Coordinated Distribution Network Reconfiguration and Distributed Generation Allocation via Genetic Algorithm

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***Abstract*—The share of renewable energy sources (RESs) in the overall power production is on the upward trend in many power systems. Especially in recent years, considerable amounts of RES type distributed generations (DGs) are being integrated in distribution systems, albeit several challenges mainly induced by the intermittent nature of power productions using such resources. Optimal planning and efficient management of such resources is therefore highly necessary to alleviate their negative impacts, which increase with the penetration level. This paper deals with the optimal allocation (i.e. size and placement) of RES type DGs in coordination with reconfiguration of distribution systems (RDS). Moreover, the paper presents quantitative analysis with regards to the impacts of RDS on the integration level of such DGs in distribution systems. To this end, a tailor-made genetic algorithm (GA) based optimization model is developed. The proposed model is tested on a 16-node network system. Numerical results show the positive contributions of network reconfiguration on increasing the level of renewable DG penetration, and improving the overall performance of the system in terms of reduced costs and losses as well as a more stabilized voltage profile.**

Keywords—Distributed Generation, Genetic Algorithm, Network Reconfiguration, Renewable Energy Sources.

I. INTRODUCTION

Globally, the electric power sector is undergoing major changes in its energy production structure, with a shift in power production from a centralized to semi-centralized paradigm involving distributed generation (DG) sources, renewables in particular (especially, wind and solar). The evolution of the sector is driven by several reasons such as intensifying energy security and environmental concerns as a result of power production using conventional energy sources such as oil and coal [1]. Another major reason is the sustained growth in demand for electricity, from the consumer side. As a result, the integration of renewable energy sources (RESs) has been gaining momentum globally. Recognizing the wide-range benefits of such resources, especially in addressing the aforementioned and other underlining challenges, policy makers and planners in many states are now busy in crafting clean energy development goals. However, the paradigm shift in power production inherently brings some technical, social and economic challenges. Some of these are related to the question of power quality and cost, system reliability and integrity, and societal matters among others. Generally, the integration of RES type DGs should be carefully handled, requiring tools and methods for optimal planning and efficient management of such DGs [2]. In this work, a genetic algorithm based optimization model is proposed to deal with the optimal allocation of such DGs along with the reconfiguration problem of distribution network systems. The overall aim here is to maximize the deployment of renewables while simultaneously minimizing the ensuing technical challenges mentioned earlier by means of optimal network reconfiguration, sizing and placement of RES type DGs.

In other words, several technical challenges arise as a result of the variable and uncertain nature of RES power outputs. These challenges can however be effectively reduced via optimal planning and available technologies such as various flexibility options. Among these flexibility options is the reconfiguration of distribution systems (RDS). The concept of RDS is to optimally change the topology of network systems so that such systems are operated more efficiently. RDS makes the system capable of robustly adapting to various operational conditions. This can substantially increase system flexibility, important for accommodating more variable renewable power. At the same time, RDS may lead to an improved voltage profile in the system. The central focus of using RDS in the past has been on the minimization of network losses. However, its potential for the improvement of voltage profiles has also been demonstrated in previous studies [3]. Thus, this work proposes a method that coordinates the allocation of DGs in the system with RDS, aiming to large-scale integration of RESs while minimizing their negative effects on distribution network systems.

The impact of DGs and their optimal integration to the electricity system have been extensively studied in several works in the literature [3] and [4]. The works in [5]–[7] highlight some of the essential points that must always be considered in the DG integration: the DG placement and sizing in relation to the network topology, as well as the demand at each node in the system. For instance, mainly due to stability reasons, each node in a distribution network system has an optimal level of DG integration.

In the literature, there is a wide-range of approaches that deal with the problem of integrating DGs in distribution systems. The vast majority of these approaches are based on

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heuristic methods [10]–[16]. However, some researchers also employ analytical [21], [22] and numerical methods [17]–[20] to solve the same problem. In the category of heuristic methods, particle swarm optimization (PSO) [13], [14], [23]–[25], genetic algorithms (GA) [10]–[12], [26] and harmony search (HS) [27], [28] are some of the methods employed to solve the DG allocation problem. Despite the significant progress in the solution of the aforementioned problem, most of the analyses in many previous works mostly focus on the allocation of one or two DGs (commonly of a conventional type), and the impact of placing such DGs at various locations in distribution systems. The simultaneous consideration of RDS and DG allocation problems, and the impact analysis of RDS on the level of RES type DG integration are not adequately addressed in previous works.

