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Research Article

Deployment of Power Network Structural Topology to Optimally Position distributed Generator within Distribution System

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Abstract

Distribution system is very essential to load centre or service mains. This is because it is the final section of electric power system (EPS) to supply the consumers. Once this section is compromised, low voltage consumers will be denied of a reliable supply of electricity. One way to make supply to low voltage consumers reliable is by bringing generation close to them through distributed generators. However, location of distributed generator is very important with respect to the entire EPS security. In this study, power network structural topology (PNST) is proposed to optimally locate distributed generator within distribution system which results in minimal loss as well as maintaining voltage profile within constraint limits. 5-bus IEEE test system was used as case study to show the feasibility of the proposed method. Results obtained for both test systems were validated through the results from power world simulation tool.

Keywords: Optimal, Distributed generator, Distribution system, Power network structural topology.

1. Introduction

A direct result of meeting the need of electrical energy consumers is the concern of most of developing nations. Adequate and constant supply of electricity in some of the developing nations has been the major challenge towards their development in terms of industrialization, technological advancement, innovation, etc. [1, 2]. These problems persist mainly because daily load demand is greater than the available generated power [3]. Another problem is losses along the lines. If the difference between available generated power and load demand is very large, a new centralized generation station will therefore be of essence. However, if the difference is not very much, distributed generator (DG) can be a feasible alternative [4]. Distributed generator (DG) is referred to as a mini generation station that is installed very close to user end. It can either be stand alone or integrated into the power system network. It can be renewable energy source (i.e. biomas, hydro, wind, sun, geo-thermal and tidal) or non-renewable source (i.e. coal, gas, fuel cell). Integration of DG into distribution power system offers several benefits such as line loss reduction, improved voltage profile, increased power quality, relief in distribution capacity, etc.

One of the problems associated with the integration of distributed generator into the distribution network is optimization i.e. optimal sizing and siting of DG. This problem is usually solved as a non-linear problem using iterative approach. Several studies have considered different methods for placing and sizing DG [5]. Analytical method, based on exact loss formula, has be used by [6] on Nigerian 33-kV network to minimise real power losses which also resulted in voltage profile improvement. Loss sensitivity factor based on current injection method was proposed by [7], which was tested on 12-, 34- and 69-bus distribution systems. The proposed method was compared with Acharya's method and classical grid search algorithm. Other methods that have also been deployed are Newton Raphson method of load flow study [8], power flow algorithm [9], second-order power flow sensitivities [10], differential evolution [11], discrete particle swarm optimisation [12], ant colony optimisation [13], particle swarm optimisation [14]. Most of the previous methods deployed were based on iterative approach and varying location in order to ascertain optimal result.

In this present study, a new approach to finding optimal location and capacity of DG is proposed. This new approach is based on power network structural topology (PNST) devoid of any iterative process. Based on the results from PNST approach, power world simulation tool is used to ascertain the feasibility of this new approach to solving power system problem.

2. Methodology

In this section, power network structural topology (PNST) and power world simulation software are considered. The PNST is the proposed approach in this study while power world simulation software is used to validate the result obtained from PNST.

Power network structural Topology

Power network structural topology (PNST) is an approach that considers the inherent characteristic of electric power circuitry in order solve power system problems. PNST approach proposed in this study, is based on the two-port network technique which has been reported in previous works [15-17].

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Let us consider a n-port network given in Figure 1, where
m = number of generation buses
k = number of load buses
n = total number of buses
hence, m + k = n.

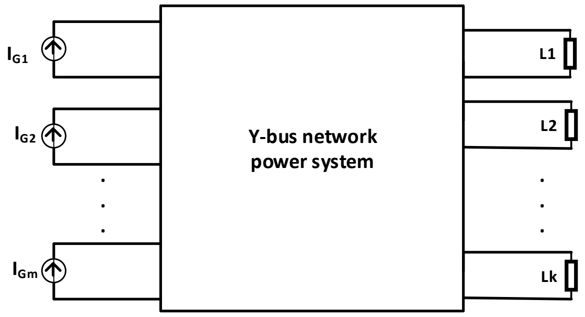

Fig. 1. n-port network

By combining all the generator buses together at one side and all the load buses at the other side, the system can be regarded as a two-port network as shown in Figure 2. Therefore, employing the circuit theory two-port network approach, equation 1 results.

