent Y diagram.

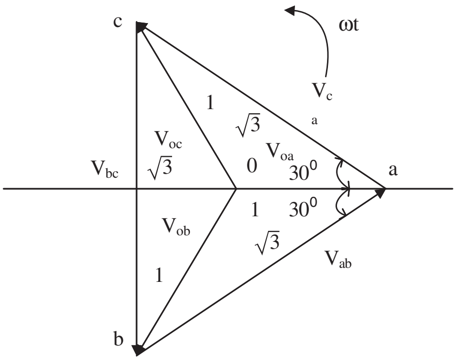


Figure 2.8 Phase and line voltage representation.

### 2.4.2 Balanced Y-Connected Three-Phase Source

In vector (phasor) form

$$\vec{V}_{AN} = \frac{V_L}{\sqrt{3}}\angle 90° \tag{2.37}$$

$$\vec{V}_{BN} = \frac{V_L}{\sqrt{3}}\angle - 30° \tag{2.38}$$

$$\vec{V}_{CN} = \frac{V_L}{\sqrt{3}}\angle - 150° \tag{2.39}$$

$$\vec{V}_{AB} = \vec{V}_{AN} - \vec{V}_{BN} \tag{2.40}$$

$$\vec{V}_{AN} + \vec{V}_{BN} + \vec{V}_{CN} = 0 \tag{2.41}$$

$$\vec{V}_{AB} + \vec{V}_{BC} + \vec{V}_{CA} = 0. \tag{2.42}$$

Similarly, for Δ-connected system

$$\vec{V}_{BA} = \vec{V}_{AC} = \vec{V}_{CB} = \vec{V}_{L}. \tag{2.43}$$

### 2.4.3 Phase and Line Voltages: Delta Connected

The line-neutral and line–line voltages with proper relations are shown in Figure 2.8.

$$\vec{V}_{CB} = \sqrt{3}\vec{V}_{NB}. \tag{2.44}$$

$\sqrt{3} \times$ Line-Neutral, $V_{BA}$ leads $V_{NA}$ by 30°, $V_{CB}$ leads $V_{NB}$ by 30°.

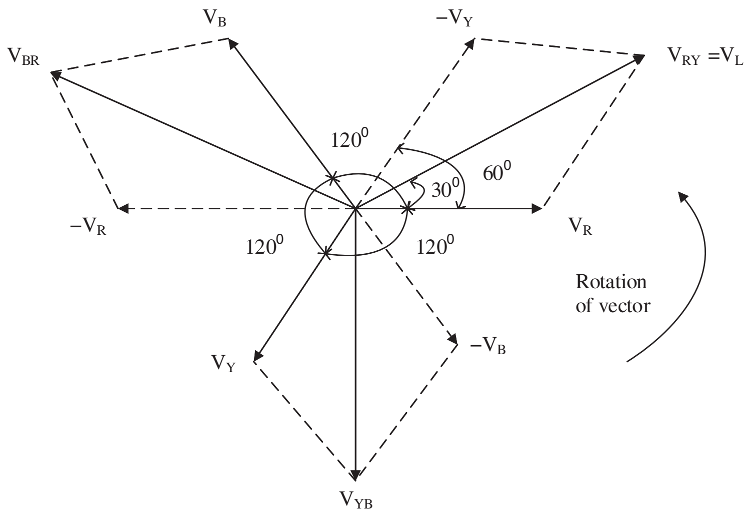


Figure 2.9 Equivalent Y-connected voltage phasor representation.

### 2.4.4 Equivalent Y-Connected Voltage Phasor Representation

Taking $V_{NA}$ as a reference from Figure 2.9,

$$V_{RY} = \sqrt{3}V_{ph}\angle 30° = V_L\angle 30° \tag{2.45}$$

$$V_{YB} = \sqrt{3}V_{ph}\angle -90° = V_L\angle -90° \tag{2.46}$$

$$V_{BR} = \sqrt{3}V_{ph}\angle 150° = V_L\angle 150°. \tag{2.47}$$

### 2.4.5 Mesh or Delta Connection

$$V_{AB} = V_{AN} = V_{ph} \tag{2.48}$$

$$V_{BC} = V_{BN} = V_{ph} \tag{2.49}$$

$$V_{CA} = V_{CN} = V_{ph} \tag{2.50}$$

These connections are not properly balanced to maintain balanced voltage across each load. A delta-connected generator Figure 2.10 is possible but not desirable for two main reasons:

**(a)** Grounding is not possible with a delta-connected generator. For safety, a generator-neutral point typical of Y is the logical point of connection to ground.

**(b)** A delta connection of the coils of the generator provides a short-circuited path in which current can flow. Third harmonics in the coil voltages cause a disturbance, which produces power loss and lowers the efficiency of the generator.