

The Relay Testing Handbook

Generator Protection Relay Testing



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Electrical Engineering Technologist

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Author's Notes

Thanks to everyone who supported [The Relay Testing Handbook](#) over the years. Your support gave me the opportunity to train hundreds of relay testers on a variety of test-sets since its publication in 2012. I get new insights from students during every class that change my perspective on relay testing. This book takes everything I have learned about relay testing to provide step-by-step details to help you create dynamic tests for the most common elements in a Generator relay.

Generator relay testing isn't hard, but you need to understand the basics first. You should not read this book if you haven't read and applied [The Relay Testing Handbook: Principles and Practice](#), and/or finished the [How to Test Protective Relays Online Seminar](#) at [RelayTraining.com](#). I often refer to other books and online courses and seminars in this book. Please do not take these references as sales pitches trying to get you to buy more. I knew this book was going to be a big one that would be near publishing limits for a book, so it only includes new material. You'll see many links to other material if I've already written about a topic and have nothing new to add, and/or it's not something specific to generator relay testing.

This final version of this book contained over 1,000 pages of content. However, 800 pages is the maximum page count for print books. You can read the full book in the digital PDF version that every customer at [RelayTraining.com](#) receives. Some of the relay testing templates have been condensed in the physical book to meet the printers limitations for a hardcover book.

I hope I've achieved my goal to create a book that helps you understand the basic principles of generator protection in a practical manner. You should be able to test any generator relay using the step-by-step guides in this book. I've written it using dynamic testing techniques, but you can apply all of the descriptions, calculations, and principles in every chapter to test a generator relay with any technique you wish to use.

Our publishing model allows us to quickly correct errors or omissions, and implement suggestions. Please contact us at store@relaytraining.com to report a problem. If we implement your suggestion, we'll send you an updated copy and/or a prize. You can also go to <https://relaytraining.com/updates> to see what's changed.

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Figure 2-19, 20, 21, and 22: VOLTAGE REGULATOR *and* PARALLEL OPERATION, http://seagrant.mit.edu/ESRDC_library/VR_parallel.pdf

Miller, Bruce; <https://www.linkedin.com/pulse/power-system-analogies-bruce-miller/>

Rustebakke, Homer M. (Editor); *Electric Utility Systems and Practices: 4th Edition*

Miller, Robert; *Power System Operation*

Reimert, Donald; *Protective Relaying for Power Generation Systems*

J.R.C. Cowling, *Electrical Equipment - Course 230.2, Generators: Part 6 - Non-Infinite Bus Operation*

WECC Control Work Group, *WECC Tutorial on Speed Governors*, February 1998

CNSC Technical Training Group, *Science and Reactor Fundamentals, Electrical, MODULE 5*, Revision 1 - March 2003

Figure 3-2: Noisy_cosine.jpg, By Kevin McClaning [Public domain], from Wikimedia Commons

Schweitzer Engineering Laboratories, Inc., *SEL-300G Multifunction Generator Relay Instruction Manual 20170804*

Beckwith Electric Co., Inc., *M-3425A Generator Protection Instruction Book*

Alexander, Ron; PHASOR DIAGRAMS II; Bonneville Power Administration

Complex Imaginary, LLC; The Conjugate ($S=VI^*$); <http://www.compleximaginary.com/videos/>

PJM State & Member Training Dept.; Electrical Theory / Generator Theory

North American Electric Reliability Corporation; *Standard PRC-024-2, Generator Frequency and Voltage Protective Relay Settings*

Beckwith Electric Co. Inc.; *Generator Protection: Relay Setting Calculations*

Welton, Drew / Hartmann, Wayne; *Generator Protection: M-3425A*; Beckwith Electric Co. Inc.

IEEE Power Engineering Committee; *IEEE Guide for AC Generator Protection - C37.102-2006*

32nd Hands-On Relay School; *Generator Track Overview Lecture*

Hartmann, Wayne; *Generator Protection Theory & Application*; Beckwith Electric Co. Inc. / 33rd Hands-On Relay School

Hartmann, Wayne; *Generator Protection Overview*; 32nd Hands-On Relay School; Beckwith Electric Co. Inc.

Mozina, Chuck; *WSU Hands-On Generator Protection Track Overview*; Beckwith Electric Co. Inc.

Hamilton, Randy / Thompson, Michael; *Overexcitation and Overvoltage Protection*, Tutorial On The Protection Of Synchronous Generators; Chapter 3, Section 2; Special Publication Of The IEEE PSRC

Hartmann, Wayne / Uchiyama, Joe T.; *Stator Ground Fault Protection*; Tutorial On The Protection Of Synchronous Generators; Chapter 2, Section 2; Special Publication of the IEEE PSRC

Tziouvaras, Demetrios / Verzosa, Jr., Quintin / Wiedman, Thomas E.; *System Backup Protection*; Tutorial On The Protection Of Synchronous Generators; Chapter 2, Section 4; Special Publication of the IEEE PSRC

Yalla, Murty V. V. S. / Gers, Juan; *Underexcitation/Loss-of-Excitation Protection*; Tutorial On The Protection Of Synchronous Generators; Chapter 3, Section 3; Special Publication of the IEEE PSRC

Gers, Juan / Thompson, Michael; *Out-of-Step Protection*; Tutorial On The Protection Of Synchronous Generators; Chapter 3, Section 6; Special Publication of the IEEE PSRC

- Ruckman, Christopher / Conrad, Stephen P. / Hartmann, Wayne ; *Voltage Transformer Signal Loss*; Tutorial On The Protection Of Synchronous Generators; Chapter 3, Section 7; Special Publication of the IEEE PSRC
- Mozina, Charles J. / Thakur, Sudhir; *Inadvertent Energization Protection*; Tutorial On The Protection Of Synchronous Generators; Chapter 4, Section 1; Special Publication of the IEEE PSRC
- Thompson, Michael J. ; *Fundamentals and Advancements in Generator Synchronizing Systems*; Schweitzer Engineering Laboratories, Inc.
- Chowdhury, Ritwik / Finney, Dale / Fischer, Normann / Young, Jason; *Generator Third-Harmonic Protection Explained*; Schweitzer Engineering Laboratories, Inc.
- IEEE Power Engineering Society; IEEE Std C37.101-1993 - IEEE Guide for Generator Ground Protection
- Malmedal, Keith / Sen, Pankaj K. / Nelson, John P. Application of Out-of-Step Relaying for Small Generators in Distributed Generation; IEEE Transactions on Industry Applications, Vol. 41, No. 6, November / December 2005
- Tziouvaras, Demetrios A. / Hou, Daqing ; *Out-Of-Step Protection Fundamentals and Advancements*; Schweitzer Engineering Laboratories, Inc.

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About the Author

Chris Werstiuk is an Electrical Engineering Technologist, a Journeyman Power System Electrician, and a state-certified Professional Engineer who has been testing relays for over two decades in environments ranging from nuclear power plants to commercial buildings. He is the author of The Relay Testing Handbook series, several articles for NETA World, and papers at both the annual InterNational Electrical Testing Association (NETA) and Hands-On Relay School conferences. Werstiuk has led training classes for testing companies, electrical utilities, and maintenance personnel at private and military installations across North America, Africa, the Middle East, and Australia. You can find out more about him at RelayTraining.com; an online resource for relay testing technicians including textbooks, online training programs, free technical content, and an online forum to exchange ideas and information.

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