VOLTAGE AND REACTIVE POWER OPTIMAL CONTROL IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

Jiachuan SHI
Shandong University – China
jc.shi@mail.sdu.edu.cn

Yutian LIU
Shandong University – China
liuyt@sdu.edu.cn

ABSTRACT

Distributed generation (DG) is gaining wide attention for the possible influences on the power system. Considering the effects of DG, the voltage and reactive power optimal control in distribution networks is modelled as a multi-objective combinational optimization. The objectives, voltage profiles, power losses and voltage variation, are evaluated by membership functions respectively, so that the satisfactions of different objectives can be compared. To facilitate the solving process, a compromised objective is formed by the weighted sum approach. The weightings of the objectives are calculated by fuzzy judgement matrix. The reactive tabu search algorithm is employed to get the solutions. Simulation results demonstrated that the proposed method is effective in improving the voltage profiles and all the other objectives as well.

INTRODUCTION

Voltage and reactive power (volt/var) optimal control aims to improve the voltage profiles and reduce active power losses by adjusting reactive power distribution. Generally, regulating means in distribution systems are transformer tap-changers, voltage regulators and shunt capacitors, which are both discrete variables. Conventionally volt/var problem is formed as a constrained combinatorial optimization problem to minimize the active power losses without voltage violation.

With the environmental consciousness and development of high-efficiency small generators, increasing number of distributed generators (DG) are embedded in distribution networks. The possible influences of DG on distribution networks are gaining wide attention. The DG connection impacts many aspects of distribution network operating and planning. The detailed models of synchronous and induction machines for DG and their impacts on distribution networks are presented in [1]. Steady-state voltage profiles may be impaired for the DGs output and their influences on voltage regulation apparatus. The voltage rise problem caused by reverse power flow is introduced in [2], and the optional techniques that can alleviate the problem are compared in detail. The under-voltage problem, which is associated with interaction between DG and conventional voltage regulating means, is introduced and analyzed in [3, 4]. The DG can not always reduce energy losses. Different influences of various DG technologies, penetration and concentration levels on energy losses are compared in [5]. Besides power losses and voltage profiles, voltage variation and short circuit current are taken into consideration to evaluate the impact of DG [6].

A multi-objective optimization formulation is constructed for volt/var optimization in distribution network with DG embedded. The objectives include improving the voltage profiles, minimizing voltage variation due to DG disconnection and decreasing the active power losses. Regulating means are transformer tap-changers and shunt capacitors.

MODELING

Characteristics of volt/var optimal control with DG

The active power injection from DG affects the voltage significantly for the R/X ratio of branches trends to be high. But considering the uncertainty of DG and variation of its output, DG can not serve as a voltage regulating means.

The objective of voltage regulation is to maintain the customer's voltage in permissible limits. In peak load conditions, the voltage drop is high. The network maintains voltage profiles without relaying on the output of DG. In valley load conditions, the reverse power flow may cause over-voltage. Several regulating means, including switching tap-changer and adjusting DG output, can be utilized to alleviate the over-voltage problem [2].

The voltage variation caused by uncertain DG output should also be considered in volt/var optimal control. The worst situation happens on DG disconnection.

Voltage Profiles Assessment

The membership function is introduced to evaluate voltage profiles.

$$F_v(V_i)=\begin{cases}\dfrac{L_0^{upper}-V_i}{L_0^{upper}-L_1^{upper}} & \left(L_1^{upper}<V_i<L_0^{upper}\right)\\ \dfrac{V_i-L_0^{lower}}{L_1^{lower}-L_0^{lower}} & \left(L_0^{lower}<V_i<L_1^{lower}\right)\\ 1 & \left(L_1^{lower}<V_i<L_1^{upper}\right)\\ 0 & (others)\end{cases} \quad (1)$$

where V_i is the voltage of node i; L_0^{upper} and L_0^{lower} are unacceptable voltage limits; L_1^{upper} and L_1^{lower} are acceptable voltage margins.

The membership function of the network voltage profiles is：

$$F_{vol} = \frac{\sum_{i=1}^{N} F_v(V_i)}{N} \quad (2)$$

where N is the number of nodes; V_i is the voltage of node i.

