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Intrinsic geometric analysis of the network reliability and voltage stability

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A B S T R A C T

This paper presents the intrinsic geometric model for the solution of power system planning and its operation. This problem is large-scale and nonlinear, in general. Thus, we have developed the intrinsic geometric model for the network reliability and voltage stability, and examined it for the two and three parameter systems. The robustness of the proposed model is illustrated by introducing variations of the network parameters. Exact analytical results show the accuracy as well as the efficiency of the proposed solution technique.

1. Introduction

The goal of this research paper is to advance the state-of-art in the power system reliability [1–3] and voltage stability [4–6]. It is well known that for effective power system planning, the appropriate reactive compensation [3,6–11] is essential with a set of proper network parameters (resistance (R) and reactance (X and C)) and associated planning. Subsequently, such a planning facilitates to reduce apparent power, by saving reactive power loss on the network.

Noticeably, in the varying reactive load scenario [12], where the stability of voltage profile is necessary [13], the addition of the reactive components of a desired bus or line has a significant from the perspective of efficient power system design. As the result, it is obligatory to choose a finite value of the capacitance and reactor to keep voltage in the stability limit [13,14]. The value of such parameters leads to design an interesting set of control power flow protection devices, i.e. tap changer, controlled switched compensator [15,16]. Compensation strategy is used to improve voltage profile and power factor correction in AC transmission lines [17–19]. Notice that the concept of reliability and voltage stability is related to the power quality issues [20,21]. Most of the power quality issues are resolved by appropriate reactive powers [8,22], which are controlled by capacitor bank [10,16,18,23]. Such a scheme maintains the system performance, with almost stable system voltage profile and efficiency of the transmission line by improving impedance angle, steady-state controls and avoids blackouts.

From the perspective of power factor correction and highly disturbed bus (gradual or abrupt change of reactive load), an appropriate selection of the stabilizing compensation is essential [3, 6–8,11,22,24]. Previous studies show that since available dynamic models are computationally expensive thus static techniques were suggested [25]. With increasing complexity in the power system operational structure under restructured environment [26], the available linear and static methods yield a slow convergence (even non-convergence, as well). This follows from the fact that the linear analysis faces a number of nonrealistic implementation due to the uncertain behavior of load and contingency of the transmission lines, and thus the necessity of the restructuring.

Thus, our intrinsic geometric technology offers a self-consistent non-linear optimal solution and provides a resolution towards such disadvantages. In addition, there are myriads of methodologies and mathematical models for the selection of network parameters and compensation in the power system planning and operations, e.g., optimization techniques, genetic algorithm (GA), trial and error methodologies, fuzzy integrated with dynamic programming, artificial neural network (ANN) and heuristic analysis [3,6–8,10,11,16,22–25,27–30] which have been in use in the most of the existing software's [31,32]. It is worth emphasizing that the precise estimation of the transmission line parameters and associated compensation could hinder an occurrence of blackout in the power system with an increasing efficiency.

Up to the linear approximation, the prior solutions based on static modeling give a set of premature prominent results [25]. This

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stipulates the need for an incorporation of the underlying non-linear effects. In this concern, our intrinsic geometric proposition yields an ample room to improve the network performance by the stable voltage profile of the power system. The previously revealed methodologies yield a set of approximate solutions, which are mostly iteratively accomplished. Such an implementation is generically realized by linearizing the corresponding flow equations, in a limited domain. Based on the above class of methodologies, the designed compensations are inefficient as per the need of modern society, due to slow convergence.

The present geometric model is a bootstrap towards these notions and indeed it is capable to provide strategic planning criteria for the most effective use of the network and the issue of network reliability. In fact, the above framework can be extended for arbitrary component finite parameter networks, namely, the series reactors, shunt capacitors and the line parameters. From the perspective of the power grid operators, it is worth mentioning that a self consistent determination of the shunt inductance and series capacitance of the components may play an important role in the voltage control. At this juncture, it is interesting to note that our framework can be extended and is well capable to cope up with the inclusion of finitely many compensation components, such as the series capacitances and shunt inductances. Form the very out-set of our geometric proposition, the voltage stability of the network and safety modes are an immediate consequence of the admissible network parameterization. With the help of correlation techniques [33–36] and critical point of an arbitrary network, the set of appropriate parameters and components can be identified for any finite component network. Interestingly, the global quantities of our model provide required set of safety alerts for the owner as well as to the regulator of the network. For a given total (complex) power, the proposed model is described as the subsequent of the innovation. The overall methodology can be implemented for any finite parameter network. For the purpose of an explicit demonstration, we illustrate the fluctuation properties for the two and three parameter networks such as a given IEEE 5-bus system. The results thus demonstrated give the expected feature of the proposed geometric model. The voltage levels of all the buses are assumed equal. This condition holds by the concept of the reverse engineering; where the results obtained show that the planning could be based on the calculated parameters, which keep the power system at a fixed voltage profile about which the network fluctuations are analyzed.

