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ELECTRIC DISTRIBUTION SYSTEMS AND EMBEDDED GENERATION CAPACITY

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ABSTRACT

The increasing Distributed Generation (DG) capacity in future distribution networks will involve more complex control systems and a shift towards active network management. Distribution System Operators (DSOs) will, therefore, forced to change their role into an active one. On these basis, a reconfiguration methodology based on a Genetic Algorithm (GA) is proposed in order to assist DSOs in planning and managing DG connections and in maximizing DG penetration and renewable sources exploitation. The methodology, tested on a 70-bus system with DG units, confirmed its effectiveness in increasing the overall DG penetration allowing, thus to exploit network capability, while limiting power losses under a benchmark value.

KEY WORDS

Distributed power generation, Genetic algorithms, Network reconfiguration, Power distribution planning.

1. INTRODUCTION

Sustainable energy supply promotion and liberalization of energy markets represent the main policy issues of European States, which introduced market competition in electricity production and created support mechanisms to encourage renewable electricity production and consumption. As a consequence of liberalization, any generator, including small-scale and renewable energy based units, can sell electricity on the free market. Therefore, connection of a higher number of Distributed Generation (DG) units to the electrical power system is expected, in order to meet future sustainability targets. This event would require changes in the design and operation of distribution electricity systems, as well as changes in electricity network regulation. Moreover, connection of DG to distribution networks generates both long-term and short-term operational and capital costs and benefits which can be network-related or energy-related. Both costs and benefits should be identified, assigned a monetary value and allocated between DG developers and Distribution System Operators (DSOs). It should be also stressed that, depending on the particular situation, the increasing capacity of DG may generate positive or negative effects and, sometimes, may negatively affect the business of DSOs. As regards network losses, for example, depending, among other factors, on its penetration level, DG may have positive or negative impacts on distribution losses [1]. Moreover, regarding DG penetration, the present first-come first-served policy for DG connection represents an obstacle to maximum DG penetration and to renewable development. In fact, once a developer gives a connection agreement for new DG units, the successive new generation expansions must impact positively on the access of the prior connection. In this way, sometimes, a minor generation connection can avoid further and larger DG expansions [2]. On the basis of these considerations, DSOs, by optimally managing DG access rights to the network, could be able to maximize the total DG penetration and renewable sources exploitation and to avoid power losses exceeding a benchmark value. Considering the DSOs opportunities related to DG and, in order to provide a suitable tool for network planning, a Genetic Algorithm (GA) based reconfiguration methodology is described and tested in this paper. The use of GA well adapts to the optimal reconfiguration problem, since, in large-scale distribution systems, a reconfiguration problem represents a complicated combinatorial, nondifferentiable constrained optimization problem in which many tie switches must be properly determined by considering various operational constraints.

Before describing the proposed GA based reconfiguration methodology, some related papers are analyzed.

A research on feeder reconfiguration for loss reduction is conducted in [3], while in [4], the problem of loss reduction and load balancing is modeled as an integer programming problem. In [5,6], a genetic algorithm is used to look for the minimum loss configuration. In [7–9], the use of the power flow method based on a heuristic algorithm is presented in order to determine the minimum loss configuration to radial distribution networks. In [10] an expert system is applied to solve the problem of distribution system reconfiguration, while simulated annealing is applied to minimize power loss in [11,12]. Tabu search is applied to solve the reconfiguration problem in distribution system in [13,14]. Recently, simulated annealing, genetic algorithm, and tabu search are integrated for solving optimization problems in power system [15–21]. In [22], a fuzzy multi-objective approach to solve the network reconfiguration problem is proposed. In [23,24], evolutionary programming and the fuzzy theory are used to solve the problem of feeder reconfiguration. In [25], an economic operation model to solve distribution network configuration is employed. In [26] an operational scheme, using network reconfiguration as real time operation tool for loss reduction is presented. In [27], a reconfiguration method is applied to distribution networks for voltage stability enhancement. GA and fuzzy methods have been used for power distribution reconfiguration problems in [28]. In [29] the integration of DG units into future power systems operation and planning schemes is presented, considering DGs integrated in network reconfiguration for loss reduction and service restoration. In [30] reconfiguration is solved through a heuristic methodology and a losses based allocation function. In [31] an optimal reconfiguration method, based upon a maximum loadability index for radial distribution systems, is presented.

