# Voltage Sag Mitigation by Network Reconfiguration

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## 1. Introduction

The electric power distribution system must be designed to operate and supply acceptable level of electrical energy to customers. Power utilities must ensure that the power supply to customers is with voltage magnitude within standard levels. Other features like minimal interruptions and minimal system power loss also must be considered. Hence, the quality and reliability of supply must be maintained in an acceptable level even during contingencies.

Voltage magnitude is one of the parameters that determine the quality of power supply. A decrease in voltage magnitude may result in voltage sag which is currently considered as one of the main power quality problems. Voltage sag is defined as a decrease in magnitude between 0.1 and 0.9 pu in rms voltage at a power frequency of duration from 0.5 cycle to 1 min (IEEE Std 1159, 1995). Voltage sag may cause sensitive equipment to malfunction and process interruption and therefore are highly undesirable for some sensitive loads, especially in high-tech industries. However, loads at distribution level are usually subjected to frequent voltage sags due to various reasons.

Voltage sag can be treated as a compatibility problem between equipment and power supply. When installing a new piece of equipment, a customer needs to compare the equipment sensitivity with the performance of the supply. There are various engineering solutions available to eliminate, correct or reduce the effects of power quality problems (Kusko &Thomson, 2007). Currently, a lot of research works are under way to solve the problem of voltage sag in distribution systems. Most of these research works focus on installing voltage sag mitigation devices (Sensarma et al., 2000). Other researchers focus on improving the immunity level of customer equipment by installing custom power devices to improve the voltage sag ride through capability (Shareef et al., 2010). Some other research works focus on utility efforts in finding feasible solutions to mitigate voltage sag problem. Since system faults are considered as main causes of voltage sags, utilities try to prevent faults and modify the available fault clearing practice in power systems. Normally, voltage sag assessment at a particular site in the network consists of determining the frequency of sags of specified sag magnitude and duration over a period of interest (Conrad & Bollen, 1997). It is also dependent on the utility fault performances, the way the fault affects propagation of disturbance in the system, and the customer's service quality requirements (Shen et al., 2007). For voltage sag assessment, voltage sag characteristics has to be

accurately reproduced by means of a time-domain simulation tool, and using a stochastic prediction to incorporate the random nature of voltage sag in the mitigation process (Qader et al., 1999, Heine & Lehtonen, 2003, Aung & Milanovic´, 2006 & Martinez et al., 2006).

A method of minimising cost of losses due to voltage sag by employing network reconfiguration was introduced by (Sanjay et al., 2007). (Chen et al., 2003) introduced a voltage sag mitigation method by means of implementing a series of utility strategies for a period of 10 years. Network reconfiguration was proposed as a voltage sag mitigation method by using feeder transfer switches in power distribution systems. Switches at sectionalizing points of a distribution network are used to find the weak points during voltage sags and to transfer the customers at the weak points to other sources (Sang et al., 2000). The graph theory was employed as a tool in finding suitable solution to alter system switches to reconfigure distribution networks (Sabri et al., 2007 & Assadian et al., 2007). The power distribution network can be reinforced against voltage sag propagation, where the graph theory is selected as an efficient tool to find the shortest path between the main power source and every fault location (Salman et al., 2009). Based on the electrical distance towards the fault current, network reconfiguration is employed for voltage sag mitigation where the exposed weak area in distribution network is initially identified.  Then the size of the exposed weak area of specified voltage sag is reduced by network reconfiguration. Based on the new technique of switching action, the weak areas in distribution systems can be identified and placed as far away as possible from the main source considering distribution system operation.

This chapter focuses on the utility efforts towards voltage sag mitigation in particular employing the network reconfiguration strategy. The theoretical background of the proposed method is first introduced and then the analysis and simulation tests on a practical system are described to highlight the suitability of network reconfiguration as a method for voltage sag mitigation. The analysis of simulation results suggest some significant findings that may assist utility engineers to take the right decision in network reconfiguration.

## 2. Overview of utility efforts in voltage sag mitigation

The utility engineers considered faults as the main source of voltage sags.  Reducing the number of faults is a considerable way of mitigating voltage sags. The duration of voltage sag can be reduced by the reduction of fault clearing time of power protection equipment. The change in the distribution system design and structure may affect the voltage sag performance and propagation. An overview about the utility efforts on voltage sag mitigation was introduced by (Sannino et al., 2000). Brief overview on utility efforts in voltage sag mitigation are explained in the following sections 2.1, 2.2 and 2.3.

### 2.1 Reducing the number of faults

Limiting the number of faults is an effective way to reduce not only the number of voltage sags, but also the frequencies of short and long interruptions. Fault prevention actions may include the institution of tree trimming policies, the addition of lightning arresters, insulator washing and the addition of animal guards. A considerable reduction in the number of faults per year can otherwise be achieved by replacing overhead lines by underground cables, which are less affected by adverse weather.

## 2.2 Reducing the fault-clearing time

Reducing the fault-clearing leads to less severe voltage sags. This method does not affect the number of events, but their durations. The modern static circuit breakers are able to clear the fault well within a half cycle at the power frequency, thus ensuring that no voltage sag can last longer. Moving from the load to the source, the tripping delay increases from 300 to 500 ms. If faster fault clearing is needed, then the whole system has to be redesigned and all the protective devices have to be replaced with faster ones. This would greatly reduce the grading margin between the breakers, thus leading to a significant reduction in fault-clearing time.

## 2.3 System design and configuration

Many actions in distribution system design can be employed for mitigating voltage sag. A certain improvement can be achieved by installing current-limiting reactors or fuses in all the other feeders originating from the same bus as the sensitive load. These actions increase the "electrical distance" between the fault and the common bus, thus decreasing the depth of the sag for the sensitive load. The increase in the electrical distance can also be achieved by change in system configuration.

# 3. Network reconfiguration in power distribution systems

Network reconfiguration is a process of altering the topological structures of distribution feeders by changing the open/closed status of the sectionalizing and tie switches. A whole feeder, or part of a feeder, may be served from another feeder by closing a tie switch linking the two while an appropriate sectionalizing switch must be opened to maintain radial structures (Civanlar, et al., 1988). In other words, network reconfiguration is a switching action which may be applied to change the network configuration for improving operation performance.

