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Effect of Distributed Generators on the Optimal Operation of Distribution Networks

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Abstract**—**This paper presents an approach for daily optimal operation of distribution networks considering Distributed Generators (DGs). Due to private ownership of DGs, a cost based compensation method is used to encourage DGs in active and reactive power generation. The objective function is summation of electrical energy generated by DGs and substation bus (main bus) in the next day. A genetic algorithm is used to solve the optimal operation problem. The approach is tested on an IEEE34 buses distribution feeder.

Keywords**—**Distributed Generator, Daily Optimal Operation, Genetic Algorithm.

I. INTRODUCTION

DURING some last decades due to a great increase in operation efficiency and encouragement of financiers, electric power industry has encountered basic changes in the light of management and ownership, in a way that for making a proper competitive condition, various parts such as generation, transmission and distribution have been independent from each other[1]-[3].

These changes along with factors like environment pollution, transmission line establishment and technology advancement in economical construction of small-scale generation units in comparison with large ones have resulted in an increase in the usage of small-scale ones under the topic named Distributed Generators that mostly connect to distribution networks without needing transmission lines[1]-[3].

Research made by researching centers such as EPRI have anticipated that until the year 2010, about 25 percent of electric power is generated by DGs[1]-[3]. Therefore with developing usage process of these generators, management and operation of distribution networks should be studied more carefully. Generally, optimal operation management of power systems is applied to optimal usage of active and reactive power generation equipment entirely and controlling devices.
In the past, distribution networks only consisted of reactive power generation sources. Because of this, most of explorations done in this part of power systems had to do with optimal operation of reactive power. But these days due to existence of DGs, the effects of various types of these generators in the light of active and reactive power generation should be considered[4]-[13].

This paper presents a method for daily optimal operation of distribution networks regarding DGs. Due to ownership of DGs, a cost based compensation method is used to encourage owner of DGs in active and reactive power generation. The aim of this article is to determine active and reactive power generated by DGs, main substation (distribution offices), capacitors and also tap of tap-changer transformers in a manner to minimize objective function and regard the physical and technical constraints.

In overall view, because optimal operation of distribution networks is an optimization problem including continuous and discrete variables, evolutionary methods due to independence on primary conditions, being differentiable and continuous can be considered more and more. An approach based on genetic algorithm is used to solve the optimization problem.

II. DAILY OPTIMAL OPERATION IN DISTRIBUTION NETWORKS IN THE PRESENCE OF DGS

From From a mathematical standpoint, daily optimal operation in distribution networks with regard to DGs is a nonlinear optimization problem with continuous and discrete parameters and variables. The proposed objective function is defined as following:

$$f(X) = \sum_{t=1}^{Nd} (\mathrm{Pr}\ ice^{t} * P_{Sub}^{t} * \Delta t_t + \sum_{i=1}^{N_g} C_{Pgi}(P_{gi}^{t}) * \Delta t_t)$$

$$\overline{X} = [\overline{Tap}, \overline{Q_G}, \overline{U_C}, \overline{P_G}]$$

s.t:

$$\begin{aligned} &1.\quad ({P_{gi}}^{t})^2 + ({Q_{gi}}^{t})^2 \le S^2{}_{gi,\max} \qquad \mathrm{i} = 1,2,3,\ldots.\ \mathrm{N}_{\mathrm{g}} \\ &\quad\ {P_{gi}}^{\min} \le {P_{gi}}^{t} \le {P_{gi}}^{\max} \\ &\quad\ {Q_{gi}}^{\min} \le {Q_{gi}}^{t} \le {Q_{gi}}^{\max} \\ &2.\quad \left|P_{ij}^{Line}\right|^{t} < P_{ij,\max}^{Line} \\ &3.\quad \mathrm{Tap}_{\mathrm{i}}^{\min} < \mathrm{Tap}_{\mathrm{i}}^{\mathrm{t}} < \mathrm{Tap}_{\mathrm{i}}^{\max} \qquad \mathrm{i} = 1,2,3,\ldots.\ \mathrm{N}_{\mathrm{t}} \end{aligned} \qquad (1)$$

