

SpringerBriefs in Electrical and Computer Engineering

For further volumes:
<http://www.springer.com/series/10059>

Stefano Bellucci · Bhupendra Nath Tiwari
Neeraj Gupta

Geometrical Methods for Power Network Analysis

Stefano Bellucci
Laboratori Nazionali di Frascati
Istituto Nazionale di Fisica Nucleare
Frascati, Rome
Italy

Neeraj Gupta
Department of Electrical Engineering
Indian Institute of Technology Kanpur
Kanpur, UP
India

Bhupendra Nath Tiwari
Laboratori Nazionali di Frascati
Istituto Nazionale di Fisica Nucleare
Frascati, Rome
Italy

ISSN 2191-8112
ISBN 978-3-642-33343-9
DOI 10.1007/978-3-642-33344-6
Springer Heidelberg New York Dordrecht London

ISSN 2191-8120 (electronic)
ISBN 978-3-642-33344-6 (eBook)

Library of Congress Control Number: 2012948426

© The Author(s) 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To our parents and teachers

Preface

This book presents an intrinsic geometric model for power system planning and operation. This problem is generally large scale and nonlinear. We have thus developed an intrinsic geometric model for network reliability and voltage stability, and applied it specifically to the IEEE 5 bus system. The robustness of the proposed model is illustrated by introducing variations of the network parameters. Exact analytical results demonstrate the accuracy as well as the efficiency of the proposed solution technique.

Moreover, from the perspective of intrinsic state-space geometry, we explore power system instability problems introduced by the competitive market mechanism, system failures, and contingency effects, i.e., unforeseen and unexpected events involving system devices, in the face of the widespread deregulation of the global power industry. From the perspective of electrical engineering, we examine the state-space formulation pertaining to:

- voltage regulation phase shift corrections,
- voltage instability of the maximum deliverable power for a given load in the steady-state sinusoidal regime, and
- stabilization of a large-scale voltage instability under the power law characterization.

Finally, regarding the formulation of the intrinsic geometry, we offer a detailed account of complex power optimization in both the steady and nonsteady state regimes. The book can be summarized as follows.

In [Chap. 1](#), we explain the motivation for power network flow analysis and introduction of the geometrical method. The goal of this research is to advance the state of the art in power system reliability and voltage stability. Indeed, power system stability is a potentially attractive target in the emerging deregulated power market, not only to maintain efficient operation of power systems while meeting the demand, but also to optimize the economics of the power system. In addition, deregulation of the electricity market has introduced power flow uncertainty, and hence also fluctuations. This means that power system planners and operators are required to run electricity network components close to their physical capacities,

under a given equilibrium operation point. Our scheme maintains system performance with almost stable system voltage profile and transmission line efficiency by improving impedance angle and steady-state controls and by avoiding blackouts. In this respect, planning aimed at providing a stable power supply has recently been in wide demand in power system technology. From the perspective of transmission theory, we report new developments involving power flow properties as a function of the power factors of a finite parameter network configuration.

In [Chap. 2](#), we show how to formulate the intrinsic geometric characterization of admissible component(s) and discuss the associated theoretical motivations from the perspective of circuit planning, and the validity of the proposed model.

In [Chap. 3](#), we provide an intrinsic geometric characterization by incorporating the proposed methodology. We begin with a brief introduction to the network fluctuation problem, recalling the underlying motivation for the intrinsic geometric analysis, and setting up the notation for the computations in subsequent chapters. Implementing the notation for a given network local equilibrium, we can fix a set of optimal values of the network parameters, e.g., L , C , and R , and the corresponding phases of the chosen power network. The logic simply follows from the fact that the sum of the three angles of a triangle is constant. To illustrate these intrinsic geometric considerations, we derive exact formulas for the case of the two- and three-parameter statistical configurations. We also outline the above notion for a network with finitely many parameters.

