

Analysis and prediction of vulnerability in smart power transmission system: A geometrical approach [☆]



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ABSTRACT

The paper proposes a novel methodology to analyze and measure the impact of line tripping on grid vulnerability which may lead to cascade failure in smart power transmission system. The key contributions are analysis of current flow path and identification of critical line from normal to perturbed grid with the knowledge of grid topology. To achieve this two performance indices i.e. power flow index and vulnerability index have been defined on the bases of geometry of current flow path. A power flow index is defined to analyze impact of topological changes on current flow path and identify underloaded and overloaded lines. Probability of the critical line and the location of vulnerability center are identified by the vulnerability index. Analytically defined performance indices are applied analyzed and validate using the benchmark IEEE 30 bus power system. The critical line identified by proposed indices is also verified with the probabilistic framework. The proposed methodology allows to focus attention on the power grid vulnerable areas and can help the control system operator to investigate the changes in power flow on transmission lines and initiate the necessary corrective action. The methodology proposed in this paper can be used in security assessment and centralized monitoring of power flow in future smart grid wide area monitoring protection and control system.

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1. Introduction

Power system is a complex interconnected network. It is an integration of green energy and communication technology with power system that has made the grid smart. At the same time, growth in generation and demand without network expansion further increases the complexity of power network and creates various security issues. It may disturb security margin and create unplanned line outage that may lead to cascade failure. Cascade failure due to line loading in power transmission system is one of the prime issues [1–3]. Cascade modelling using time dependent phenomena in [4], showed that sympathetic tripping and weather conditions have the most significant impact on the load interruption costs and it depends on the operating scenarios under consideration.

In literature, researchers have applied considerable efforts in analysis and understanding of cascade failures in power networks.

Among such efforts, deterministic, probabilistic and topological models have been used widely. In the deterministic (N-1) security model, (N-1) checking and contingency ranking methods [5–7] are used commonly to carry out the overloaded line or bus for successive line tripping. Power grid is a huge and complicated interconnected network where tracing of any uncertainty by checking each and every line is a very tedious task. Probabilistic and topological models to power flow analysis is computationally less complex compared to deterministic model. These models replace detailed analysis of the power system equations and provides additional insights such as higher order moments in probabilistic approach [8,9] and spectral analysis of current flow path in the topological approach [10–13] which allows to focus attention on the power grid vulnerable areas. Analysis and prediction of grid vulnerable area is now becoming more feasible with the advancement in WAMS, [14,15] such as online, GPS time tag PMU data. Availability of online PMU data from WAMS helped in making simulation based modelling to data centric modelling.

Disturbances in power transmission system increase with increase in complexity such as integration of green energy in smart power system. To reduce computational complexity and increase the security of smart power transmission system, two performance index based on grid geometry has been proposed in this paper. It captures the geometry of load flow path, analyze and measure

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the effect of topological changes on load flow path and identify the critical line in the perturbed grid. With the use of proposed methodology, an operator at the central monitoring system can visualize the effect of line tripping on vulnerability in transmission system and can identify where the bottleneck lies in the network, thereby taking the corrective action well in advance. Early prediction of critical link may prevent the onset of blackouts by initiating remedial action such as load shedding, load balancing or controlled islanding [16–18] before it affects the entire power network.

The rest of the paper is organized as follows: Section 2 explains the topology of power network. Geometry of current flow path has been introduced in Section 3 along with the concept of auxiliary grid. Section 4 presents the proposed methodology and formulation of PFI and VI metrics. Section 5 presents a case study to validate the proposed methodology using the benchmark IEEE 30 bus system. Some open research issues are discussed in Section 6 along with conclusions.

2. Topology of power network

A model of a transmission line of power network is shown in Fig. 1. Where, $|V_i|, |V_j|$ is respective voltage magnitude at bus i and j . p_i and p_j are injected active power, Z_{ij} is an impedance of the transmission line connecting to bus i and j . δ_i and δ_j are voltage phase angle at bus i and j respectively. For DC power flow the voltage magnitude at all buses is maintained at 1 per unit (pu). Further, as the system synchronization is always maintained under normal operating conditions the angular difference between two neighboring nodes is very small. Hence, active power on transmission line expressed as

$$p_{ij} = \frac{(\delta_i - \delta_j)}{Z_{ij}} \quad (1)$$

Power flow on transmission lines is varying as per supply and demand with time. A slight change in grid parameters will change power flow on transmission line. Hence traditional contingency analysis using AC or DC load flow equations [19] is a complex and tedious task. This issue can be handled by the topological framework of power grid wherein load flow can be analyzed on the bases of changes in physical topology between buses and transmission lines.