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4. $\mathrm{DOT}_i^{\mathrm{Trans}} \le \mathrm{MADOT}_i^{\mathrm{Trans}} \qquad i = 1,2,3,....N_t$
5. $\sum_{t=1}^{Nd} \mathrm{U}_{ci}^{t} \le \mathrm{MADOT}_i^{\mathrm{Cap}} \qquad i = 1,2,3,..., N_c$
6. $\mathrm{Pf}_{\min} \le \mathrm{Pf}^{t} \le \mathrm{Pf}_{\max}$
7. Unbalanced - three - phase - power - flow equations
8. $\mathrm{V}_i^{\min} \le V_i^t \le \mathrm{V}_i^{\max}$

where N_c, N_g , N_d *and* N_t are the number of capacitors, DGs, load variation steps and transformers, respectively. t is an index which represents the time step of load level. $\overline{X}$ is the vector of state variables. $\overline{Tap}$ is the tap vector which represents the tap positions of transformers for the next day. $\overline{Q_G}$ is the DGs reactive power vector including the reactive powers of all DGs for the next day. $\overline{U_C}$ is the capacitors switching vector including the states of all capacitors for the next day. $\overline{P_G}$ is the DGs active power vector including the active powers of all DGs for the next day. Δt_t is the time interval. $\mathrm{Pr}\,ice^t$ is the electrical energy price for the t^th^ load level step. $C_{Pgi}\left(P^t{}_{gi}\right)$ is the cost of electrical energy generated by the i^th^ DG during time “t”. V_i^t is the current voltage magnitude at the i^th^ bus during time “t”. $V^{min}{}_i$ and $V^{max}{}_i$ are the minimum and maximum values of voltage at the i^th^ bus, respectively. $MADOT_i^{Trans}$ and $MADOT_i^{Cap}$ are the maximum allowable daily operating times of the i^th^ transformer and capacitor, respectively. $\left|P_{ij}^{Line}\right|^t$ and $P_{ij,\max}^{Line}$ are the absolute power flow over distribution lines and maximum transmission power between the nodes *i* and *j,* respectively. $Tap_i^{\min}$, $Tap_i^{\max}$ and $Tap_i^{\,t}$ are the minimum, maximum and current tap positions of the i^{th} transformer, respectively. $Pf_{\min}$, $Pf_{\max}$ and $Pf^{\,t}$ are the minimum, maximum and current power factor at the substation bus during the time step t. $Q_{gi}^{\,t}$, $P_{gi}^{\,t}$ *and* $\mathrm{S}_{\mathrm{gi,max}}$ are the reactive and active powers for the t^th^ load level step and the apparent power of the i^th^ DGs, respectively. $U_{ci}^{\,t}$ is the state of the i^th^ capacitor in the light of turning on and off during time “t” ,which equals 0 or 1.

III. GENETIC ALGORITHM

A genetic algorithm (or GA) is a search technique used in computing to find true or approximate solutions to optimization and search problems. Genetic algorithms are categorized as global search heuristics. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination)[13].

Genetic algorithms are implemented as a computer simulation in which a population of abstract representations (called chromosomes or the genotype or the genome) of candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem evolves toward better solutions. Traditionally, solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (recombined and possibly mutated) to form a new population. The new population is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. If the algorithm has terminated due to a maximum number of generations, a satisfactory solution may or may not have been reached.

GA procedure

A typical genetic algorithm requires two things to be defined:

- a genetic representation of the solution domain,
- a fitness function to evaluate the solution domain.

A standard representation of the solution is as an array of bits. Arrays of other types and structures can be used in essentially the same way. The main property that makes these genetic representations convenient is that their parts are easily aligned due to their fixed size that facilitates simple crossover operation. Variable length representations were also used, but crossover implementation is more complex in this case. Tree-like representations are explored in Genetic programming and free-form representations are explored in HBGA.

