OPTIMAL RECONFIGURATION AND CAPACITOR ALLOCATION IN UNBALANCED DISTRIBUTION NETWORK CONSIDERING POWER QUALITY ISSUES

Hamid Reza ESMAEILIAN
Graduate University of Advanced Technology – Iran
hamidreza_89esm@yahoo.com

Roohollah FADAEINEDJAD
Graduate University of Advanced Technology – Iran
rfadaein@ieee.org

ABSTRACT

This paper presents a methodology to reduce the power loss and improve the system performance by simultaneous applying the network reconfiguration and capacitor placement using a Fuzzy-Genetic Algorithm (FGA). The fuzzy multi-objective function comprises the overall annual cost of the network loss and that of shunt capacitors, total harmonic voltage distortion (THD_V), voltage profile, and voltage unbalance factor at the network buses. An unbalanced 33-bus radial distribution system is studied in several cases to demonstrate the effectiveness of the proposed algorithm.

INTRODUCTION

The loss reduction in distribution network is the main goal in efficient operation of the network. Due to low voltage level and in consequence high flowing current in the distribution system, the most power loss portion is related to the distribution section in comparison to transmission and generation sections. Hence, many alternatives have been done to decrease the losses in the distribution networks. Reconfiguring network is an effective method to solve this problem as possible. Nevertheless, the network reconfiguration can't satisfy the aimed loss reduction. Therefore, the reconfiguration has been employed combined with other methods such as capacitor placement and the distributed generation resources to reduce the power loss in the distribution networks [1- 3].

In a real distribution network, the considerations of the power quality issues are indispensable in optimal operation problem of the network, due to the high penetration of the non-linear loads and the existence of the unbalanced multi-phase loads. Without considering harmonic sources in the network, the operation of network may lead to resonance between the shunt capacitors and the inductive elements in the network and in consequence high distortion levels [4]. Unbalance existence in the network causes an excess loss in transformers, motors, and lines and as a result temperature and failure rates increasing at the equipment. Therefore, the harmonic distortion and the voltage unbalance should be taken into account in optimal operation of the network.

The network reconfiguration and capacitor placement have been applied in previous research to reduce the loss [1, 2], but the power quality issues haven't been considered so far in none of them. In [4], the capacitor placement is applied on an unbalanced radial distribution system to reduce the power loss with and without harmonics consideration. They have shown that the operation of the network will lead to a high harmonic distortion level if the harmonic producers in the system aren't considered in sitting and sizing of capacitors. The present paper employs the network reconfiguration and capacitor placement simultaneously to reduce the power loss and improve the network operational conditions using a Fuzzy-GA approach.

HARMONIC POWER FLOW

The three-phase Backward/Forward harmonic power flow is utilized in this paper to obtain the terms of the objective function. The computations are divided in fundamental frequency and then in other harmonic orders so that are briefly described as follows [5]:

Fundamental Power Flow

The relationship between the bus voltages and branch currents in an unbalanced system are expressed as equation (1) and illustrated in Fig.1. In backward sweep, the branches currents at each phase is calculated by applying KCL in the network buses. Thereafter, the buses voltages are obtained by applying KVL in forward sweep as equation (1). These two steps will be repeated until the convergence is achieved.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \cdot \begin{bmatrix} I_{Aa} \\ I_{Bb} \\ I_{Cc} \end{bmatrix} \qquad (1)$$

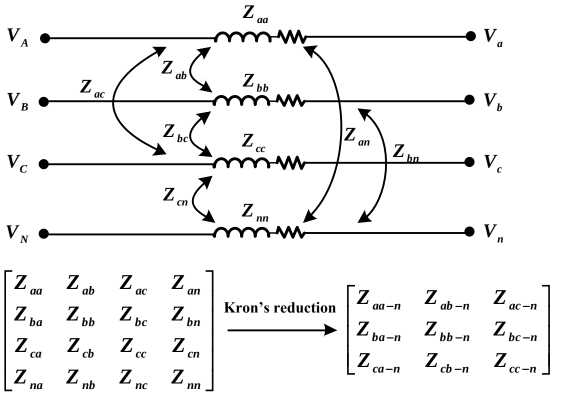

Fig. 1 : Three-phase line section of an unbalanced system

Harmonic Power Flow

The nonlinear and linear loads can be expressed as currents injected into the system according to harmonic spectrum and equivalent impedance at each harmonic order. The harmonic currents vector absorbed by shunt capacitors, $[I_s]$, in a system with three-phase unbalanced loads can be calculated as following equation:

