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Effect of network reconfiguration on power quality of distribution system

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ABSTRACT

Effect of network reconfiguration on power quality issues of distribution system has been investigated. The problem of network reconfiguration is reformulated with an objective to improve the power quality of the distribution system. Along with the traditional objective of loss minimization, power quality related objectives such as minimization of harmonic distortion of the voltage waveform, minimization of voltage unbalances at the nodes and maximization of sag voltages are identified as the objectives of reconfiguration. Branch exchange technique has been used to establish each of the objectives. The problem has also been formulated as a multi-objective optimization problem. The multiple objectives are, however, incorporated into a single objective using weighting multipliers and branch exchange technique has been judicially applied to take care of all the objectives. It is found that network reconfiguration can be used as an effective tool to improve the power quality of distribution system. Besides, the distributed energy sources also have great impacts on distribution network, as their size and locations are found to have great importance on the power loss, voltage sag, voltage harmonic distortion and unbalance. The effectiveness of the network reconfiguration on power quality issues have been studied on 25-bus network and IEEE 33-bus network with and without presence of distributed generation and VAr sources.

Introduction

Reconfiguration of distribution network has long been identified as a very useful method for the improved performance of the system. Merlin and Back [1] were the first to propose the network reconfiguration technique for loss minimization of the system. Later on many researches have been reported in the literature with the objective of loss minimization [2–9], load balancing [10–12], service restoration [8,12], voltage profile improvement [9,13,14,33]. Initial attempts were restricted to the balanced radial networks [2,7]. More recently, attempts have been reported to apply the technique on unbalanced networks as well [15–17].

Placement of shunt capacitors is an established technique for voltage and reactive power control in distribution system and researches on the placement and sizing of shunt capacitors have been reported extensively in the recent past [15–21], other form of 'VAr' compensators, like STATCOM are also being used [22].

Installation of small capacity Generating sources, popularly known as the Distributed Generation (DG) sources, in the low voltage distribution network is being encouraged during the recent years for several reasons [24–27]. Network reconfiguration problem has been solved in association with the solution of the capacitor placement problem [15,21,22].

Reconfiguration technique has also been applied on distribution system having DG penetration [24,27]. Some of the publications have formulated and solved the complexity of the DG and capacitor placement problem along with network reconfiguration [9].

In recent years power quality issues have received considerable attention from the researchers and system engineers. Of the various power quality problems, voltage sag and harmonics issues are treated with intense attention because of the increased use of sensitive loads [18,30] in the distribution system.

In this context the impact of network reconfiguration on voltage sag, harmonics and unbalance in distribution system has been investigated in this paper. Several researches have also been reported to have considered the network reconfiguration problem along with the power quality improvement problem. In [23,34] reconfiguration problem has been solved to minimize power loss and voltage sag problem. In [14], loss minimization, reliability and voltage sag enhancement are incorporated in the reconfiguration

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problem. In [22], and all the power quality issues are included in the formulation of the network reconfiguration problem along with the minimization of power loss. In the present paper a new formulation of the problem has been presented. Branch exchange technique [2,29] has been applied to determine the optimum reconfiguration strategy so as to minimize the effects of various power quality issues along with the networks losses. Simulation results performed on a 25-bus network has been presented to justify the proposed concept.

The problem of network reconfiguration

Distribution network is radially configured for operational advantages [2,7,19,31,33]. However, in medium voltage networks tie/sectionalizing switches are provided such that network configuration may be altered to satisfy some operational requirements. The change of the configuration alters the power flow path in the network resulting in altered line currents, node voltages, and degree of unbalances and also level of distortion of the node voltages in presence of harmonics. Since the impedance of the power flow path also changes due to reconfiguration, the voltage available at a node during a voltage sag condition is also liable to be changed. As voltage sag may involve tripping of the sensitive loads, it is apparent that having an improved sag voltage has the potential to reduce the loss of the system under a voltage sag condition. Moreover, change in the effective impedance of the power flow path and the mutually induced voltage due to changes in the line current distribution will result in the change of the harmonic content of the node voltages. Thus, a better and more desirable reconfiguration scheme would take care of all these issues to maximize the benefit of network reconfiguration in distribution system.

Thus, the objectives of network reconfiguration may be formulated as:

Minimize Power loss in the network.
Maximize Sag voltage in the network during fault or switching.
Minimize Harmonic distortion of the node voltages.
Minimize System unbalances.

The above stated objectives may be expressed as:

(i) *Minimization of power loss*

$$\mathit{Minimize},\ P_{loss} = Re\left(\sum_{m=1}^{l}\left(\sum_{j=a}^{c}(V_j(p) - V_j(k))I^*(m)\right)\right) \tag{1}$$

where
l = number of lines,
$V_j(p)$ = voltage at pth node of jth phase,
$V_j(k)$ = voltage at kth node of jth phase,
$I^*(m)$ = current conjugate of mth line between pth node and kth node,
$j = a, b, c$ phases.