The network reconfiguration process is generally used for loss reduction, load balancing and voltage profile improvement in distribution systems. It may be used to reinforce the network against voltage sags propagation by increasing the line impedance towards fault current during short circuit events (Salman et al., 2009). A brief overview of network reconfiguration to reinforce against voltage sag propagation is presented below. The idea is based on the principles of circuit theory. To understand this idea, consider a typical distribution system shown in Fig. 1. If the substation is treated as a point of common coupling (PCC) between the power source and fault location, $V_{source}$ is main source voltage, $Z_s$ is he Thevenin's impedance behind the source, $Z_f$ is fault impedance and $Z_i$ is a line impedance of the feeder i. Then the substation bus voltage $V_{pcc}$ during a fault event at bus i can be derived as:

$$V_{pcc} = \frac{Z_i + Z_f}{Z_i + Z_f + Z_s} V_{source} \qquad (1)$$

From (1), it can be understood that $V_{pcc}$ can be improved by finding another higher impedance route between substation and bus i. For example, if $Z_n > Z_i$, the bus i can be supplied through feeder, n by closing the tie switch, $SW_n$ and opening sectionalizing switch, $S_i$ as shown in Fig. 1. This change in configuration will increase the substation bus voltage magnitude. After reconfiguration, if $Z_f = 0$, the new substation voltage magnitude can be written as:

$$V_{pcc1} = \frac{Z_n}{Z_n + Z_s} V_{source} \tag{2}$$

where $V_{pcc1}$ is the voltage magnitude of substation which is taken as the point of common coupling after reconfiguration.
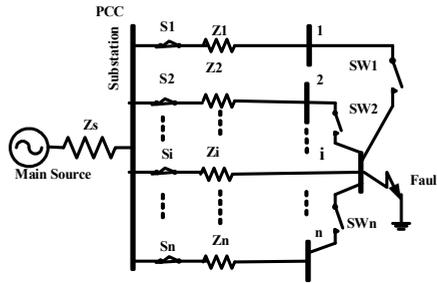


Fig. 1. Typical distribution system

The feasible reconfiguration must be valid according to the operation constraints of the distribution network. The operation constraints are summarized as:
i.    The network must be of radial structure.
ii.   All the network nodes and loads must be connected,
iii.  The nominal bus voltages must be within standard limits, $V_{min} \leq V_i \leq V_{max}$ where $V_{min}$ is the lower limit of nominal voltage magnitude; $V_i$ is the voltage magnitude of bus i and $V_{max}$ is the upper limit of nominal voltage magnitude.
iv.   The current flows must be within the thermal limits of the lines, $I_i \leq I_{imax}$. where $I_i$ is the current of line i and $I_{imax}$ is the thermal limit of the line i.
v.    System line loss ($F_{loss}$) must be within acceptable limits. $F_{loss}$ can be formulated as:

$$F_{loss} = \sum_{1}^{n} R_i \frac{P_i^2 + Q_i^2}{V^2_i} \tag{3}$$

where  $R_i$    : branch resistance;
         n    :  number of branches;
         $P_i$    : branch i active power flow;
         $Q_i$    : branch i reactive power flow;
         $V_i$    : voltage magnitude at  the end bus of line i.
Although, this change in network configuration improves the voltage magnitude during the fault event, sometimes it may cause unacceptable voltage drop in the lines and hence inadequate nominal voltage at various buses during steady state operation. It means that the network reconfiguration must be done in such a way that it does not violate the limits of system voltage profile at steady state condition.
Network reconfiguration can be employed as a siutable tool for voltage sag mitigation as well as for line loss reduction in distribution systems. Based on the right decision of reconfiguring a distribution network, a suitable objective function of network reconfiguration can be formulated. If the decision to be taken is for reducing the financial losses, voltage sag can be mitigated by a very cheap and feasible method, that is by  only switching action.

In network reconfiguration, the switching action must be done in the manner of improving voltage magnitudes for a considerable number of system buses. It is important to determine the weak area in the system before implementing the switching action for network reconfiguration. Weak area is defined as a bus or group of buses that can be considered as effective in voltage sag propagation throughout the same distribution system. It means that the system buses that experience voltage sag during the occurrence of short circuit event are considered as buses in  the weak area. By implementing appropriate switching actions, the distribution network can be reconfigured. Thus, the aim of network reconfiguration is to place the weak area as far away as possible from the main power source.

## 4. Distribution system reinforcement by network reconfiguration

This section illustrates the proposed method of distribution system reinforcement by network reconfiguration. The procedure includes system modelling, power flow and short circuit analysis, application of graph theory and network reconfiguration. The graph theory technique is utilized to find the shortest path between the main power source and the defined weak buses. Based on the graph theory, a feasible solution can be obtained for solving the distribution network reconfiguration problem considering voltage sag mitigation. Mitigating of voltage sag can be achieved by increasing the number of buses reaching the healthy condition due to network reconfiguration. In this case a bus is said to be healthy when its voltage magnitude lies between 0.9 pu and 1.06 pu. Based on the selection of a suitable path by the graph theory, the objective of increasing the number of healthy buses ($N_{hlth}$) can be carried out by changing the status of predefined switches (i.e. the tie and sectionalizing switches) in the distribution system. The principle behind the graph theory is described as follows:
 A graph G = (V,E) consists of a set of vertices (or nodes) V = {A, B, C & S} and edges E = {1, 2, 3, 4, 5 & 6}. Generally, every edge connects two vertices. Fig. 2(a) shows an undirected graph consisting of four vertices connected with six edges. For example vertex A has three incident edges: 1, 3 & 4 while  Vertex B has three incident edges: 2, 3 & 5 and etc. In the graph theory, a path π in a graph is a sequence of vertices such that from each of its vertices there is an edge to the next vertex in the sequence. The first vertex is called the start vertex and the last vertex is called the end vertex. A path is the m-th path starting from any start vertex and ending at a specified vertex. The set of m alternative paths ending at vertex, i can be described as:

$$\Pi_m^i = \left\{\Pi_1^i, \Pi_2^i, \dots\dots, \Pi_m^i\right\} \tag{4}$$



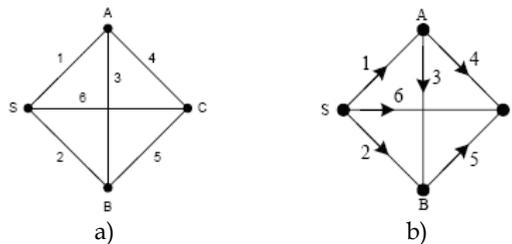a)                          b)