$$[HLF^{(h).k}]_{3s\times 3s}\,[Is^{(h).k}]_{3s\times 1} = -[HA_{sh}^{(h).k}]_{3s\times 3n}\,\,[Ih^{(h).k}]_{3n\times 1} \quad (2)$$

where s and n are the number of three-phase shunt capacitors and the number of buses in the system, respectively. The a_{ii} diagonal entry of the HLF matrix is acquired as the sum of the *ith* capacitor phase impedance and the branches impedance in path capacitor i toward slack bus. The a_{ij} off-diagonal entry is acquired as the sum of the branches impedance in common path between two capacitors i and j toward slack bus. The a_{ij} entry of the HA_{sh} matrix is the sum of the branches impedance in common path between capacitor i and linear or nonlinear load j toward slack bus.

The branch currents and the bus voltages at each harmonic order can be calculated using backward and forward sweeps so that are described in [5]. After performing the power flow for all harmonic components, the network power loss and the *rms* and *THD* values of the buses voltage are calculated by following equations.

$$P_{Loss} = P_{Loss}^{1} + \sum_{h=2} P_{Loss}^{h} \quad (3)$$

$$V_{rms_i} = \sqrt{\sum_{h=1} \left|V_i^{\,h}\right|^2} \quad (4)$$

$$THD_i\,\% = \frac{\sqrt{\sum_{h=2} \left|V_i^{\,h}\right|^2}}{\left|V_i^{\,1}\right|} \times 100 \quad (5)$$

The voltage unbalance factor at each bus can be calculated as equation (6), where V^{+} and V^{-} are the bus voltage positive and negative sequences, respectively.

$$K_i = \frac{V_i^{\,-}}{V_i^{\,+}} \times 100 \quad (6)$$

OPTIMIZATION PROBLEM FORMULATION

The considered objectives to improve the system efficiency are aggregated into a single fuzzy objective function as follows:

$$f = \left(w_1 \times \mu_{\overline{Cost}} + w_2 \times \frac{1}{n}\sum_{i=1}^{n} \mu_{\overline{V}_i} + w_3 \times \mu_{\overline{THD}} + w_4 \times \mu_{\overline{K}} \right) \quad (7)$$

where μ_{cost}, μ_V, μ_{THD}, and μ_k are membership functions adopted for cost, the bus voltage, harmonic voltage distortion, and voltage unbalance factor as are depicted in Fig.2, respectively. The coefficients w_i are weighting factors so that $\sum_{i=1}^{4} w_i = 1$. The parameters considered in Fig.2 are defined as follows:

$Cost_{min}$: the obtained cost in single objective optimization;

k_p: the power cost (168 \$/kW/year [4]);

k_c: the annual cost of the installed capacitor (Table I [4]);

V^{max}, V^{min}: the acceptable upper and lower limits of the bus voltage, respectively (1 and 0.95 p.u.);

V^{-}: the lowest bus voltage in initial configuration;

V^{+}: the predefined upper value of the bus voltage (1.05);

THD^{max}: the maximum acceptable limit of voltage harmonic distortion (5%);

THD^{+}: the harmonic voltage distortion in the base case;

k^{0}: the maximum voltage unbalance factor in the base case;

k^{max}: the maximum acceptable voltage unbalance limit (0.5%);

