OPTIMAL SIZING AND LOCATION OF CAPACITOR BANKS IN DISTORTED DISTRIBUTION NETWORKS WITH DISTRIBUTED WIND GENERATION

Akram ELMITWALLY
Mansoura University – Egypt
kelmitwally@yahoo.co. uk

ABSTRACT

In this paper, a modified simulated annealing technique is proposed for simultaneous improvement of power quality and optimal placement and sizing of fixed capacitor banks in a modern distribution network. The later is supplying a mix of linear and nonlinear loads imposing voltage and current harmonics. Besides, they include integrated variable-speed wind turbines as distributed generation. The stochastic power output of the wind generation is considered by performing Monte-Carlo simulation of the distribution power flow. Operational and power quality constraints include the bounds of node voltage magnitude, node voltage total harmonic distortion and the number/size of installed capacitors. The net annual economic saving is defined as the associated objective function. Solution results are discussed for a model distorted distribution system under different conditions.

INTRODUCTION

The extensive applications of harmonic-generating devices in distribution system make it vital to take harmonics into account [1]. Proper placement and sizing of shunt capacitor banks in distorted networks can result in reactive power compensation, improved voltage regulation, power factor correction, power/energy loss reduction, as well as power quality improvement [1]- [3]. Nonlinear loads produce considerable harmonic currents into the distribution system which should be considered on formulating the problem of capacitor placement [4]. Application of analysis method for solving the shunt capacitor placement problem with power quality constrains (e.g., voltage total harmonic distortion (THDv) and fundamental voltage magnitude) is quite difficult. The gradient search method works well with continuous variables. However, the shunt capacitor placement is an optimization problem of discrete variables. Furthermore, the presence of harmonic resonance makes the gradient search method very difficult to produce global optimal results [3], [4].

Distributed generation (DG) is related with the use of small generating units installed in strategic points of the electric power system close to load centers. DG can be used in an isolated way, supplying the consumer's local demand, or in an integrated way, supplying energy to the remaining of the electric system. DG can provide benefits for the consumers as well as for the utilities [5] - [9].

Wind power is a potential choice for smaller energy producers due to numerous benefits [6]. The wind farms need to be located in places with a favourable wind pattern. They can not be pre-dispatched by the utility but only according to the availability and the velocity of the wind. The large uncertainty present in wind farms generation influences strongly on the system reliability. The amount of energy daily available can vary a lot from a season to another at the same site. The intermittent nature of wind power generation introduces special technical and economic challenges that must be overcome if wind power is to be effectively incorporated into the supply of electricity. Wind power has random-like output characteristics due to the effect of weather conditions. It is necessary to implement Monte-Carlo simulation of distribution power flow to incorporate wind generation in distribution system. Hence, probabilistic evaluation of the nodal voltage is obtained [8].

Many papers have studied the problem of sizing and placement of shunt capacitors banks in undistorted or distorted distribution systems without DG [1]-[4]. A variety of optimization techniques, with different solution capabilities, have been utilized to solve the associated constrained optimization problem [8] – [12]. Very little is reported about sizing shunt compensation devices in distribution systems with DG.

In this paper, a modified simulated annealing (MSA) technique is proposed for simultaneous improvement of power quality (PQ) and optimal placement and sizing of fixed capacitor banks in a modern distribution network. The later is supplying a mix of linear and nonlinear loads imposing voltage and current harmonics. Besides, it includes integrated variable-speed wind turbines as a dominant form of DG. The stochastic power output of the wind DG is considered by performing Monte-Carlo simulation of the distribution power flow. Operational and PQ constraints include the bounds of node rms voltage, node THDv and the number/size of installed capacitors. The net annual economic saving is defined as the associated objective function.

SYSTEM DESCRIPTION

The system under study is a typical Egyptian suburban distribution system shown in Fig.1. It comprises a 66 kV primary bus and 11 kV secondary buses coupled through the 25 MVA main transformer. 5 feeders originate from the 11kV bus to supply 28 load centres. The system data are given in [11]. Each load is assumed to have 40% linear part and 60% nonlinear part. The nonlinear component of the load is assumed to be a 3 phase rectifier load [3], [4]. Wind DG is connected to selected nodes of the system. As the distribution network extends over a limited land area, the wind regime is assumed to be similar at any node site. Load duration curve is formed as in Table 1.