Fig. 2. Example of graph with 4 nodes in a) undirected b) directed type

For example, all alternative paths from the start vertex, S to the end vertex, A can be searched in both graphs as depicted in Fig. 2. In the undirected graph, it is realized that five alternative paths can be obtained as:

$$\Pi_1^A = 1, \Pi_2^A = 2-3, \Pi_3^A = 6-4, \Pi_4^A = 2-5-4, \Pi_5^A = 6-5-3 \tag{5}$$

Meanwhile, in the directed graph, only the end node with one path can be achieved: $\Pi_1^A = 1$. Graph theory is employed to determine the shortest path between the main source and fault location after every switching action. The shortest path is considered as the fault current route during fault events. The impedance of the fault current route is considered as significant element of fault current reduction. To understand the employment of graph theory in finding suitable impedance for the fault current path, the 16-bus distribution system shown in Fig. 3a is selected. If a fault location at bus 12 is appointed, the graph representation of the system is shown in Fig. 3b. The shortest path between the main source and fault location can be presented as:

$$\Pi_i^{12} = 1.2 - 2.8 - 8.9 - 9.12 \tag{6}$$

where i=1, 2, 3, . . . , maximum number of configurations. 1.2 indicates the branch joining between the buses 1 and 2, 2.8 is the branch joining between 2 and 8 and etc.
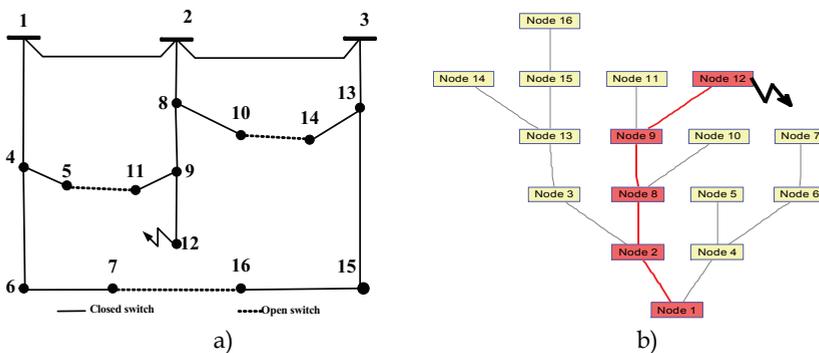


Fig. 3. 16-bus distribution system before reconfiguration a) one line diagram, b) graph representation

The total impedance of the path $\Pi_i$ ( $Z_{\Pi}$) can be calculated as:

$$Z_{\Pi_i} = Z_{1.2} + Z_{2.8} + Z_{8.9} + Z_{9.12} \tag{7}$$

where $Z_{1.2}$, $Z_{2.8}$, $Z_{8.9}$, and $Z_{9.12}$ are the series impedances of the branches 1.2, 2.8, 8.9 and 9.12 respectively.

If some switching action is done by opening the branch 1.2 and closing the branch 5.11, the 16-bus system is reconfigured as shown in Fig.4a. The 16-bus system can be presented by applying graph theory to find the new shortest path between the main source (bus 1) and fault location (bus 12) as shown in Fig. 4b. The shortest path can be presented as:

$$\Pi_{i+1}^{12} = 1.4 - 4.5 - 5.11 - 11.9 - 9.12 \tag{8}$$

where $\Pi_{i+1}$ is the next path after reconfiguration, comprising of the corresponding branches and the total impedance of the path $\Pi_{i+1}$, $Z_{\pi i+1}$ can be calculated as:

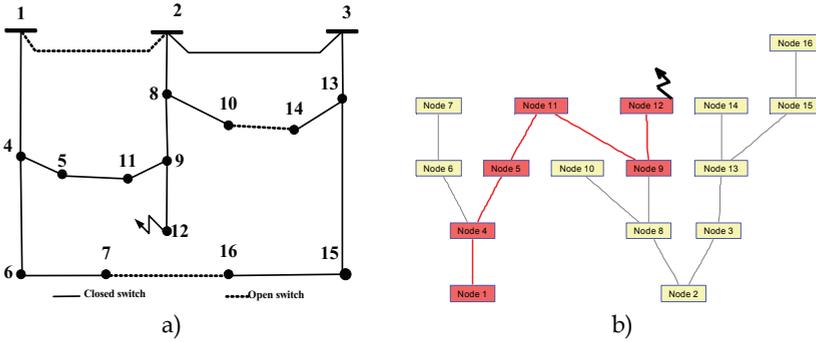$$Z_{\Pi_{i+1}} = Z_{1.4} + Z_{4.5} + Z_{5.11} + Z_{11.9} + Z_{9.12} \tag{9}$$



Fig. 4. 16-bus distribution system after reconfiguration a) one line diagram b) graph representation

The increase in the impedance of fault current path results an increase in the electrical distance between the main source and the fault location. Based on the increase of impedance path the exposed area of the fault location is reduced. The reduction of the exposed area means mitigating the voltage sag propagation. In other words, the system network can be reconfigured to mitigate voltage sag by using the graph theory algorithm as a tool for finding the suitable electrical distance between the main source and the weak bus.

During reconfiguration process, for every change in the system configuration the number of healthy buses ($N_{hlth}$) and system losses ($F_{loss}$) must be calculated by the short circuit analysis and steady state load flow. In other words, an algorithm is to be developed to maximize the number of healthy buses ($V \geq 0.9$ pu) due to reconfiguration action. If $C_i$ is the healthy condition (0 or 1) for bus i during voltage sag duration, then it can be formulated as:

$$C_i = \begin{cases} 1 \cdots \cdots 0.9 \leq V_i \leq 1.06 \\ 0 \cdots \cdots else \end{cases} \tag{10}$$

If $N_{bus}$ is the total number of the system buses, the number of healthy buses ($N_{hlth}$) can be calculated as:

$$N_{hlth} = \sum_{i=1}^{Nbus} C_i \tag{11}$$

Equation (11) is used for calculating the number of healthy buses ($N_{hlth}$). The calculation must be done before and after each reconfiguration process. The reconfiguration process is subjected to the system operation constraints as mentioned earlier in Section 3.

If $N_{hlth}b$ and $N_{hlth}a$ represent the calculated number of healthy buses before and after reconfiguration, respectively, the calculated improvement of the number of healthy buses due to reconfiguration process ($N_{imp}$) can be expressed as:

$$N_{imp} = \frac{N_{hlth}a - N_{hlth}b}{N_{hlth}b} \times 100 \qquad (12)$$

An acceptable increment of losses of the system (INd) must be defined before the reconfiguration. The value of INd can be defined according to the required improvement of the number of healthy buses  for the system reliability level.