(ii) *Maximization of Voltage sag*: Sag voltage is measured as the remaining voltage of a bus during a voltage sag condition. For the present work, we have attempted to maximize the average sag voltage of the network which is represented as

$$V_{sag,av} = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{1}{n}\sum_{i=1}^{n}V_i^j\right) \tag{2}$$

V_i^j = voltage magnitude in p.u. at ith node for a fault at node j,
$i = 1, 2, 3, \ldots, n$, n = number of busses,
$j = 1, 2, 3, \ldots, m$, m = number of fault events considered, and
$V_{sag,av}$ = average node voltage under voltage sag condition.

(iii) *Minimization of Harmonic distortion:* It is measured in terms of the total harmonic distortion of the node voltage (V_{THD}) measured as

$$\%V_{THD,i} = \frac{V_{di}}{V_{rms,i}} \times 100 \tag{3}$$

where

$V_{rms,i} = \sqrt{(V_{1,i}^2 + V_{d,i}^2)}$
$V_{d,i}$ = distortion component of the node voltage
$V_{d,i} = \sqrt{\sum_{h=2}^{m} V_{h,i}^2}$

For the minimization of the voltage harmonic distortion, the maximum value among all the node voltage THD's are minimized. Mathematically, the problem is written as:

$$\mathit{Minimize\ Max}(V_{THD,i}), \quad i = 1, 2, 3, \ldots, n \tag{4}$$

(iv) *Minimization of System unbalance:* It is basically due to unbalanced loading of the system. In this paper system unbalance is measured in terms of the average value of the node voltage unbalances $V_{unb,av}$ [37] and the problem is represented as

$$\mathit{Minimize},\ V_{unb,av} = \frac{1}{n}\sum_{i}^{n}\left(\sum_{j=a}^{c}\left(100\frac{|V_{Neg,i}|}{|V_{Pos,i}|}\right)\right) \tag{5}$$

where

$V_{Pos,i} = \frac{1}{3}(V_i^a + \alpha_1 V_i^b + \alpha_2 V_i^c)$
$V_{Neg,i} = \frac{1}{3}(V_i^a + \alpha_2 V_i^b + \alpha_1 V_i^c)$
$\alpha_1 = complex(-0.5, 0.866)$,
$\alpha_2 = complex(-0.5, -0.866)$,
$V_{Pos,i}$ = positive sequence voltage at ith node,
$V_{Neg,i}$ = the negative sequence voltage at ith node,
V_i^j = voltage at ith node of jth phase.

The above mentioned objectives are to be established subject to the satisfaction of the following constraints:

Equality constraint: Power balance at the nodes

$$P_i + jQ_i = V_{ai}I_{ai}^* + V_{bi}I_{bi}^* + V_{ci}I_{ci}^*, \quad i = 1, 2, 3, \ldots, n \tag{6}$$

Inequality constraints are:

Node voltage limits: $V^{\min} \leqslant V_{pi} \leqslant V^{\max}$, $p = a, b, c$, $i = 1, 2, 3, \ldots, n$.
Line 'p' capacity limits: $I_{pl} \leqslant I_{pl}^{\max}$, $p = a, b, c$, $l = 1, 2, 3, \ldots, L$.

Node voltage unbalance limit:

$$\frac{|V_{Neg,i}|}{|V_{Pos,i}|} \leqslant V_{unb}^{\max}, \quad i = 1, 2, 3 \ldots, n.$$

Voltage distortion limit : $V_{THD,i} \leqslant V_{THD}^{\max}$
Limit on voltage sag : $V_{sag,av} \geqslant V_{sag}^{\min}$

where $V_{sag}^{\min}$ is the specified minimum voltage under voltage sag condition.

In addition to the above, network configuration in distribution system is restricted to be radial.

This may be represented as:

$$n_b = n - 1 \tag{7}$$

where n_b = number of active branches i.e., Total number of branches–total number of tie branches. Also, no node would remain islanded. This is represented as:

$$\sum_{j=1}^{L} |A(i,j)| \geqslant 1, \; i = 1 - n, \tag{8}$$

where A is the node-element incidence matrix of the network.

In the present work the above mentioned problem is solved by forming a single objective function as the weighted representation of all the objectives as:

$$\text{Minimize}\, f_{\cos t} = k_1 P_{loss} + k_2 V_{sag,av} + k_3 V_{THD} + k_4 V_{unb} \tag{9}$$

where

$k_1 = 1,$

$k_2 = 0, \text{ for } V_{sag,av} \geqslant V_{sag}^{critical},$

k_2 is set at a high value for $V_{sag,av} < V_{sag}^{critical},$

$k_3 = 0, \text{ for } V_{THD} \leqslant V_{THD}^{\max},$

k_3 is set at a high value for $V_{THD} > V_{THD}^{\max},$

$k_4 = 0, \text{ for } V_{unb,av} \leqslant V_{unb}^{\text{limit}},$

k_4 is set at a high value for $V_{unb,av} > V_{unb}^{\text{limit}}.$

Solution of the problem

Solutions of the above problems require the solutions of the power flow problem, harmonic flow problem and the voltage sag analysis problem. An optimization technique is necessary to search for the optimum network configuration, while the performance of the generated configuration is determined by the above mentioned analyses. For the purpose of generation of the new configurations and the determination of the optimum solution, the branch exchange technique is applied [2]. The branch exchanges, however, are decided based upon the newly proposed indices depending upon the objectives to be optimized. The analysis techniques are discussed very briefly in the following.