Even if several papers in literature deal with the problem of distribution networks reconfiguration, some issues related to the relationships between power losses and DG penetration are not considered, yet. The proposed GA based reconfiguration methodology, therefore, aims at improving DSOs benefits, by identifying the maximum DG capacity which allows to constrain power losses under a benchmark value. The methodology is based on a multi-objective function, built in order maximize DG capacity at given locations, while controlling lines loading, buses voltages and power losses.

2. STRUCTURE OF FUTURE ELECTRICITY SYSTEMS

The expected growth of DG penetration will significantly affect the operation and control of distribution systems with DG and will promote a more significant utilize of distribution automation. Nevertheless, before adopting complex and innovative control systems, the conditions to develop the future distribution networks will be aided by meshed networks, which can improve the capability of networks to accommodate DG. In most cases, since distribution networks are already meshed but radially managed, the changing towards meshed network does not require building new lines, but only few modifications to the net.

Three models have been considered in literature for future distribution networks with high DG penetration: active networks, supported by Information and Communication Technology (ICT), microgrids and the Internet model.

The active networks have been specifically conjectured as facilitators for increased penetration of DG. They are based on ICT and on strategies used to manage actively the network. The active network model employs two novel concepts: at first the primary role of the network is to provide connectivity between the points of power supply and demand, besides the distribution network must interact with the customers. The structure of this model is based on increased interconnection as opposed to the current mostly linear/radial connections, relatively small local control areas and the charging of system services is based on connectivity. In order to assure connectivity and guarantee interaction among generators and loads, one of the operational scheme is network reconfiguration, that is defined as altering the topological structures of distribution feeders by changing the open/closed states of the feeder switches. Feeder reconfiguration allows to transfer loads and generators from feeder to feeder and, consequently, to change the network connectivity characteristics.

Microgrids are small low-voltage distribution systems connecting several customers to several small, modular generators of less than 100 kWs and can be connected to the main power network or be operated autonomously. An innovative operation of distribution networks based on ICT, network reconfiguration and special control and generator protection systems are required in order to integrate microgrids in the power systems and to facilitate the connection of DG units. Microgrids allow providing power supply to remote communities, where connection to transmission supply is expensive. Moreover, microgrids could cause profits both to the customers, by reducing the energy price and increasing the reliability and to the DSOs, which could reduce investments or activate new business.

The internet model considers the active network and takes it to the global scale by distributing control around the system. According to the internet model: “every node in the electrical network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming and interconnected with everything else” [32]. Each supply node will be controlled and the control tasks will be more and more complex because of a large number of supply and switching nodes to be monitored and controlled. In particular, intelligent Flexible Alternating Current Transmission Systems (FACTS) at the nodes between producers and consumers, network reconfiguration and the integration of ICT into the network will transform it into a fully interactive intelligent network.

3. A RECONFIGURATION METHODOLOGY TO MAXIMIZE DG PENETRATION WHILE CONSTRAINING POWER LOSSES

Considering the opportunities offered by DG, which can bring a reduction both in variable costs and in fixed costs, including a reduction in energy losses and reinforcement costs, DSOs should change their role from passive network managers, responsible only for network reliability and connection of passive customers, to active network managers. With a shift towards active network management, DSOs could, instead, carry on profitable actions, such as encouraging DG at given locations and with desirable capacities in order to reduce network investment and losses, promoting demand side management, managing ancillary services, etc. Nevertheless, it's worth noting that a DG connection could at times increase losses or anticipate the date of future restructuring, thus increasing network costs.

Distribution losses are, in fact, an important factor to deal with when deciding on the amount and type of DG capacity, influencing generation location decisions, too. In some countries the power losses issue is tackled by rewarding DSOs for losses reductions below a target level and penalizing them for failure to reach the target [33].

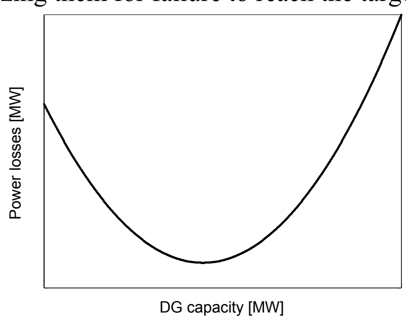

Fig. 1 Power losses vs DG capacity

Injections of power from DG at lower voltages generally reduce losses but, where injections exceed demand at any time, additional generation may increase overall losses. While the impact of DG on losses is site and time specific there is a tendency for losses to follow the pattern described in Fig. 1. As when DG penetration exceeds a certain level, losses marginally increase and can usually overtake losses benchmark value [34], the establishment of DG maximum power injection, allowing to constrain losses, represents an important issue for DSOs, whishing to reduce power losses while maximizing DG penetration.

