

An Optimal Procedure for Sizing and Siting of DGs and Smart Meters in Active Distribution Networks Considering Loss Reduction

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Abstract – The presence of responsive loads in the promising active distribution networks (ADNs) would definitely affect the power system problems such as distributed generations (DGs) studies. Hence, an optimal procedure is proposed herein which takes into account the simultaneous placement of DGs and smart meters (SMs) in ADNs. SMs are taken into consideration for the sake of successful implementing of demand response programs (DRPs) such as direct load control (DLC) with end-side consumers. Seeking to power loss minimization, the optimization procedure is tackled with genetic algorithm (GA) and tested thoroughly on 69-bus distribution test system. Different scenarios including variations in the number of DG units, adaptive power factor (APF) mode for DGs to support reactive power, and individual or simultaneous placing of DGs and SMs have been established and interrogated in depth. The obtained results certify the considerable effect of DRPs and APF mode in determining the optimal size and site of DGs to be connected in ADN resulting to the lowest value of power losses as well.

Keywords: Active Distribution Network (ADN), Smart Meters (SMs), Demand Response Programs (DRPs), Distributed Generations (DGs), Optimal siting and sizing.

Nomenclature

Indices and Sets

i, j, Ω_B	Indices and set of buses.
k, Ω_{Br}	Index and set of branches.
s, Ω_S	Index and set of substations.
Ω_i	Set of buses connected to bus i .

Parameters

R_k	Resistance of k -th branch.
P_L, Q_L	Active and reactive powers of distribution feeders.
Y_{ij}, θ_{ij}	Magnitude and phase angle of feeder's admittance.
S_s^{\max}	Maximum allowable apparent power that could be flowed through s -th distribution substation.
S_k^{\max}	Maximum allowable apparent power flowing each substation.
$P_{DG}^{\min}, P_{DG}^{\max}$	Minimum and maximum limits for DGs active power.
$Q_{DG}^{\min}, Q_{DG}^{\max}$	Minimum and maximum limits for DGs reactive power.
S_{DG}^{\max}	Maximum apparent power limit for DGs.
S_L	Apparent power of distribution feeders.
$PF_{DG}^{\min}, PF_{DG}^{\max}$	Minimum and maximum power factor for

DGs.

V_{\min}, V_{\max}	Minimum and maximum limits of bus voltages.
I_k	Current magnitude in k -th branch.
N_{DG}	Number of DGs installed in the network.
N_{SM}	Number of SMs to be installed in the AND.
PF_L	Constant power factor of load in each bus subjected to be equipped with SMs.

Functions and Variables

P_{Loss}	Total power losses.
x, u	Vector of dependent and independent variables.
V	Bus voltage.
P_s, Q_s	Active and reactive power imported from s -th substation.
P_{DLC}, Q_{DLC}	Active and reactive power reduction by DLC responsive load.
P_k, Q_k	Active and reactive power flowing k -th branch.
P_{DG}, Q_{DG}	Active and Reactive power generation by DG at bus i .
PF_{DG}	Power factor for DGs.

1. Introduction

The well-known technical features such as power loss minimization and voltage profile improvement as well as economical benefits such as reduction in long-term planning and short-term operational costs are some of the main factors motivating the worldwide nations to cater the utilization of distributed generations (DGs) in their networks [1, 2]. DGs are mainly fostering in the territory

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of distribution networks to accommodate the electrical requirements of consumers locally and hence, reducing the power losses greatly. Different sorts of DGs can be envisaged, but the most common types are the conventional diesel-based and renewable-based DGs [3, 4]. Due to the technological improvements, it has been made possible to deploy DGs in different modes such as adaptive power factor (APF) mode. In APF mode, a DG unit is speculated to be apt for both providing active and reactive power support to the network. Consequently, it would have a more impressive effect in both active power loss reduction and voltage profile improvement [5, 6].

On the other hand, there is now a common sense between the industry and academia on the ongoing transition changing the passive distribution network to a more intelligent and efficient one known as active distribution networks (ADNs) [7-9]. ADNs are mainly benefitting from the rapid evolution in the information and communication technology (ICT). General packet radio services (GPRS) is one of the most applied media in the wireless and online engineering control actions. In this way, versatile types of intelligent electronic devices (IEDs) such as distribution remote terminal units (DRTUs) and smart meters (SMs) have been developed to yield an online and efficient control on ADNs ingredients. ADNs are characterized with both renewable-based and controllable diesel-based DGs, responsive loads and flexible network structures realized with remotely controlled switches [10-13]. The active participation of end-side consumers in demand response programs (DRPs) could be divided mainly in two folds encompassing incentive-based programs and time-based programs [14-16]. In incentive-based programs such as direct load control (DLC), the distribution network operator (DNO) controls the consumers demand up to a pre-specified contracted value and prices through SMs. These programs are the best tools for DNOs to handle the emergency conditions such as peak load hours and forced outages in some feeders. Time-based programs, with respect to the forecasted price of electricity in different hours of next 24-hour ahead, are mainly activated by the consumers themselves and there is no any direct control on them by the DNOs.