Load flow analysis at fundamental frequency

Forward and backward sweep based load flow is used for three phase power flow analysis. Each line section is represented as 3 × 3 matrices of the self and mutual impedances. Distributed generations are represented as negative P, Q loads.

Power flow analysis is performed by using repeated application of backward and forward sweep steps [2,28], for the calculation of the branch currents and node voltages respectively until the convergence is reached.

The steps followed are:

i. Assume three phase node voltages equal to the source (substation) node voltages.
ii. Determine the load/DG currents at the three phases.
iii. Set the branch current of the load/DG connected branch = load/DG current.
iv. Perform backward sweep step: Starting from the end nodes of the network and moving towards the source nodes update the upstream branch current as,

Upstream branch current = $\sum$ Downstream branch current originated at the terminating node of the upstream branch.

Repeat step 'iv', until all upstream branch currents are updated.

v. Perform forward sweep step: Starting from the source node move towards the end node to compute the end node voltage as,

$$V_{down}^{a,b,c} = V_{up}^{a,b,c} - Z_{up.down}^{a,b,c} I_{up.down}^{a,b,c} \tag{10}$$

where

$V_{down}^{a,b,c}$ is the three phase voltage at the load side node referred to as the down node in Fig. 1.

$V_{up}^{a,b,c}$ the three phase voltage at the source end of the line joining up and down nodes, $Z_{up.down}^{a,b,c}$ the 3 × 3 branch impedance matrix for the branch between the up and the down nodes.

$I_{up.down}^{a,b,c}$ is the current through the line joining the 'up' and 'down' nodes.

Repeat step 'v', until all node voltages are updated.

vi. Repeat from step 'iv', until convergence is achieved.

Convergence of the load flow problem generates the fundamental frequency voltage at the nodes.

Harmonic flow problem

Harmonic flow problem is solved using the Direct Harmonic Analysis (DHA) [13], by solving the equation

$$I_h = Y_h V_h \tag{11}$$

where

h is the set of significant harmonic orders.

I_h is the vector of injected harmonic currents at the nodes.

Y_h is the bus admittance matrix with harmonics.

V_h is the vector of harmonic node voltages.

Harmonic generating loads are represented by their Norton's equivalents. Generators, transformers, lines and linear loads are represented by their relevant admittances determined at harmonic frequencies. Motor loads are represented by their harmonic admittances relevant to the corresponding sequence components.

Eq. (11) is solved separately for each of the significant harmonic frequencies.

The distortion in node voltage is then determined as

$$V_{di} = \sqrt{\sum_{h=1}^{m} |V_{h,i}|^2} \tag{12}$$

$V_{h,i}$ is the hth harmonic component of the voltage at node i.

m = Maximum harmonic order considered in the node voltage.

$V_{THD,i}$ (Total voltage harmonic distortion of node i) is computed from (3).

Voltage sag analysis

Voltage sag analysis is performed by performing fault analysis of the network.

Fault current, for a fault at bus p is determined as [32]

$$I_{p(Fault)}^{a,b,c} = Y_F^{a,b,c} \left(U + Z_{pp}^{a,b,c} Y_F^{a,b,c}\right)^{-1} E_{p(0)}^{a,b,c} \tag{13}$$

Voltage drop at the system busses are then determined as

$$V_{Bus(F)}^{a,b,c} = Z_{Bus}^{a,b,c} I_{Bus(F)}^{a,b,c} \tag{14}$$

where $I_{p(Fault)}$ is the pth component of the bus injected current vector $I_{Bus(F)}$.

$E_{p(0)}^{a,b,c}$ is the pre-fault voltage at bus p.

$Z_{Bus}^{a,b,c}$ is the three phase bus impedance matrix of the network.

$Z_{pp}^{a,b,c}$ is the self-impedance of bus p.

$Y_F^{a,b,c}$ is the admittance matrix with fault.

$V_{Bus(F)}^{a,b,c}$ represents the drop in bus voltage of all the three phases of the network.

"U" is the unity matrix.

The sag voltage is the remaining voltage at a bus during the voltage sag condition.

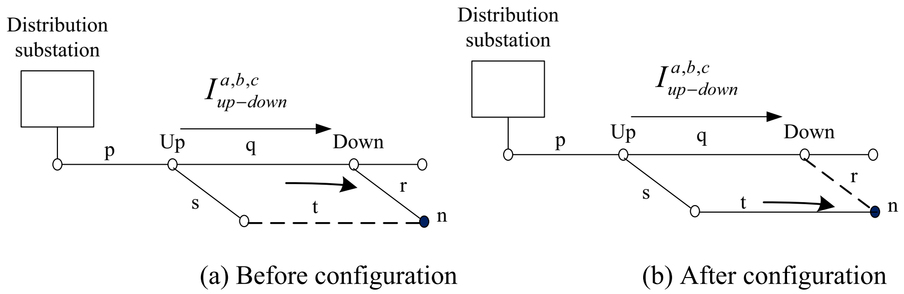

Fig. 1. Power flow paths in a radial distribution network before and after reconfiguration.

For the present study voltage sag is considered due to faults only. The remaining voltage at the busses are calculated as

$$V^{a,b,c}_{sag} = E^{a,b,c}_{Bus(o)} - V^{a,b,c}_{Bus(F)} \tag{15}$$

where $E^{a,b,c}_{Bus(o)}$ represents the three phase bus voltages before the fault and is obtained from the load flow analysis at the fundamental frequency of the system.

