6/1/05

Outline

Power Quality in Electrical Systems

by

Alexander Kusko, Sc.D., P.E.

Marc T. Thompson, Ph.D.

<u>Authors</u>

- Alexander Kusko, Sc.D, Corporate Vice President, Exponent Failure Analysis Associates, Natick, MA. Forty years experience on UPS, power-system design, and power quality. Former associate professor of Electrical Engineering at MIT, Author, co-author, 150 papers, 7 books; IEEE Life Fellow.

- Marc Thompson, Ph.D, President, Thompson Consulting, Inc., Harvard MA and Adjunct Associate Professor of Electrical Engineering, Worcester Polytechnic Institute. Teaches graduate-level power electronics and analog circuit design; twenty years industrial experience in analog and power electronics design; author, co-author, 10 papers; 7 US Patents.

Overview

- Tremendous requirement for reliable, uninterruptible electric power service for all consumers, particularly manufacturing facilities, data-processing centers, and other locations with critical and sensitive loads.
- Power Quality is a measure of the reliability of electric power service.
- Multi-million dollar industry to provide engineering and equipment to resolve Power Quality problems.
- Book is based on a professional course sponsored by IEEE and taught by the authors.
- Book is directed toward real problems and solutions, rather than a total theoretical treatment.
- Book can be used as the text for a course and as a reference.
- Dr. Kusko wrote early book in field in 1989 entitled "Emergency/Standby Power Systems", published by McGraw Hill.
- Book will include treatment of switch-mode power supplies and other loads that produce conducted and radiated interference. Levels are regulated by FCC and other codes.
- Book will include description of standby power systems for emergency and independ operation to solve Power Quality problems.

Market

- Managers, concerned with reliable electric power service
    - Computers/Date Centers
    - Manufacturers
    - Manufacturing facilities
    - Office buildings
    - Electric utility companies
    - Government/Military agencies
    - Healthcare facilities

- Engineers concerned with standards compliance and reliable operation of equipment and systems
    - Electrical design
    - Electric and telecom utilities

- Transportation
- Computer/Telecom
- Unconventional power (e.g. wind)

* Students seeking knowledge and entrance to an active field
  - Fourth year and graduate engineer
  - Two-year associate engineer
  - Professional engineer

Focus

* Identification and correction of power quality problems.
* Listing of definitions and standards
* Case studies from authors' experience and in references of power quality problems and solutions.
* References to significant articles in the professional and trade journals.

Organization of Book

* See Table of Contents
* Based on original six lectures expanded to 12 chapters.
* Figures suitable for PowerPoint presentation; can be emailed to students prior to each class.
* Preface of book will describe how the book can be used, for example, for a six- lecture professional course or for an 18-plus lecture academic course.
* Estimated length of book, 400 pages, including up to 100 figures (already done). See Attachment A for some representative figures.

Competitive Books

* "Power Quality Analysis", Dranetz – Bmi, Edison, N.J. 2003
* J. Arillaga, N.R. Watson, S. Chen, "Power Quality Assessment", John Wiley, 2000.
* A. Ghosh, G. Ledwich, "Power Quality Enhancement Using Custom Power Devices", Kluwer, 2002.
* R. C. Dugan, M. F. McGranayhan, and H. W. Beaty, "Electrical Power Systems Quality," McGraw Hill, New York, 1996

TABLE OF CONTENTS

- Utility, state and federal standards
- EMI standards
    - US: FCC Class A and B
    - International: CISPR 16-1, EN 61000

Chapter 3. Voltage Distortion

- Definitions
    - Amplitude, sags, swells, transients
    - Harmonic distortion
    - Interruptions
- Causes, External to Facility
    - Utility outages
    - Lightning
    - Utility switching
- Causes, Internal to Facility
    - Converters
    - Non-linear loads
    - Motor starts
- Impact on Connected Equipment
    - Compliance with CBEMA Curve
    - Erratic operation and shutdown of equipment
    - Damage

Chapter 4. Harmonics

- Definitions
    - Multiples of line frequency, characteristics.
    - Non-characteristic
- Fourier Analysis
    - Combined waveforms
- Total harmonic distortion, THD
- IEEE Std. 519
- Effects on equipment; case study

