Discrete Stochastic Process Monitoring for Large-scale Distributed Circuits

G. L. Viviani
Textron Defense Systems
Wilmington, MA 01887, USA

Abstract A motivation and basis for a new type of state space mapping which will find various applications, including power system control centers, is presented. The underlying principle involves the characterization of pertinent stochastic information in a three dimensional manner. Traditionally, such information has been manipulated with two dimensional approaches. Some features of the proposed framework are similar to electromagnetic monitoring schemes applied in optics and radar backscattering problems, with the exception that appropriate means for automatic control of the associated stochastic events are also provided.

I. INTRODUCTION

There is widespread agreement that the state of a power system constitutes some sort of a stochastic process. Widespread agreement beyond this point is difficult to quantify, especially when specific subjects such as state estimation, system security, reliability analysis, voltage collapse, transient stability, optimal load flow, etc. become the focus of attention. As a result, most power system control centers rely on a "variety" of techniques. The bottom line is that with all the techniques, computer automation and algorithms that currently exist, we can still not design a power system control center that is fully automated (no humans). These problems have persisted for years and a contemporary synopsis of the associated concerns is found in [1].

By and large, the techniques that are applied are two dimensional in nature. The power system is commonly referred to as a "grid," the computer assisted display panels present two dimensional images (and text) and even the underlying algorithms such as load flow, optimal load flow, transient stability, state estimation, etc., rely on manipulations of two dimensional representations of the state of the system. All these efforts, combined with the fact that we still don't have fully automated operations suggests that, perhaps, it would be easier to come to a universally accepted fully automated control scenario if we reposed the problem. By drawing upon precepts in a variety of disciplines, especially those associated with optics and controlled flight dynamics, as well as power system dynamics and control, a three-dimensional formulation of the power system control problem comes to mind.

Ultimately, the motivation for the proposed approach to control in the power system comes from the weather. In both the case of a power system and the weather, the situation is more one of optimal reactions to a monitored stochastic process. Hence, if one wishes to fully automate control of the associated power system equipment, in order to achieve optimal reactions, it is first necessary to know how to optimally react. In many cases, for power systems, the character of the optimal reaction is still not known. Therefore, conventional operations tend to assure avoidance of circumstances to which a viable reaction is not certain. By comparison, we cannot control the weather at all, yet many means of reacting skillfully are in widespread use. Indeed, power control centers often rely on weather forecasts to better control their own systems. The associated time constants are different and the nature of reactions are also different, however, the weather does represent a very large scale stochastic dynamic process that is spatially distributed over a wide area, like a power system. Unlike a power system, the weather presents itself to the observer in a three-dimensional format, which even a child can understand. Ergo, the motivation for this work stems from a desire to present a "picture" of the stochastic dynamical system, which is a power system, that is more easy to understand, assimilate (and devise control algorithms) than what is currently being pursued. If such a presentation format is achievable, not only will operator initiated controls be simpler to implement, but it will likely suggest new approaches to system control, especially in the face of uncertainty. Actual implementation of control schemes, designed to account for uncertain dynamics in power systems, is an area of particular interest and experience of the author [2, 3].

As is well known, the state of the power system is fully described by a state vector which is comprised of complex quantities representative of the voltages and currents at each node in the "grid." The actual observations are typically associated with so-called real and reactive power measurements at each of the nodes in the system. The power flow problem is one of determining the mapping from that of power measurements to a state vector. This

0-7803-0720-8/92 $3.00

problem has received widespread attention. Hence, the core problem stems from a need to be responsive to real and reactive power flow variations as a function of both time and position. The purpose of this paper will be to present a means for presenting the stochastic process of a power system state vector in a manner that is both responsive to the needs of a system operator and amenable to future control algorithms.

II. APPROACH

The first step is to produce a suitable three dimensional mapping which intuitively should "paint" a "picture" of the power system. In addition, the presentation should be made in a sufficiently controlled manner as to allow for eventual full automation of associated control operations. Under most circumstances, such as normal operating conditions, the "picture" should be slowly varying as swift variations have a tendency to imply imminent danger.