The above mentioned procedure is used for voltage sag analysis while performing the network reconfiguration.

Branch exchange technique

Distribution networks generally have radial configurations. Reconfigurable distribution networks, however, have tie branches which are normally kept unenergized. These tie branches may be included into the network by closing the tie switches at the ends of the branches. In branch exchange technique, one such tie branch is included into the network and another branch, which was normally closed, is opened to restore the radial configuration. The process may be explained considering the network in Fig. 1(a), where branch *'t'* is the normally open tie branch.

A load connected at node 'n' is fed through branches *p–q–r*. The power flow path to the node *'n'* may be changed by closing the line 't' and opening line *'r'* thus, changing power flow path as *p–s–t* to the node *'n'*. The resulting network configuration is shown in Fig. 1(b). The greatest advantage of branch exchange technique is that, radial configuration is automatically maintained and no computation and search procedure is needed for this purpose.

Branch exchanges for loss minimization

The minimum-power loss configuration is obtained by following the method proposed in [29], where an optimum flow pattern is established through a number of branch exchange operations. A normally open tie switch is closed to form a loop. Optimum flow pattern is identified in the loop by solving the KCL and KVL equations of the loop, where the KVL is written as the summation of the resistive voltage drops in the loop to be equal to zero. Such a power flow pattern in the loop corresponds to the minimum loss power flow. To restore the radial configuration, the branch having the minimum current is opened. The process is repeated for all the tie lines, one after another, so long as a branch exchange operation results in a reduction of the loss.

Branch exchanges for minimization of harmonic distortion

For the minimization of the total harmonic distortion, we identify the node where the maximum voltage THD. Tie line to be closed is selected such that the node having the maximum voltage harmonic distortion is included in the loop. The modified voltage and harmonic distortion of the nodes of the loop and the current through the branches of the loop are determined. For the restoration of the radial configuration the branch in the loop having minimum flow is selected. This process is repeated so long as such branch exchanges result in the reduction of the harmonic distortions.

Branch exchanges for minimization of voltage unbalances

For the minimization of voltage unbalances we start with an initial radial configuration. Load flow of the network is performed and the voltage unbalances at the nodes are determined following Eq. (5).The node having the maximum voltage unbalance is identified and a tie branch is selected such that closing the tie switch a loop can be formed including the identified node. The modified voltages of the nodes included in the loop are calculated and the flows through the loop branches are determined. Line having the minimum flow is then selected to be opened such that in the restored radial configuration node voltages are minimally disturbed. The calculation of the modified voltage and line flows of the branches of the loop are done following the methods in [2]. The above procedure reduces voltage unbalance as due to formation of the loop, the flow of currents are redistributed. Because of the availability of the alternative paths, maximum branch flows are reduced, resulting in the reduction of the branch voltage drops. This helps in improving the node voltages and the unbalances. When the branch having the minimum flow is opened, the flow pattern of the loop is least disturbed and resulting radial network gets modified to an improved one.

Branch exchanges for compounded problem

The compounded formulation of the reconfiguration problem attempts to satisfy all the objectives simultaneously, thus minimization of any single objective is avoided. However, priority is assigned to the objectives depending upon their importance and their values in the prevailing configuration of the network. Since power loss is a major issue, as loss involves continuous wastage of money, it is given the highest priority. The effort therefore is to attempt for the reduction of the system losses if there is no violation of the indices related to power quality. In case of violation of the power quality indices, attempt is made for the reduction of the most severe one of the violations. Starting from a radial configuration, load flow, harmonic flows are solved and the system losses, harmonic distortion and voltage unbalances are determined. Voltage sag analysis is then performed. The power quality indices are then evaluated and compared with their limiting values. In case of any violation, the most severe one is identified and tie branch is such selected that a loop can be formed to include the problematic node in the loop following the method as discussed in the earlier sections. The modified quantities of the loop formed are determined and a branch is selected to open following the method discussed in the earlier sections.

If, however, no limit violation is observed loss minimization is attempted following the method discussed in section 'Branch exchanges for loss minimization'. The detailed procedure is shown in the form of a flowchart in Fig. 2.