PROBLEM FORMULATION

Due to capacitor installation at some nodes of the system, there will be an economic benefit in the form of net financial savings. This emerges from the reduction of both the peak power demand, due to power loss reduction, and the energy losses deducting the cost of the installation of capacitors. The net savings is taken as the objective function. The problem is to determine the optimal shunt capacitor sizes and locations in the distribution system maximizing the objective function and satisfying the defined constraints.

Table 1 Load duration curve

	Load level (p.u)	Duration, (hours)
1	0.6	2500
2	0.7	2500
3	0.8	2000
4	0.9	1200
5	1	560

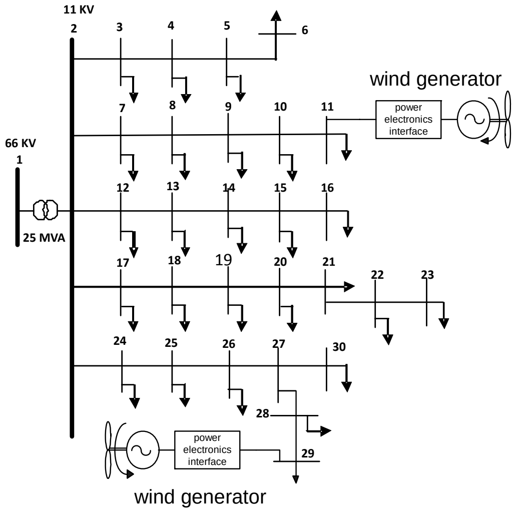

Fig.1 One- line diagram of the studied distribution system

Constraints

Fundamental voltage magnitude will be taken into account by specifying upper limit (V_{max}) of 1.1 p.u and lower limit (V_{min}) of 0.90 p.u [1].

$$V_{min} \le \left| V_{ik} \right| \le V_{max} \qquad (1)$$

$THDV_{ik}$ is to be kept lower than a limit value $THDV_{max}$ as:

$$THDV_{ik} \le THDV_{max} \qquad (2)$$

The total number of the prospective fixed capacitor banks (u_c) in the distribution system is limited by a maximum allowed value (u_{max}) as:

$$u_c \le u_{max} \qquad (3)$$

The size of a capacitor bank (C) is kept lower than a maximum allowed value (C_{max}) and should be a standard capacitor size as:

$$C < C_{max} \qquad (4)$$

$$C \in D_s \qquad (5)$$

Where, D_s is the discrete set of the standard capacitor size. The output of the wind power generation (P_w) is randomly determined by Monte-Carlo simulation. Wind power generation is kept between 0 and an upper limit $P_{w,max}$ as:

$$0 \le P_w \le P_{w,max} \qquad (6)$$

Objective function

It is desired to find which combination of capacitors will result in maximum value of economic savings, considering harmonic sources and different load levels, and subject to the specified constraints. Thus, the objective function used for capacitor placement is the net annul financial savings (S) given by:

$$\max S = k_l * \Delta p_l + k_E * \Delta E_l - k_C \qquad (7)$$

Where,

k_l is a constant to convert power into money (in $/kW/year).

k_E is a constant to convert energy into money (in $/kWh/year).

Δp_l is the reduction in peak power demand which results from power loss reduction at full load due to capacitors.

ΔE_l is the reduction in the distribution system energy loss due to capacitors.

K_c is the annual cost of the installed fixed capacitors (in $/Kvar/year).

The energy loss at the k^{th} load level which lasts T_k hours per year is given by:

$$E_{loss,k} = T_k * P_{loss,k} \qquad (8)$$

The total annul energy loss E_{loss} is computed as:

$$E_{loss} = \sum_k E_{loss,k} \qquad (9)$$

ΔE_l is the difference between E_{loss} without capacitors and E_{loss} with capacitors $E_{loss,c}$ calculated as:

$$\Delta E_l = E_{loss} - E_{loss,c} \qquad (10)$$

SOLUTION ALGORITHM

An optimization technique based on a modified resilient simulated annealing technique (RSA) is adopted to solve the capacitor locating and sizing problem. The simulated annealing optimization technique is described in many references [8], [12]. It is mainly employed to solve minimization problems [12]. Therefore, the objective function given in (7) is converted to be minimization of the right hand side multiplied by -1 as:

$$\min\ S = -(k_l * \Delta p_l + k_E * \Delta E_l - k_C) \qquad (11)$$

The adopted RSA-based solution algorithm for the capacitor identification problem is as follows.