As is often the case in the field of nonlinear dynamical systems, Poincare [4] has provided the germ of an idea which finds widespread application. Today, such techniques are often applied in target recognition algorithms, especially when the polarization of radar signals contains useful information [5]. The Poincare sphere is a convenient means for presenting information about polarized electromagnetic radiation. It stems from the premise that:

$$E(z,t) = \begin{bmatrix} E_H(z,t) \\ E_V(z,t) \end{bmatrix} = \mathbf{p} \exp[j(wt - kz)]$$

represents a general plane harmonic wave propagating in the z-axis [5]. In this formulation, $H \equiv y$ and $V \equiv x$ denote the horizontal and vertical components, respectively. Here, the vector **p** is expressed as:

$$\mathbf{p} = \begin{bmatrix} a_H \exp(j\delta_H) \\ a_V \exp(j\delta_V) \end{bmatrix}$$

with $|\mathbf{p}|^2 = (a_H)^2 + (a_V)^2$ and $\delta \equiv \delta_V - \delta_H$. As can be found in any standard reference on polarized E/M propagation, the horizontal and vertical phasors (assuming constant frequency) maintain a time-invariant polarization which is described by the vector **p**.

The idea of a stochastic process associated with polarization of various E/M waves has value in the context that the scattered radar returns are seen to result in an ensemble of polarized waves whose statistics are useful for identifying objects of interest. In the analog to a widely distributed circuit (power system), with synchronized "monochromatic" operation (60 Hz +/- ε), it is proposed to consider the discrete observations of real and reactive power (or voltage and current) at each node in the network and to consider the relative magnitudes and phase of each complex phasor between simultaneous observations, at a particular node. Hence, the state of a particular node, j, will be determined as follows:

$$\mathbf{X_j(k)} = \begin{bmatrix} a_V(k)\exp(j\delta_V(k)) \\ a_I(k)\exp(j\delta_I(k)) \end{bmatrix},$$

for each time epoch, **k**. Here, the subscripts V, and I denote voltage and current and they correspond to the x and y axis, respectively.

For each node in the network, the state of the system, at a given time, is characterized in Figure 1.

The set $C_j \equiv \{a_V(k), \delta_V(k), a_I(k), \delta_I(k))\}$ of random variates will be associated with each node in the network, j. Or, as is commonly observed in power systems (and optics) to be sufficient, the equivalent set of stochastic parameters is reduced to the set

$$\psi_j \equiv \{a_V(k), a_I(k), \delta(k))\},$$

where $\delta(k) \equiv \delta_V(k) - \delta_I(k)$. Hence, by defining the analog to Stoke's [6] parameters for a power system:

$$\begin{aligned} s_0 &= \langle a_V(k)^2 \rangle + \langle a_I(k)^2 \rangle, \\ s_1 &= \langle a_V(k)^2 \rangle - \langle a_I(k)^2 \rangle, \\ s_2 &= 2\langle a_V(k)\, a_I(k) \cos \delta(k) \rangle, \\ s_3 &= 2\langle a_V(k)\, a_I(k) \sin \delta(k) \rangle, \end{aligned}$$

a multi-dimensional framework for characterizing the stochastic nature of the power system dynamics is proposed. s_2 is directly related to so-called real power, P, and s_3 is directly related to so-called reactive power, Q, where the complex power at each node is commonly specified as $S = P + jQ$. Systematic manipulation of such quantities is shown in [7]. The intensities provided by s_0 and s_1 will be useful in determining which base voltage and power is associated with a particular node [8]. Note: the symbol $\langle\,\rangle$ denotes ensemble average.

At each individual node, these parameters will vary according to the statistics of the underlying process, which is ultimately a random process akin to people turning lights on and off according to their own prescribed interests. In the following sections, these process variations shall be generally characterized with some simplifying assumptions about the associated statistics.

Keeping in mind the "polarized" nature of complex power at each node in the network, a more indicative set of stochastic variables (as compared with ψ_j) comes to mind. Since power systems tend to be slowly varying, it is useful to "watch" for apparent "motion" in the shape of the associated ellipse which characterizes the state of each node. The instantaneous intensity is defined as:

$$I(k) \equiv a_V(k)^2 + a_I(k)^2 = a^2 + b^2 \approx s_0,$$

which takes advantage of the geometry of the ellipse. If we consider the ellipse to be in the x-y plane and I is positive in the z direction, the state ellipse for each node will "swivel" around the z axis according to the angle χ, as shown in Figure 1. This angle, χ on the interval [$-\frac{1}{2}\pi \leq \chi < \frac{1}{2}\pi$] is defined as follows:

$$\tan 2\chi = (\tan 2\alpha)\cos \delta,$$

with

$$\tan \alpha = \frac{a_I(k)}{a_V(k)} .$$

Finally, it is necessary to keep track of the ratio of the minor axis, and the major axis, b. The quantity, $\varepsilon \equiv \frac{a}{b}$ is defined for this purpose. For convenience, the quantity,

$$h = \frac{2\varepsilon}{(1 + \varepsilon^2)} ,$$

will be used to characterize the shape of the ellipse, without loss of generality.