Physical topology of a power grid maps a complex power network in a graph G by converting generators and substations as a node and transmission lines and transformers as a link with line impedance as a path length. This physical topology gives undirected and sparsely connected graph G and is represented by (2).

$$G = (V, E, Z) \quad (2)$$

where V is a set of nodes or vertices (buses), $V = (v_1, v_2, \dots, v_N)$ and E is a set of edges (transmission lines) $E = (e_1, e_2, \dots, e_M)$ of G . The weight of the corresponding line i.e. Z_{ij} , is the line impedance between nodes v_i and v_j .

A spectral graph theory inter connectivity between nodes and links and can be described by the graph Laplacian (L_G) matrix [20]. Consider the weighted adjacency matrix (A_{ij}) of size $N \times N$ symmetric matrix, where N is the total number of vertices and ij

is the i th row and j th column of elements ($i = j = 1, \dots, N$) of the matrix. The A_{ij} in (3) represents physical topology of a network which defines adjacent vertex connectivity in a graph. For an undirected graph,

$$A_{ij} = A_{ji} = Z_{ij} \begin{cases} \text{for,} & v_i v_j \in V \\ \text{otherwise,} & 0 \end{cases} \quad (3)$$

The diagonal matrix D_{ii} , ($j = i$), contains the weight of vertex v_{ii}

$$D_G = D_{ii} = \sum_{j=1}^N Z_{ij} \quad (4)$$

To understand the geometry of power network the graph Laplacian (L_G) matrix is defined from (3) and (4). The L_G matrix is known to be symmetric and positive semidefinite [20], and its real eigenvalue defines graph connectivity.

$$L_G = D_G - A_{ij} \quad (5)$$

$$L_G = L_{ij} \begin{cases} \text{if } i \neq j \text{ and } (i, j) \in V, & -Z_{ij} \\ \text{if } i = j, & D_G \\ \text{otherwise,} & 0 \end{cases} \quad (6)$$

The weighted L_G matrix (6) has all the off-diagonal entries non positive and diagonal entries non negative. The sum of matrix elements in each row is zero. Hence, L_G is a positive semidefinite singular matrix [20] which defines graph connectivity. Authors of [16] used algebraic connectivity (eigenvalues) of L_G matrix for sequential islanding of power system in order to provide security strategy.

3. Geometry of current flow path

The issues before applying the geometrical approach to power grid is that the power network should be expressed by such a simple way as the rate of commodities passing through a node or link. However, electrical power requires two variables to be identified, a generalized coordinate (charge) and a generalized force (voltage). Another challenge is that the electrical power, flows along all transmission lines from generating source to consuming loads according to power flow equations. To analyze power flow on transmission line by geometry of current flow path, it is important to describe physical topology (line and node connectivity) in terms of electrical topology (resistive paths between pair of vertices). These issues are addressed and solved in the literature [5,13], by introducing the concept of Auxiliary Grid (AG).

3.1. Concept of auxiliary grid

To employ the geometrical concept in the power flow problems, physical topology of power network is transformed into electrical topology with the help of spectral graph theory and named as auxiliary grid (AG). PG to AG transformation carried in such a way that the geometry of power flow in the power grid can be concluded from the geometry of resistive path difference in AG. To achieve this physical topology of power grid is defined graphically by (L_G) (6). In graph theory for computation of grid connectivity, state of the art Jacobian methodology is used. However, this methodology compute only few eigenvalues of L_G matrix which do not provide any insight into the individual path lengths between pair of vertices. To obtain better insights of grid connectivity and explore hidden geometry of path between pair of vertices v_i, v_j the L_G matrix transforms into AG by using Laplacian pseudo inverse (LPI) transformation (Fig. 2). Isomorphism (same number of vertices, edges, and also the same edge connectivity) between PG to AG is established by LPI kernel. The LPI is inverse of L_G which is defined here as L^+ matrix, where each matrix element is represented as

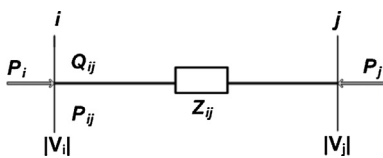


Fig. 1. Power grid transmission line model.

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