If $F_{loss}b$ and $F_{loss}a$ represent the system losses before and after reconfiguration, respectively, the calculated percentage increase of system losses after each reconfiguration process (INc) can be expressed as:

$$INc = \frac{F_{loss}a - F_{loss}b}{F_{loss}b} \times 100 \qquad (13)$$

where $F_{loss}b$ and $F_{loss}a$ can be calculated by (3). The reconfiguration process is constrained by computed INc ≤ INd and other system operation constraints as mentioned in Section 3.

### 4.1 Distribution system modeling

All distribution system components, i.e., lines and cables, loads, transformers, large motors and generators have to be converted into equivalent reactance (X) and resistance (R) on common bases. The main system components models are described below.

i.    Lines and cables: Lumped parameter models are adopted for lines and cables, as they are much simpler to model and still provide results of appropriate accuracy. R is the resistance, X is the reactance and B is the line Susceptance (Martin et al., 2006).  The line or cable model is shown in Fig. 5.



Fig. 5. Equivalent circuit for lines and cables

ii.    Loads: The static loads can be approximated as constant impedance, where each load is converted into equivalent impedance of same values for positive and negative sequence (Martin et al., 2004). The load model is shown in Fig. 6.



Fig. 6. Equivalent circuit for load

In Fig.6, if the load bus voltage is $V_L$ and the load is $P_L + jQ_L$, the load impedance ($R_L + jX_L$) can be calculated using (13).

$$R_L + jX_L = \frac{V_L^2}{P_L + jQ_L}$$ (13)

iii. Generators: There are three values of reactance defined in generator, namely subtransient reactance ($X_d''$), transient reactance ($X_d'$) and synchronous reactance ($X_d$) (J. J. Grainger, 1994) as shown in Fig. 7a, Fig. 7b and Fig. 7c respectively. Because most short-circuit protecting devices, such as circuit breakers and fuses, operate well before steady-state conditions are reached, generator synchronous reactance is excluded in calculating fault currents (K. R. Padiyar, 1995). Generators are modelled in short circuit analysis by resistance and sub-transient reactance in series with a constant driving voltage (K. R. Padiyar, 1995) as shown in Fig. 7a.
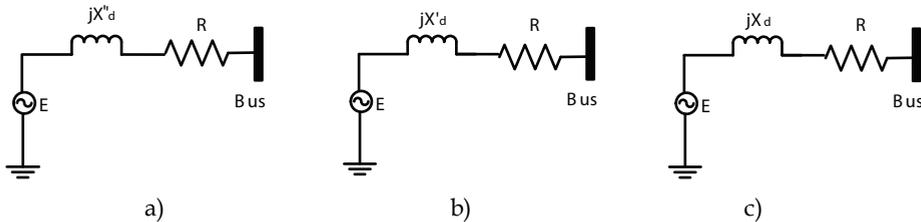


Fig. 7. Equivalent circuit for synchronous generator with internal voltage E and
a) subtransient reactance $X''_d$ b) transient reactance $X'_d$; c) synchronous reactance $X_d$

iv. Transformer: Transformer modelling is one of the most important issues in voltage sag simulations. Linear models of transformers are suitable if the sag is caused by short circuit faults. It can be used to obtain accurate voltage sag characteristics (Martin et al., 2006). Voltage sag characteristics is significantly affected by the difference in winding connections, grounding methods, and tap settings, where transformers introduce different sequence representation and different values of voltage and current resulting in quite different fault current flows in fault calculation. The transformer is modelled as series impedance ($Z_T = R_T + jX_T$), where $R_T$ and $X_T$ are transformer resistance and reactance respectively. The parameters $R_T$ and $X_T$ can be determined by short circuit test and they are equal in value for bath positive and negative sequence representation. The connections of the primary and secondary windings of three phase transformer are considered main principles to derive the zero sequence equivalent circuit and to determine the phase shift in the positive and negative sequence circuits. Fig. 8 shows the five commonly used transformer connections and their zero sequence equivalent circuits.

The impedance, $Z_0$ accounts for the leakage impedance, $Z_T$ and the neutral impedances, $Z_N$ and $Z_n$ where applicable which can be calculated as $Z_0 = Z_T + 3Z_n$. $Z_N$ and $Z_n$ are the neutral impedances of primary and secondary windings of the transformer, respectively (Grainger, 1994). The tap-changing ratio must be taken into account in the transformer impedance calculation. The different types of delta-wye connections of transformer winding result in a phase shift of n×30 ( n =1, 5, 11, . . ., etc ). The voltage sag propagation is affected by these phase shifts and therefore must be considered in the models (IEEE Std-1346, 1998). The admittance matrix can be built at first using the above models and the impedance system matrix can be determined by using the inversing admittance matrix.
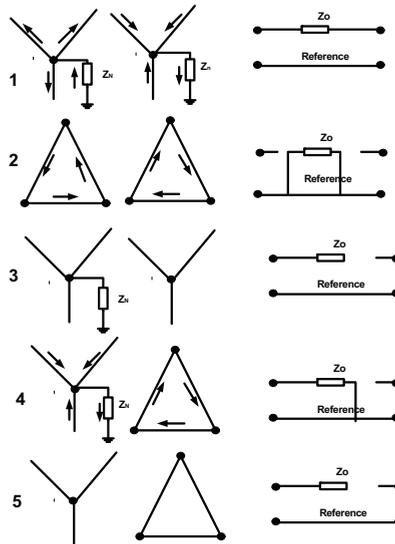
Fig. 8. Zero sequence representation of transformer connections (Grainger, 1994)

## 4.2 Simulation procedure

The simulation procedure for implementing network reinforcement using the graph theory is described as follows:

i.    Prepare all the required system data for load flow, fault analysis and voltage sag calculation i.e.; lines and cables, buses, transformers, loads and generators.

ii.   Define the permitted increase percentage of system losses (INd) and the maximum permitted improvement in the number of healthy buses ($N_{hlth}$).

iii.  Run load flow analysis program to identify the steady state voltage profile and system losses before reconfiguration.

iv.   Simulate faults at all buses in the system except system substations to determine the weak area in terms of voltage sag. The fault locations are considered as the main sources of voltage sag propagation and the number of healthy buses due to fault at the weak bus must be calculated by (10) and (11).

v.    Apply the graph theory algorithm to change the network configuration and to find a path in the network with suitable line impedance between the weak area and the main power source by (8) and (9).

vi.   Evaluate the new configuration by running load flow analysis to check the limitations of system buses voltage magnitudes (0.9pu ≤ V ≤ 1.06pu) and lines Currents (I ≤ Imax) as well as the checking of the increase in system losses (INc ≤ INd).

vii.  Check the improvement in voltage magnitude of all buses and calculate the number of healthy buses ($N_{hlth}$) by (10) and (11).

viii. Repeat steps v to vii until the number of healthy buses is improved significantly during the fault at weak bus.

ix.   Repeat step iv after network reconfiguration to confirm that there is no weak area.