For a given power system load under normal operating conditions, it is worthwhile to assume (at least initially) that the value of δ will be uniformly distributed over the entire range of $[-\pi, \pi]$. This assumption can be refined later. In addition, for convenience, we assume that the complex vector $\mathbf{X_j(k)}$ is gaussian distributed [9]. For a zero mean process, the p.d.f. for the state ellipse for each node is determined as:

$$f(I, \chi, h) = \frac{2I}{\pi\langle I\rangle^2(1 - P^2)} \exp[-\frac{2I}{\langle I\rangle (1 - P^2)} M(\chi, h)]$$

where

$$M(\chi, h) = 1 - Ph_1h - P(1-h_1^2)^{0.5}(1-h^2)^{0.5}\cos(2\chi - \chi_1).$$

This follows directly from [9] and is also presented in [10, equations 3.24 and 3.25]. The notation $(\ )_1$ indicates an average or nominal value and these quantities, in the above equation, are defined as:

$$h_1 \equiv \frac{s_3}{(s_1^2 + s_2^2 + s_3^2)^{0.5}},$$

$$\tan 2\chi_1 = \frac{s_2}{s_1}$$

$$P \equiv \frac{(s_1^2 + s_2^2 + s_3^2)^{0.5}}{s_0} \text{ (polarization).}$$

In the context of this presentation, the precise nature of the p.d.f. is not the main point. What is important is the fact that such a presentation exists and that it can be used in conjunction with the probabilistic detection scheme of the next section. Alternative representations are also possible and exist in the literature.

III. IDENTIFICATION and CONTROL

In addition to the individual nodal variations, there are macroscopic properties which result from the nature of power systems themselves. Most noticeable is the fact that since a system operates at various voltage levels (with correspondingly different power levels) a suitable three-dimensional subset of $\{s_0, s_1, s_2, s_3\}$ will provide observations from a variety of similar loads which will tend to coagulate about specific regions in the three dimensional space, at least under steady state operations.

Ultimately, for control and identification (decision making), it will be necessary to determine decision rules based on the observed three dimensional mappings of interest. If we assume that s_0 is mapped to the z-axis, and also assuming a suitably chosen x and y axes, we can envision an entire power system grid described by a series of ellipses at varying intensities, with certain concentrations of ellipses at various points along the z-axis. If we consider the ellipse to be the vertebrae of a backbone, with each having its own shape and orientation, we can imagine the power system to be similar to a backbone with vertebrae that are slowly changing shape and orientation at relatively constant locations in the z direction. Unusual events will be marked by a sudden twisting or "rupturing" of the individual vertebrae. Hence, a suitable control strategy should be composed of something that is able to detect sudden twisting or turning, or other shape distortions, as projected to the x-y plane.

Random Perturbations", IEEE Transactions on
CAS, CAS-34 No. 6 (June), 1987.

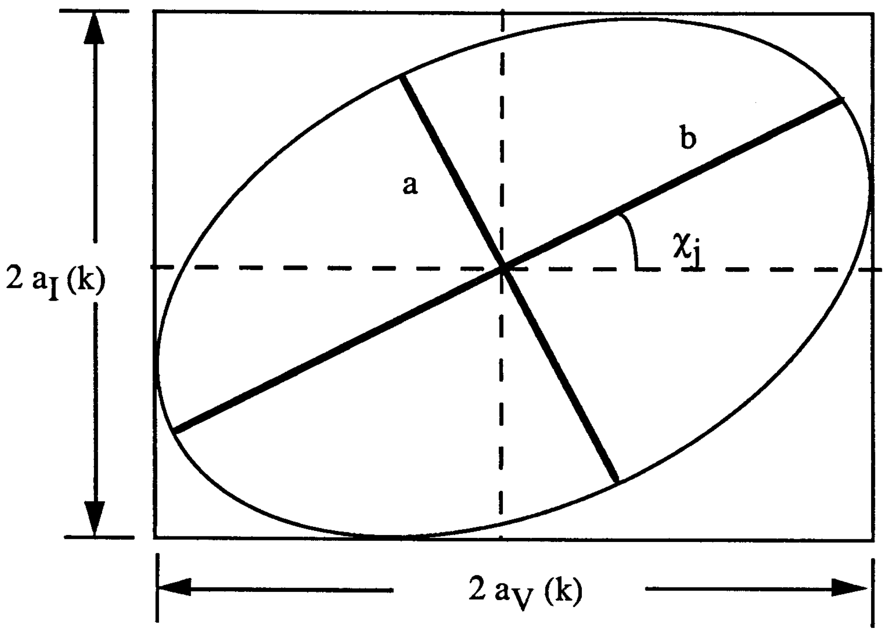

Figure 1

In principle, what is needed is a "sheath" that can be imagined to encase the "backbone" like a skin. This skin should be sensitive to the motion of the backbone, but also have an ability to vary with slow variations of the backbone. Such a control mechanism will likely have elliptic symmetry in the x-y plane.