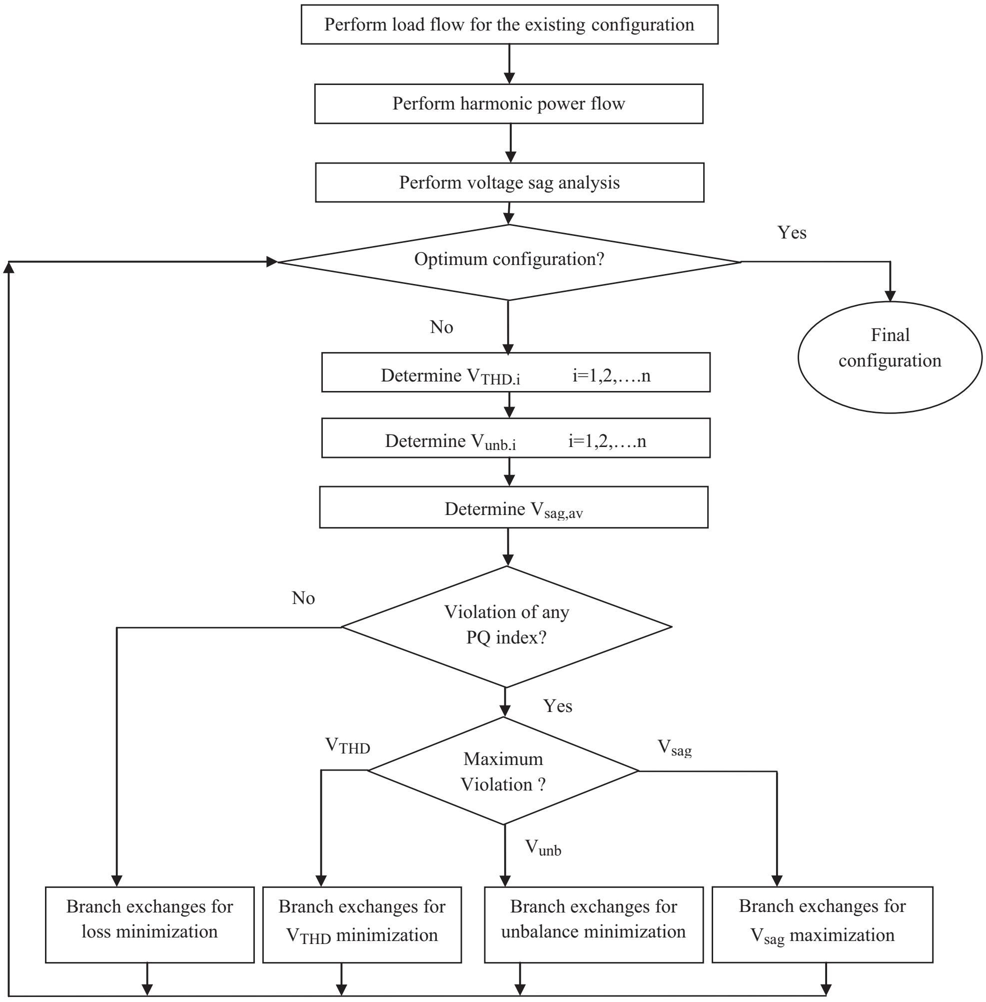

Fig. 2. Flowchart for the solution of the multi-objective reconfiguration problem.

Simulation results

The effect of network reconfiguration on the Power quality of distribution network has been studied on several unbalanced radial distribution systems in *MATLAB R2013b* environment. However, detailed studies are reported on a 25-bus network [16,27,35] first. The25-bus unbalanced radial distribution network is shown in Fig. 3. To have an extensive study, a number of variations of the basic networks in the form of added distributed generating sources and shunt capacitive compensators are also considered. The details of these additional components were already discussed in [27,35,36] and also given in Tables A.I–A.III. Various modifications of the base network are.

i. The base case network with no DG or Capacitors.
ii. Network with four shunt capacitors of 600 kVAr, 150 kVAr, 300 kVAr, 450 kVAr capacities installed at nodes 9, 12, 14 and 15 respectively [36].
iii. Network with a single DG source of 215 kW, 0.85PF lagging per phase capacity located at node 13 [35].
iv. Network with three DG sources of 100 kW, 0.9 PFlagging, 100 kW, unityPF, 100 kW, 0.9 PF lagging capacities located at nodes 12, 15, and 22 respectively [27]. Network with a single DG source as mentioned in (iii) and four shunt capacitors as mentioned in (ii).
v. Network with 3 DG sources as mentioned in (iv) and four shunt capacitors as mentioned in (ii).

Case-1: Reconfiguration of the basic network without any DG or compensation source

The results obtained for the base network without any DG or compensating capacitors are reported in Table 1 after satisfying the four objectives mentioned in section ‘Solution of the problem’.

The optimum solutions were reached after only a few branch exchanges for each of the individual objectives. It may be noted here that, though the feasible configuration are 242 for the 25-bus network, the optimum solutions were reached after 22 exchanges.

From the above results it may be said that branch exchange technique, when applied judiciously, can obtain the optimum solution of the network reconfiguration problem for power quality enhancement in a reasonable number of iterations.

In order to have a better visualization of the impact of network reconfiguration, power losses and power quality measures in terms of harmonic distortion of the node voltages, average node voltage unbalance and average voltage sag are plotted in Fig. 4 for all the 242 feasible configurations of the system.

The plotted variation of the harmonic power loss, node voltage THDs, average voltage sag and average node voltage unbalances highlight the fact that even though the magnitude and location of the loads are kept fixed, variations in the network configurations cause variation in the harmonic currents generation and their distribution in the network which results in the variation in the distortion of the node voltages and line power losses. Similar

