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Network reconfiguration for enhancement of voltage stability in distribution networks

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Abstract

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Keywords

enhancement, voltage, network, stability, reconfiguration, distribution, networks

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Network reconfiguration for enhancement of voltage stability in distribution networks

M.A.Kashem, V.Ganapathy and G.B.Jasmon

Abstract: Network reconfiguration is performed by altering the topological structure of distribution feeders. By reconfiguring the network, voltage stability can be maximised for a particular set of loads in distribution systems. A new algorithm is formulated for enhancement of voltage stability by network reconfiguration. Initially, a certain number of switching combinations is generated using the combination of tie and its two neighbouring switches, and the best combination of switches for maximising the voltage stability in the network among them is determined. Then the search is extended by considering the branches next to the open-branches of the best configuration one by one to check whether there is any other switching combination available which gives further improvement in voltage stability. The enhancement of voltage stability can be achieved by the proposed method without any additional cost involved for installation of capacitors, tap-changing transformers and the related switching equipment in the distribution systems. The method has been tested on a 69-bus test system, and the results indicate that it is able to determine the appropriate switching options of the optimal (or near optimal) configuration for voltage stability enhancement with less computation. It has also been shown that power losses are reduced when voltage stability is improved by network reconfiguration.

1 Introduction

Recently, there has been a growing interest in optimising the operation of distribution networks particularly in the area of distribution system automation. Distribution systems are normally configured radially. From time to time, modifying the radial structure of the feeders by changing the on/off status of the sectionalising and tie switches to transfer loads from one feeder to another may significantly improve the operating conditions of the overall system. As the distribution systems normally have a combination of industrial, commercial, residential and lighting loads and the peak load on the substation transformers and feeders occur at different times of the day, the systems become heavily loaded at certain times of the day and lightly loaded at other times. If the distribution loads are rescheduled more efficiently by network reconfiguration, the voltage stability in the system can be improved. Reconfiguration also allows smoothening out the peak demands, improving the voltage profile in the feeders and increasing the network reliability.

The voltage stability phenomenon has been well recognised in distribution systems. Several analytical techniques have been proposed to assess the risk of voltage instability. Voltage stability is important for power system operation and planning because voltage instability may lead to voltage collapse and hence outage and monetary losses, and possibly total system black out [1, 2]. Furthermore, a stable system contributes to reliability and reduction in system

losses [3]. Voltage instability occurs when a power system is subjected to heavy loading of transmission lines and insufficient local reactive power supply [4, 5]. The authors in [6, 7] have studied the line voltage stability in a radial network using the universal radial voltage stability limit curves. The system instability and radial voltage instability problems can be solved by appropriate load shedding [7, 8]. Sterling *et al.* [9] have studied the voltage collapse at a load bus using Thevenin equivalent circuit. A voltage stability index for a stressed power system has been derived by Jasmon and Lee [10] from a reduced system model, and this index could identify how far a system is from its point of collapse. Using this index, one can measure the level of stability and thereby appropriate action may be taken if the index indicates a poor level of stability. A relationship between voltage stability and power losses has been proposed in [11] to show that voltage stability is improved when power losses are reduced.

In this paper, a new scheme for the automation of distribution networks for voltage stability enhancement by network reconfiguration is proposed. The best configuration for maximum improvement in voltage stability in the system is obtained by considering all possible branches which are candidates for branch exchanges. The enhancement of voltage stability is obtained by the proposed method by reconfiguring the network structure without any additional capacitor installation, tap-changing transformer and related switching equipment.

2 Mathematical formulation of voltage stability measurement

The real distribution network consisting of many lines can be reduced to a system with only one line [10]. By applying the single-line method for the reduction of distribution network, the occurrence of voltage collapse can be studied

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easily, and it is not necessary to consider every line of the network separately. For a reduced single-line network, the voltage stability index has been derived in [10] and is reproduced as,

$$L = 4 \left[(x_{eq}P_{leq} - r_{eq}Q_{leq})^2 + x_{eq}Q_{leq} + r_{eq}P_{leq} \right] \quad (1)$$

where, P_{leq} and Q_{leq} are the total real and reactive loads respectively.