Step 1

Initialize the annealing parameters such as the initial temperature T_0, frozen temperature T_f, and the control parameters including the cooling rate B, and specified maximum iteration number N_{iter} at each temperature. Give an arbitrarily candidate solution, a vector of a length equals the number of low voltage buses in the distribution system, that meets the constraints. Then, calculate the initial value S_0 of the energy function using (11).

Step 2

Create a new solution. Simulated annealing generally perturbs some values of the solution vector from the old solution configuration to obtain a new solution. If any constraint (3) – (5) is violated, discard the candidate solution and repeat step 2.

Step 3

Generate wind power generation output. Run distribution harmonic power flow and check all constraints. If some constraints are violated, discard the last updated solution. Then go back to step 2 to create another updated solution. If all constraints are met then calculate the accumulative value of the objective function in (11). If the number of wind generation output is enough, go to step 4. Otherwise, repeat step 3.

Step 4

Calculate the new value of the accumulative energy function S_{new}. Find out the difference value $\Delta S=S_{new} - S_{old}$. Increase the iteration counter N_{itr} by one and go to step 5.

Step 5

Determine if the new solution should be acceptable or not. If the new solution decreases the energy function value, i.e. $\Delta S < 0$, then it will be accepted. It is also accepted if rand (0,1)<exp (-ΔS /T), where rand (0,1) is a random function between 0 and 1, T is the current annealing temperature. Otherwise, reject that last solution.

Step 6

Check whether the iteration number N_{iter} has reached the specified maximum number N_{limit} or not. If N_{iter} has not reached the specified maximum number N_{limit} then go back to step 2. Otherwise, check whether the current annealing temperature T has reached the frozen temperature T_f or not. If T is lower than T_f, then stop search. Otherwise, if it is still higher than T_f then, decrease the annealing temperature T to a value $T = B * T$. B is usually taken as a constant value around 0.8 [8], [12]. However, it is proposed in this work to compute the factor B as a variable parameter expressed as:

$$B= a+0.054*b \tag{12}$$

Where, a is an adjustable weighting factor. The coefficient b is given by:

$$b = (\Delta S_i - \Delta S_{i-1}) / \Delta S_{i-1} \tag{13}$$

Where, i is the iteration number. This modification offers resiliency feature to the simulated annealing algorithm resulting in considerably accelerating the convergence of the research procedure to the optimal solution. If B is grater than 0.8 then take B=0.8.

Reset N_{iter} to 0, go back to step 2 and repeat process.

CASE STUDY RESULTS

The presented algorithm is applied to the radial distribution system shown in Fig.1. The substation line voltage is 11 kV. The cost coefficients are taken as the average prices in the Egyptian market: k_l = 120 \$/kW, k_E = 0.064 \$/kWh and k_C = 500 \$/MVA [3], [4]. The set of allowable standard capacitor size to choose from is taken as: 0.5, 0.75, 1, 1.5, and 2 Mvar.

Two wind generators

Two wind generators (WGs) are included in the system of Fig.1. The integration node of the WG, its active power rating and its reactive power capacity are varied. The optimization problem is solved using the RSA to determine the sizes and locations of the prospective capacitors for each case. The total number of the prospective capacitor banks is constrained to 3 units. The results are indicated in Table 2. For all cases cited in Table 2, the maximum node voltage magnitude is below 1.045 p. u. The maximum value of THD_v of node voltages is less than 3.7%. Changing the size and/or integration node of the WGs causes tangible variation in the net economic savings. Also, the required capacitor banks sizes and locations are clearly affected by the WGs conditions.

