ON-LINE NETWORK RECONFIGURATION FOR LOSS REDUCTION IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

G. CELLI, M. LODDO**, F. PILO**, A. ABUR***
****Department of Electrical and Electronic Engineering - University of Cagliari - Italy**
pilo@diee.unica.itT
***Department of Electrical Engineering - Texas A&M University - USA**
abur@ee.tamu.edu

ABSTRACT

This paper presents a network reconfiguration method for power flow optimization and, consequently, loss reduction in distribution networks with Distributed Generation (DG). The network reconfiguration problem is formulated and solved using a simple linear programming approach. Optimal configurations are determined by considering the effects of DG outputs, load variations, and various other contingences such as faults and maintenance outages. Demand Side Management actions have also been taken into account. Simulation results for test distribution network confirmed the effectiveness of the proposed method.

INTRODUCTION

Network reconfiguration is the procedure of varying the topological structures of distribution feeders by changing the open/closed states of the sectionalizing and tie switches. This important operating practice is typically used to reduce the system real power loss (loss reduction), to relieve network overloads (load balancing) and to improve system security. A distribution network is commonly characterised by a weakly meshed structure with a certain number of closed and normally open switches arranged in order to achieve a radial operation scheme. The number of switches is generally high; consequently, the number of possible switch combinations is really vast, making the feeder reconfiguration a complex and time-consuming process for system operators. With the advent of Distributed Generation (DG), the complexity of the network reconfiguration problem is increased since power distribution systems will no longer remain passive radial networks with unidirectional power flows, but they will support bi-directional power flows and will contain meshes. Furthermore, the recent development of the distribution system automation, that enables remote real-time control of sectionalizing and tie switches, provides utilities with the opportunity to reconfigure their networks in response to load variations for significant loss reduction and reliability improvement. All these considerations justify the need to develop effective solution algorithms for real-time network reconfiguration of large scale distribution systems.

The topic of the distribution network reconfiguration has been investigated by numerous researchers in the past, mostly for planning purposes [1-4]. The objective function assessment (loss reduction, load balancing and system reliability), normally requires several power flow calculations, with high computational burden for practical size distribution networks. In order to accelerate the optimization process and facilitate on-line network reconfiguration, simplified loss reduction and line flow formulae have been proposed in the literature [5,6]. In [6], the reconfiguration problem is formulated starting from the power balance equations at each node and neglecting network losses and voltage constraints. These assumptions allow solving the problem of the network reconfiguration for loss reduction by using a simple and fast linear programming approach, without losing the solution feasibility. Moreover, despite neglecting voltage constraints, the voltage profile is also improved as a result of the reduction in power flows through all network branches.

In the new liberalized electricity markets, one can envision an entity called the Distribution Network Operator (DNO), which is responsible for the connection of loads and generators to the distribution network in an optimal manner. This may be accomlished by simultaneously minimizing the operation costs derived from losses, overloads and penalties due to service interruptions or insufficient use of “green power”. Possible actions that can be taken by the DNO are building new lines, upgrading existing ones, network automation, partial control of loads (Demand Side Management – DSM) and generators, and, finally reconfiguration of the network [7].

In this paper, the simplified approach developed in [6] is extended in order to consider the presence of DG and potential DSM actions caused by excessive power demand. It is further assumed that the required automation devices for implementing on-line network reconfiguration are available. In the envisioned set up, the distribution network is considered to be actively managed by the DNO. Hence, the DNO can control, within prefixed limits, the power generated by some DG units and the demand of some loads, in order to reduce the power losses and avoid possible branch overloads. Consequently, the objective function is defined as the weighted sum of the absolute power flows through all the network branches, the power generation from each controllable DG unit and, if necessary, the load constrained by the DSM actions. The proposed algorithm can reconfigure meshed or radial networks. In this paper only radial schemes have been considered in accordance with the present situation. Simulations performed on a test system are presented in order to show the effectiveness of the proposed method. The effects of the DG energy cost variations, the load variations, and different contingences such as outages of lines or generators are also investigated.