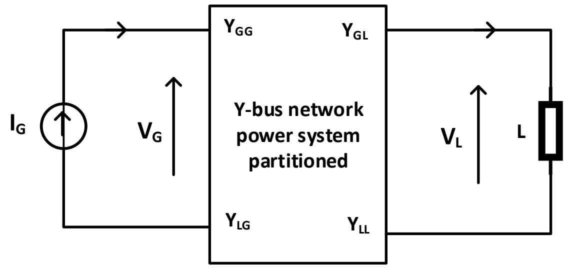

Fig. 2. Two-port network representation

$$\left[I\right]=\left[Y\right]\left[V\right]=\begin{bmatrix} I_G \\ -I_L \end{bmatrix}=\begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix}\begin{bmatrix} V_G \\ V_L \end{bmatrix}, \quad (1)$$

Where

$[I_G]$ = Vector element of generator bus injected currents;
$[I_L]$ = Vector element of load bus injected current;
$[V_G]$ = Vector element of complex voltage of the generator bus;
$[V_L]$ = Vector element of complex voltage of the load bus;
$[Y_{GG}]$ = Admittance matrix for buses with generator;
$[Y_{GL}]$ = Admittance matrix relating generator to load;
$[Y_{LG}]$ = Admittance matrix relating load to generator; and
$[Y_{LL}]$ = Admittance matrix of the load buses.

In the matrix of equation (1) above, the Y-admittance matrix is partitioned to justify the exceptional differences among generator buses, load buses, generator-load relationship and load-generator relationship. However, in a practical network, load buses cannot exist alone without connection to any other bus. In order to achieve this kind of relationship, equation (1) is separated into two simultaneous equations as represented in equations (2) and (3) and further modified.

$$\left[I_G\right]=\left[Y_{GG}\right]\left[V_G\right]+\left[Y_{GL}\right]\left[V_L\right] \quad (2)$$

$$\left[-I_L\right]=\left[Y_{LG}\right]\left[V_G\right]+\left[Y_{LL}\right]\left[V_L\right] \quad (3)$$

Dividing equation (2) by $\left[Y_{GG}\right]$, gives

$$\frac{\left[I_G\right]=\left[Y_{GG}\right]\left[V_G\right]+\left[Y_{GL}\right]\left[V_L\right]}{\left[Y_{GG}\right]^{-1}}$$

$$\left[Y_{GG}\right]^{-1}\left[I_G\right]=\left[Y_{GG}\right]^{-1}\left[Y_{GG}\right]\left[V_G\right]+\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]\left[V_L\right]$$

Making $\left[V_G\right]$ the dependent variable, gives

$$\left[V_G\right]=\left[Y_{GG}\right]^{-1}\left[I_G\right]-\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]\left[V_L\right] \quad (4)$$

Substitute equation (4) into (3) yields

$$\left[-I_L\right]=\left[Y_{LG}\right]\left[\left[Y_{GG}\right]^{-1}\left[I_G\right]-\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]\left[V_L\right]\right]$$
$$+\left[Y_{LL}\right]\left[V_L\right]$$

$$\left[-I_L\right]=\left[Y_{LG}\right]\left[Y_{GG}\right]^{-1}\left[I_G\right]+$$
$$+\left[\left[Y_{LL}\right]-\left[Y_{LG}\right]\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]\right]\left[V_L\right] \quad (5)$$

Combining equations (4) and (5) in a matrix form, gives

$$\begin{bmatrix} \left[V_G\right] \\ \left[-I_L\right] \end{bmatrix}=\begin{bmatrix} \left[Y_{GG}\right]^{-1} & -\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right] \\ \left[Y_{LG}\right]\left[Y_{GG}\right]^{-1} & \left[Y_{LL}\right]-\left[Y_{LG}\right]\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right] \end{bmatrix}\begin{bmatrix} I_G \\ V_L \end{bmatrix} (6)$$

In compact form, equation (6) can be represented as

$$\begin{bmatrix} V_G \\ -I_L \end{bmatrix}=\begin{bmatrix} Z_{GG} & M_{GL} \\ N_{LG} & D_{LL} \end{bmatrix}\begin{bmatrix} I_G \\ V_L \end{bmatrix}, \quad (7)$$

where

$\left[Z_{GG}\right]=\left[Y_{GG}\right]^{-1}$;

$\left[M_{GL}\right]=-\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]$;

$\left[N_{LG}\right]=\left[Y_{LG}\right]\left[Y_{GG}\right]^{-1}$; and

$\left[D_{LL}\right]=\left[Y_{LL}\right]-\left[Y_{LG}\right]\left[Y_{GG}\right]^{-1}\left[Y_{GL}\right]$.

