Implication of DG Incorporation in Criticality Assessment of Power Network Buses Using Betweenness Metric

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***Abstract*—Concepts in complex network theory has emerged as an effective tool in dealing with investigations related to failures in power networks. The topological betweenness can be redefined as electrical betweenness subjected to power flow conditions and constraints. In this paper the power grid can be modeled as a directed graph in analyzing the properties of the complex network theory to identify critical buses which can create vulnerable failures of the network if removed due to unforeseen fault or an attack. The electrical betweenness metric has been considered for this purpose in order to assess the vulnerability of a power network. Simulation of an IEEE 57 bus network has revealed that the most critical bus has high degree of electrical betweenness. This paper has also highlighted the application of Distributed Generation (DG) in improvement of the betweenness metric as well as the voltage profile of the critical bus along with reduction in total system power loss following its incorporation at the most critical bus.**

***Index Terms*—complex network theory, electrical betweenness, distributed generation**

I. Introduction

Modern power grid is highly interconnected and plays a pivotal role in fuelling infrastructure and electric market. Proper understanding of the vulnerable and critical locations in interconnected power grid provides invaluable information that may be used to inform power grid management practices leading to more realistic risk assessments and the development of defensive strategies to ensure network survival. Occurrences of grid failures in power system have been observed in many utilities across the world. In most of the cases it is initiated as a sequence of equipment failures or attack on the system that successively deteriorates the ability of the power network to continue its desirable functionality [1]. Such types of grid failures have caused large scale blackouts [2]-[3] and several researches have been reported in the literature in order to assess critical outages [4]-[7].

Complex network theory represents a useful framework in order to analyze the structure, dynamics and evolution of events or states in complex power network. In recent years there have been significant involvements in modelling the power grid from the perspective of complex network theory [8]-[10]. Cao *et al.* [11] considered weighted line betweenness as an indicator to assess the network vulnerability. Lin *et al.* [12], Cheng *et al.* [13] considered directed electrical betweenness in order to examine the criticality of the power system.

Since the study of topological structure of a power network can identify the physical behaviour of a power network hence it can provide useful information about vulnerability of the power grid when used in conjunction with electrical characteristics of the network using complex network theory [14]-[16]. In this paper an attempt has been made to measure the electrical betweenness of the IEEE 57 bus test system in order to assess the criticality of load buses. Renewable energy sources (DG) has been employed at the most critical bus to highlight its role in reducing the criticality of the key bus. The increase in steady state voltage profile and reduction in power loss following DG penetration in the selected location of the network has also been investigated in this paper.

II. Topological Model of a Power Grid

The power grid can be abstracted into the complex network through the topological graph $G=\{V_x,E_x\}$. It consists of two sets V_x and E_x, where the elements of $V_x=\{v_1,v_2, ..., v_N\}$ are the nodes (or vertices, or buses) of the graph G, while the elements $E_x=\{e_1,e_2, ..., e_L\}$ are its links(or edge, or lines). Denoting total number of nodes and links of the graph as$N$ and L respectively, the association of nodes with each other can be related using adjacency matrix (A). This matrix would have order N×N if an edge e_{ij} exits between two nodes i and j, whose entry a_{ij} becomes one and zero otherwise.

The graph theory is the basic concept from which complex network theory has been derived. As in graph theory, in complex network theory also, there are sequences of lines and nodes by which all vertices are connected in a network. The length of a sequence is the summation of edges constituting that sequence. A path between two nodes is defined as a sequence in which no node is repeated more than once. The path of minimal length between two vertices is known as geodesic distance i.e. shortest distance between them. It is obvious

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that the transfer of energy between two nonadjacent buses depends on the buses and lines of the geodesic paths connecting those buses. Thus the vulnerability measure of a network element can be found out by counting the number of geodesics going through it and is defined as betweenness centrality of that element. The concept of pure topological betweenness has been extended by introducing some electrical properties.