The proposed network reconfiguration method for mitigating voltage sag by improving the number of healthy buses during fault events can be shown in terms of a flowchart as in Fig. 9.
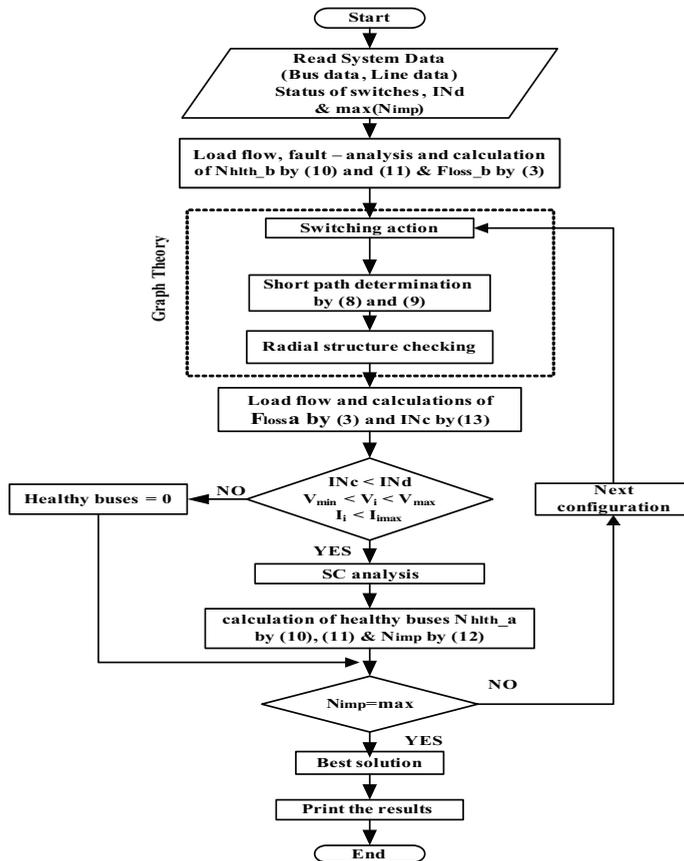
Fig. 9. Proposed distribution system reinforcement using network reconfiguration

## 5. Results and analysis

A practical distribution system shown in Fig. 10 is selected to validate the proposed method. The system is composed of 47 buses and 42 lines supplied by a 132KV sub transmission system through four substations which are connected to buses 2, 17, 34 and 39. The substations 2 and 17 are fed by 132/11KV, 30MVA, while the substations 34 and 39 are fed by 132/33KV, 45MVA and bus 1 is the swing bus. The seven tie switches (SWs) between buses 25-38, 29-38, 24-29, 20-23, 16-18, 4-19 and 4-14 may be used as alternatives to change the configuration of the system in case of some events or contingencies.

The selected system represents multi voltage levels of 132KV, 33KV, 11KV, 6.6KV, 3.3KV and 0.433KV, where the voltage levels are fed through 15 transformers of difference sizes. The system includes three large induction motors of 2000 KW which are connected to buses of numbers 9 (3.3KV), 10 (0.433KV) and 21 (3.3KV). Capacitor banks of 2 MVAR are also used in the system and are connected to buses 42 (33KV) and 38 (11KV). Two mini hydro power plants of capacities 2000 KVA, 6.6KV and 3000 KVA, 3.3KV are connected to the buses 32 and 8, respectively. These power plants are used as distributed generation units to

control voltage magnitudes of the buses to which they are connected. The system can be represented in terms of a graph by using the graph theory algorithm. Fig. 11 shows the 47-bus distribution system represented in the graphical form, where the shortest path of the fault current between the main source and fault location is shown.
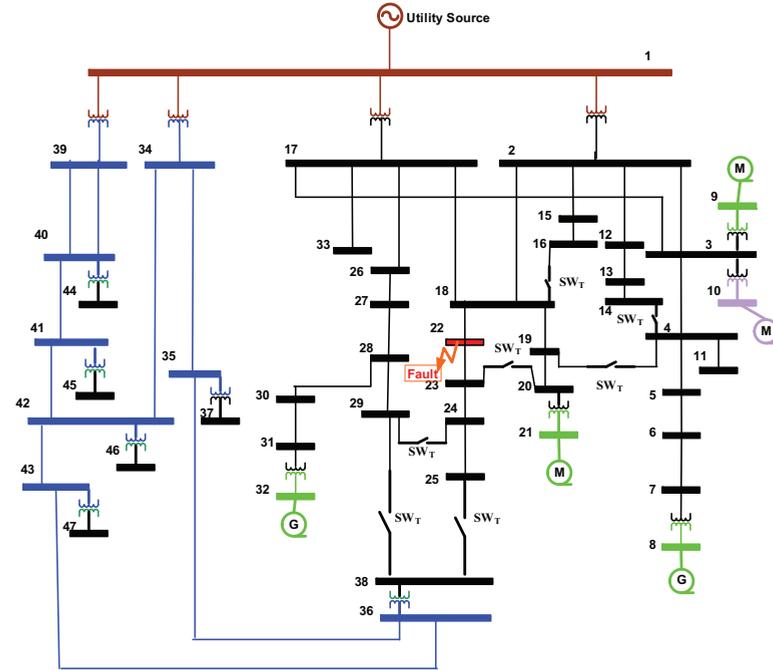