PROBLEM FORMULATION

In [6] the network reconfiguration problem is formulated and solved using a simple linear programming approach starting from the power balance equations. The objective is to minimize the power flows in order to minimize the losses. A simplified linear transportation model is used, hence voltage constraints are not taken into account in that work. However, by penalising flows through higher resistance branches and encouraging flows through lower resistance branches, the algorithm permits obtaining the optimisation of power flows that results in the configuration with minimum losses. Despite this simplification, the different optimal power flow solutions (with or without losses) yield the same optimal network structure. Moreover, even though voltage constraints are ignored, the widespread power flow reduction through all network branches also improves the voltage profile.

The problem is formulated as follows: Let F_i be the power flow through the i^{th} branch, then the objective function $J(F)$ can be defined as the weighted sum of the absolute power flows through all the network branches, where the weights correspond to the resistances of the corresponding branches. Consequently, the network reconfiguration problem can be formulated as follows:

$$\min \ J = \sum_{i=1}^{N_L} r_i \cdot \left| F_i \right| \tag{1}$$

Subject to:

$$\left[A\right] \cdot \left[F\right] = \left[P\right] \tag{2}$$

$$\left[\left|F\right| + S\right] = \left[P^u\right] \tag{3}$$

where r_i is the resistance of the i^{th} branch (hence penalizing high flows through branches with higher resistance), N_L is the number of branches, $[A]$ is the node-to-branch reduced incidence matrix, $[P]$ is the vector of nodal injections, $[P^u]$ is the vector of branch power capacity limits, and $[S]$ is the vector of the slack variables, containing the residual branch power capacity ($S_i = P_i^u$ - $|F_i|$).

Let us introduce two variables such that $F_i = X_i – Y_i$, where both X_i and Y_i are non-negative variables which can not be nonzero simultaneously. Therefore the above optimization problem can be transformed into the following linear programming (LP) problem:

$$\min \ J = \sum_{i=1}^{N_L} r_i \cdot \left(X_i + Y_i \right) \tag{4}$$

Subject to:

$$\begin{bmatrix} A & -A & 0 \\ I & I & I \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ S \end{bmatrix} = \begin{bmatrix} P \\ P^u \end{bmatrix} \tag{5}$$

$$\left[X\right], \left[Y\right], \left[S\right] \geq 0 \tag{6}$$

were I is the identity matrix.

The main difficulty in this formulation is how to preserve the radial structure of the distribution system. However, this obstacle has been successfully surmounted in [6] with some adjustment to the Simplex method, that ensures a radial system reconfiguration within the flow capacity limits. In fact, if at least one of the line flows reaches its capability limits, the LP problem solution provides a system containing loops.

PROPOSED METHOD

In this paper, the previous problem formulation is extended to take into account the presence of DG and the use of possible DSM actions. Only the real power injections and the branch resistances are considered in the optimisation procedure.

By referring initially only to the presence of DG, it is assumed that the DNO, in order to reduce power losses, can dispatch the power of some generators from a minimum value, fixed by contract, to the maximum DG power output. In other words, the DNO allows the connection of controllable generators such as CHP, to the distribution network, provided that they make part of their power capacity available to the DNO for network operation.

Therefore, the objective function (4) is modified to include the cost of modulated DG power used to reduce network losses.

$$\begin{aligned} C_{DG} &= \sum_{j=1}^{N_{gen}} c_j^{DG} \cdot \Delta t \cdot \left(P_{gj} - P_{gj}^{\min} \right) = \\ &= \sum_{j=1}^{N_{gen}} \left(c_j^{DG} \cdot \Delta t \right) \cdot P_{gj} - \sum_{j=1}^{N_{gen}} c_j^{DG} \cdot \Delta t \cdot P_{gj}^{\min} \end{aligned} \tag{7}$$

where c_j^{DG} is the costs of 1 kWh purchased from the j^{th} DG unit, Δt is the interval between two successive real-time network reconfiguration calculations, N_{gen} is the number of the controllable generators connected to the distribution network, P_{gj} is the real power output of the j^{th} DG unit and P_{gj}^{min} is its minimum stipulated power output. Obviously, it is possible to consider also the presence of DG plants not controllable, like wind generators, by simply assuming a fixed power output value, that corresponds to the actual value measured on the network. In this case, this power is included in the nodal power balance equations (5).