A. Topological Betweenness of Nodes

Node betweenness of a node v in a topological network can be expressed as [17].

$$B(v)=\sum_{i}^{N}\sum_{j}^{N}\frac{\sigma_{ij}(v)}{\sigma_{ij}}\ i\neq j\neq v\epsilon Vx \quad (1)$$

where $\sigma_{ij}(v)$ is the number of geodesics from node i and node j through node v and σ_{ij} is the total number of geodesics between i and j.

B. Electrical Betweenness

Though the pure topological approach can be employed to find critical elements of a topological graph of an electrical network, it does not serve the purpose of finding critical elements in power network as power system operation is subjected to some typical characteristics and constraints. Hence it is prudent to consider the topological betweenness in conjunction with electrical characteristics and may be redefined as electrical betweenness.

Power transmission capability C_{ij} being defined as the power injection at bus i when the first line of all the paths connecting the generation node i and the load node j reaches its limit, it can be expressed as [18]

$$C_{ij}=min_{l\in L}\left(\frac{P_{max}^{l}}{\left|f_{ij}^{l}\right|}\right) \quad (2)$$

where P_{max}^{l} is the transmission limit of transmission line l and f_{ij}^{l} is the power transmission distribution factor of line l of the path joining generation node i to load node j. This is the change of power on line l for injection at generation bus i and withdrawal at load bus j. f_{ij}^{l} is obtained as the difference between the entries f_{li} and f_{lj} of the power transmission distribution factor (PTDF) matrix and can be calculated as [19]

$$f_{ij}^{l}=f_{li}-f_{lj} \quad (3)$$

However PTDF matrix (f_{ij}^{l}) can be expressed as

$$f_{ij}^{l}=H'B'^{-1} \quad (4)$$

where $B=N\times N$ admittance matrix

$$B_{ij}=-\frac{1}{x_{ij}},i\neq j$$

$$B_{ii}=\sum_{j\neq i}\frac{1}{x_{ij}}$$

B' = Submatrix of B where slack bus column and row are eliminated from B (to avoid singularity slack bus column and row are eliminated),

H = Transmission matrix of order $L\times N$

$$H_{li}=-H_{ij}=\frac{1}{x_{ij}}$$

$$H_{lk}=0 \qquad \forall k\neq i,j$$

H'= Sub matrix of H where slack bus column is eliminated from H.

Betweenness of a bus (node m) in a power network can then be defined as [20]

$$\beta(m)=\frac{1}{2}\sum_{g\epsilon G}^{N_G}\sum_{d\epsilon D}^{N_D}C_g^d\sum_{l\epsilon L^v}\left|f_l^{gd}\right| \quad (5)$$

where $m\neq g\neq d\in Vx$

$\sum_{l\epsilon L^m}\left|f_l^{gd}\right|$ is the sum of PTDF of all the lines connecting bus m, when power is injected at bus g and withdrawn at bus d.

$\frac{1}{2}C_g^d\sum_{l\epsilon L^m}\left|f_l^{gd}\right|$ is the transmission power taken by bus m when the power is transmitted from generator bus g to load bus d; G is the set of generation buses, D is set of load buses, N_G is the number of generation buses, N_D is the number of load buses and L^m is the set of lines connecting bus m. The set of electrical betweenness qualifies the contribution of a component to power transmission in a whole power grid and in this respect the criticality of the elements of the power grid can be assessed.

III. Incorporation of Distributed Generation

Distributed Generation (DG) is one of the most promising solutions to meet the increasing load demand by reconfiguration of long lines carrying power over larger distances. Proper incorporation of DG not only facilitates desired performance of DG resources but also improves voltage profile, minimize optimum real power losses, increase reliability and improve power quality. Researchers have proposed several techniques [21]-[24] for suitable allocation of DGs for improving voltage profile and reduction of losses. Several methods of DG placement strategies are available in literature, although few have approached towards complex network theory [25]. But the improvement achieved with installation of DG has been limited to traditional aspects of power system only.