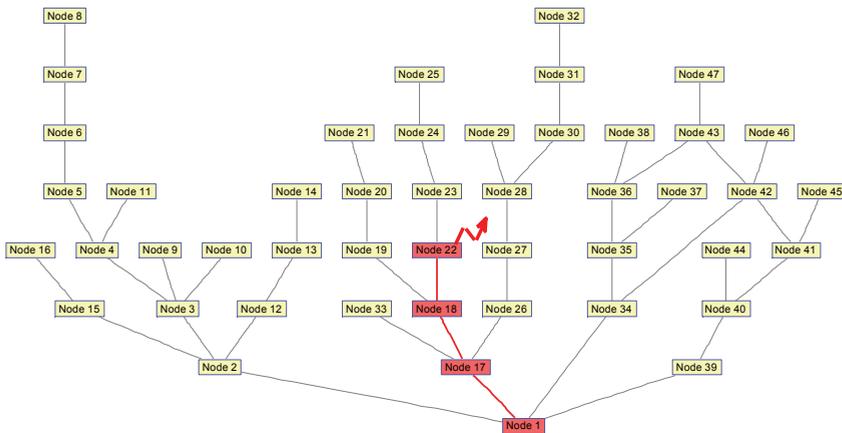Fig. 10. A practical 47-bus test distribution system



Fig. 11. Graph presentation of the practical 47-bus test distribution system

## 5.1 Determination of weak area

Fault analysis simulations were done for all the buses of voltage level of 11kV and below except the main substations and the buses that are supplied through more than one feeder. The buses 1, 2, 3, 17, 18, 33, 34, 35, 36, 39, 40, 41, 42, and 43 are excluded from simulation, where bus 1 is the main source, buses 2 and 17 are the main substations, buses 3 and 18 are supplied by two feeders, bus 33 is a service bus for local loads and the buses 34, 35, 36, 39, 40, 41, 42 and 43 are at 33KV voltage level. The voltage sag distribution on all system buses for three phase fault and fault resistance ($Z_f$=0) is shown in Fig. 12.
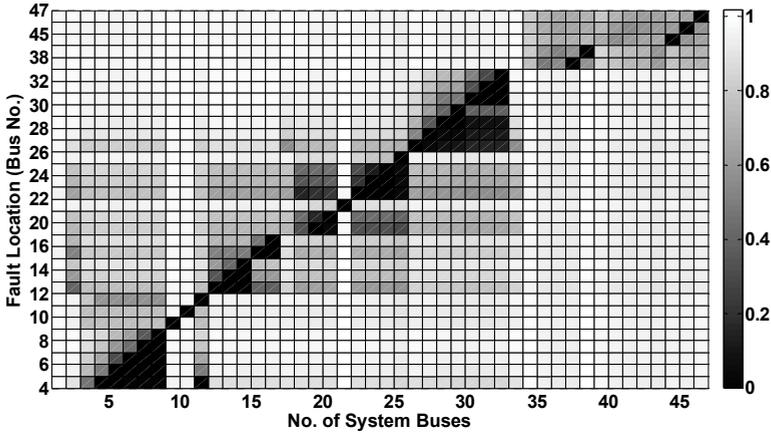


Fig. 12. Voltage sag distribution on system buses due to three phase fault
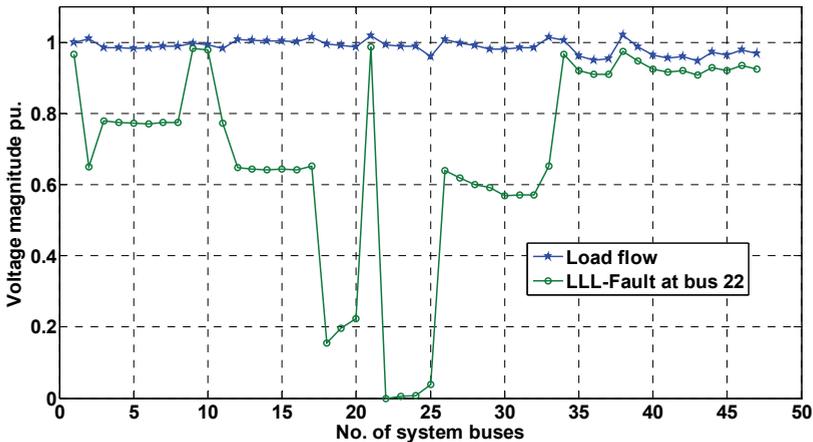


Fig. 13. Voltage magnitudes of system buses after steady state load flow and during three phase fault at bus 22

From Fig. 12, it is obvious from the dark points of voltage sag distribution (Z-axis) that buses 19, 20, 22, 23 and 24 are the most sensitive in propagating voltage sags throughout the system. This group of buses is considered as weak area in the system. In the same manner

bus 22 is considered as the weakest bus in this group and in the system. It is considered as the most sensitive bus in propagating voltage sags, where most system buses are affected due to the fault event at this bus. The voltage distribution due to three phase fault at bus 22 is shown in Fig. 13 along with base case voltage profile of the system. From this figure it is clear that all bus voltage magnitudes are within standard limits during steady state but causes voltage sag at most buses due to a three phase fault at bus 22.

Fig. 14 shows the voltage distribution with varying degree of darkness of phase A at all the system buses due to single line to ground fault at various fault locations. The same fault locations are again noted as the most sensitive buses in propagating sags throughout the whole system. Bus 22 is considered as the weakest bus in the system. The determination of the weak bus is a significant step in voltage sag assessment and mitigation.

Fig. 15 shows the effect of single line to ground fault at bus 22 on voltage distribution of all system buses. It is noted that most of the buses also experience voltage swell at the other two phases.
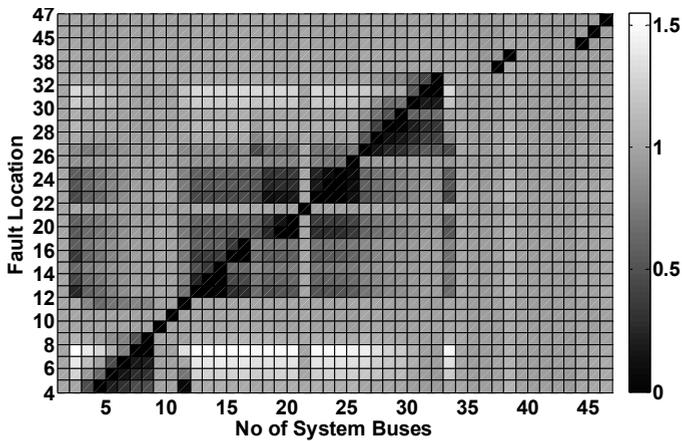