The equivalent resistance and reactance of a reduced single line network have been defined in [12] and rewritten here.

$$r_{eq} = \sum P_{loss} / \left\{ (P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2 \right\} \quad (2)$$

$$x_{eq} = \sum Q_{loss} / \left\{ (P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2 \right\} \quad (3)$$

It is noted that for a stable system, the value of stability index, L is very much less than 1.0. However if the value of L approaches 1.0, this would indicate that the system is close to voltage collapse. If the network is loaded beyond this critical limit, the power becomes imaginary and it is at this point that the voltage collapse occurs.

3 Enhancement of voltage stability by network reconfiguration

In a radial distribution system, network reconfiguration is performed by closing/opening the tie and sectionalising switches. However, it may lead to infeasible configuration by forming a closed loop or leaving out one or more branches unconnected. This can be avoided by checking the connectivity from the source to all the nodes during the network reconfiguration.

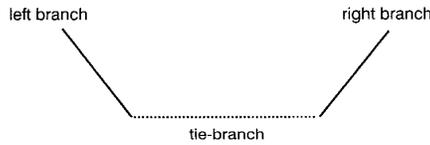


Fig. 1 Three branches forming a switch group

3.1 Determination of switching combinations

Fig. 1 shows a tie branch with its two neighbouring branches forming a switch group. The number of switch groups will be equal to the number of tie branches in the system. When a sectionalising switch is opened for reconfiguration, it will play the role of a tie switch in the next stage where this open branch and its adjoining branches again form a switch group. The above recursive procedure is terminated when a node with three or more branches is encountered, since the other branches will be considered in the formation of the switch groups of the respective feeders. This constraint is imposed to avoid the combinatorially explosive nature of the problem which results in NP completeness [13].

The switching options in a switch group can form three combinations with one of them only open for each combination. The three combinations can be named as zero-connect (0), left-connect (1) and right-connect (2), where, zero-, left- and right-connect represent the configuration at which the middle, right and left branches are open respectively. 0, 1 and 2 are used to represent connectivity of the switches during formulation of the switching combinations.

Let us consider all the switch groups in a system. If there are n tie switches in the system, there will be n switch groups forming 3^n different switching combinations. Each switch position in a switching combination is found out by using the formula,

$$SW_i = [P_{i1}, \dots, P_{i2}, P_{i1}] \quad (4)$$

and the switch positions of the j th switch in i th combination, P_{ij} can be obtained as,

$$P_{ij} = \left[(i-1)/3^{(j-1)} \right] \text{ mod } 3 \quad (5)$$

where, i is the combination number (one of 3^n), j is the switch number (one of n), and SW_i is the positions of the various switches in the i th switching combination.

The status of each switch in a switch group is realised for each switching combination. For zero-connect, the configuration will remain unchanged, but for left-connect or right-connect, the configuration will change according to the left or right-connect logic. Left and right-connect logic are developed using the power flow in the adjoining branches of the tie branch in the system. When a system is reconfigured by closing the tie branch and opening either of the adjoining branches, the power flow in the open-branch which was flowing before reconfiguration, shifts to the newly connected tie branch. If the left-connect is performed, then the power flow of the right branch of the tie branch will be shifted to the tie branch. Similarly, when the right-connect is performed, the power flow of the left branch of the tie branch will be shifted to the tie branch.

3.2 Permissible switching combinations

A distribution system after reconfiguration, may become infeasible because there can be some loads which may be isolated from the source of power and some closed loop may be formed. The infeasible switching combinations are determined based on maintaining radiality and avoiding isolated lines. This can also be extended to include operationally imposed switching constraints such as plant/cable ratings, temporary embargoes, etc. These infeasible combinations must be removed from the total switching combinations to obtain the permissible switching combinations. The infeasible combinations are evaluated by checking the connectivity of each branch in the network using the connectivity logic explained below:

- (i) Check the existence of physical connections of a node or branch from the source. If it is feasible, assign the connectivity to be active.
- (ii) Repeat the above step for all nodes in the network.
- (iii) Repeat steps (i) and (ii) for all the switching combinations obtained using eqn. 4.