However, incorporation of DG not only enhances the traditional features of power system described above but also improves topological parameters of complex network theory when power grid is abstracted as a complex network. In this paper, the role of application of

DG have been proposed for improvement of the betweenness metric as well as the voltage profile of the critical bus along with reduction in total system power loss. Simulation has been conducted to highlight that how incorporation of DG reduces the betweenness and hence the criticality of the most critical load bus.

IV. SIMULATION

The IEEE 57 bus system [26] has been considered in this paper to apply the concept presented here in order to study electrical betweenness of buses and check the ranking of their criticality. The modified single line diagram of the standard IEEE 57 bus system is shown in Fig. 1. Fig. 2 represents the topological network of IEEE 57 bus system.

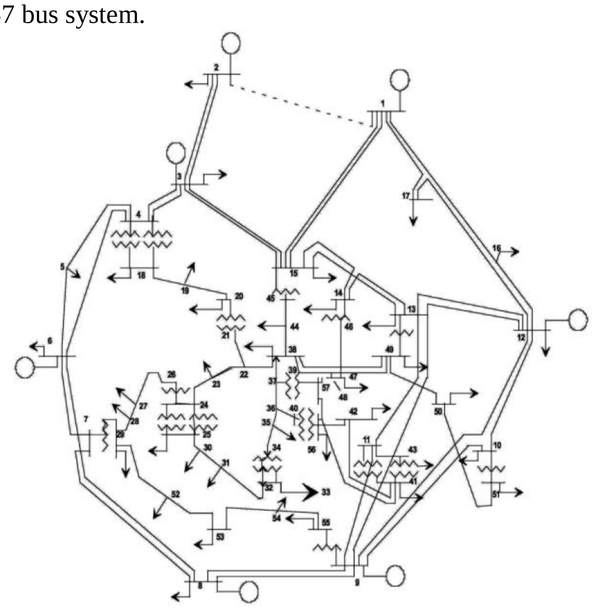

Figure 1. IEEE 57 bus system.

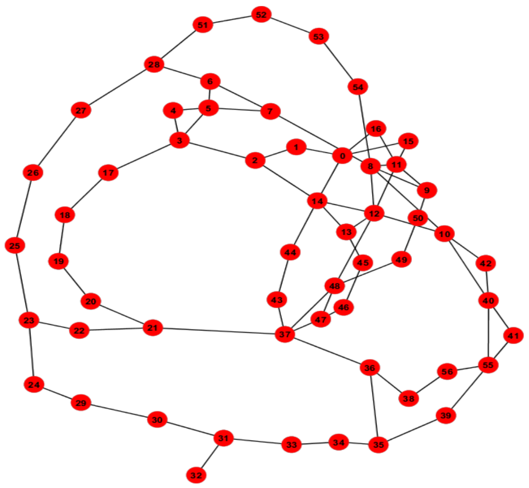

Figure 2. Complex network topology of IEEE 57 bus.

Fig. 3 represents the graphical plot of criticality magnitudes as obtained from the measure of betweenness of load buses. The electrical betweenness of load bus 11 being the maximum; it is followed by the load bus numbers 13, 16, 10. Thus the most critical load bus is bus number 11 and it is vulnerable against any unplanned outage and attack. Following incorporation of distributed generation in the most critical load bus (i.e. bus 11); the criticality magnitude for this bus reduces. Thus application of distributed generation reduces the criticality and ensures lesser vulnerability of most critical bus following unplanned outage or attack on the power network.