Chapter 5. Harmonic Current Sources

- Converters, definitions
  - Single–phase rectifiers
  - Multi-phase rectifiers
  - Controlled rectifiers
- Single-phase rectifiers
  - Inductor filter
  - Capacitor filter
  - Commutation, waveform notching
  - Voltage effect
- Multi-phase rectifiers, applications
  - Motor drives
  - UPS
  - Industry, transit, electrochemical
- Three-phase rectifiers
  - Operation
  - Control
  - Waveforms
  - Line current
  - Harmonics
- Three-phase rectifiers
- Analysis
  - IEEE Std. 519 Method
  - Harmonic sources, assumptions
- System Effects
  - Line and neutral current
  - Harmonic voltage
- IEEE Std. 519
  - Individual Harmonics
  - Total Harmonics, THD

- Case study

Chapter 6. Power Capacitors

- Purpose
    - Utility, facility, location
    - Power factor correction
    - Power harmonic filter
    - Switching
- Ratings
    - Reactive power, kvar
    - Voltage, current
- Resonance
    - Circuit
    - Calculation
    - Prevention

Chapter 7. Corrections for Power Quality Problems

- Converters
    - 12 pulse
- Power Harmonic Filters
    - Passive
    - Active
- Uninterruptible Power Supplies, UPS
    - Static
    - Rotating
- Transformers
    - Harmonic Cancellation
    - Saturable Magnetic, SOLA
- Standby Power Systems

Chapter 8. Switch-Mode Power Supplies

- Applications
- Sources of EMI
- Standards
  - US and European
- Measurements
  - LISN method
- Mitigating strategies
  - EMI filters

Chapter 9. Uninterruptible Power Supplies

- Purpose
  - Provide uninterruptible power
  - Isolate load from line
  - Features
- Types
  - Static
  - Rotary
- Systems
  - Engine-generator sets
  - Batteries
  - Maintenance, 24/7 concept

Chapter 10. Power Quality Events

- Effects on equipment
  - Utility equipment
  - Motors
  - Transformers
- 12-Pulse Motor Drives, Examples
  - Elevators
  - Power plant boiler feed pump
- Resonance, Example

- Extruder plant

Chapter 11. Standby Power Systems

- Purpose
  - Emergency power, long time outages
  - Economic, rate supplement, peak power
  - Back up UPS, batteries
  - Independent supply
- Types of power sources
  - Diesel/gas engine-generator sets
  - Combustion-turbine generator sets
  - Batteries
- Typical systems
  - Single E/G set, emergency power
  - Multiple E/G sets
  - Combined cycle
  - Battery

Chapter 12. Power Quality Measurement

- Purpose
  - Trouble analysis
  - Contractual
- Commercial equipment
  - Power factor
  - Harmonics
- Recorders
  - Sampling
  - Presentation

Attachment A
Representative Figures

Typical Lightning-Induced Transient

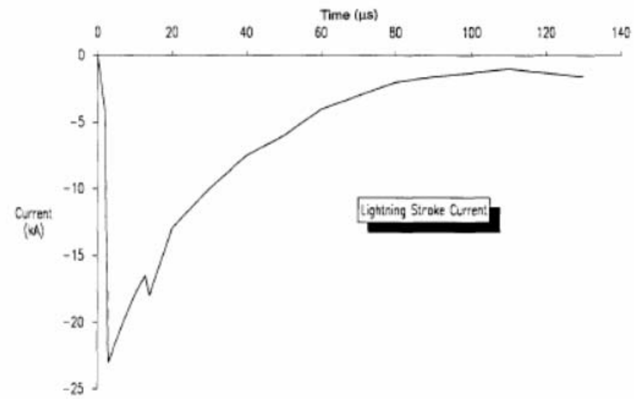


Figure 1—Lightning stroke current that can result in impulsive transients on the power system

References: IEEE Standard 1159-1995, "IEEE Recommended Practices for Monitoring Electric Power Quality," pp. 7

UPS: Static Inverter

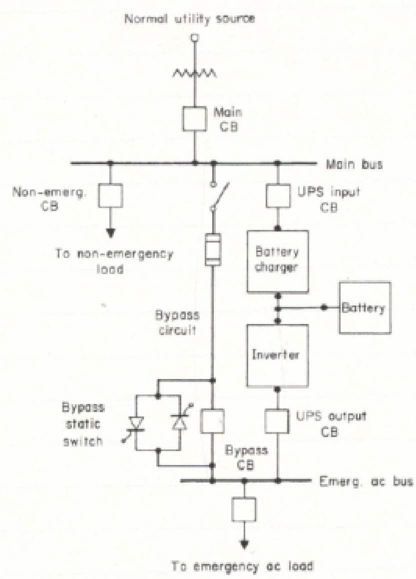


Figure 2.3 Emergency system with a static UPS.