Equation (7) gives the intrinsic structural topology of power system networks. $\left[D_{LL}\right]$ is the matrix for load buses from which optimal location will be determined and it clearly indicates the removal of other buses from the load buses.

By applying the Singular Value Decomposition (SVD) approach to matrix $\left[D_{LL}\right]$, singular values connected to the system load buses are obtained as

$$\left[D_{LL}\right] = XZY^T = \sum_{i=1}^{n} x_i \vartheta_i y_i^T \ , \tag{8}$$

where x matrix is orthogonal to y matrix, and x_i & y_i represent their singular vectors respectively. The diagonal matrix Z can be expressed as

$$Z\left(D_{LL}\right) = diag\left\{\vartheta_i\left(D_{LL}\right)\right\} \tag{9}$$

where $i = 1,2,...n \quad \vartheta_i \geq 0 \quad \forall \quad i$

The absolute value of diagonal elements of matrix R are put in order such that $\vartheta_1 \leq \vartheta_2 \leq ...\vartheta_n$

From equation (7), the following expression is obtained

$$\left[-I_L\right] = \left[N_{LG}\right]\left[I_G\right] + \left[D_{LL}\right]\left[V_L\right] \tag{10}$$

Making $\left[V_L\right]$ the dependent variable, gives

$$\left[V_L\right] = \left[D_{LL}\right]^{-1}\left[\left[-I_L\right] - \left[N_{LG}\right]\left[I_G\right]\right] \tag{11}$$

Substituting equation (8) into (11) gives

$$\left[V_L\right] = \left[\sum_{i=1}^{n} m_i \vartheta_i v_i^T\right]^{-1}\left[\left[-I_L\right] - \left[N_{LG}\right]\left[I_G\right]\right] \tag{12}$$

Hence, from equation (12), the load bus voltages can be expressed as

$$\left[V_L\right] = \left[\sum_{i=1}^{n} \frac{v_i m_i^T}{\vartheta_i}\right]\left[\left[-I_L\right] - \left[N_{LG}\right]\left[I_G\right]\right] \tag{13}$$

Equation (13) clearly shows that the singular value of matrix D_{LL} determines the impact on the load bus voltages. The critical load bus is the bus with the highest eigenvalue in matrix D_{LL}. This is because of the reciprocal relationship between it and the entire load voltages. Therefore, the connected load bus with the highest eigenvalue has the most significant impact on the network. Mathematically, this expression plays a significant role in proffering optimal solution to the identification of the best bus for power injection and optimal size of distributed generator required to guarantee system voltage within constraint limits and line loss reduction.

Power world simulator

Power world simulator is an interactive power system simulation software developed to simulate electric power system operation. The software contains a highly effective power flow analysis package capable of efficiently solving power systems up to 250,000 buses. It has the following features: intuitive, user-friendly GUI, model explorer, solution options, presentation tools, interactive, animated diagrams, contingency analysis, geographic information system (GSI), time-step simulation (TSS), automated diagram creation and modification tools, compatibility, modeling capabilities, sensitivities, area generation control (AGC), difference flows, contoured displays, script actions and customer support [18].

3. Results and Discussion

In this section, the proposed approach is tested on the IEEE 5-bus network displayed in Figure 3 using Matlab 2018 environment as the simulation tool and power world simulator. Bus data and line data for the IEEE 5-bus network are contained in [19].

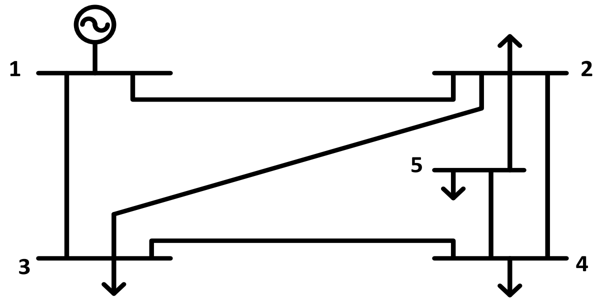

Fig. 3. IEEE 5-bus network

$$D_{LL} = \begin{pmatrix} 21.5519 & 8.4369 & 5.2705 & 7.9057 \\ 8.4369 & 40.0284 & 31.6228 & 0 \\ 5.2705 & 31.6228 & 40.8200 & 3.9528 \\ 7.9057 & 0 & 3.9528 & 11.8396 \end{pmatrix}$$

In this test system, there are four load buses. One of these must be identified as the best location. That is why the result of D_{LL} matrix is 4 x 4

$$EigenVal[D_{LL}] = \begin{pmatrix} 4.4273 & 0 & 0 & 0 \\ 0 & 11.6816 & 0 & 0 \\ 0 & 0 & 24.0009 & 0 \\ 0 & 0 & 0 & 74.1301 \end{pmatrix}$$

The bus with the highest eigenvalue depicts the optimum location for distributed generator for minimal line loss without voltage magnitude constraint being exceeded. In this case, the optimum location is bus 5.