As it turns out, the work of the author in the area of multi-stable devices [11-15] exactly meets the required need. Basically, by choosing the domain of attraction for the inner most limit cycle, for a suitable multi-stable device [13], to circumscribe the ellipse associated with each node, a sudden twisting or change in shape will cause the multi-stable device to change state. This assumes that information about the state vector for each node (or group of nodes), $\mathbf{X_j(k)}$, is periodically provided in the form of initial conditions to the associated multi-stable device [14].

The time varying nature of the shape of the ellipse can be accounted for by slowly varying the shape of the domains of attraction. Assuming such a system were to operate in real-time, this would provide highly localized information regarding the change in system dynamics as well as avoid false indications of pertinent variations. With such a capability, a framework for suitable control actions follows directly.

IV. CONCLUSION

This work has provided a motivation and approach for altering the means by which the stochastic dynamics for a power system are represented in order that more suitable control actions (reactions) are likely to occur. Additionally, the presentation is general enough to allow for other applications involving distributed sources of electromagnetic radiation.

Other three dimensional formulations are possible and more conventional identification schemes may indeed be appropriate. However, the one presented appears to be well suited to the needs of more conventional representations of complex power and well developed mental images of the dynamics associated with each transmission level in the utility grid. A more thorough analysis will follow in a later publication.

ACKNOWLEDGMENT

The comments and constructive criticisms of Dr. P.W. Sauer, of the University of Illinois, are greatly appreciated.

REFERENCES

[1] A.V. Machias, J.L. Souflis, B.C. Papadias, " Application of a Deep Level Knowledge Model to Dynamic Behavior Analysis of Power Systems," IEEE Transactions on Systems, Man and Cybernetics, Vol 20. No. 3, 1990, pp. 701- 708.

[2] G.L. Viviani, C.E. Lin, M.G. Webb, "A Real Time Approach for Revising Generation Unit Performance Characteristics, IEEE Trans., PAS-104, No. 7, pp. 1691-1695.

[3] A.H. Noyola, W.M. Grady, G.L. Viviani, "An Optimized Procedure for Determining Incremental Heat Rate Characteristics," IEEE Transactions on Power Systems, Vol 5., No. 2, May 1990.

[4] H. Poincare, Theorie Mathematique de la Lumier, Paris, Georges Carre, 1892.

[5] D. Giuli, "Polarization Diversity in Radars," Proceedings of the IEEE, Vol. 74, No. 2, 1986, pp. 245-269.

[6] M. Born, E. Wolf, Principles of Optics, New York, Pergamon, 1980.

[7] G.L. Viviani, "Complex Vector Load Flow," Electric Machines and Power Systems, 10:443-452, 1985, Hemisphere Publishing Corporation.

[8] O. I. Elgerd, Electric Energy Systems Theory: An Introduction, McGraw Hill, 1971.

[9] N.R. Goodman, "Statistical Analysis Based on a Certain Multivariate Complex Gaussian Distribution (An Introduction)," Annals of Mathematical Statistics, Vol. 34, 152-177, 1963.

[10] R. Barakat, "The statistical properties of partially polarized light," OPTICA ACTA, 1985, Vol. 32, No. 3, 295-312.

[11] Y. A. Saet, G.L. Viviani, "Quasilinear and Relaxational Realms in Self-Oscillations", International Journal of Non-linear Mechanics, Vol. 26, No. 5., pp. 701-709, 1991 .

[12] Y. A. Saet, G. L. Viviani, "On the Simulation of a Paradigm of Nonlinear Dynamics", in Dynamical Systems Approaches to Nonlinear Problems in Systems and Circuits, SIAM, 1988.

[13] G. L. Viviani, "On Synthesis and Design of Multi-stable Devices", IEEE International Conference on CAS, Helsinki, Session on Nonlinear and Neural Devices, June 1988.

[14] G.L. Viviani, Y.A. Saet, "A new type of multi-state detector for adaptive control: an application to network switching", International Journal of Electronics, Vol. 60, No. 4, pp. 531-533, Taylor and Francis, London, 1986.

[15] Y.A. Saet, G.L. Viviani, "The Stochastic Process of Transitions Between Limit Cycles for a Special Class of Self-Oscillators under