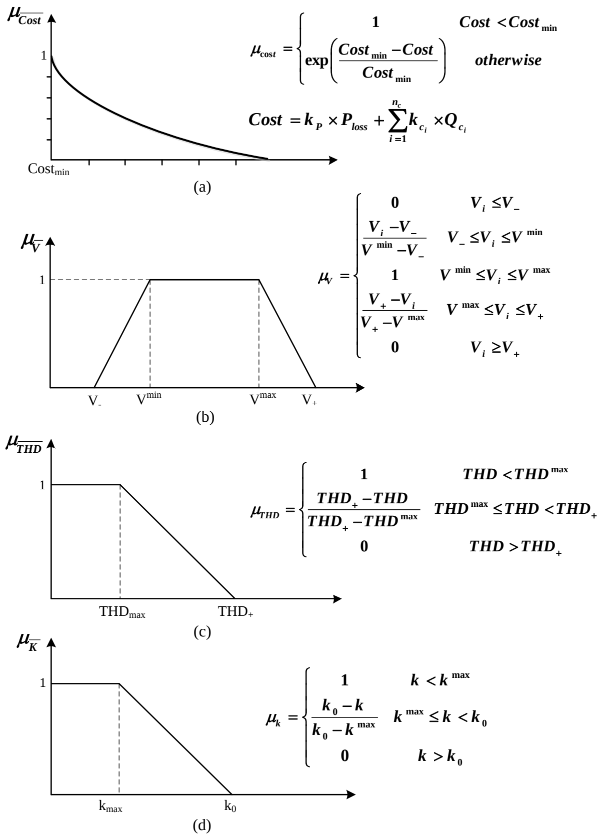

Fig. 2: the membership functions for (a) cost, (b) THD, (c) the bus voltage, (d) voltage unbalance factor.

PROPOSED ALGORITHM

The flowchart of the proposed algorithm to improve the system efficiency is illustrated in Fig.3. The GA is adopted in order to maximize the single fuzzy objective function expressed in equation (7). Each chromosome in GA shows binary code related to the switches number that should be opened as well as the capacitor values at each bus.

The harmonic power flow is performed to assess each chromosome provided that the configuration be radial. The structure of each chromosome is evaluated by graph theory [6]. If configuration isn't radial, a penalty factor will be applied in the objective function. Afterwards, the GA's operators are employed to generate new population. The algorithm will repeat until the convergence criterion is met.

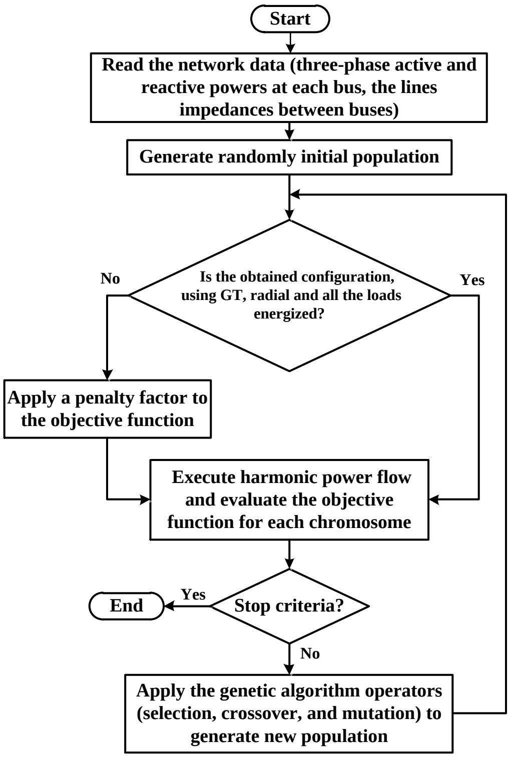

Fig. 3: the flowchart of proposed method

SIMULATION RESULTS

The applicability of the proposed method is demonstrated on a three-phase unbalanced 33-bus radial distribution system with 5 tie switches and 32 sectionalizing switches. The total active and reactive power demands are 3715 kW and 2300 kVAr, respectively. The network data, including lines impedance and loads power at each phase, are given in [7]. The initial configuration of the network is illustrated in Fig.4. In order to study the impact of non-linear loads on the network operational conditions, it is considered that the main harmonic producers in the system are 25% ASD, 15% fluorescent, and 10% non-specific loads at buses 8, 22, 24, and 30. The harmonic spectra of non-linear loads and the annual costs of commercially shunt capacitors utilized in this paper are given in Table I and Table II, respectively.
Three different cases are investigated on the studied network as follows:

- **Case 1** represents the network reconfiguration according to equation (7);
- **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, equation (7).