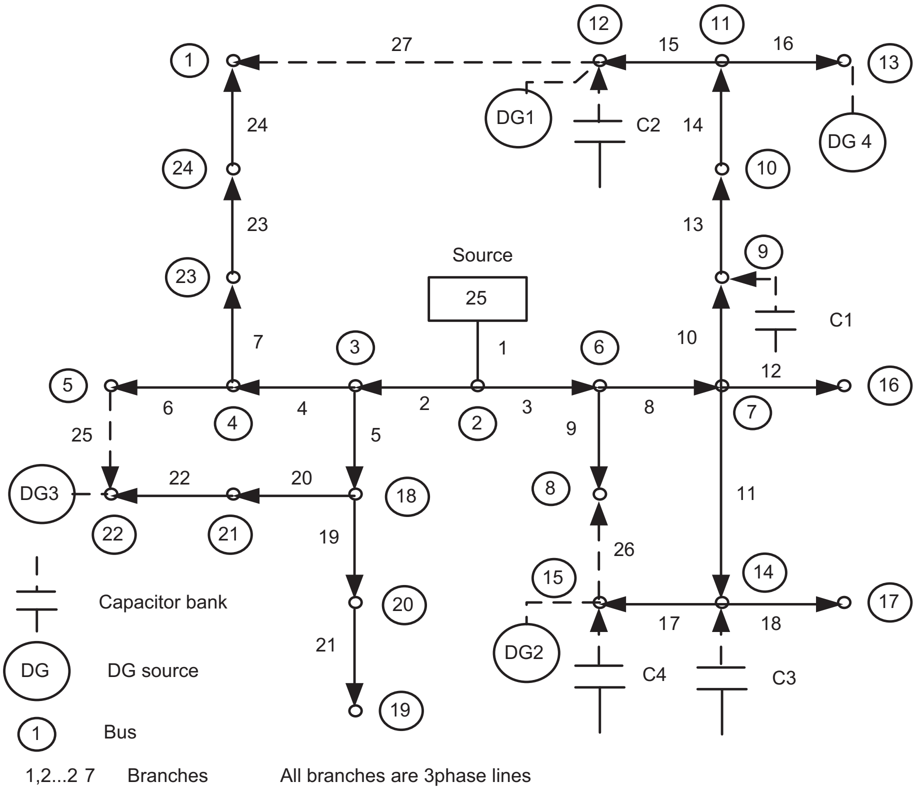

Fig. 3. A 25-bus unbalanced radial distribution network with DGs and Capacitors.

Table 1
Optimum configurations without any distributed energy and VAr sources for base 25-bus unbalanced radial distribution system.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	150.129	181.782	4.8375	0.4302	0.8067
Min. P_{loss}	15, 17, 22	133.498	162.064	4.3351	0.4199	0.813
Min. V_{THD}	11, 15, 22	138.128	167.590	4.3126	0.4198	0.8147
Max. V_{sag}	11, 15, 22	138.128	167.590	4.3126	0.4283	0.8147
Min. V_{unb}	6, 15, 17	137.835	167.145	4.3279	0.4168	0.8141

observation may also be made in respect of the average voltage sag and unbalance in the node voltages.

A comparative study of the results for the three objectives with those of the loss minimization are shown in Table 1. The significant observations that can be made from the study of Table 1 are:

i. As expected, minimum power loss, when the reconfiguration is performed with the objective of minimizing the power loss. However, attempts to minimize voltage THD, maximization of system voltage sag and minimization of voltage unbalance also have positive impacts on the system losses. The effect however, is the maximum when unbalance voltage is attempted to be minimized, followed by the minimization of voltage THD and maximization of voltage sag.
ii. As expected, maximum reduction in voltage THD, when the reconfiguration is performed for minimization of voltage THD. However, maximization of voltage sag and minimization of voltage unbalance also reduce THD effectively. Reduction in power loss has less impact on the voltage THD reduction.
iii. It is possible that reconfiguration is performed to have improved voltage sag. However, node voltage THD minimization and reduction of voltage unbalance help improving the voltage sag effectively. Even, the minimization of power loss helps improving the voltage sag.
iv. It is possible that reconfiguration is performed to have improved percentage unbalance voltage. The effect however is more when power loss is attempted to be minimized, followed by the minimization of voltage THD and maximization of voltage sag.

Case-2: Reconfiguration of network with DG and compensation source (Tables 2–6)

The impacts of the above objectives on the reconfigured network with DG and Capacitors have also been studied and the optimum configurations for various network conditions are obtained.

The following observations may be made.

Minimization of power loss

It may be observed that minimum power loss with one DG and four capacitors combination, three DGs and four capacitors combination has the second lowest loss.

This shows that proper size and location of DG is more important than the distribution of the DG sources in respect of loss reduction. It may be observed that effectiveness of the reconfiguration in reducing the loss in presence of DG and capacitors is less in comparison with no DG and no capacitor network .

Where P_{loss} is power loss, $P_{loss(H)}$ is power loss with harmonics, V_{THD} is voltage THD, V_{unb} is voltage unbalance, V_{sag} is voltage sag.