The fitness function is defined over the genetic representation and measures the quality of the represented solution. The fitness function is always problem dependent. For instance, in the knapsack problem we want to maximize the total value of objects that we can put in a knapsack of some fixed capacity. A representation of a solution might be an array of bits, where each bit represents a different object, and the value of the bit (0 or 1) represents whether or not the object is in the knapsack. Not every such representation is valid, as the size of objects may exceed the capacity of the knapsack. The fitness of the solution is the sum of values of all objects in the knapsack if the representation is valid or 0 otherwise. In some problems, it is hard or even impossible to define the fitness expression; in these cases, interactive genetic algorithms are used.

To implement the GA to solve daily Volt/Var control, the following steps should be repeated.

Step1. Initialization

Initially many individual solutions are randomly generated to form an initial population. The population size depends on the nature of the problem, but typically contains several hundreds or thousands of possible solutions. Traditionally, the population is generated randomly, covering the entire range of possible solutions (the search space). Occasionally, the solutions may be "seeded" in areas where optimal solutions are likely to be found.

Step2. Selection

During each successive generation, a proportion of the existing population is selected to breed a new generation. Individual solutions are selected through a fitness-based process, where fitter solutions (as measured by a fitness function) are typically more likely to be selected. Certain selection methods rate the fitness of each solution and preferentially select the best solutions. Other methods rate only a random sample of the population, as this process may be very time-consuming.

Most functions are stochastic and designed so that a small proportion of less fit solutions are selected. This helps keep the diversity of the population large, preventing premature convergence on poor solutions. Popular and well-studied selection methods include roulette wheel selection and tournament selection.

Step3. Reproduction

The next step is to generate a second generation population of solutions from those selected through genetic operators: crossover (also called recombination), and/or mutation.

For each new solution to be produced, a pair of "parent" solutions is selected for breeding from the pool selected previously. By producing a "child" solution using the above methods of crossover and mutation, a new solution is created which typically shares many of the characteristics of its "parents". New parents are selected for each child, and the process continues until a new population of solutions of appropriate size is generated.

These processes ultimately result in the next generation population of chromosomes that is different from the initial generation. Generally the average fitness will have increased by this procedure for the population, since only the best organisms from the first generation are selected for breeding, along with a small proportion of less fit solutions, for reasons already mentioned above.

Step4. Mutation

Each bit of a chromosome can be modified with a very low probability p (p= 0.001-0.1) set by the user by considering the contingency time of generations.

Step5. Termination

This generational process is repeated until a termination condition has been reached. Common terminating conditions are

- A solution is found that satisfies minimum criteria
- Fixed number of generations reached
- Allocated budget (computation time/money) reached
- The highest ranking solution's fitness is reaching or has reached a plateau such that successive iterations no longer produce better results
- Manual inspection
- Combinations of the above.

IV. DISTRIBUTED GENERATOR MODELING

Generally, DGs in distribution networks can be modeled as PV or PQ models.

Since distribution networks are unbalanced three phase systems, DGs can be controlled and operated in two forms: Simultaneous three-phase control

- Independent three-phase control or single phase control

Therefore, regarding the control methods and DGs models, four models can be defined for simulation of these generators (Fig.1):

- PQ model with simultaneous three-phase control
- PV model with simultaneous three-phase control
- PQ model with independent three -phase control
- PV model with independent three -phase control

It must be taken into account that when DGs are considered as PV models, they have to be able to generate reactive power to maintain their voltage magnitudes. In order to model DGs as PV buses many researchers have presented several procedures [21] and [22]. In this paper, DGs are modeled as the PQ buses with simultaneous three-phase control.