Hence, this work deals with the optimal allocation of RES type DGs in coordination with the optimal reconfiguration of distribution network systems. In addition, the work simultaneously quantifies the impacts of network reconfiguration on the integration level of such DGs in distribution systems. The analysis also includes the effects of network reconfiguration and RES-based DG integration in distribution network systems on the operational performance of such systems. To this end, a tailor-made genetic algorithm (GA) based optimization model is developed.

The main contributions of this work include:

- mathematical model for simultaneously optimizing distribution network reconfiguration and integration of RES type DGs;
- quantitative and qualitative analysis in relation to the effects of DG allocations along with distribution network reconfiguration on relevant system variables in distribution networks.

The rest of this paper is organized as follows. Section III presents a description of the developed optimization model. Numerical results are presented and discussed in Section IV. The last section presents some conclusions drawn from the entire work in this paper.

II. MODEL FORMULATION

In this work, a modified genetic algorithm, which is based on Darwin's theory of evolution, is employed to solve the reconfiguration and DG allocation problems of distribution systems. This algorithm is selected because it is suitable for solving complex constrained and unconstrained optimization problems. The type of problem addressed in this work is of a non-linear and combinatorial nature for which the proposed algorithm can efficiently provide "good-enough" solutions.

The process that normally guides the GA is mostly initialization, mutation, evaluation and selection. As stated earlier, in this work, GA is used to solve the reconfiguration of a distribution system as wells as the sizing and placement of DGs. The algorithm employed here is described as follows.

A. Objective Function

The objective function of the algorithm (1) is to minimize the total operation cost of power production in the system, under an AC OPF approach.

$$F = \min C_i \tag{1}$$

In the above equation, C_i is the total cost of each population, which is alternatively called as the fitness function.

B. Initialization

To set the statuses of branches, binary values are randomly generated and associated to each line. The population size is equal to the number of branches that make a radial and connected network. This means a population size equal to the difference of the number of buses and the number of substations is first generated.

The DG sizing and location problem undertakes integer values. Whereas, the DG chromosome randomly generates integer numbers, representing the size of a DG and with a dimension equal to the number of buses to simultaneously determine the location problem. This will imply that each individual DG population has the size and the location information.

C. Mutation and Crossover

For the branch populations, a uniform crossover and a Boolean mutation are employed. As for the DG population, integer mutation is applied for new populations, based on their corresponding fitness functions. Crossover utilizes the information of two or more individuals to create new fit individuals. Mutation will diversify when new information is introduced in the new individuals, and consequently will diversify the population.

D. Selection

Tournament selection is chosen to select the minimum cost in the fitness function. In such a selection process, *n* equally probable individuals of the population are generated randomly. The fittest individual is selected, and accepted to an intermediate population. The process is terminated when a predetermined number of intermediate populations is reached.

E. Restrictions

To preserve the radiality of the distribution network, the subsequent criteria should be checked to see if the generated individuals fulfill the radiality constraint, given by:

$$N_{closed\ branches} = N_{buses} - N_{substations} \tag{2}$$

where $N_{closed\ branches}$, N_{buses} and $N_{substations}$ refer to the numbers of closed branches, buses and substations in the system, respectively.

The above condition is a necessary but not sufficient to ensure a radial topology. In addition to radial configuration, it is necessary to ensure that all buses are connected; this prevents island systems from being formed as this is not desired in many cases.

Therefore, more constraint is required to make sure that all buses are connected. This condition is met by [30]:

$$\forall_{z_i,z_j} \in k, \ni \ \{P_i \ \cup \ P_j\} \left(\prod_{l}^{k} u_{i_l} \prod_{l}^{k} u_{j_l} = 1 \right) \tag{2}$$

where k is the set of buses; $P_i \cup P_j$ is exclusive path linking bus i and j; u_{i_l} and u_{j_l} refer to the states (0 or 1) of branch l along the path $P_i \cup P_j$ which is given by each individual of a given population; l is the set of branches that establish a path.