[Chapter 4](#) discusses current research trends and knowledge of the intrinsic geometric model in an accessible manner for application to the solution of power system planning and operation. This problem is large scale and nonlinear, in general. In order to test network reliability, we have developed an intrinsic geometric model for network reliability and examined it for the IEEE 5 bus system at the forefront of research on the physical aspects of local and global flow properties. In fact, the robustness of the proposed model is illustrated by introducing variations of the network parameters. The exact analytical results here offer a compact and up-to-date discussion of the accuracy and efficiency of the statistical technique.

[Chapter 5](#) extends the aforementioned techniques of intrinsic geometry and examines the problem of voltage stability in network theory. In order to carry out this investigation, we formulate the problem of voltage stability by following the previously described mathematical specifications of the three-parameter model. Hence, in order to test for voltage stability, we describe this innovation for single component LCR networks and show that the voltage stability achieved using the results proven by the proposed work lies within the desired accuracy limits. From the outset of the present investigation, we offer specific remarks and outlook for further research prospects.

From the perspective of network theory, [Chap. 6](#) illustrates how the parametric intrinsic geometric description exhibits an exact set of pair correction functions and global correlation volume, with and without the inclusion of the imaginary power flow. The Gaussian fluctuations about the equilibrium basis for the phases

of a power network system generate a well-defined, nondegenerate, curved regular intrinsic Riemannian surface for the purely real and the purely imaginary power flows and their linear combinations. An explicit computation demonstrates that the underlying real and imaginary power correlations involve ordinary summations of the power factors, with and without their joint effects. The novel aspects of intrinsic geometry allow one to propose stable designs for power systems.

In [Chap. 7](#), we examine the phase shift correction under the hypotheses of fluctuation theory. In particular, from the state-space perspective for the voltage instability of a connected power system, we illustrate how, for 2 bus systems, the voltage of the relevant buses, i.e., bus 1 and bus 2, varies in the same way as the transmitted power. In the sequel, we explore the state-space formulation pertaining to voltage regulation and phase shift correction. In the state-space formulation, some assumptions have been made, i.e., the shunt admittance has been neglected, no reactive support on the load bus is allowed, the generator terminal voltage phasor is assumed to coincide with the rotor position, and the load is defined by the real and reactive power demand.

In [Chap. 8](#), we analyze the voltage instability pertaining to the maximum deliverable power and the complex power optimization problem for a given load. We thus illustrate the role of state-space geometry in complex power flow optimization. In the fast-growing and competitive power market, optimization is essential in order to define the loadability limit of the power network. Here, one must consider not only the real power, but also the reactive support.

[Chapter 9](#) uses the intrinsic state-space geometry to explore power system instability problems introduced by the competitive market mechanism, system faults, and contingency of instruments in the face of the widespread deregulation of the global power industry. From the standpoint of electrical engineering, we examine the state-space formulation using the notions from (1) the voltage regulation phase shift correction and (2) the voltage instability of the maximum deliverable power for a given load in the steady-state sinusoidal regime to discuss the stabilization of the large-scale voltage instability under the power law characterization. In the proposed formulation of this problem, the same assumptions are made as in [Chap. 7](#). Finally, regarding the intrinsic geometry formulation, we offer a detailed account of complex power optimization of large-scale voltage instability in both the steady and non-steady state regimes.

[Chapter 10](#) brings together the conclusions from the intrinsic geometric approach for the power network stability problem and discusses the outlook for future research in the subject. The main highlight of the present intrinsic geometric model is that it can be applied to analyze random variations of circuit parameters. It can be used for planning and operation of networks, so a variational analysis can be described from the perspective of operation and maintenance. For a unified analysis of electrical networks, the proposed geometric model offers simultaneous consideration of the following three scenarios: (1) lossless power networks, (2) networks with power loss, and (3) voltage collapses occurring in the network.