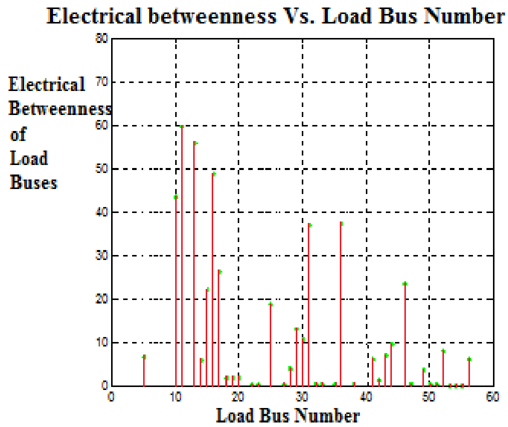

Figure 3. Electrical betweenness of load buses in IEEE57 bus system.

Fig. 4 exhibits the decrement in magnitude of electrical betweenness of four successive load buses (which have high level of betweenness) following incorporation of DG at most critical load bus (i.e. bus 11 which has highest magnitude of betweenness).

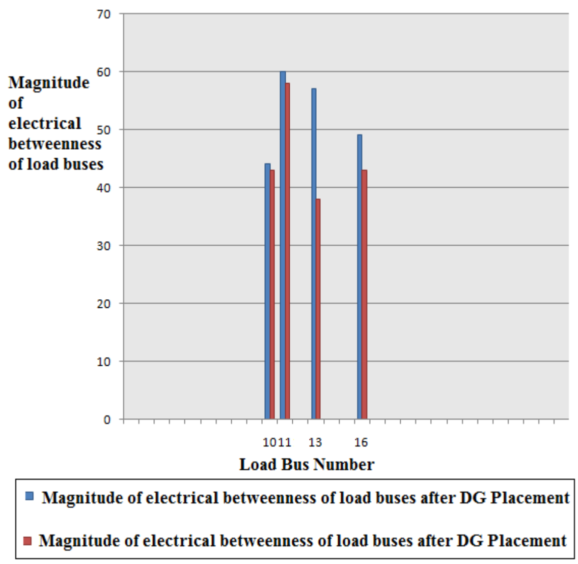

Figure 4. Magnitude of electrical betweenness of 4 successive load buses.

Load flow study was carried out after incorporation of DG to evaluate the losses. DG incorporation not only gave increased efficiency with reduced losses but also enhanced the voltage profile. It has been observed that the steady state voltage profile (Fig. 5) of load buses improve with incorporation of DG while the power loss in the network reduce from 28.12 MW to 24.32 MW.

Hence employment of DG unit not only reduces betweenness (criticality) but at the same time decreases system vulnerability, improves power transmission, increase in voltage profile making the grid more efficient. The role of DG penetration in improvement of complex network theory parameters is an important tool which can be employed to strengthen the infrastructure of power grid.

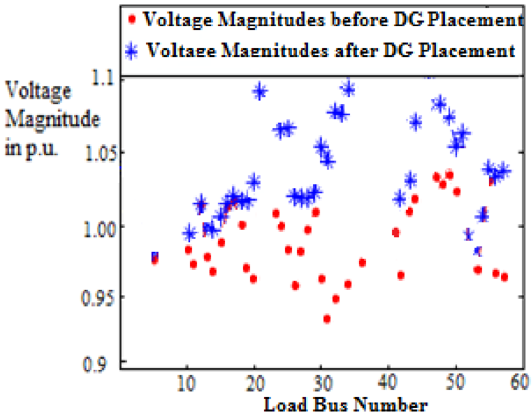

Figure 5. Voltage magnitude enhancement with implementation of Distributed Generation

V. Conclusion

In this paper, a typical power system (IEEE 57 bus system) has been considered as a complex network and it has been analysed in topological frame to assess the electrical betweenness of load buses. The results reveal that the most critical bus has high degree of betweenness indicating its proximity to vulnerable failure following unplanned outage and attack. Incorporation of DG at this critical bus reduces the magnitude of electrical betweenness thereby reducing the possibility of vulnerable failures against unplanned outage and attack. The DG incorporation has also benefitted the successive critical load buses to have their voltage magnitude improved while the system real power loss has reduced substantially.

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