In addition, constraints related to the voltage limits, active and reactive power generation and flow limits are being considered.

III. RESULTS AND DISCUSSIONS

A. *Cost Functions and Assumptions*

The entire analysis is carried out considering an AC optimal power flow (AC OPF) model. The AC OPF is solved by the popular MatPower in a MATLAB environment. The test system that is used for carrying out the simulations is a 16-bus radial distribution system, shown in Fig. 1. Additional information and data for this test system can be found in [31].

Voltages are allowed to vary within a maximum of ±5% of the nominal voltage. The power factor of DGs is set equal to 0.95. The cost of power production at the substations is assumed to be a quadratic function of the power injection as:

$$C(P) = 150 + 20P + 0.01P^2 \text{ €/h} \tag{4}$$

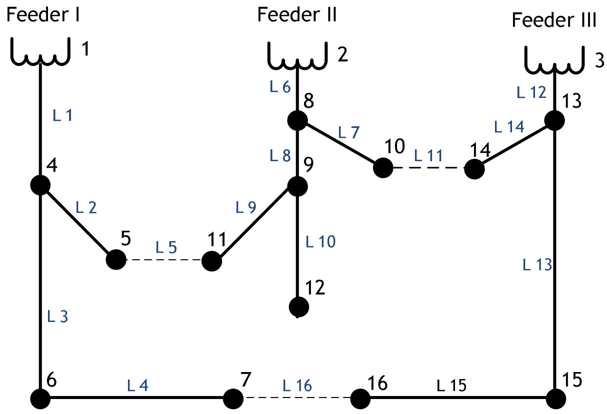

Fig. 1. A 16-bus radial distribution system

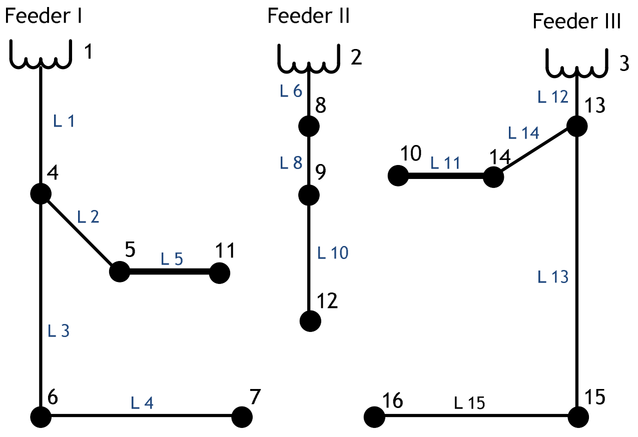

Fig. 2. Final topology for Case 2

$$C(P) = 180 + 30P + 0.03P^2 \text{ €/h} \tag{5}$$

In this work, all DG nodes are considered as a PV bus. The cost of power production by DGs is assumed to be linear (6):

$$C(P) = 8P \text{ €/h} \tag{6}$$

Furthermore, it is assumed that all nodes in the system are suitable for allocating DGs, except the substation buses 1 through 3. Throughout the analysis, base power is set to 1 MVA. With all this, the following case studies are analyzed:

- Case 1 – Base case topology (see Fig. 1) with importing power through the substations considering the same cost functions;
- Case 2 – The same as Case 1 but with reconfiguration;
- Case 3 – The same as Case 2 but with the sole objective of minimizing network losses;
- Case 4 – The same as Case 3 but considering different cost functions at the substations;
- Case 5 – This considers reconfiguration of the base case topology along with placement and sizing of DGs capable of producing and consuming reactive power;
- Case 6 – This considers reconfiguration of the base case topology along with placement and sizing of DGs capable of producing only active power;
- Case 7 – This considers reconfiguration of the base case topology with the allocation of DGs capable of producing and consuming only reactive power;