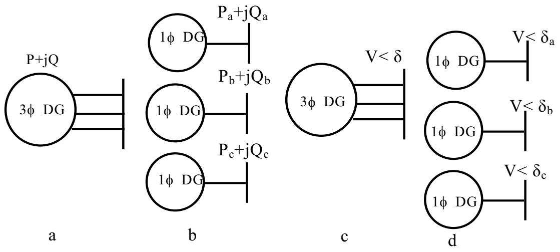

Fig. 1 Models of DGs

(a). PQ Model with simultaneous three-phase control
(b). PQ Model with separately three- phase control
(c). PV Model with simultaneous three- phase control
(d). PV Model with independent three- phase control

V. SIMULATION

In this part, GA has been implemented to solve the Volt/Var control on the 34 Bus IEEE test feeder, whose one line diagram is given in Fig.2. The feeder lines and load data are taken from [14].

It is assumed that there are 3 generators whose specifications are given in Table I.

Daily energy price variations and daily load variations are shown in Figs.3 and 4.

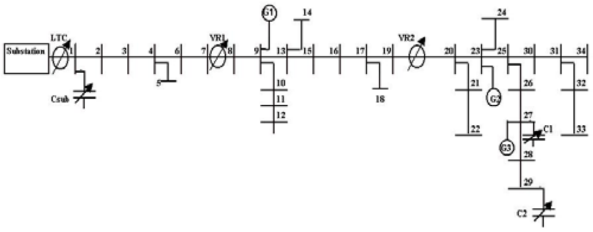

Fig. 2 Single Line Diagram

TABLE I
CHARACTERISTIC OF GENERATORS

	Capacity (kW)	Max Reactive Power (kVar)	Min Reactive Power (kVar)	Capital cost ($/kW)	Life time (Year)	Fuel cost ($/kWh)	O & M cost ($/kWh)
G1	300	240	-180	3674	12.5	0.029	0.01
G2	500	400	-300	1500	20	0	0.005
G3	1000	800	-600	715	20	0.067	0.006

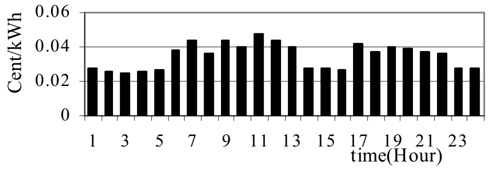

Fig. 3 Daily energy price variations

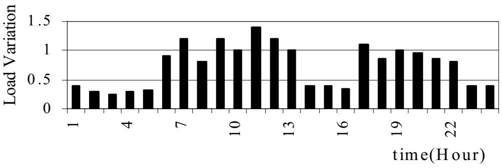

Fig. 4.Daily load variations

Capacitors characteristics are in Table II.

TABLE II
CHARACTERISTICS OF CAPACITORS

Capacitor Number	Location (bus No)	Size (kVar)
C_{Sub1}	1	100
C_{Sub2}	1	300
C_1	27	450
C_2	29	300

In this paper, it is assumed that cost of each kilowatt-hour of electric energy generated by each DG is composed of the following components:

- Investment (equipment purchasing, establishment)
- Operation & maintenance cost
- Fuel cost.

The hourly cost function of DGs can be defined as follows:

$$C_{Pg}(P) = a + b * P \tag{2}$$

Coefficients "a" and "b" are calculated as follows:

$$a = \frac{Capital\quad Cost(\$/kW)\ *Capacity(\ kW)*Gr}{LifeTime(Y\ ear)*365*24*LF} \tag{3}$$

$$b = FuelCost(\$/kWh) + O\,\&\,MCost(\$/kWh) \tag{4}$$

where *Gr* and *LF* are the annual rate of benefit and DG loading factor respectively.

In this paper, it is supposed that maximum numbers of switching operations for capacitors along feeder and substation (main station) are 1 and 3 respectively. Also, it is assumed that transformers and VRs have 21 tap positions ([-10, -9… 0,1,2…10]) and MADOT of them in a day is 30. They can change voltage from –5% to +5%.

The voltage changes of some buses for three cases (Controllable DGs(Case1), Uncontrollable DGs(Case2) and without any control(Case3)) are shown in Figs.5, 6 and 7.