The emergent of ADNs would greatly affect the power system studies such as DGs optimal siting and sizing problem. In the passive distribution networks, DGs are solely handled in the peak load hour considering loss or cost reduction, voltage profile improvement, and reliability enhancement [17-20]. More recently, some of the features of ADNs such as automatic online reconfigurations realized through remotely controlled switches (RCSs), has been adopted in DGs optimal placement problem. Rao et.al [21] have proposed an optimal strategy for DGs placement which besides the optimal size and site of DGs, determines the open or closed status of each RCSs as well. They have shown the extra loss reduction and change in the size and site of connection for DGs as the result of applying RCSs.

The author in [22] has developed an optimal framework for concurrent allocation of DGs and capacitors in ADNs making use of online reconfigurations. He has also provided some interesting results in this context. However, the presence of responsive loads and DRPs have neglected in the aforementioned studies.

Keeping the foregoing discussions in mind, this study initiates to examine the effect of DRPs effect in optimal placement of DGs in ADNs. DLC as one of the most effective DRPs in peak load management is considered to be contacted between the DNO and some large consumers in the network. By this way, DNO can reduce the consumption of these loads up to a pre-specified value at contracted prices by the signals released through SMs. Thus, as an innovative point, this paper coordinates the determination of installation buses for limited number of SMs due to the limited investment capabilities of DNO with the problem of DGs optimal placement. To do so, different scenarios have been devised which investigate both the individual and simultaneous placement of DGs and SMs. By determination of installation buses for SMs, the effect of DLC responsive loads in optimal siting and sizing of DGs would be analyzed in depth. It will be discussed that the inclusion of DLC buses as DRPs, would affect both the size and site of DGs to be installed in the future ADNs. Hence, it would be indispensable for DNOs to take into account the presence of DRPs in solving the DG placement problem and finding the best installation buses. Also, the effect of DLC in extra power loss reduction and voltage profile improvement would be highlighted. By speculating the DNO to be apt for remotely controlling the DGs active and reactive power injections, APF mode has been considered for DGs whereas in most of the previous studies, DGs are treated in constant power factors. In this manner, the optimal power factor would be determined for DGs as well. The optimization procedure has been formulated as a non-linear problem (NLP) and tackled with genetic algorithm (GA) seeking to minimize total power losses in the network. To validate the well performance of the proposed methodology, the IEEE 69-bus test system has been considered for numerical studies.

The remainder of the paper is organized as follows. The mathematical formulation of the optimization problem is presented in section 2. In the sequel, Section 3 addresses the GA fundamentals and introduces the proposed chromosome for the problem. Afterwards, different scenarios have been devised and simulated numerical results are provided in section 4. Eventually, concluding remarks are presented in Section 5.

2. Problem Statement and Mathematical Formulation

This section is devoted to present the mathematical formulation for optimal placing of DGs and SMs in ADN.

In the following subsections, the main assumptions, objective function considered to be optimized and also running constraints are introduced in more detail.

2.1 Assumptions

The following assumptions are made as the main features envisaged in the optimal placement of DGs and SMs in the ADN:

- ADN is assumed to be balanced;
- Total loads are modeled with constant powers and constant power factor;
- There is limited budget for placing of both DGs and SMs; hence, the number of DGs and SMs would be limited;
- DGs are operated in APF mode allowing them possible to generate both active and reactive power.

2.1 Objective function

Each bus that is selected for placing SM would be exposed to reduce its load up to a pre-specified amount denoted by $S_{DLC_i}^{\max}$. Also, DGs are considered to be installed at different buses injecting both active and reactive power to the network. DGs, due to their excellent capabilities, could be utilized to attain several objectives such as power loss minimization and voltage profile improvement. Herein, the most important purpose is to minimize the total real power losses in the network represented in (1):

$$\begin{aligned} & \text{Minimize} \\ & \left[P_{\text{Loss}}(x, u) = \sum_k |I_k|^2 R_k \right], \quad k \in \Omega_{Br} \quad (1) \\ & \text{Subject to } h(x, u) = 0 \\ & \quad \quad \quad g(x, u) \leq 0 \end{aligned}$$

2.3 Constraints

The problem of optimal siting and sizing of DGs and SMs in an ADN is subjected to the following equality and inequality constraints namely, $h(x, u)$ and $g(x, u)$.

2.3.1 Load flow equations:

The equality constraints (2) and (3) are taken for ensuring the governing of Kirchhoff's current and voltage laws in the network's load flow process. The presented load flow equations are amended to include the effect of DGs and SMs presence as follows:

$$P_{g_i} + P_{DG_i} + P_{DLC_i} - P_{L_i} = \sum_{j \in \Omega_i} P_{ij}(V_i, V_j, Y_{ij}, \theta_{ij}) \quad (2)$$

$$Q_{g_i} + Q_{DG_i} + Q_{DLC_i} - Q_{L_i} = \sum_{j \in \Omega_i} Q_{ij}(V_i, V_j, Y_{ij}, \theta_{ij}) \quad (3)$$