Active Power Losses Assessment

The active power losses are also scaled by a membership function to compare between the objectives. Different from evaluating voltage profiles, there is not a standard or reference value for active power losses reduction.

In this paper, the membership function for active power losses is determined by two parameters. P_{l_ori} represents the active power losses before optimization, and the membership value for P_{l_ori} is set 0.5. P_{l_min} is the active power losses only caused by active power current, and its membership value is 1.[7]

The membership function of the active power losses is shown as Fig. 1

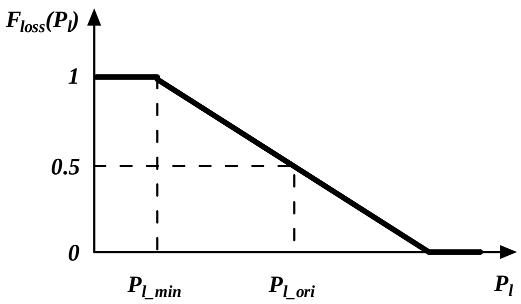

Fig. 1. Membership function for active power losses assessment

The two parameters, P_{l_ori} and P_{l_min}, are determined by the system structure and original operating conditions. Therefore, the assessment results of trial solutions under different operating conditions are comparable.

Voltage variation assessment

Voltage variation may be caused by the DG output changing. The DG influence on voltage variation is represented by the largest voltage difference in the worst situation, DG disconnection.

The satisfaction of voltage variation is defined as：

$$\Delta V = Max(\Delta V_i)$$

$$F_{\Delta V} = \begin{cases} 1 & \Delta V \le L_1^{\Delta V} \\ \dfrac{\Delta V - L_0^{\Delta V}}{L_1^{\Delta V} - L_0^{\Delta V}} & L_1^{\Delta V} < \Delta V < L_0^{\Delta V} \\ 0 & \Delta V \ge L_0^{\Delta V} \end{cases} \quad (3)$$

where ΔV_i is the voltage variation of node i before and after DG disconnection; $L_1^{\Delta V}$ is the acceptable variation margin; $L_0^{\Delta V}$ is the unacceptable variation limits.

Multi-objective optimization model

Based on the fuzzy evaluation functions, the multi-objective volt/var optimization model is constructed to maximize the satisfactions of different objectives by adjusting transformer tap-changers and shunt capacitors. The objectives include voltage profiles, active power losses and voltage variation caused by DG disconnection. The multiobjective optimization model is represented as:

$$\begin{aligned} & Max\ F_{vol} \\ & Max\ F_{loss} \\ & Max\ F_{\Delta V} \\ & s.t. \quad T_k^{\min} \le T_k \le T_k^{\max} \\ & \qquad 0 \le Q_j \le Q_j^{\max} \end{aligned} \quad (4)$$

in which F_{vol} is the membership function for voltage profiles; F_{Loss} is the membership function for active power losses; $F_{\Delta v}$ is the membership function for voltage variation caused by DG disconnection; T_k is the ratio of transformer k; Q_j is the capacity of capacitors at node j. The restriction of power flow is not listed here.

SOLUTION METHOD

Fuzzy judgement matrix method

The weighted sum approach is utilized to facilitate the solving process. Generally, the weightings are decided according to the experiences. With the increase of objectives number, it is hard to decide the weightings. The fuzzy judgement matrix is introduced to calculate the weightings.

The judgement matrix can be formed as:

$$M = \begin{pmatrix} 1 & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & 1 & \cdots & \alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & 1 \end{pmatrix} \quad (5)$$

$$\alpha_{ij} = \frac{1}{\alpha_{ji}} \quad (i, j = 1, \cdots n)$$

in which α_{ij} represents the importance comparison between objective *i* and objective *j* with an integer from 1 to 9[8].

The weighting for objective *i*, w_i , is calculated as:

$$w_i = \frac{\pi_i}{\sum_{j=1}^{n} \pi_j} \quad (6)$$

in which

$$\pi_i = \left(\prod_{j=1}^{n} \alpha_{ij} \right)^{\frac{1}{n}} \quad (7)$$

With the weighting calculated, the single-objective optimization problem can be formed.