On the other hand, case 1 in Table 2 is solved again when the total allowed number of the prospective capacitor banks is increased to 6 units. Only 5 capacitors are needed to attain the maximum savings. Their ratings are 0.75, 2, 0.75, 1.5, and 0.75 Mvar at nodes 2, 3, 14, 24, and 29, respectively. The total capacity of capacitors is increased to 5.75 Mvar compared to 4.5 Mvar for case 1. Also, the net economic savings is increased to 13419 \$/year. The capacitor cost is elevated to 2875 \$/year. Thus, the savings to capacitors cost ratio is lowered from 5.83 for allowing only three capacitors to 4.7 on allowing 6 capacitors. Fig.2 compares the average node voltage magnitudes in Fig. 2a and the THDv of node voltages in Fig.2b for case 1 in Table 2 with 3 and 6 capacitor banks.

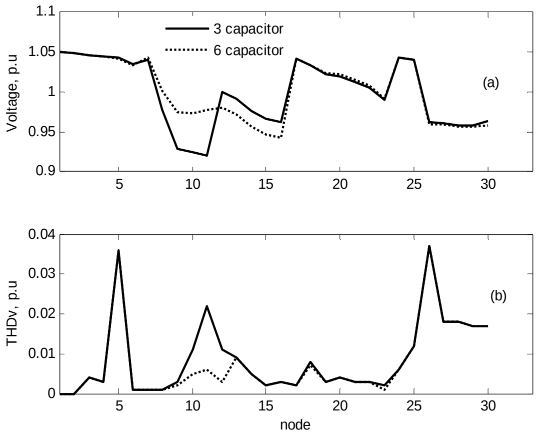

Fig.2 Node voltage and THDv for two 1 MW, 1 MVAr WGs at nodes 19 and11

Table 2 Solution results for two WGs

case	Wind generation						estimated capacitor banks						Minimum voltage	Capacitor Cost $/year	Savings $/year
	WG1			WG2			C1		C2		C3				
	node	Pw	Qw	node	Pw	Qw	size	node	size	node	size	node			
1	19	1	1	11	1	1	2	12	1.5	13	1	28	0.94	2250	13115
2	19	1	1	11	2	1	0.75	8	1.5	22	0.75	30	0.933	1500	4307
3	19	2	1	11	2	1	2	2	1	14	0.75	22	0.951	1875	4655
4	29	1	1	16	2	1	1	10	2	12	1	22	0.923	2000	12156
5	29	2	1	16	1	1	1	8	1.5	16	1	20	0.912	1750	14364

It is noted that the bus voltages are kept within the required limits of 0.9 p.u and 1.1 p.u. Also, the THDv of the system buses is maintained within the IEEE standard limit of 5%.

Three wind generators

Three WGs of 1 MW, 1 MVAr capacity are integrated into the system of Fig.1 at nodes 11, 19, and 29. The solution results are provided in Table 3 for two situations of allowing 3 and 6 capacitor banks. It is noticed that the results are ultimately identical. Only two capacitor banks are required to achieve the maximum savings. The negligible difference in the system performance in terms of the average voltage of each node and its THDv is owing to the modeling of the WGs active power output as a random variable of limited, even large, vector length. The capacitors cost is 1250 $. The savings to capacitors cost ratio is 14.8.

Table 3 Solution results for three WGs

Allowed capacitor number	estimated capacitor banks				Average minimum voltage	Savings $/year
	C1		C2			
	size	node	size	node		
3	1	22	1.5	25	0.93	18727
6	1	22	1.5	25	0.927	18659

CONCLUSION

A modified simulated annealing technique is proposed for simultaneous improvement of power quality and optimal placement and sizing of fixed capacitor banks in a model radial distribution network. The later is supplying a mix of linear and nonlinear loads imposing voltage and current harmonics. Besides, it includes integrated variable-speed wind turbines as distributed generation. The stochastic power output of the wind DG is considered by performing Monte-Carlo simulation of the distribution power flow. Operational and power quality constraints set the bounds of node voltage magnitude, node voltage total harmonic distortion, and the number/size of installed capacitors. The net annual economic saving is defined as the associated objective function. The optimization problem is solved for different scenarios. The number of installed capacitors becomes fewer for increased wind DG units. It does not exceed 20% of the system nodes. The obtained economic savings tend to be case-specific depending on number and distribution of wind DG units.

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