The present model is technically sound and could be directly implemented by the technological application of intrinsic Weinhold geometry. Furthermore, such

models are robust and are intrinsically parameterized in terms of the reactance, resistance, and capacitance of the considered network. Since we offer a nonlinear improvement of the stability and reliability of the power system, the present investigation eliminates the disadvantages inherent in standard regression techniques. Moreover, the voltage instability results from the fact that the operating point lies beyond the maximum deliverable power. Beyond this limit, the maximum deliverable power leads to a varying load. Thus, a more realistic outage regarding the deliverable power flow is obtained when one takes into account (as in the present nonlinear analysis) fluctuations in the voltage, occurring along with fluctuations in the input real and imaginary power. Finally, in the previously mentioned hypothesis of complex power optimization (see for instance [Chap. 8](#)), there exists a set of computational disadvantages, viz., integration with the existing methodologies, lack of economic analysis, and lack of sensitivity analysis, together with possible combined effects. By considering the state-space geometry, several of these problems are nonlinearly improved. Using the results of the present model, it should be possible to produce an engineering demonstrator application. In short, this book gives an accurate load-shedding strategy with respect to network reliability and system instability.

As a bridge between advanced graduate study and the forefront of engineering research, we offer here a detailed examination of intrinsic geometry, network analysis, and statistical configurations aimed at postgraduate students and non-specialist researchers in physics and related applied areas.

Regarding the present research, BNT would like to thank Prof. V. Ravishankar, Prof. P. Jain, Prof. U. B. Tewari, Prof. M. K. Harbola, Prof. R. K. Thareja, and Prof. S. G. Dhande for their encouragement and support while this research was underway at the Indian Institute of Technology in Kanpur, India. The project was initiated while BNT was supported by the Council of Scientific and Industrial Research in New Delhi, India, under the doctoral research fellowship CSIR-SRF-9/92(343)/2004-EMR-I, and completed during a postdoctoral research fellowship at the INFN-Laboratori Nazionali di Frascati in Rome, Italy. NG would like to thank Prof. Prem K. Kalra and Prof. R. Shekhar for the basic motivation, as well as the continued guidance and support for the completion of this work. Finally, we would like to thank our parents and family members for their constant support since the commencement of this research.

Frascati, Italy, July 2012

Kanpur, India, July 2012

S. Bellucci
B. N. Tiwari
N. Gupta

Contents

1	Introduction	1
	References	8
2	Proposed Methodology	11
2.1	Proposition	12
2.2	Admissible Choice of Component(s).	14
2.3	Theoretical Motivation	14
2.4	Circuit Planning	17
2.5	Validity of the Proposed Model	17
	References	18
3	Intrinsic Geometric Characterization	19
3.1	Origin of Thermodynamic Geometry	19
3.2	Network Fluctuation Theory	20
3.3	Power Flow Fluctuations.	21
3.4	Stability of Minimally Coupled Buses	23
3.5	Intrinsic Network Stabilization.	23
	References	26
4	A Test of Network Reliability	29
	References	32
5	A Test of Voltage Stability	33
5.1	Surface Stability.	35
5.2	Volume Stability	36
5.3	Global Stability	37
5.4	Specific Remarks	38
5.4.1	Limiting Voltage Stability.	38
5.4.2	Limiting Reliability	38
5.4.3	Non-linear Reliability and Stability	39

6	Phases of Power Network	41
6.1	Network Power Flow	41
6.2	Intrinsic Geometric Basis	42
6.3	Real Power Flow	44
6.4	Imaginary Power Flow	49
6.5	Complex Power Flow	53
	References	60
7	Phase Shift Correction	61
	References	66
8	Complex Power Optimization	67
	Reference	75
9	Large Scale Voltage Instability	77
10	Conclusion and Outlook	85
	Appendix A: Factors of the Scalar Curvature for Complex Power Optimization	89
	Appendix B: Tilde Factors of the Scalar Curvature for Complex Power Optimization.	91
	Appendix C: Components of the Metric Tensor for Large Scale Voltage Instability	93
	Appendix D: Scalar Curvature for Large Scale Voltage Instability.	95