Therefore, in this section a GA based reconfiguration methodology with the task of achieving the maximum DG penetration while constraining power losses under a benchmark value and observing thermal and voltage constraints, is presented and tested. In addition, the proposed reconfiguration methodology aims at overcoming the current first-come first-served policy for DG penetration. The proposed methodology, consequently, represents a suitable tool for network developers in order to increase, as much as possible, the power produced by DG units and furnished to consumers, constraining losses and keeping the power system in a secure state, in terms of branch loading and voltage levels. As regards the GA, in order to take into account the parameters of the optimization problem, the chromosome consists of two parts. The first part consists of a string of binary values (0,1), representing the open/closed status of the switches, while the second part is a vector representing the amount of power injected by DG units. The length of the chromosome is, thus, equal to the number of the lines of the network, that can be switched on/off, plus the number of DG units allocated in the network. Furthermore, the operators of reproduction, crossover and mutation are considered as genetic operators and an elitism mechanism, ensuring the best member of the population is not lost is also adopted. As far as the fitness function is concerned, it is built in order to penalize network configurations leading to overloads of distribution lines, over or under voltages at buses and losses to exceed the benchmark value. For a given network configuration, the fitness function is obtained by considering both the maximum allowed power supplied by DG sources and power losses value, together with lines exploitation and buses voltages. For a preset location of DG units, the proposed GA based methodology aims at solving the following optimization problem:

$$\begin{cases} \max\limits_{S,P} f(S,P) & \\ S(i) \in \{0,1\} & i = 1,\dots,N_{line} \\ 0 \le P(j) \le P_{\max} & j = 1,\dots,N_G \end{cases} \quad (1)$$

where **S** is the status vector of the lines switches, **P** the vector of active powers supplied by the DG units, N_G is the total number of generators, N_{line} is the total number of lines for a given network configuration. The fitness function is defined as:

$$f = \xi(f_{line}, f_{bus}, f_{Losses}) \times \sum_{i=1}^{N_G} P_{Gi} \quad (2)$$

where P_{Gi} is the active power supplied by the *i-th* generator [MW],

$$\xi(f_{line}, f_{bus}, f_{Losses}) = \begin{cases} 1 & if\ f_{line} = f_{bus} = f_{Losses} = 1 \\ 0 & otherwise \end{cases}$$

f_{Losses} is a function related to power losses, it's equal to 1 if power losses are below the benchmark value, otherwise it decreases exponentially with losses, as shown in figure 2; f_{line} and f_{bus} are functions related to buses voltages and branches loading, according to the functions $C_{line,i}$ and $V_{bus,j}$ shown in figures 3 and 4 and defined as:

$$f_{line} = \prod_{i=1}^{N_{line}} C_{line,i} \quad (3)$$

$$f_{bus} = \prod_{j=1}^{N_{bus}} V_{bus,j} \quad (4)$$

N_{bus} is the total number of buses, V the voltage amplitude at bus [*p.u.*], B_L the branch loading, in per cent of the maximum line capacity, λ_{VBUS}, λ_{CLINE} and λ_{Losses} are coefficients used to modify the slop of the exponential functions, L and L^{BC} are the power losses and the power losses benchmark values.

In order to evaluate f_{line}, the function $C_{line,i}$ is computed for each line of the network: for the *i-th* line, if the value of loading is less than 100% of the line maximum capacity, C_{i}=1, otherwise it decreases exponentially with overload. In order to evaluate f_{bus}, the function $V_{bus,j}$ is computed for each bus and is equal to 1 if the *j-th* bus voltage is included between ±10% of the nominal value, otherwise it decreases with an exponential decay.

The flow chart of the algorithm is shown in fig. 5.