B. *Numerical Results*

Table I summarizes the costs, losses and other relevant results for each case. The results in this table generally reveal some differences in operation costs, active and reactive power losses. In comparison to the base case, the total cost in Case 2, which considers only network reconfiguration of the base case topology, are reduced by 0.04%. However, in terms of losses, Case 2 leads to a reduction of 7.2% in total active power losses and approximately 6% reduction in total reactive power losses. The final topology in Case 2 can be seen in Fig. 2. The voltage profile corresponding to this case is shown in Fig. 3. In this figure, it is evident to see that reconfiguration alone leads to the improvements in the voltages at each node of the system. The active and reactive power losses and total costs in Cases 3 and 4 are comparable with that of Case 2. The three subcases in Case 4 differ in the fictitious generation cost functions at the substations. E1, E2 and E3 are subcases associated with the substations 1, 2 and 3, respectively. E1 assumes an expensive power import at bus 1 while E2 and E3 also each at a time refers to the case where expensive power is imported at the respective nodes. The total costs in Case 4 are higher because of a higher cost function as stated earlier. We can state from this situation that, in this network, minimization of costs leads to minimization of losses. Analyzing the results in Cases 5 through 7, where reconfiguration is being done in coordination with the placement and sizing of different DG types, some differences are visible in the operation of the network system. Cases 5 and 6 seem to have the same cost. In

TABLE I. REVELANT RESULTS OF DIFFERENT CASES

Cases	Results from OPF			
	Total Costs (€/h)	Active Losses (MW)	Reactive Losses (Mvar)	Installed DG (MVA)
1	1029.4177	0.1064	0.1224	-
2	1029.0201	0.0987	0.1151	-
3	1029.0201	0.0987	0.1151	-
4-E1	1151.8748	0.0987	0.1151	-
4-E2	1198.3556	0.0987	0.1151	-
4-E3	1120.9084	0.0987	0.1151	-
5	790.0860	0.0290	0.0311	21
6	790.0860	0.0540	0.0583	16
7	1028.8530	0.0927	0.1054	14

TABLE II. BRANCHES OPENED AND LOCATION OF DGS

Cases	Results from GA	
	Branches Opened	Optimal DG Locations
1	5-11; 10-14; 7-16	-
2	8-10; 9-11; 7-16	-
3	8-10; 9-11; 7-16	-
4-E1	8-10; 9-11; 7-16	-
4-E2	8-10; 9-11; 7-16	-
4-E3	8-10; 9-11; 7-16	-
5	6-7; 9-11; 10-14	4; 5; 6; 7; 9 12; 15
6	6-7; 13-14; 5-11	5; 6; 11; 12; 13; 15
7	6-7; 8-10; 9-11	4; 6; 9; 15; 16

Case 5, the costs compared to those in the base case are reduced by 23.4% while the active and reactive power losses are also trimmed down by 72.7% and 74.63%, respectively. Analyzing Case 6, total costs, active and reactive power losses 23.4%, 49.3% and 52.4% lower than that of the base case, respectively.

This shows the enormous potential of reactive power sources in reducing losses in distribution networks. Similarly, in Case 7, where reactive only DGs are considered, totals costs do not show a significant reduction, only 0.05%, but active and reactive power losses are lowered by approximately 12.9% and 14% respectively. The DGs in the last case act more or less like capacitor banks, and such sources demonstrate a positive impact on the overall network operational performance.

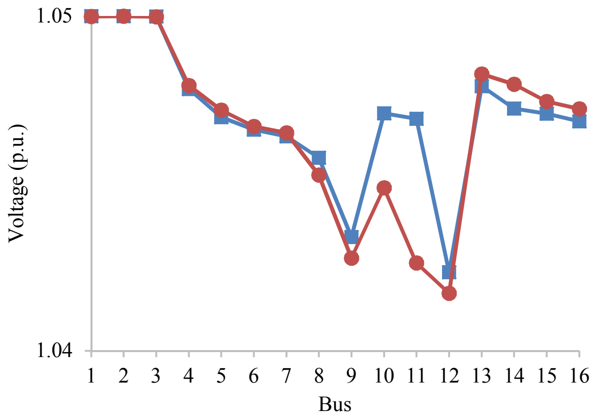

Fig. 3. Voltage profile comparisons between reconfiguration of Case 2 (blue line) and Case 1 (red line).