The above steps can be represented by the following recursive procedure:

$$\begin{aligned} & i \leftarrow 1 \\ & CC(i) \\ & \{ \quad con[i] \leftarrow 1; \\ & \quad TC[i] : CC(for[i]); \quad \} \\ & \text{If } P_{ij} > 0 \text{ then } for[i] = j; rev[j] = i; \\ & \text{If } P_{ij} < 0 \text{ then } for[j] = i; rev[i] = j; \end{aligned}$$

where, $CC()$ is the connectivity check function, $con[i]$ is the connectivity of node i , $TC[i]$ is the total numbers of connection for i th node, P_{ij} is the power flow from sending node i to the receiving node j , and for and rev are the forward and reverse nodes respectively.

To find all the connections of the node i , the following procedure is used:

If $for[i] = x$ and $rev[j] = y$

then $con[i] = x$ and y ; or x and i ; or i and y .

The connectivity check for the whole system is done as follows:

$$con[i] = 1; P_i \vee Q_i \neq NULL$$

$$Infeasible | con[i] = 0; i = 1, \dots, n$$

Check whether the connectivity flags of all the nodes of that particular configuration are active; otherwise declare the combination as infeasible.

$$\forall_i con[i] \neq 0, Feasible$$

3.3 Evaluation of voltage stability in a radial distribution network

In general, the load flow techniques take a large number of iterations and huge computational time. The proposed method uses the Simplified Distflow [12] for power flow solutions. In the Simplified Distflow, power flows are calculated in one cycle of iteration. Therefore, it is suitable for online implementation as it reduces computational time. The power flow and stability index calculations are done by using the following *volt_index logic* in the proposed method which is developed based on the Simplified Distflow equations.

volt_index logic:

Step 1: Identify the end nodes by checking the total number of connections of each node. Read one end-node and assign it as the current node.

Step 2: Consider the reverse connection of the current node as the connectivity node. Store the current node in a list named *checked*.

Step 3: If the number of connections to the connecting node is greater than or equal to 3, go to Step 4. Otherwise, identify the connectivity-node of the connecting node which is not in the *checked* list and obtain the power flow and voltage magnitude using the following equations and then go to Step 2.

$$P_i[rev(cnode), cnode] \leftarrow P_i[cnode, for(cnode)] + P_L[cnode] \quad (6a)$$

$$Q_i[rev(cnode), cnode] \leftarrow Q_i[cnode, for(cnode)] + Q_L[cnode] \quad (6b)$$

$$V_i^2[rev(cnode)] \leftarrow V_i^2[cnode] - 2.0 \\ \times \left\{ r_i[rev(cnode), cnode] \times P_i[rev(cnode), cnode] \right. \\ \left. + x_i[rev(cnode), cnode] \times Q_i[rev(cnode), cnode] \right\} \quad (6c)$$

where, *cnode* is the current node and, P_i , Q_i and V_i are the real power, reactive power and voltage at the sending end respectively.

Step 4: Update a list named *list_up* with all the connections of the current node and store the node name in a list called *current*.

Step 5: Check whether the nodes in the *list_up* are in the *checked* list. If so, count the number of nodes matched, and subtract it from the number of nodes in the *list_up*. If it is not equal to 1, go to Step 2 using the next end node as the current node. Otherwise, calculate the power flow and voltage magnitude using the following formulas and then go to Step 2.

$$P_i[rev(cnode), cnode] \leftarrow \sum_{x=1}^{Tfc} P_i[cnode, con((cu)(x))] + P_L[cnode] \quad (7a)$$

$$Q_i[rev(cnode), cnode] \leftarrow \sum_{x=1}^{Tfc} Q_i[cnode, con((cu)(x))] + Q_L[cnode] \quad (7b)$$

$$V_i^2[rev(cnode)] \leftarrow V_i^2[cnode] - 2.0 \\ \times \left\{ r_i[rev(cnode), cnode] \times P_i[rev(cnode), cnode] \right. \\ \left. + x_i[rev(cnode), cnode] \times Q_i[rev(cnode), cnode] \right\} \quad (7c)$$

where, *con*, *cur* and *Tfc* are the connectivity, current node and total number of forward connections of the current node respectively.