The cost of eq. (7) has to be added to the cost of power losses. With this goal, it is not yet possible to use the approximation described in the previous section, because the two terms of the objective function must be homogeneous to be summed. Therefore, in order to better estimate the cost of losses and preserve the linearity of the objective function, an average value of the branch power flow has been calculated. Then, this value, F_{avg}, assumed equal for each network branch in order not to penalize specific paths in the optimisation process, is multiplied by the effective power flow derived from eq.(2), so that the power losses cost can be assessed as:

$$C_{loss} = \sum_{i=1}^{N_L} \left(\frac{c_l \cdot \Delta t \cdot r_i \cdot F_{avg}}{3 \cdot V_n^2} \right) \cdot \left| F_i \right| \tag{8}$$

where c_l is the unit cost of the energy lost, and V_n is the nominal voltage of the distribution system.

Note that the second term in eq. (7) is a constant, thus can be disregarded. Letting α_i represent the quantity in brackets in eq. (8) and β_j represent the quantity in brackets of the first term in eq. (7), the LP problem given by equations (4), (5), and (6) can be rewritten as follows:

$$\min \quad J=\sum_{i=1}^{N_L}\alpha_i\cdot\left(X_i+Y_i\right)+\sum_{j=1}^{N_{gen}}\beta_j\cdot P_{gj} \qquad (9)$$

Subject to:

$$\begin{bmatrix} A & -A & 0 & B_g & 0 \\ I & I & I & 0 & 0 \\ 0 & 0 & 0 & B_{cg1} & B_{cg2} \\ 0 & 0 & 0 & B_{cg3} & B_{cg4} \end{bmatrix}\cdot\begin{bmatrix} X \\ Y \\ S \\ P_g \\ S_g \end{bmatrix}=\begin{bmatrix} P \\ P^u \\ P_g^{\max} \\ P_g^{\min} \end{bmatrix} \qquad (10)$$

$$[X],[Y],[S],\left[P_g\right],\left[S_g\right]\geq 0 \qquad (11)$$

where $[S_g]$ is the vector of generation slack variables containing the residual power for each generator, $[P_g^{Max}]$ and $[P_g^{min}]$ are the vectors containing the upper and the lower power generation limits for each DG unit, $[B_g]$ is a coefficient matrix relating DG power generation to nodal power injections, and $[B_{cg1}]$, $[B_{cg2}]$, $[B_{cg3}]$, $[B_{cg4}]$ are binary matrixes derived from the use of the slack variables, as illustrated below:

$$\begin{aligned} P_{gj}+S_{gj}^{\max}&=P_{gj}^{\max} \\ P_{gj}-S_{gj}^{\min}&=P_{gj}^{\min} \end{aligned} \qquad (12)$$

When the system load increases beyond safe limits, DSM actions may have to be taken. It is assumed that specific contracts exist between the DNO and certain customers, that allow the DNO to shed part of the customer loads in order to avoid overloads in the distribution network. Thus, the goal in this case is to find the optimal network configuration that allows minimum load shedding. In the presented approach, load shedding is activated when the total power demand of the network exceeds a predetermined threshold. However, other types of events such as overloading a specific branch in the network can be used to trigger load shedding to avoid the violation of some branch's thermal limit. Hence, when an overload condition is detected, the LP problem given by equations (9), (10), and (11) will be modified as follows:

$$\min \quad J=\sum_{i=1}^{N_L}\alpha_i\cdot\left(X_i+Y_i\right)+\sum_{j=1}^{N_{gen}}\beta_j\cdot P_{gj}+\sum_{k=1}^{N_{ls}}\gamma_k\cdot P_k^{ls} \qquad (13)$$

Subject to:

$$\begin{bmatrix} A & -A & 0 & B_g & 0 & B_{ls} & 0 \\ I & I & I & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B_{cg1} & B_{cg2} & 0 & 0 \\ 0 & 0 & 0 & B_{cg3} & B_{cg4} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & I \\ 0 & 0 & 0 & 0 & 0 & B_{cls} & 0 \end{bmatrix}\cdot\begin{bmatrix} X \\ Y \\ S \\ P_g \\ S_g \\ P_{ls} \\ S_{ls} \end{bmatrix}=\begin{bmatrix} P \\ P^u \\ P_g^{\max} \\ P_g^{\min} \\ P_{ls}^{\max} \\ P_{ls}^{Tot} \end{bmatrix} \qquad (14)$$

$$[X],[Y],[S],\left[P_g\right],\left[S_g\right],\left[P_{ls}\right],\left[S_{ls}\right]\geq 0 \qquad (15)$$