Minimization of waveform distortion

DGs are very effective not only for loss minimization, but for minimization of waveform distortion as well. A study on the

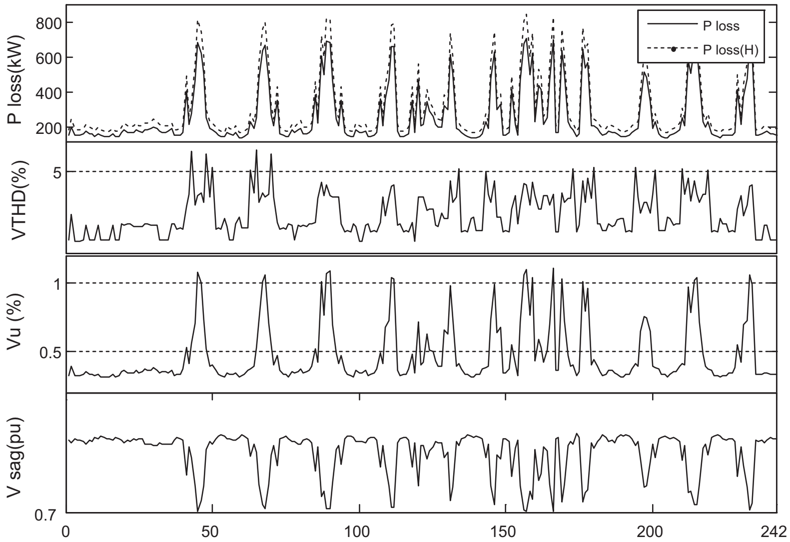

Fig. 4. Power losses and Power quality measures of various configurations of the 25-bus network without distributed energy and VAr sources (i) Power loss. (ii) Harmonic distortion voltage. (iii) Average node voltage unbalance. (iv) Average voltage sag.

Table 2
Optimum configurations for 25-bus unbalanced radial distribution system with distributed VAr sources.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	105.879	128.218	5.104	0.3617	0.8207
Min. P_{loss}	15, 17, 22	94.145	114.306	4.5246	0.3499	0.8253
Min. V_{THD}	11, 15, 22	97.036	117.756	4.4944	0.3494	0.8272
Max. V_{sag}	11, 15, 22	97.036	117.756	4.4944	0.3494	0.8272
Min. V_{unb}	6, 15, 17	98.513	199.431	4.5168	0.3476	0.8264

Table 3
Optimum configurations for 25-bus unbalanced radial distribution system with single distributed generator.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	91.202	110.660	2.7279	0.3367	0.8231
Min. P_{loss}	17, 22, 27	85.525	103.929	2.5371	0.3317	0.8257
Min. V_{THD}	17, 22, 27	85.525	103.929	2.5371	0.3317	0.8257
Max. V_{sag}	14, 17, 22	89.006	107.978	2.8064	0.3381	0.8296
Min. V_{unb}	6, 17, 27	90.108	109.315	2.8943	0.3294	0.8263

Table 4
Optimum configurations for 25-bus unbalanced radial distribution system with three distributed generators.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	124.686	151.060	1.6261	0.395	0.8248
Min. P_{loss}	15, 17, 22	114.321	138.745	2.7652	0.3876	0.8267
Min. V_{THD}	22, 26, 27	124.125	150.409	1.5832	0.4121	0.8236
Max. V_{sag}	14, 17, 22	114.403	138.952	2.0877	0.394	0.83
Min. V_{unb}	6, 15, 17	117.1	142.007	2.728	0.3853	0.8291

Table 5
Optimum configurations for 25-bus URDS with one distributed generator and four capacitors.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	69.900	84.653	2.7891	0.2824	0.8361
Min. P_{loss}	13, 17, 22	62.214	75.455	2.918	0.2761	0.8407
Min. V_{THD}	17, 22, 27	64.821	78.637	2.5973	0.2785	0.8379
Max. V_{sag}	10, 17, 22	65.676	79.493	2.9415	0.2889	0.8418
Min. V_{unb}	6, 17, 27	69.288	83.885	2.9565	0.2713	0.8386

Table 6
Optimum configurations for 25-bus URDS with three distributed generators and four capacitors.

Objective	Tie-lines	P_{loss} (kW)	$P_{loss(H)}$ (kW)	V_{THD} (%)	V_{unb} (%)	V_{sag} (pu)
Initial	25, 26, 27	85.016	103.012	1.6666	0.3271	0.8382
Min. P_{loss}	15, 17, 22	77.343	93.876	2.853	0.3171	0.8387
Min. V_{THD}	22, 26, 27	84.467	102.37	1.6454	0.3315	0.8369
Max. V_{sag}	11, 15, 22	79.322	96.238	2.8086	0.3263	0.8416
Min. V_{unb}	6, 15, 17	80.160	97.188	2.8148	00.3155	0.8411

presented results reveals that distributed DGs are more effective than single DG because of the increased number of parallel paths which reduces the system impedances and thus reduces the distortion in bus voltages. Capacitors aggravate the harmonic composition of the network.

With distributed DGs reconfiguration is less effective in respect of THD minimization. With three DGs, THD values are almost always less than the single DG network for all possible configurations. Thus, it may be inferred that, reconfiguration is less effective with distributed DG case.

Maximization of voltage sag

It is apparent that capacitors are more useful in improving the sag voltages than the DGs. Installations of DGs also help in the improvement of sag voltage, but capacitors are more effective. With distributed capacitors, reconfiguration is less effective as the elements that can retain voltage are already distributed.

It has been found that a good number of configurations have sag voltages close to the maximum values, which may easily be identified to be due to the presence of distributed compensating capacitors.

Minimization of voltage unbalances

For the reduction of the voltage unbalance, the combination of DG and capacitors has been found to be very effective. Suitable size and locations of the DG is found to be more important in this context in comparison to the distribution of the DG source. Again, voltage unbalance is quite low for a good number of reconfiguration. This again shows the impact of the suitability of the DG locations and the distribution of the capacitors.