Step 6: Calculate the stability index value for the current configuration using eqn. 1.

3.4 Automating the search process for voltage stability enhancement

For the process of automation of the search, a method has been developed to identify the best combination among all the permissible switching combinations. This solution may not be the optimal or near optimal since the search has been restricted to only a limited number of combinations. In the next stage of automation, the search is extended to find the global optimum for voltage stability enhancement by moving to the left or right of each of the open or tie branches, depending upon whether the right or left adjoining branch of the tie branch is open. This is done by considering the open sectionalising or tie branches as the tie branches for the next operation of the reconfiguration. From the switching status of each switch group obtained in the best combination, the connectivity of the switch group is examined for the identification of zero-, left-, or right-connect. The switch group remains unaltered for zero-connect. The connection is moved towards right (if it is left-connect) or left (if it is right-connect), by opening the next neighbouring branch of the left or right of the current tie branch respectively, and closing the current tie branch to form a new switch group. The stability value for the newly formed combination is compared with that of the best combination found earlier, and if it is less, the current combination is considered as the best combination and the search is further carried out in the same direction; otherwise the best combination remains the same. The other switch groups are also examined in succession by applying the above procedure and the overall best combination and its corresponding configuration is obtained for the maximum improvement of voltage stability.

4 Test results and discussions

The test system is a 69-bus hypothetical 12.66kV radial distribution system with 7 laterals which has been taken from a portion of the PG&E distribution system [14]. The system consists of 5 tie lines, and there are sectionalising switches on every branch of the system. The schematic diagram of the test system is shown in Fig. 2 and the data for the base configuration used are the same as in [11] or [14]. The total system loads for the base configuration are 3802.19kW and 2694.60kVAR.

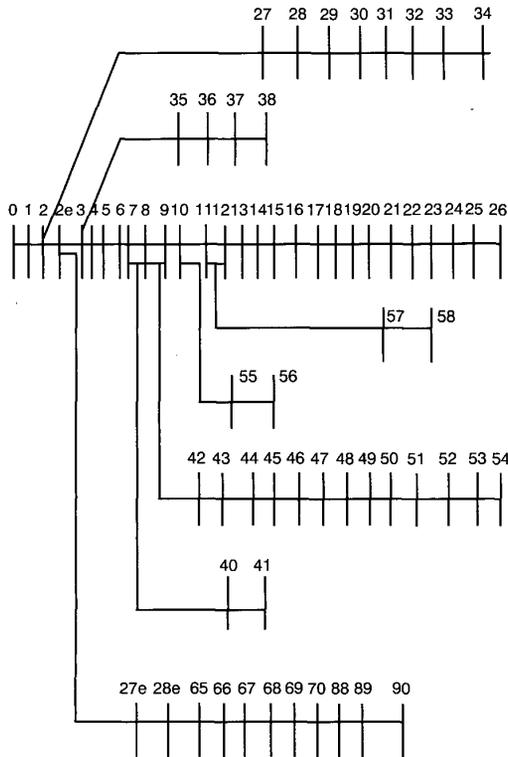


Fig.2 The schematic diagram of a 69-bus distribution system. Tie lines are connected from node 10-70, 12-20, 14-90, 38-48 and 26-54

Table 1: Generation of switching combinations

Number	1	2	3	..	3 ⁿ
Switch status	00000	00001	00002	..	22222

The software developed for the proposed automated scheme has been implemented using Borland C++. The program reads the data pertaining to the base configuration of the system and then generates 3ⁿ switching combinations as shown in Table 1, where *n* is the number of tie branches. The permissible switching combinations are identified by the connectivity logic. From the simulations of the test system, it is found that there are 54 infeasible and 189 feasible combinations among the total combinations of 243. Among the permissible combination the best combination for voltage stability has been obtained for the test system. Investigation is extended to check whether any other combination gives further improvement in voltage stability. The search has been carried out by moving towards left or right of each open branch of the best configuration as the case may be. The configuration, which gives the minimum value of the stability index, is declared as the best solution for the enhancement of voltage stability.