In order to validate this result, power world simulator was used to simulate the operation of system. This operation was carried out one after the other. The results are displayed in Figures 4a to 4e.

From the power world simulation results, Figure 4a gives the base case result without distributed generator while Figures 4b, 4c, 4d and 4e display results with distributed generator included in the system from buses 2 to 5 one at a time. It is recorded as shown in Table 1, that minimal loss on the system is obtained with distributed generator at bus 5 just as suggested by the proposed single value decomposition (SVD) method used alongside with power network structural topology (PNST).

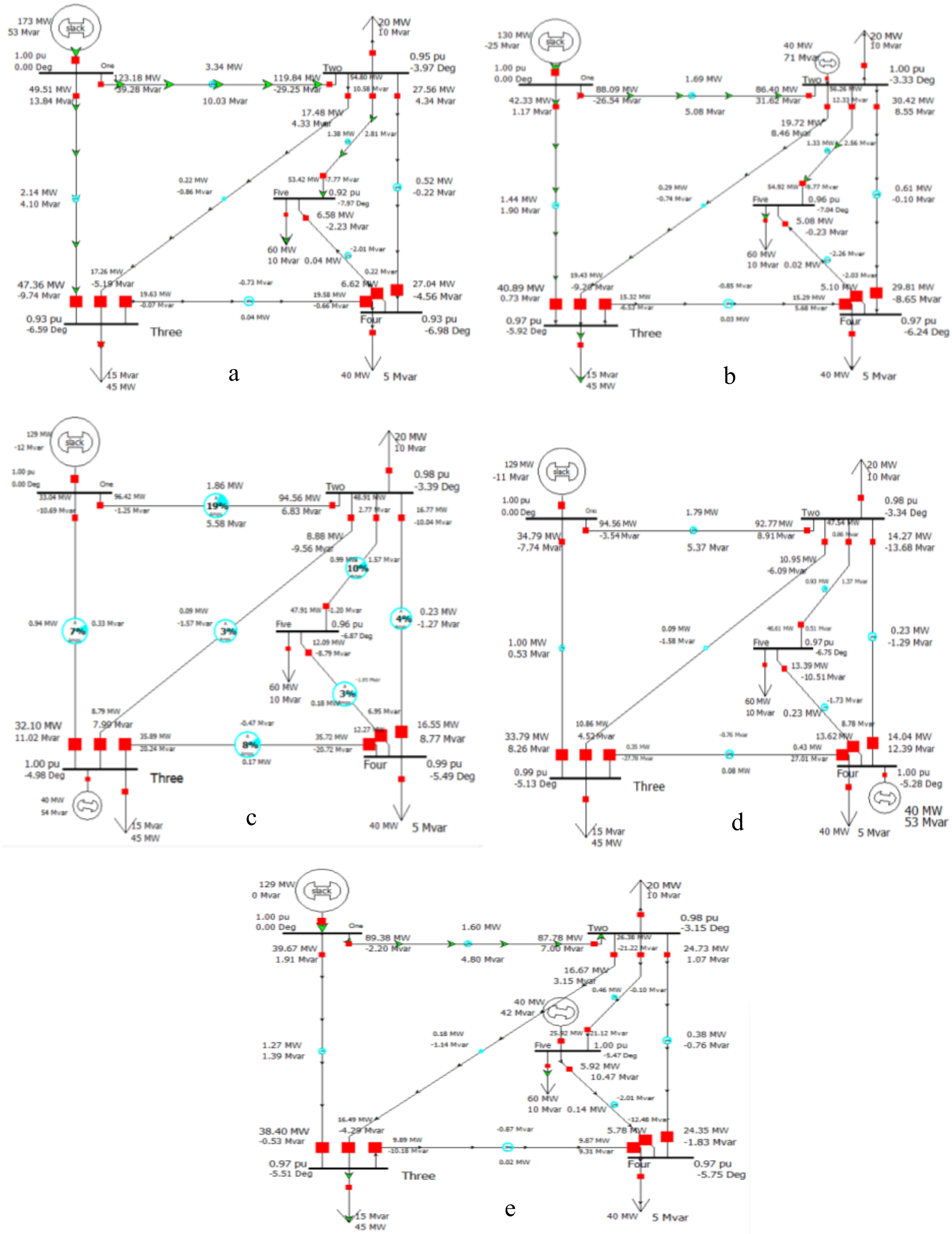

Fig. 4. Power world simulation results

Table 1. Total Loss on the 5-bus system with and without distributed generator

S.No	Conveyor Type	Advantage	Application
1.	Chute Conveyors	Can transport unit/bulk materials	Packing sectors of scraps, cement bags, postal packages, etc.
2.	Wheel Conveyors	Unpowered wheels are used Orientation can be altered based on requirement	Loading & Unloading operations in trucks, finished product handling in packing sectors, etc.
3.	Roller Conveyors	Can be powered or unpowered based on requirement Used for rigid object transportation	Utilized in baggage handling, loading and unloading sectors, instrument assembly paths, etc.
4.	Chain Conveyors	Chains enhance the speed of conveyance	Utilized in systems with many discharge vents, industrial baskets, etc
5.	Slat Conveyors	Flexibility in position & orientation is the main feature of the conveyor	Used for heavy loads, oily parts in dryers, bottling & canning processes, etc

6.	Flat Belt Conveyors	Longer life with lower power consumption. Highly reliable and adaptable	Raw material supply unit in industries, Wheel excavators, Harbours, Bakeries & flour mills, etc.
7.	Magnetic Belt Conveyors	Least maintenance required Longer life using strong magnets and SS plates.	Metal Cutters, conveyance of metallic parts and stampings, etc
8.	Troughed Belt Conveyors	Problem causing materials can be conveyed with higher capacities. Lightest form of conveying with minimum labour requirement.	Can be used for conveying all sort of materials like wet, dry, oily, sticky, etc. Used for underground mine transport.
9.	Bucket Conveyors	Can be used with different shapes and sizes. Can be used in all kinds of environmental conditions	Used in mining, oil mills, construction works, etc
10.	Vibrating Conveyors	Can be utilized for conveying different kind of materials without mixing to a longer distance. Supplementary processes like heating, dehydrating, chilling, etc can be performed along with conveying.	Can be used as feeder, spreader, extractor, grizzly, segregation of materials, recycling process, etc.