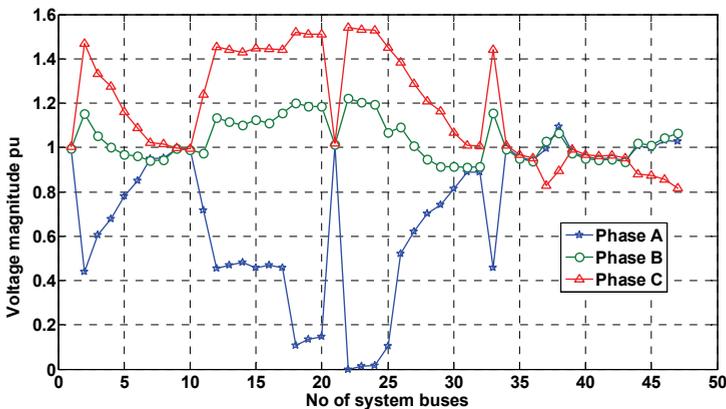Fig. 14. Voltage sag distribution of phase A on system buses due to single line to ground fault



Fig. 15. Voltage magnitudes of system buses during single line to ground fault at bus 22

## 5.2 Network reconfiguration and reinforcement

Based on the results of the weak area determination (bus 22), network reconfiguration is carried out by performing switching actions. The graph theory algorithm is applied to find a new path of the fault current in terms of the electrical distance between the main power supply and the fault location. Network configuration is carried out according to the proposed algorithm shown in Fig. 9, where the permitted increase of system losses (INd) is defined by a large value (20%) and the maximum improvement of healthy buses ($N_{imp}$) is also defined by a big value (100%). The one line diagram of the practical system after reconfiguration is shown in Fig. 16, where the change in switches status can be observed. Fig. 17 shows the graphical presentation of the studied system after reconfiguration.
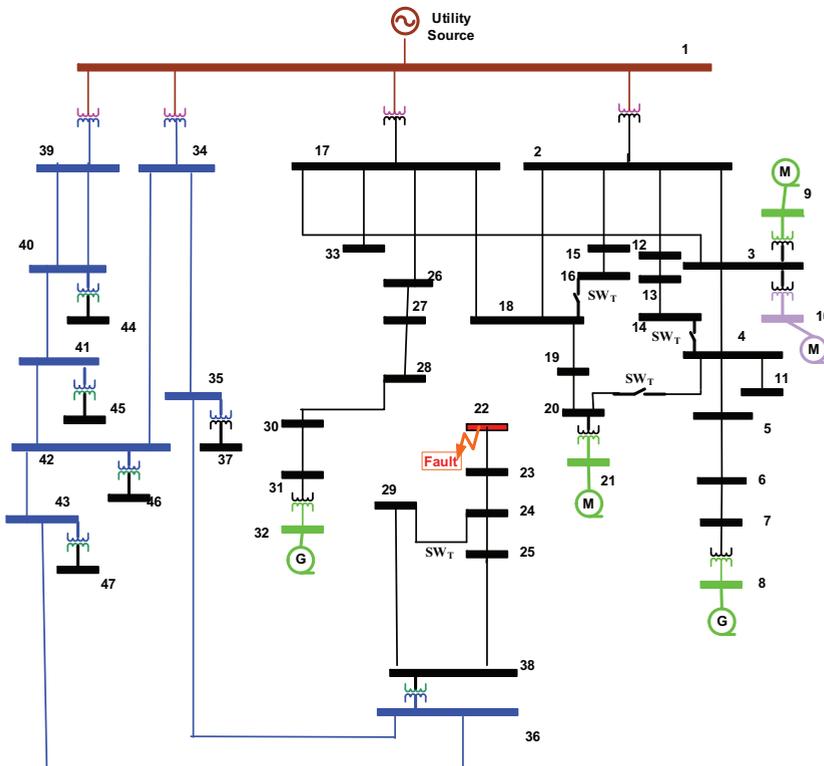


Fig. 16. One line diagram of the practical 47-bus system after reconfiguration

In comparison with Fig. 11, there is a significant increase in the electrical distance of the path of fault current between the main source and the fault location (bus 22). Table 1 shows the system status before and after reconfiguration where the group of open switches is changed and the number of healthy buses is improved in which the bus number is 36 out of 47 compared with the number 18 out of 47 before reconfiguration. It means that the percentage improvement in the number of healthy buses ($N_{imp}$) is increased up to 100%. The exposed voltage sag area due to a fault event at bus 22 is reduced from 61.7% to 23.4%. But the

improvement of voltage sag performance is accompanied by an increase in system losses, where the percentage increase in system losses becomes 18.24%.
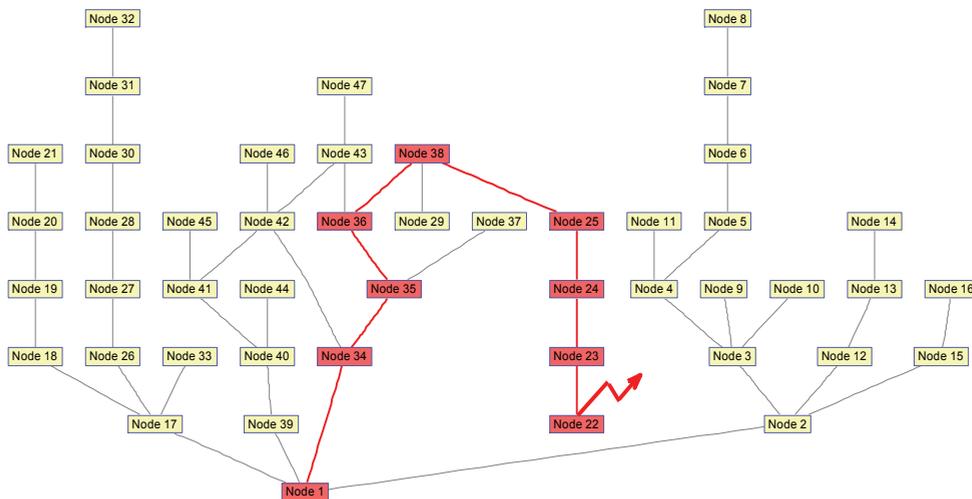


Fig. 17. Graph presentation of the studied practical system after reconfiguration

| System status | Open Switches | No. of Healthy Buses | Sag Exposed Area % | System Losses MW |
|---|---|---|---|---|
| Before Reconfiguration | 19-4, 14-4, 16-18, 20-23, 24-29, 25-38, 29 -38 | 18 | 61.7 | 2.119 |
| After Reconfiguration | 2-18, 17-3, 19-4, 14-4, 16-18, 20-23, 24-29, 18-22, 28 -29 | 36 | 23.4 | 2.505 |
| The Results | | Improvement $N_{imp}$=100% | Reduction 38.3 | INc=18.24 |