The proposed method has found the best switching-options that give the optimal or near optimal solution for voltage stability improvement in the above test system and the results are given in Table 2 and Fig. 3. Test results show that the proposed algorithm can give the appropriate switching options for voltage stability enhancement within a reasonable computer time and effort for network of any size and complexity. At every search level of the proposed algorithm, the power losses have also been investigated and it is found that when voltage stability is improved power losses in the system are reduced. Table 2 shows the real

power loss at every search level carried out to find the voltage stability enhancement by the proposed method. It is observed that most of the bus voltages have been improved after network reconfiguration for voltage stability. The test results show that before reconfiguration, the minimum bus voltage was 0.9092p.u. at the end of line 65, and after reconfiguration it has increased to 0.9428p.u. at the end of line 61.

Table 2: Test results obtained by the proposed method

Search level	Branch exchange (in-out)	Stability index value, L	Power loss (kW)
0	Base config.	0.1894	225.05
1	73-59	0.1552	134.07
2	72-13	0.1481	122.99
3	74-62	0.1204	99.86
4	13-15	0.1200	99.66
5	*None	—	—
Selection of final branch exchange		73-59, 72-15, 74-62	

* No branch exchange is considered due to the increase of stability index value

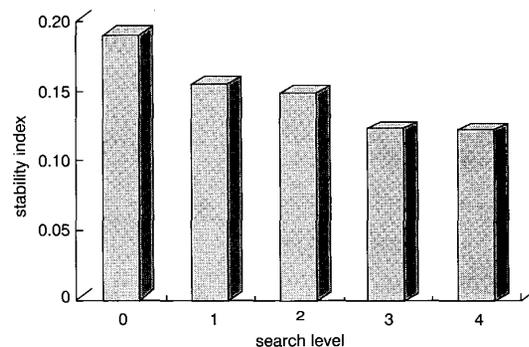


Fig.3 Voltage stability improvement

In our attempt to develop a scheme for the automation of distribution network for voltage stability enhancement by network reconfiguration, we have made use of the already established Simplified Distflow [12] and voltage stability index measurement [10] techniques. The proposed method is flexible to incorporate other load flow and stability index measurement techniques also.

In any distribution system, variations in load profile need to be covered with automated switching patterns to improve voltage stability to a maximum. The proposed algorithm is most suited to be used with SCADA (Supervisory Control and Data Acquisition Systems) and DAC (Distribution Automation and Control) as the algorithm requires only the inputs to be supplied and any other subsequent manipulations such as partitioning, forming loops or subsystems etc., are not necessary. Whatever may be the combination of consumer types (industrial, commercial, domestic, etc.), the proposed method will offer reliable solutions for the voltage stability problems by properly reconfiguring the distribution systems.

5 Conclusion

A new approach for enhancement of voltage stability by network reconfiguration is presented in this paper. The method proposed has introduced a consolidated algorithm using logical concepts which involves determination of

permissible switching combinations from the possible combinations, realisation of the status of the individual switches, and identification of the optimal or near optimal solution. In the first stage of the proposed method a limited number of switching combinations has been generated using the combination of each of the tie branch and two of its immediate neighbouring branches in the network. This is because, in most cases, the solution rests around the exchange of one of the immediate neighbouring branches and the tie branches. However, to explore the possibility for the best solution existing beyond this limited number of combinations, an extensive search has been made by moving to the left or right of every tie branch until a node having more than two feeders/laterals is encountered. To prove the utility of the proposed scheme for its efficiency and the reduction of computational complexity, a complex system with 69-bus and 7 laterals has been considered as the test system. From the test results it is found that the most effective switching-options for maximum improvement of voltage stability can be achieved by the proposed method. Also, it is observed that the power losses are minimised when voltage stability is maximised in the network. The proposed method can be applied for efficient operation for online systems, since any change in loads does not need any change to be made in the algorithm and the optimum or near optimum switching configuration can be easily found without much effort. The problem of noncoincidence of peak loads and diversity of load categories are not a matter of concern in the proposed system. The scheme proposed would be much beneficial if real-time control is resorted to. The additional switching operation would be justified by the benefits of voltage stability enhancement. The method can also be used for planning and design of power systems before constructing the actual distribution networks for locating the tie switches and providing minimum number of sectionalising switches in the branches to reduce installation and switching costs.

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