The computational results are shown in Table III. The power loss, THD^{max}, and K^{max} are reduced to 29.92%, 23.77%, and 1.66% respectively by the network reconfiguration. In case 2, the loss is reduced to 46.50% whereas THD^{max} and K^{max} increase to 59.44% and 0.66%. Therefore, operation of the network isn't practical in this case. In case 3, considering the power quality constraints in the reconfiguration and capacitor placement problem, the power loss, THD^{max}, and K^{max} are reduced to 39.38**%**, 25.12**%**, and 21.19% respectively. The cost saving values obtained by the network reconfiguration and also by the reconfiguration and capacitor placement in case 3 are **10664.64** $/yr and **13282.53** $/yr, respectively.
The harmonic voltage distortions and three-phase voltage profiles of the network buses in base case, case 1, as well as case 3 are compared in Fig.5 and Fig.6, respectively. It is observable that the network buses voltages are improved; the voltage unbalances and the network harmonic distortion are reduced after reconfiguration and capacitor placement. Moreover, the convergence rate of the proposed FGA approach for the optimal reconfiguration and capacitor placement problem in case 3 is depicted in Fig.7.

CONCLUSION

The majority of real distribution networks are unbalanced and the existence of non-linear loads is inevitable part of them. In order to achieve an appropriate performance, the power quality constraints should be taken into account in optimal operation of distribution network too. This paper applies optimal network reconfiguration and capacitor placement to improve the system efficiency using a fuzzy multi-objective method. The obtained results show the improvement of the system operational conditions in comparison with the system situation before study.

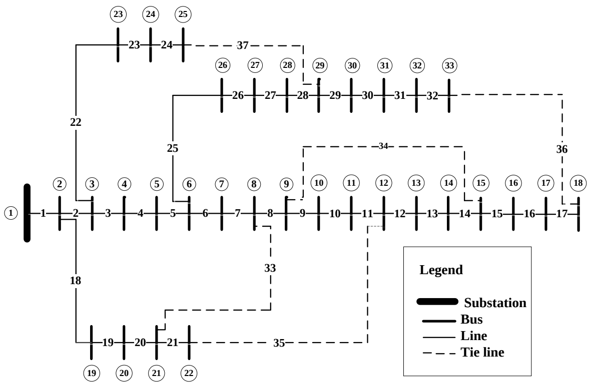

Fig. 4: The 33-bus radial distribution network

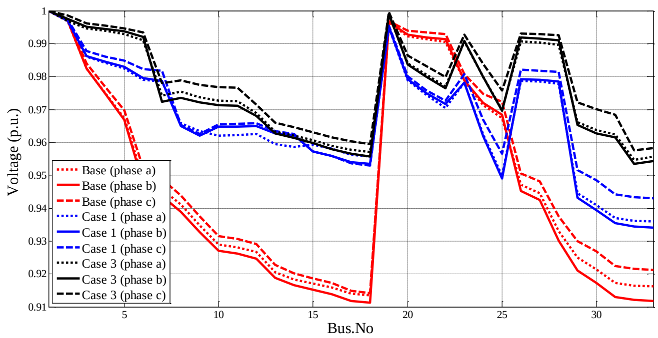

Fig. 5: the network buses three-phase voltages profiles.

Table III: Simulation results of the 33-bus unbalanced distribution network

Item	**Tie switches**	**Capacitors**				**Power loss (kW)**	**Annual cost ($/yr)**	**%THD^{max} Phase A Phase B Phase C**	**V^{min} Phase A Phase B Phase C**	**Voltage Unbalance Factor (max)**
		Bus	**kVar**	**Bus**	**kVar**					
Base case	33,34,35,36,37	———				212.17	35644.56	4.221 6.47 5.972	0.913 0.911 0.914	0.604
Case 1	7,9,14,28,36	———				148.69	24979.92	3.291 4.932 4.475	0.936 0.934 0.943	0.594
Case 2	7,8,14,32,37	25 23 30	450 150 900	12 2	300 300	113.506	19632.558	7.111 10.316 9.109	0.948 0.944 0.943	0.608
Case 3	6,11,28,31,34	8 14 18	450 150 450	24 23 4	600 750 450	128.61	22362.03	3.315 4.845 4.411	0.955 0.953 0.958	0.476

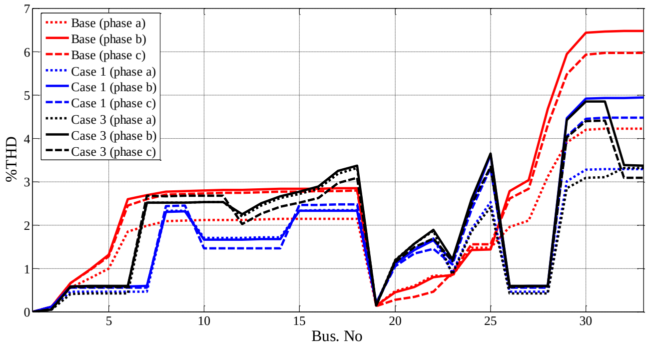

Fig. 6: the voltages harmonic distortions.