The rest of the paper is organized as follows: Section 2 provides the formulation of the problem. Section 3 describes the details of the innovation and shows how it works in general. Section 4 evaluates the test of the network reliability and voltage stability and as the result proves the proposed work accuracy. The specific remarks of the present investigation are enlisted in Section 5. Finally, in Section 6 we draw conclusions and sketch the outlook for future investigations.

2. Prior mathematical model specification

In this section, to eliminate the effect of voltage fluctuation the optimum values of required L and C are determined. Also, we shall set up the method to predict the exact value of R and L in order to increase the reliability and efficiency of the network. From the described criteria, one can decide for single circuit or double circuit line between two buses to ensure the reliability of the network. All prior conventional solutions use load flow equations and characteristics and performance equations of transmission lines [16,27]. In general, the power conservation equations associated with the real (resistive) and imaginary (reactive) branch parameters are respectively given by

$$P_i = \sum |V_i||V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{1}$$

$$Q_i = \sum |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \tag{2}$$

In the above equations, the phases are defined as: $\tan\theta_{ij} = \frac{X_{L_{ij}} - X_{C_{ij}}}{r_{ij}}$. Subsequently, we define impedance: $Y_{ij} = \frac{1}{z_{ij}} = \frac{1}{r_{ij} + j(X_{L_{ij}} - X_{C_{ij}})}$ and phase $\delta_j = \frac{V_j}{|V_j|}$.

The steady state condition $|V_i| = 1$ makes the ith bus of the configuration in equilibrium under voltage fluctuations. The respective cases of our interest reduce to the following standard network considerations:

(i) For the real power flow with the considered resistances $\{r_i\}$, the θ_{ij} are defined by $\tan\theta_{ij} = \frac{X_{L_{ij}}}{r_{ij}}$

(ii) In general, when the reactive power flow is allowed to possess a nonzero voltage fluctuation, the θ_{ij} are defined by $\tan\theta_{ij} = \frac{X_{L_{ij}} - X_{C_{ij}}}{r_{ij}}$

At this juncture, we propose that the local variations of the load are defined as the Hessian matrix of the total effective power in the network or at the chosen component. The robustness of the proposed model is further illustrated by introducing variations in the chosen circuit parameters and load. We share with the fact that the power fluctuations can be described by the critical exponent of the correlation equations. This model is able to predict the condition and state of the every branch of the network and thus whether it is robust from the perspective of power system planning.

3. Proposed methodology

In case of abrupt load change at any disturbed bus of the power system the framework of the Riemannian geometry supports the proposal of an intrinsic network reliability and global voltage stability [33–36]. To begin with the novelty of the present advancement, we propose an admissible characterization of the network variables.

3.1. Proposition

The impedances variables of the power network form an admissible basis.

Proof. By performing a coordinate transformation, we demonstrate that the above proposition holds. To do so, let L, R, C be a set of mutually independent effective parameters of the network. Let us consider the following coordinate transformations on the LCR configuration. □

$$(r, X_L, X_c) = \left(R, \omega L, \frac{1}{\omega C}\right) \tag{3}$$

Thus, we notice that the Jacobian of the transformation is given by

$$J = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & -\frac{1}{\omega C^2} \end{bmatrix} \tag{4}$$

We observe that the determinant of the matrix J is $|J| = -\frac{1}{C^2}$. This provides a sort of fine tuning for the voltage fluctuations. This shows that the voltage fluctuations problem can be solved by a variable capacitor along with the variations of the other parameters. Consequently, we can analyze LCR fluctuations either in the impedance basis or in the basic component parameter basis, as