Reference: A. Kusko, *Emergency Standby Power Systems*, McGraw Hill, 1989

Phase Current and Voltage

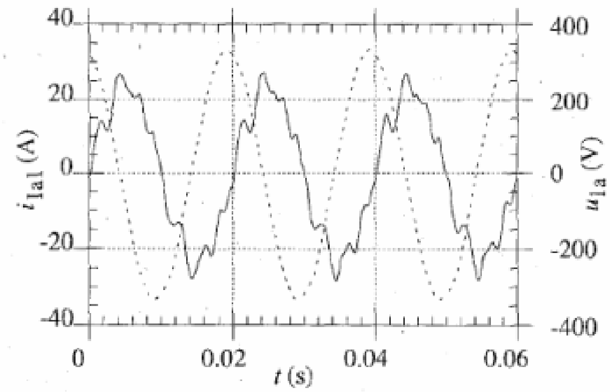


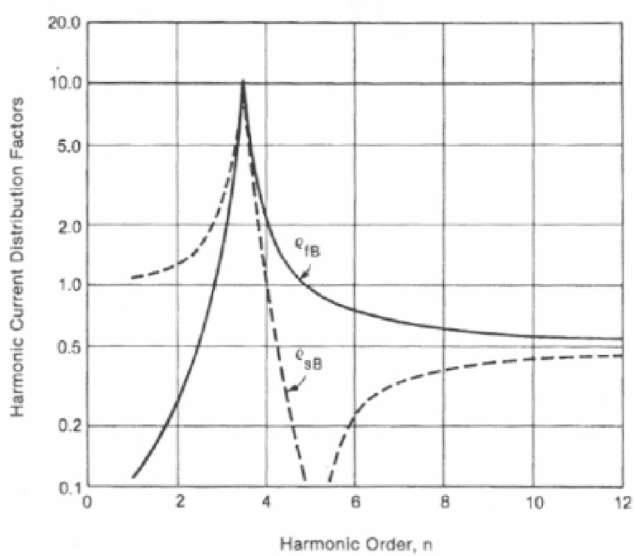
Fig. 9. Measured current (solid) and voltage (dashed) at 5 m/s.

Table 1. Relative harmonic content of the voltages.

order n	5	7	8	9	11	13	15
frequency (Hz)	250	350	400	450	550	650	750
$U_{1(n)}$ (%)	1.1	0.72	0.11	0.072	0.097	0.056	0.018
$U_{2(n)}$ (%)	1.0	0.54	0.09	0.048	0.047	0.016	0.008

Reference: T. Thiringer, "Power Quality Measurements Performed on a Low-Voltage Grid Equipped with Two Wind Turbines," *IEEE Transactions on Energy Conversion*, vol. 11. No. 3, September 1996, pp. 601-606

Resonance: Distribution Factor, with Reactor



$\rho_{fB} \rightarrow 1$ at $n = 5$

$\rho_{sB} \rightarrow 0$ at $n = 5$

Reference: T. J. E. Miller, *Reactive Power Control in Electric Systems*, John Wiley, pp. 341

Chapter 11: power quality monitoring. Electrical Power Systems Quality, Second Edition. CHAPTER 1: INTRODUCTION What is Power Quality? Power Quality -- Voltage Quality Why Are We Concerned About Power Quality? The Power Quality Evaluation Procedure Who Should Use This Book Overview of the Contents. CHAPTER 2: TERMS AND DEFINITIONS Need for a Consistent Vocabulary General Classes of Power Quality Problems Transients Long-Duration Voltage Variations Short-Duration Voltage Variations Voltage Imbalance Waveform Distortion Voltage Fluctuation Power Frequency Variations Power Quality Terms Ambiguous Provides theoretical and practical insight into power quality problems of electric machines and systems. 134 practical application (example) problems with solutions. 125 problems at the end of chapters dealing with practical applications. 924 references, mostly journal articles and conference papers, as well as national and international standards and guidelines. Readership. Engineers, researchers, and postgrads working in power systems, energy conversion, power system protection, and power electronics. Table of Contents. Preface. Acknowledgments. Chapter 1: Introduction to Power Quality. Abst