where γ_k is the unit cost of shedding power by load k, N_{ls} is the number of busses where the load shedding service is made available, P_{ls} is the vector of shed load, S_{ls} is the vector of load shedding slack variables, P_{ls}^{max} is the vector containing the maximum load to discard, P_{ls}^{Tot} is a constraint variable introduced to avoid overshedding loads, B_{ls} is a matrix introduced to incorporate load shedding into power flow equations. The two identity matrices are introduced to allow inclusion of DSM actions as follows:

$$P_k^{ls}+S_k^{ls}=P_{ls}^{\max} \qquad (16)$$

while B_{cls} is a matrix relating load shedding limits as illustrated below:

$$\sum_{k=1}^{N_{ls}}P_k^{ls}=P_{ls}^{Tot} \qquad (17)$$

TEST RESULTS

The 16 bus test system shown in Fig.1 is used for simulations. It has an existing meshed topology, with automatic sectionalizers installed in each branch, in order to permit a real-time network reconfiguration. The branch and bus data are given in Table 1 and Table 2 respectively. These data are suitably chosen to illustrate the reconfiguration algorithm. Two DG units are connected to buses 9 and 13: it is supposed that the DNO can dispatch their real power output within the following limits: from 400 kW to 450 kW for the generator G_9, and from 350 kW to 630 kW for the generator G_{13}. In case of a network overload, busses 6, 8 and 16 can be subjected to DSM action, with a maximum allowed load shedding limit of 100 kW, 500kW and 400kW respectively. Once the optimal configuration is established by the program, a power flow for the corresponding configuration is performed to determine the effective losses, the minimum

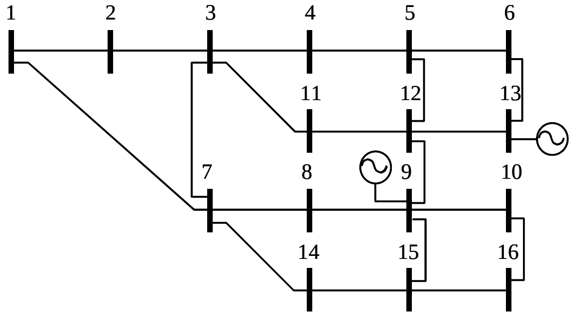

Fig. 1 – Test system

TABLE 1 – Branch data.

n°	Line	R	n°	Line	R	n°	Line	R
1	1-2	.4368	8	8-9	.52	15	11-12	.4108
2	2-3	.5148	9	9-10	.3588	16	12-13	.286
3	3-4	.0624	10	9-15	.3068	17	5-12	.1976
4	4-5	.13	11	7-14	.2511	18	6-13	.3276
5	5-6	.156	12	14-15	.4264	19	10-16	.0104
6	1-7	.1058	13	15-16	.1664	20	10-12	.3744
7	7-8	.2052	14	3-11	.364	21	3-8	.1269

TABLE 2 – Load data.

Bus	P[kW]	Bus	P[kW]	Bus	P[kW]	Bus	P[kW]
1	Slack	5	260	9	420	13	360
2	660	6	100	10	100	14	210
3	820	7	800	11	500	15	440
4	400	8	1000	12	1540	16	860

TABLE 2-bis – Load data for case 8 of table 3.

Bus	P[kW]	Bus	P[kW]	Bus	P[kW]	Bus	P[kW]
1	Slack	5	500	9	420	13	360
2	660	6	100	10	200	14	210
3	820	7	1000	11	800	15	440
4	550	8	1200	12	1540	16	1000

nodal voltage and the maximum branch power flow.

The simulation results are summarized in Table 3. As evident from the table, the algorithm can reduce power losses in all studied cases. Furthermore, even though voltage constraints are not included, the best reconfiguration also improved the bus voltage profile as seen from the minimum bus voltage value. It can be observed from the comparison of cases 1 and 2 that, if the network configuration and the location of DG are not optimized, the power losses in a network with DG can be more than those in the optimal configuration without DG. Hence, optimization tools, like the one presented in this paper, will significantly improve the planning and operation of distribution networks.