Table. 1. System status before and after network reconfiguration

Fig. 18 shows the voltage distribution on all system buses with varying degree of darkness due to three phase fault at various fault locations, after reconfiguration. In comparison with Fig. 12, there is a significant improvement in voltage sag performance for most number of system buses considering all fault locations and  network reconfiguration.
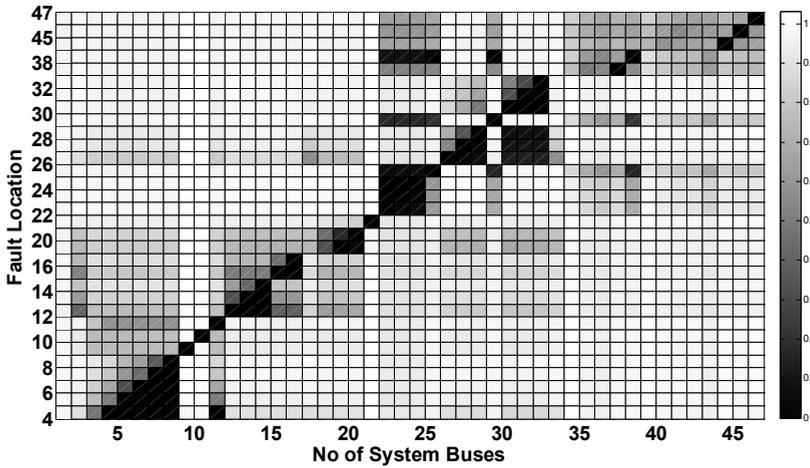
Fig. 18. Voltage sag distribution on system buses due to three phase fault

Simulation results of short circuit analysis after reconfiguration due to a fault at bus 22 is shown in Fig. 19 along with the steady state voltage profile. An improvement in voltage magnitudes at most number of system buses can be observed after reconfiguration as compared with the results of Fig. 13. The improvement in voltage sag performance after reconfiguration can also be observed in case of unbalanced faults. Fault analysis results of the studied system due to single line to ground fault at bus number 22 (weak bus) is shown in Fig. 20. The results of Fig. 20 can be compared with the results of Fig. 15 to prove the effect of network reconfiguration on voltage profile improvement.
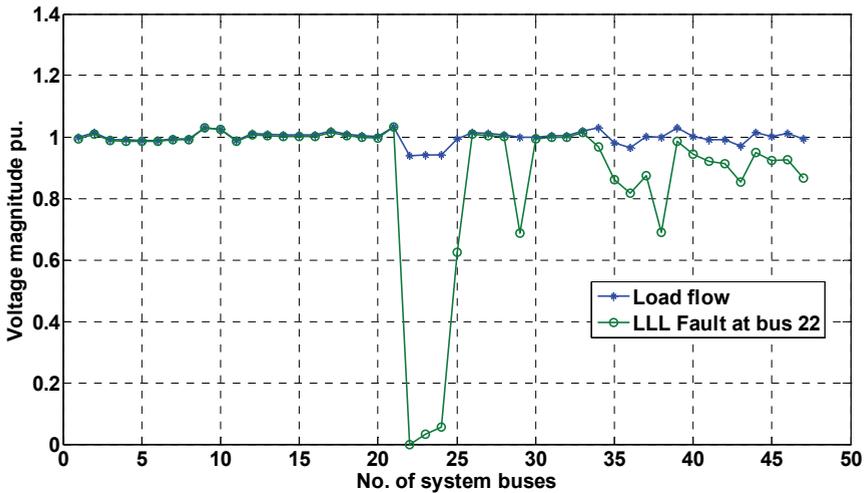


Fig. 19. Voltage magnitudes of system buses at steady state load flow and during three phase fault at bus 22 after reconfiguration
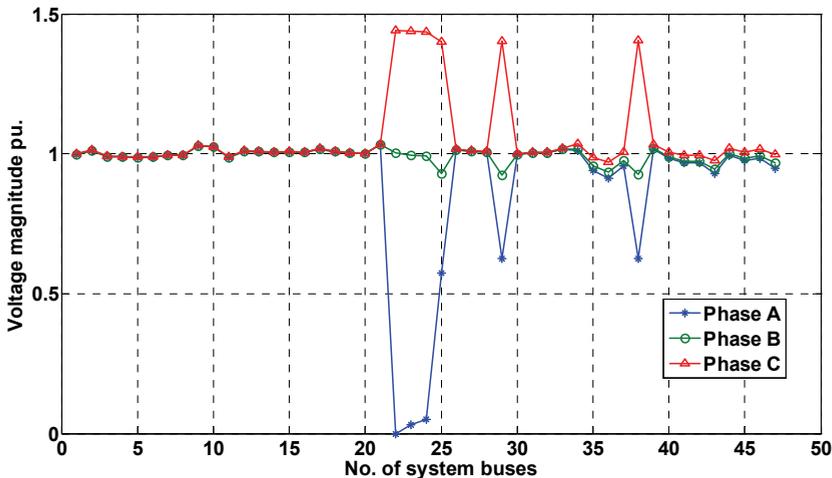
Fig. 20. Voltage magnitudes of system buses during single line to ground fault at bus 22 after reconfiguration

## 6. Conclusions

The simulation results prove that the proposed network reconfiguration method based on the graph theory algorithm is efficient and feasible for improving the bus voltage profile. The weak area is first determined before performing the appropriate switching action in network reconfiguration. The network reconfiguration solution is achieved by placing the weak area or the voltage sag sources as far as possible away from the main power supply. This method is also efficient for network reinforcement against voltage sag propagation. By applying the proposed method, voltage sag at some buses can be completely mitigated while other buses are partially mitigated. However, the voltage sag problem at the partially mitigated buses can be solved by placing other voltage sag mitigation devices. Although the reconfiguration process involves just a change is switching status, it solves majority of the voltage sag problems.    The proposed method may assist the efforts of utility engineers in taking the right decision for network reconfiguration. The right decision can be taken after evaluating the benefits from line loss reduction and    financial loss reduction due to implementation of network reconfiguration.

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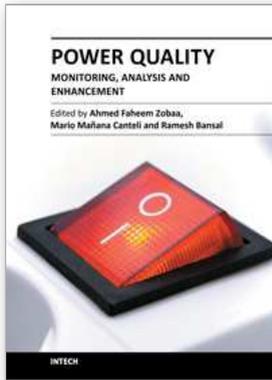
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