Table II summarizes the results of reconfiguration (opened branches) as well as the location and size of DGs for the different cases. This table shows that Cases 2 through 4 ultimately lead to the same topology. This may be due to the fact that minimization of costs leads to minimization of losses and vice-versa. The optimal

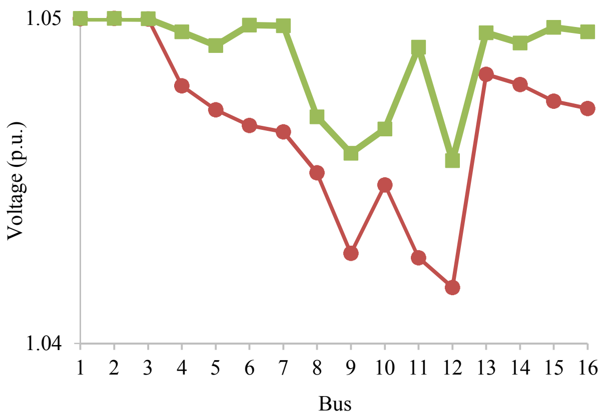

Fig. 4. Voltage profile comparison between reconfiguration with placement of DGs in Case 5 (green line) and Case 1 (red line)

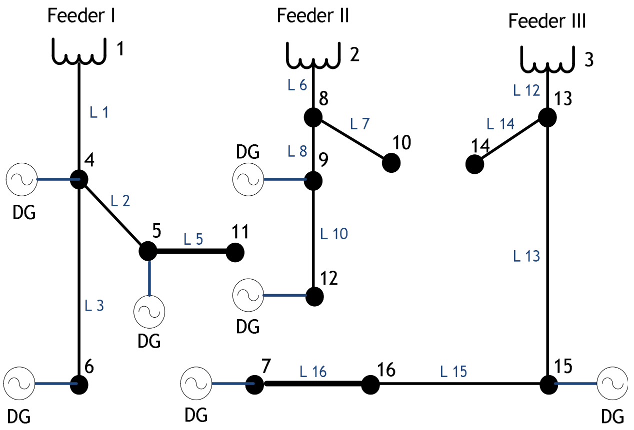

Fig. 5. Optimal location for DGs and reconfiguration of Case 5.

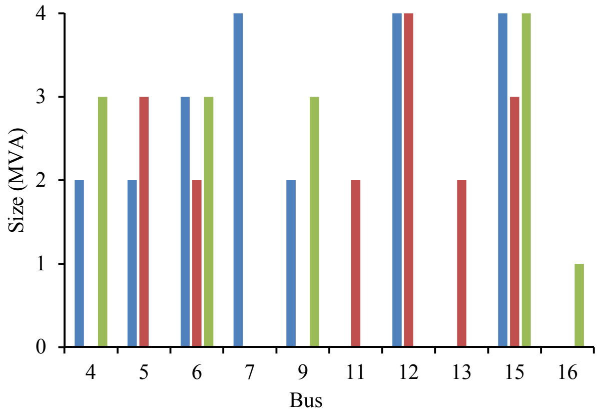

Fig. 6. DG size and placement in the 16-bus test system for Cases 5 (blue), 6 (red) and 7 (green).

configuration of the network for these cases is illustrated in Fig. 2. Voltage profiles of Case 2 through 4 are the same, and again illustrated in Fig. 3. However, for Cases 5 through 7, the voltage profiles are significantly improved, and the location and size of DGs have some similarities but they have one opened branch in common (node 6 to node 7). Even if Case 5 and 6 have the same total costs, the optimal network reconfigurations are different. This may be because of the similarities in the DG allocation (buses 5, 6, 12 and 15). In general, different DG allocation may lead to different network configurations even if costs are the same.