Table I: Annual costs of shunt capacitors [4]

Q_c (kVar)	150	300	450	600	750	900	1050
k_c ($/kVar)	0.5	0.35	0.253	0.22	0.276	0.183	0.228

Table II: Harmonic spectra of non-Linear loads [8]

Harmonic order	ASD		Fluorescent		Non-specific	
	Mag	Phase	Mag	Phase	Mag	Phase
1	100	-1.45	100	-107	100	105.5
3	84.6	-8.34	19.2	76	3.6	-44.4
5	68.3	-14.23	10.7	10	3.2	139.4
7	47.8	-20.13	2.1	37	0.9	-176
9	27.7	-29.02	1.4	31	0.5	-60
11	0.2	-27.91	0.9	36	0.5	139
13	6.1	158.2	0.6	47	0.3	-126
15	4.2	122.3	0.5	20	0.3	112

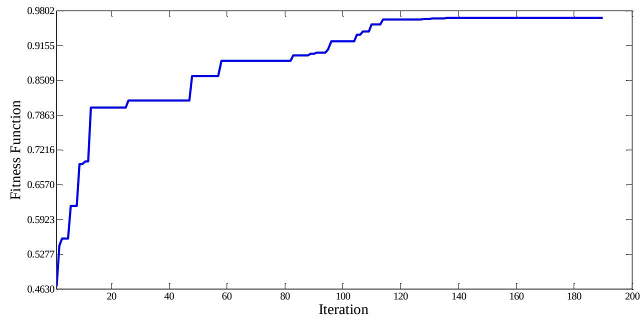

Fig. 7: Convergence characteristic of the FGA for case 3.

REFERENCES

[1] C.F. Chang, 2008, "Reconfiguration and capacitor placement for loss reduction of distribution systems by ant colony search algorithm", *IEEE Trans. on Power Syst.*, vol.23, 1747– 1755.

[2] V. Farahani, B. Vahidi, and H.A. Abyaneh, 2012, "Reconfiguration and capacitor placement simultaneously for energy loss reduction based on an improved reconfiguration method", *IEEE Trans. on Power Syst.*, vol.27, 587 - 595

[3] Y. Wu, C. Lee, L. Liu, and S. Tsai, 2010, "Study of reconfiguration for the distribution system with distributed generators," *IEEE Trans. on Power Del.*, vol.25, 1678–1685.

[4] A.A. Eajal and M.E. El-Hawary, 2010, "Optimal capacitor placement and sizing in unbalanced distribution systems with harmonics consideration using particle swarm optimization", *IEEE Trans. on Power Del*, vol.25, 1734–1741.

[5] J.H. Teng and C.-Y. Chang, 2007, "Backward/ Forward Sweep-Based Harmonic Analysis Method for Distribution Systems", *IEEE Trans. on Power Del.*, vol. 22, 1665–1672.

[6] H.R. Esmaeilian, S. Jashfar, R. Fadaeinedjad, S. Esmaeili, and S.M. Attari, 2012, "Bardsir network reconfiguration using graph theory-based binary genetic algorithm to reduce loss and improve voltage profile", *17th Electric Power Distribution Conference (EPDC), IEEE, Iran.*

[7] A. Swarnkar, N. Gupta, and K.R. Niazi , 2011, "Adapted ant colony optimization for efficient reconfiguration of balanced and unbalanced distribution systems for loss minimization", *Swarm and Evolutionary Computation*, vol.1, 129–137.

[8] A. Bonner, T. Grebe, E. Gunther, L. Hopkins, 1996, "Modelling and Simulation of the Propagation of Harmonics in Electric Power Networks", *IEEE Trans. on Power Del.*, vol. 11, pp. 466-474.