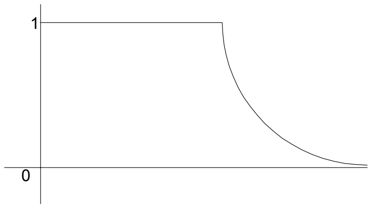

Fig. 2 Function related to power losses

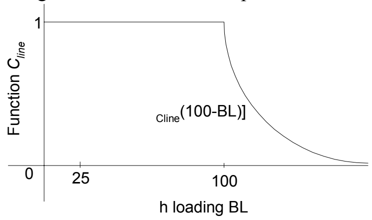

Fig. 3 Function related to branch loading

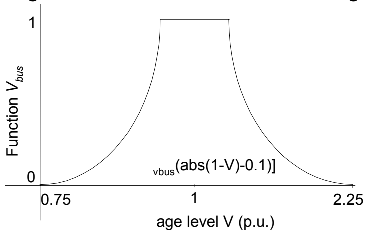

Fig. 4 Function related to voltage levels

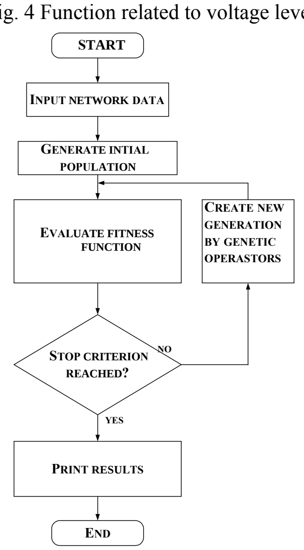

Fig. 5 Flow chart of the implemented methodology

In the defined fitness function, other criteria such as costs of reclosing are not taken into consideration at this stage of the research.

4. CASE STUDY

In order to establish the effectiveness of the proposed methodology, and using a tool developed in Matlab® environment, simulations were carried out on a 11-kV distribution system having two substations, four feeders, 70 nodes and 78 branches (including tie branches), data for this system are given in [35]. In the tested system three DG sources are assumed to be connected to nodes 37, 45 and 65, as shown in figure 6.

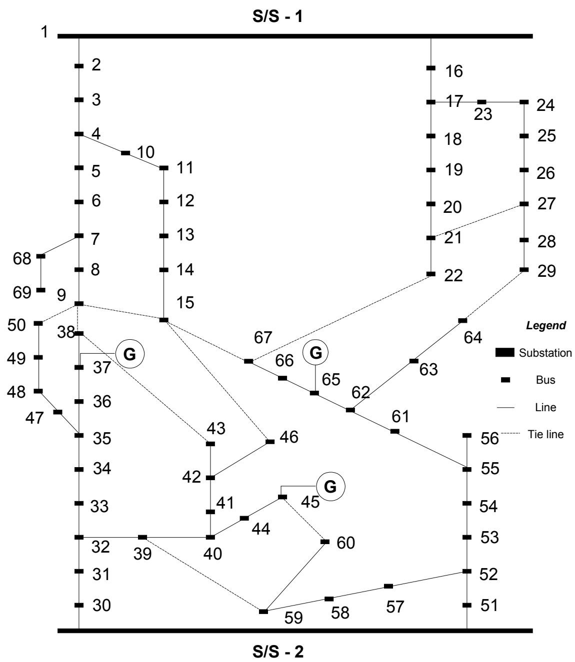

Fig. 6. Tested distribution system

As regards the DG typology, in general, two types of primary sources can be distinguished: generators by aleatory source and generators by deterministic sources. The first group of generators supplies only if the source is physically present, the second group supplies according to production programs. In this paper generators with a programmed power have been considered and a unitary contemporary factor between generation and loads has been assumed [2]. Nevertheless, further works are in progress to extend the planning procedure also in the presence of aleatory DG sources.

With regards to the binary GA, a normalized geometric ranking scheme is used as selection mechanism, while the simple crossover and the binary mutation are employed as genetic operators. For tuning the GA, a population size of 20 and a number of 200 generations are set. The simulation experience shows that these values, for the power system under study, guarantee the convergence of the algorithm to a satisfactory solution. A first analysis has been conducted by considering each DG unit, one by one, connected at given locations without considering the losses related function f_{Losses}.

In detail, two different kinds of simulations have been carried out. The first assumes to fix network topology to its basic configuration and disables reconfiguration chance, while the second enables reconfiguration chance. In both cases the GA based methodology has been applied to three different situations, considering, respectively, a DG unit connected only to bus 37 or 45 or 65.

Table I: Maximum capacities available at individual locations without reconfiguration

Bus location	Power Factor	Maximum Capacity [MW]	Violated Constraint
37	0.9	2.23	Voltage
45	0.9	2.70	Voltage
65	0.9	1.94	Voltage

Table I shows the maximum capacities available at individual locations for the considered DG units, operating at 0.9 lagging power factor and for the network basic configuration. The voltage limits constraint injections for all connections, in these cases. Therefore, connection application with generator capacities exceeding these values will require alleviation and, perhaps, network reinforcement. Instead, the maximum capacities available at individual locations with reconfiguration chance are shown in table II.