Reactive Tabu Search algorithm

Reactive Tabu Search algorithm (RTS) is utilized to solve the constrained combinational optimization problem [7]. In conventional tabu search, the two searching strategies, diversification and intensification, are balanced by the length of tabu list, which is determined by experiences. The feedback mechanism is introduced in RTS to adjust the length of tabu list. Therefore, the two opposing strategies can be balanced according to characteristics of the problem and the optimization process. Therefore, compared with traditional TS, the RTS is more robust and effective.

TEST RESULTS

The proposed method is tested in a 33-bus distribution system (Fig.2). The parameters of on-load tap-changer, DG and shunt capacitors are shown in table1. In peak loads condition the source node voltage is 1.0 p.u.. In valley loads condition, the loads are one sixth of the peak loads, and the source node voltage is 1.03p.u..

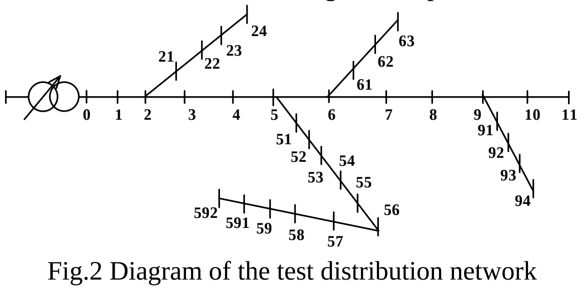

Fig.2 Diagram of the test distribution network

Table.1 Parameters of equipments

New-Added Apparatus	Position	Parameters
OLTC	0#	1.0±0.0125×8
DG	55#	1000 kW 0 kVar
	6#	800 kW 0 kVar
Shunt capacitors	55#	150×4 kVar
	59#	150×2 kVar
	4#	300×3＋150×1 kVar

The fuzzy judgement matrix and weightings of objectives are shown in Table 2. The volt/var optimal control schemes for the peak and valley loads conditions are represented in Table 3, and the result comparisons in Table 4 and 5.

Table.2 Fuzzy judgement matrix and weightings of objectives

	F_v	F_{Loss}	$F_{\Delta v}$	W_i
F_v	1	3	7	0.6694
F_{Loss}	1/3	1	3	0.2426
$F_{\Delta v}$	1/7	1/3	1	0.0879

Table.3 Optimal control schemes

	Position	Peak Load	Valley Load
OLTC	0#	0.975	1.025
Shunt Capacitors	55#	600 kVar	300 kVar
	59#	300 kVar	150 kVar
	4#	1050 kVar	150 kVar

Table.4 Optimization results in peak load condition

	Before Optimization		After Optimization	
DG Output ratio (%)	100	0	100	0
Max volt (p.u.)	1.00	1.00	1.026	1.026
Min volt (p.u.)	0.949	0.930	0.982	0.963
P_l (kW)	188.377	324.231	116.322	241.172
Max ΔV(p.u.)	0.01963		0.01891	

Table.5 Optimization results in valley load condition

	Before Optimization		After Optimization	
DG Output ratio (%)	100	0	100	0
Max volt (p.u.)	1.038	1.030	1.03	1.03
Min volt (p.u.)	1.030	1.019	1.005	0.996
P_l (kW)	10.912	7.720	9.741	6.377
Max ΔV(p.u.)	0.01728		0.01768	

In peak load condition, the network relies on DG to maintain the voltage profiles before optimization. Some nodes endure under-voltage (0.93p.u.) when DG disconnects. After optimization, conventional regulating means are adjusted to improve the voltage profiles. The voltages of all the nodes are eligible with or without DG output. The active power losses and voltage variation are also reduced.

In valley load condition, reverse power flow raises the voltage and power losses. After optimization, the over-voltage is alleviated, and the voltage profiles are improved. The power losses comparison shows that, the volt/var optimal control scheme decrease the power losses by reducing reactive power transferred. Although the maximum voltage variation increases very slightly, the integral satisfaction improved evidently.

CONCLUSION

The volt/var optimal control is modeled as a multiobjective optimization problem and solved by weighted-sum approach. The weightings are calculated by fuzzy judgement approach according to the importance comparison of every two objectives. Reactive tabu search is employed to find the solutions.

Simulation result shows the efficiency of the proposed method. The negative influences of DG in different operating conditions are lightened by adjusting the conventional volt/var regulation means.

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