As a conclusion, the numerical results for the 16-bus distribution network system clearly demonstrate the benefits of integrating small DGs. The operation costs and losses are considerably reduced. The voltage profile corresponding to Case 5 is shown in Fig. 4. Improvements in the voltage profile may be seen in almost every node in the system. Introducing DGs with the ability to support reactive power has a larger impact in total losses than DGs capable of supplying only active power or reactive power. The results reinforce this argument. Moreover, total installed size of DGs is lower for Case 5 through Case 7. This can be due to the contribution of DGs with reactive power support capability in meaningfully improving the controllability of the system, substantially reducing costs and losses. Fig. 5 shows the optimal location of DGs and the configuration of the system for Case 5. In Fig. 6, we can see the location and size of the DGs in the considered distribution system. The nodes 6 and 15 are common for the 3 cases (5, 6 and 7). The total installed DGs amounts to 70% of the essential demand in Case 5, 53% in Case 6 and 46% in Case 7.

C. *Algorithm Performance*

The performance of the GA based solution algorithm in Case 2 is depicted in Fig. 7. The costs represent the best fitness function that we get in each generation. The steep descent reveals that fast convergence is achieved in the 16-bus radial distribution system. Yet, since the algorithm is heuristic based, the global optimality of the solution cannot be verified. The simulation time is, however, drastically reduced, which is highly needed to solve a complex NP-hard problem, addressed in this work.

As it can be observed in Fig. 7, the difference between the best solutions in each generation is very small. In fact, for the first generation, the total cost related to the best solution sums to 1030.3622 €/h, and that of the final solution is 1029.0201 €/h. After 10 generations, we reach the best solution. The deviation between these two solutions is about 0.13%. More puzzling that may seem is the algorithm's performance in Case 7, where the best solution is reached only in the first iteration, as could be seen in Fig. 8. Nevertheless, this may happen very rarely, and may not be replicated in the same or other problems, even with a smaller system.

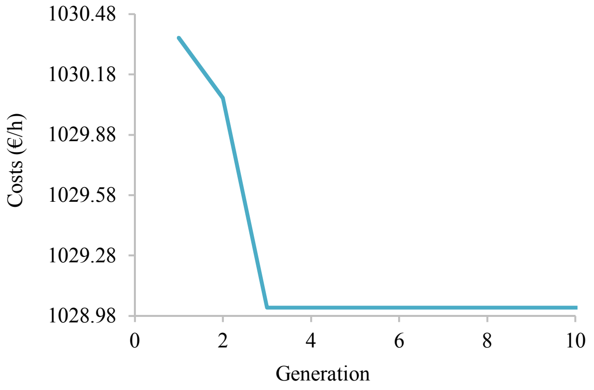

Fig. 7. Convergence process of Case 2

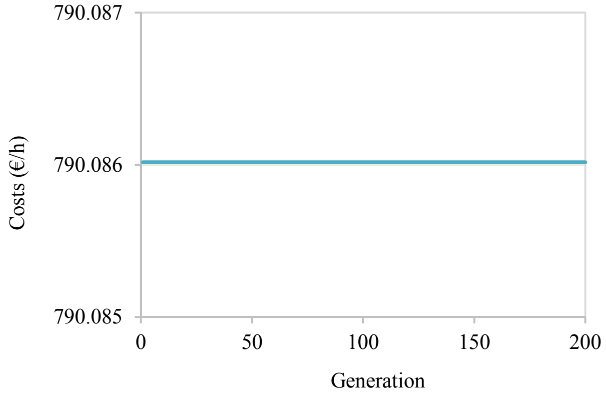

Fig. 8. Convergence process of Case 5

IV. CONCLUSIONS

This paper has developed a tailor-made approach based on a genetic algorithm to investigate the potential benefits that reconfiguration along with allocation of DGs can have in operating distribution systems. Simultaneous minimization of operation costs and losses is the objective function of the proposed GA-based approach subject to radiality and other techno-economic constraints. In this work, the optimal solutions of DG allocation and reconfiguration have been compared with the base case. The resulting model has been tested on a 16-bus distribution network system. Numerical results show the benefits of reconfiguration in reducing overall costs and losses in the system. In addition, the optimal allocation of DGs (both size and placement) along with reconfiguration show the positive impacts of these two technologies on total operation costs, total losses and voltage profiles. It can be said that a proper coordination of DGs and reconfiguration generally leads to an increasingly optimized distributed system, capable of accommodating significant amount of RES type DGs.

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