Comparison with other methods

In [15] network reconfiguration problem has been solved for loss minimization, node voltage improvement, voltage unbalance reduction and minimization of total harmonic distortion of the node voltages. A fuzzy-Genetic algorithm (GA) approach has been used where the fitness function for optimization through GA has been formed using fuzzy membership functions for the cost, bus voltage, harmonic voltage distortion and voltage unbalance factor. Results are produced for the IEEE 33-bus test system with 5 tie switches.

The formulation in the present paper is very close to that in [15], with the only difference in the objective function is that, voltage sag maximization has been considered instead of node voltage improvement. The solution algorithm however is totally different from that in [15]. The network configuration obtained also is somewhat different from [15]. For the purpose of comparison, the results obtained are shown in Table 7. The network, load and harmonics data used for the study are as given in [15]. The three cases mentioned in the table are those defined in [15] and are mentioned as below.

Case 1 represents the network reconfiguration without any distributed energy and VAr sources.

Case 2 represents the network reconfiguration and capacitor placement to minimize cost.

Case 3 represents the network reconfiguration and capacitor placement simultaneously to improve system efficiency.

It may be observed that, the network configuration obtained by the proposed algorithm results in a lower power loss than that obtained by the method in [15]. Voltage sag, voltage distortion and voltage unbalances are all well within the permissible limits, though these values are somewhat on the superior side in the configuration of [15]. This is due to the fact that in the proposed branch exchange algorithm, the loss reduction objective is given much higher priority when the power quality factors are not violated.

Conclusion

The impact of the network reconfiguration on various power quality issues such as harmonic distortion, voltage sag and voltage unbalances of distribution network has been investigated. Network reconfiguration has been formulated incorporating power loss, harmonic distortion, voltage unbalance and voltage sag components in the objective function and solution algorithm has been suggested using branch exchange technique. It has been found that network reconfiguration may be employed for the improvement of power quality in addition to the reduction of power losses. Effect of the presence of DG and reactive power source on the impact of the network reconfiguration has also been studied. It appears that reconfiguration is less effective when Distributed sources are present. Conversely, it may also be stated that in order to have the maximum benefit from the DG and capacitor placement in distribution system, the problem may be formulated and solved as an integrated problem of DG placement, capacitor placement and network reconfiguration simultaneously, such that DG and capacitors are placed at the optimum locations in respect of variable configuration of the network. Network reconfiguration, problem of distribution automation thus can earn the maximum benefit both in terms of the number and locations of the switches to be placed and extract maximum benefit from the available DGs and capacitors.

Appendix A

See Tables A.I–A.III.

Table A.I
Location and size of dg on 25-bus URDS network [27,35].

Node	Capacity (kW, p.f)	Node	Capacity (kW, p.f)
12	100, 0.9 lag	15	100, UPF
13	645, 0.85 lag	22	100, 0.9 lag

Table 7
comparison of power quality issues in a 33-bus unbalanced radial distribution system.

Initial configuration: Tie lines 33, 34,35, 36, 37

Item	Method	Tie lines	ΔP_{loss} (kW)	$\Delta P_{loss(H)}$ (kW)	ΔV_{THD} (%)	ΔV_{unb} (%)	ΔV_{sag} (pu)
Case1	Method in Ref. [15]	7, 9, 14, 28, 36	61.1362	73.5157	0.044	0.0245	0.0496
	Proposed method	7, 9, 14, 32, 37	62.9609	75.7099	−0.6844	0.0496	0.0433
Case2	Method in Ref. [15]	7, 8, 14, 32, 37	32.3829	38.9402	−1.4074	0.0123	0.0332
	Proposed method	7, 8, 14, 36, 37	37.904	45.5792	0.0274	0.0349	0.0403
Case3	Method in Ref. [15]	6, 11, 28, 31, 34	46.167	55.5154	−0.4842	0.0351	0.0382
	Proposed method	6, 11, 28, 31, 34	62.7281	75.4299	−0.6927	0.0477	0.0465

Where ΔP_{loss} is reduction in power loss from initial configuration, $\Delta P_{loss(H)}$ is reduction in Harmonic power loss from initial configuration ΔV_{THD} is reduction in voltage THD from initial configuration, ΔV_{unb} is reduction in voltage unbalance from initial configuration, ΔV_{sag} is improvement in voltage sag from initial configuration.

Case1: Reconfiguration of simple network without any VAr. Case2: Reconfiguration of network with capacitor bank set1 for minimization of cost. Case3: Reconfigurations of network with capacitor bank set2 for improving system efficiency.

Table A.II
Location and size of capacitor on 25-bus URDS network [36].

Node	Capacity in kVAr	Node	Capacity in kVAr
9	600	14	300
12	150	15	450

Table A.III
Injected harmonic current order and magnitude of 25-bus URDS network.

Node	Harmonic current injection (%) 3rd, 5th, & 7th	Node	Harmonic current injection (%) 3rd, 5th, & 7th
5	4	16	4
6	4	18	4
10	4	19	4
13	4	21	4
14	4	23	4

Assumed phase angle is 0^0 for all harmonics.

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