11.	Screw Conveyors	Can convey bulk materials with multiple inlet & discharge points with gates and valves. These are compact and adaptable.	Used for conveying wet biosolids and sticky sludges. Forms a major part of conveying in food, chemical, wood and minerals industries.
12.	Pneumatic Conveyors	Requires lower maintenance and has more flexibility. Requires lesser energy for operation & is safer.	These conveyors are used in industries like food, agriculture, pharmaceutical, cement, plastic, etc.
13.	Vertical Conveyors	These are flexible and modular and can be altered based on need. Reciprocal vertical conveyors utilize the gravitational pull which reduces the power requirement.	These systems are used in lifting operations, car parking systems, material transport to various floors, etc.
14.	Cart-On-Track Conveyors	These are simple and shorter length conveyors. They are adjustable and reliable.	These are used in automobile parking systems, airport luggage carriers, various assembly lines, etc.
15.	Tow Conveyors	These systems are more flexible, reliable and customizable. It is easy to integrate these systems with the prevailing systems.	Towline conveyors are widely used in aircraft & engine assembly lines, wind turbine assembly lines, furniture and apparel handling, agricultural equipment handling, etc.
16.	Trolley Conveyors	It is more flexible and modular. More designs are available for various applications	It is most popularly used in assembly and packaging section of automobile industries, storage lines in food industries, etc.
17.	Power and Free Conveyors	Normally uses high strength alloy castings which gives modular design, increased life span, compact and simple.	Most frequently used in elevation changing applications, transferring materials, assembly sectors, sorting units, etc.
18.	Monorail	These are noiseless and fast transport systems. Its highly available with lower investments.	These are widely used in winches, rope cars, assembly and packing sectors in automobile industries, etc.
19.	Sortation Conveyors	They can be operated using hydraulic and pneumatic lines. Cost effective and simple with wide range of operations.	These are used in sorting materials for recycling, baggage in airports, merging systems, etc.

4. Conclusion

In this study, distributed generator was considered as a viable alternative to centralized generation station which requires huge capital cost of installation. However, this study focuses more on the optimal location of the distributed generation on distribution system of a given electric power system with minimal loss and voltage profile contained within its limit. Power network structural topology (PNST) approach was deployed in this study to optimally site distributed generator on the standard IEEE networks. The results obtained validate the feasibility of the approach in solving electric power system network.

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