Table II: Maximum capacities available at individual locations with reconfiguration

Bus location	Power Factor	Maximum Capacity [MW]	Violated Constraint
37	0.9	5.72	Thermal
45	0.9	4.75	Thermal
65	0.9	5.16	Voltage

It can be observed that the maximum capacities available at individual locations have been increased by network reconfiguration for all connections. In the case of connection to buses 37 and 45 the injection is constrained by thermal limits, while in the case of connection to bus 65 the voltage limit constraints injection. Then, starting from a situation in which a DG unit, connected at bus 37 operates at its maximum individual capacity, the other two DG units have been connected, sequentially, to buses 45 and 65, and the GA methodology has been applied twice.

Simulation results showed that an early DG connection could prevent future generation expansions in other sites, as can be observed in table III.

Table III: Maximum capacities at a selection of locations

	Without reconfiguration			With reconfiguration		
Bus location	37 Only	37-45	37-65	37 Only	37-45	37-45-65
37	2.23	2.23	2.23	5.72	5.72	5.72
45	-	0	-	-	0.18	0.18
65	-	-	0	-	-	0.14
Total	2.23	2.23	2.23	5.72	5.90	6.04

In detail, for the examined network, without reconfiguration, no additional power could be connected to buses 45 and 65, and the overall capacity is connected to bus 37, instead with reconfiguration choice an overall maximum capacity for DG connection of 6.04 MW can be achieved. Nevertheless, in this case only 0.18 MW and 0.14 MW can be connected respectively to bus 45 and to bus 65 because of early connections to buses 37.

At last, the proposed reconfiguration based methodology, both with and without considering function f_{Losses} in the GA fitness function, has been applied assuming the three DG units, operating at 0.9 lagging power factor, simultaneously connected to buses 37, 45 and 65.

Table IV: Optimal capacities with reconfiguration

Bus location	Capacity [MW]	
	Without losses function	With losses function
37	2.46	1.54
45	3.80	2.59
65	4.28	3.05
Total	10.54	7.18
Losses [MW]	0.604	0.227

Simulation results for the two cases, shown in table IV, confirm that an overall increase in capacity can be observed in both cases, if compared to the results in table III. In fact, a total capacity increase of 75% and of 19% can be attained, respectively, without and with considering losses function f_{Losses}.

Nevertheless, even if a DG capacity increase of about 56% can be evidenced without considering losses function, an increase of 165% of power losses can be observed, with a losses benchmark value of 0.228 MW, relative to the network without DGs and with all tie lines open. The introduction of the losses function, instead, allowed, by constraining DG penetration, to limit power losses under the benchmark value. Therefore, the proposed methodology allows to explain the potential DG penetration network-wide, offering to DSOs a suitable tool to cope with planning of DG connection to distribution networks and furnishing information regarding the best policy they could follow in giving connection agreement for new DG units, also allowing for power losses reduction. In fact, as confirmed by simulation results, the present first-come first-served policy for DG connection is an impediment to maximum DG penetration and control of power losses in presence of DG. For this reason, DSOs should use information regarding DG penetration network-wide and power losses value for operation and planning of DG connections. Moreover, DSOs could furnish also information regarding the maximum power that can be produced by DG units at given locations and at different time during the year forcing, indirectly, in this way investors for best connections in terms of locations. On the other side, as confirmed by the simulation results, optimal network reconfiguration can increase both individual and overall DG penetration, allowing to limit power losses, thus allowing to exploit network capability.

5. CONCLUSION

The increment of DG capacity into existing networks has a great impact on electrical system operation and planning, therefore changing the DSOs role into an active one. Moreover, in future active electrical networks DG will be integrated with modern control systems, new information technologies and power electronics devices. Since new planning methodologies, able to cope with DG capacity expansion in future power systems, are essential, a GA based network reconfiguration methodology, allowing to maximize DG penetration on distribution networks, while limiting network power losses and respecting network constraints has been proposed and tested. As confirmed by simulation results, the methodology represents a suitable tool for DSOs when dealing with DG capacity expansion and power losses issue, giving information regarding the potential penetration network-wide and allowing maximum exploitation of renewable generation.

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