The last two cases reported in Table 3 consider two network overload conditions, that require DSM actions. The first refers to the new load demand reported in Table 2-bis, and involves only load shedding of at bus 16. The second is characterized by a system-wide homogeneous load growth of 15% and the simultaneous outage of generator G_9. In both cases, the network reconfiguration algorithm can find a network configuration with no overloaded branches.

CONCLUSIONS

This paper investigates the problem of distribution network reconfiguration in the presence of DG. A linear programming based algorithm is presented in order to achieve system reconfiguration with minimum losses and optimal power delivered by DG. Simulation results for the test distribution network confirm the feasibility of applying the LP program to find the optimal network configuration. It is shown that, for an optimal configuration, DG reduces losses, flows and improves overall voltage profile. In real-time operation it is important to know the amount of demand and DG availability. In fact, the optimum network configuration will change according to the changes in loading level and DG output. Hence, maintaining optimal network reconfiguration requires a communication system between distribution substation, MV/LV nodes and DG units. However, as suggested by the European Directive 2003/54 [7], distribution networks may became active in the medium term due to DG, and thus automation and communication technologies may be available for on-line network reconfiguration in the near future.

REFERENCES

[1] A. L. Morelato, A. Ponticelli, 1989, “Heuristic Search Approach to Distribution System Restoration”, *IEEE Trans. On Power Delivery*, vol.4, 2235-2241

[2] D. Shirmohammadi, 1992, “Service Restoration in Distribution Networks via Network Reconfiguration”, *IEEE Trans. On Power Delivery*, vol.7,952-958

[3] J.H. Choi, J.C. Kim, 2000, ”Network Reconfiguration at the Power Distribution System with Dispersed Generations for Loss Reduction”, *Proceedings of Power Engineering Society Winter Meeting*, 2363 - 2367

[4] Y.C. Huang, 2002, “Enhanced genetic algorithm-based fuzzy multi-objective approach to distribution network reconfiguration”, *IEE Proceedings - Generation Transmission and Distribution*, vol.149, 615-620

[5] J. C. Wang, H. D. Chiang, G. R. Darling, 1995, “An efficient algorithm for real-time network reconfiguration in large scale unbalanced distribution systems”, *Proceedings of PICA Conference*, 510 - 516

[6] A. Abur, 1996, ”A Modified Linear Programming Method for Distribution System Reconfiguration”, *International Journal of Electrical Power and Energy Systems*, vol. 18 , 469-474

[7] Directive 2003/54/EU (2003, June 26). [Online]. Available: http://europa.eu.int/eur-lex

TABLE 3 – Simulation results for different cases: all cases, except case 7, have been analysed with c^{DG} = 0.05 €/kWh.

Network configuration		Open branches	Losses [kW]	Min V_i		Max F_i		P_{g9} [kW]	P_{g13} [kW]	P_6^{ls} [kW]	P_8^{ls} [kW]	P_{16}^{ls} [kW]
				[p.u.]	i	[% of P_i^u]	i					
0	existing without DG	21, 17, 18, 10, 19, 20	144.17	0.962	13	107.6 %	1	—	—	—	—	—
1	best without DG	2, 8, 9, 15, 16, 20	103.19	0.976	12	97.1 %	6	—	—	—	—	—
2	existing with DG	21, 17, 18, 10, 19, 20	107.54	0.969	12	94.31 %	1	450	630	—	—	—
3	best with DG	2, 8, 10, 15, 18, 20	81.39	0.979	12	87.27 %	6	450	630	—	—	—
4	best – G_9 out of service	2, 9, 10, 15, 18, 20	84.74	0.978	12	90.06 %	6	—	630	—	—	—
5	best – G_{13} out of service	2, 8, 10, 15, 16, 20	99.04	0.976	12	94.2 %	6	450	—	—	—	—
6	best – DG (c^{DG} = 0.09)	2, 8, 10, 15, 18, 20	88.65	0.978	13	90.12 %	6	450	360	—	—	—
7	best – line 11 out of service	2, 11, 13, 15, 18, 20	104.55	0.975	16	97.34 %	7	450	630	—	—	—
8	best with DSM – case 1	2, 8, 10, 15, 18, 20	104.76	0.975	12	99.5 %	6	450	630	0	0	336
9	best with DSM – case 2	2, 9, 10, 15, 18, 20	99.78	0.976	12	96.81 %	6	—	630	100	136.5	400