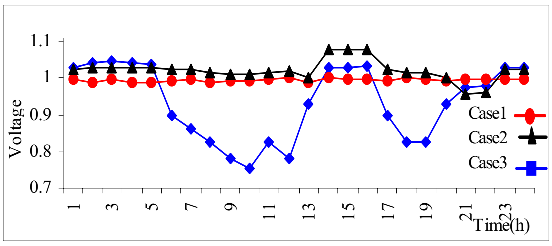

Fig. 5 Voltage variations of bus19 over a day

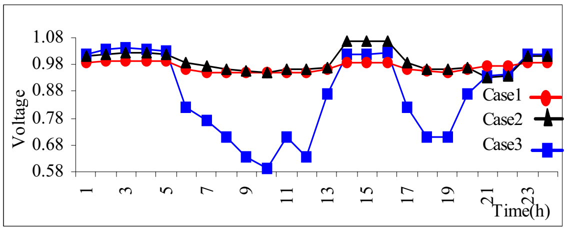

Fig. 6 Voltage variations of bus21 over a day

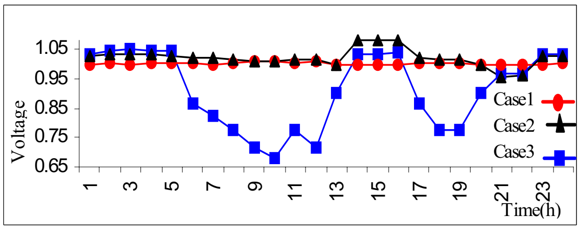

Fig.7 Voltage variations of bus34 over a day

Table III shows the simulation results in terms of the number of capacitors' allowable switching operations.

TABLE III
INFLUENCE OF MAXIMUM ALLOWABLE SWITCHING OPERATION OF CAPACITORS

Maximum number of allowable switching operation	The proposed in paper	Infinite
Energy Losses (kWh) (DG is controllable)	845.79	840.36
Energy Losses (kWh) (DG is Uncontrollable)	3289.93	2897.352

VI. DISCUSSION

In this section, with references to Tables and Figs presented in the previous section, a discussion can be summarized as follows:

1. Since most of DGs have private ownership, the cost of active power generation can be used as an encouraging signal.
2. The voltage profiles have been shown in three cases:
   Case1: With control on DGs
   Case2: Without control on DGs
   Case3: Without any controller equipments such as transformers, capacitors, DGs, etc.

The results of these Figs indicate that the voltage profiles in the first case are much better than those of in the second and third cases. In other words, in the first case, the voltage profiles are very little around their rated amounts but in other cases, the voltage magnitude in some buses reaches under 95 percent and upper 1.05 percent of its rated value for some hours in a day.

3. Summation of electrical energy losses in three cases are 845.8, 3289.93 and 3585.4, respectively. Under the proper control on DGs, electrical energy losses are much less than other cases. On the other hands, it can be concluded that the system performance can be improved under proper control.
4. The electric energy losses in the first case (Controllable DGs) have much lower sensitivity to changes in capacitor switching operation. In other words, when DGs are controllable, the daily Volt/Var control problem can be solved for each step of load levels independently. This means that convergence time decreases.
5. Distributed generations have much better performance and time response than other sources of reactive power generation like capacitors. Thus system performance can be improved considering proper factors to control them.

VII. CONCLUSION

As pointed in the previous sections, issues such as environment pollution, restructuring in electrical industry and technology advancement have resulted in an increase in the usage of distributed generators which most of the time connect to the distribution networks. Therefore, with increase in connection of these generators to the distribution networks, it is necessary to study the effects of these generators on distribution systems and define proper signals to control of them. In this paper, a new cost based compensation methodology has been used as a proper signal to encourage DGs in active and reactive power generation. The simulation results show that the defined factor has caused more reduction in the total electrical energy losses in the system.

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