2.3.2 Voltage limits:

Proper constraints are required to guarantee the voltage magnitude to be kept at admissible range at each bus. The voltage magnitude for substation buses is maintained at 1 p.u.:

$$V_{\min} \leq |V_i| \leq V_{\max}, \quad i \in \Omega_B \quad (4)$$

$$|V_{i,s}| = 1 \text{ p.u.}, \quad i \in \Omega_S \quad (5)$$

2.3.3 Limit for substations capacity:

The maximum permissible capacity of the transformer limits the maximum apparent power flow in each substation connecting the ADN to the upstream sub-transmission level:

$$\sqrt{P_s^2 + Q_s^2} \leq S_s^{\max}, \quad s \in \Omega_s \quad (6)$$

2.3.4 Flow limits for feeders:

It is necessary to keep the apparent power flowing each feeder in its admissible range:

$$\sqrt{P_k^2 + Q_k^2} \leq S_k^{\max}, \quad k \in \Omega_{Br} \quad (7)$$

2.3.5 DGs Size and total capacity:

The limited budget available for DNO may confine the total capacity of installed DGs up to PER_{DG} (%), that is, the percent of total active load of the network. Also, by applying DGs in APF mode, they should also satisfy the permissible range for PF. Meanwhile, with the aim of limiting the maximum number of installed DGs, namely N_{DG}^{\max} , the following constraints should be satisfied:

$$P_{DG}^{\min} \leq P_{DG_i} \leq P_{DG}^{\max}, \quad i \in \Omega_B \quad (8)$$

$$Q_{DG}^{\min} \leq Q_{DG_i} \leq Q_{DG}^{\max}, \quad i \in \Omega_B \quad (9)$$

$$\left[(P_{DG_i})^2 + (Q_{DG_i})^2 \right]^{1/2} \leq S_{DG_i}^{\max}, \quad i \in \Omega_B \quad (10)$$

$$\sum_{i \in \Omega_B} S_{DG_i}^{\max} \leq \frac{PER_{DG}(\%)}{100} \times \sum_{i \in \Omega_B} S_{L_i}, \quad i \in \Omega_B \quad (11)$$

$$PF_{DG_i} = \frac{P_{DG_i}}{(P_{DG_i} + Q_{DG_i})^{1/2}}, \quad i \in \Omega_B \quad (12)$$

$$PF_{DG_i}^{\min} \leq PF_{DG_i} \leq PF_{DG_i}^{\max}, \quad i \in \Omega_B \quad (13)$$

$$N_{DG} = N_{DG}^{\max} \quad (14)$$

2.3.6 Limits on SMs and DLC responsive loads maximum reduction capacity:

As the initial investment capital of DNO may be limited,

there will be a maximum cap for installing SMs in the ADN and implementing DLC demand response between some large consumers. Determination of installation buses for SMs, itself will have a great effect on the optimal solutions for DGs sites and size. Hence, it should be modeled as a part of optimization procedure. The maximum number of installed SMs would be taken as N_{SM}^{\max} . Also, each candidate bus that is selected as a DLC responsive load, should satisfy the maximum amount of permissible load reduction indicated by PER_{DLC} (%), that is, the percent of MVA reduction in each bus. The following constraints are taken to be observed:

$$N_{SM} = N_{SM}^{\max} \quad (15)$$

$$\left[(P_{DLC_i})^2 + (Q_{DLC_i})^2 \right]^{1/2} \leq \frac{PER_{DLC}(\%)}{100} \times S_{L_i}, \quad i \in \Omega_B \quad (16)$$

$$PF_{L_i} = \frac{P_{L_i}}{(P_{L_i} + Q_{L_i})^{1/2}} = \text{cte}, \quad i \in \Omega_B \quad (17)$$

$$Q_{DLC_i} = \tan(\cos^{-1}(PF_{L_i})) \times P_{DLC_i}, \quad i \in \Omega_B \quad (18)$$

3. Optimization Technique based on Genetic Algorithm

The proposed optimal placement framework is a non-linear problem (NLP) which is solved using genetic algorithm (GA). GA as an intelligent search technique imitates the biological selection process. In this process the most eligible parents would be more likely to stay alive and replace their genetic code to the upcoming offspring. This procedure is known as evolution process implemented by specific operators namely recombination and mutation. By this way, GA would be apt to carefully probe the search space and then find the optimal solutions [23, 24].

3.1 Problem codification

The problem codification denotes establishing of a probable candidate solution encompassing one chromosome. The set of unknown variables, as the constituting genes, embrace a chromosome in GA. The proposed coding strategy for DGs and SMs optimal placement is illustrated in Fig. 1. It can be observed that the implemented chromosome is composed of three strings. The first string

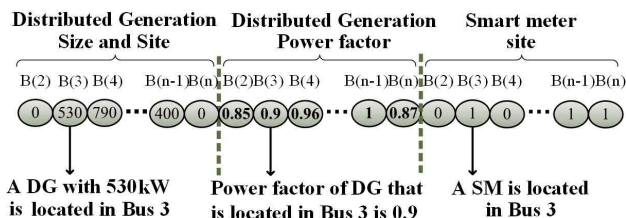


Fig. 1. Structure of the proposed chromosome.

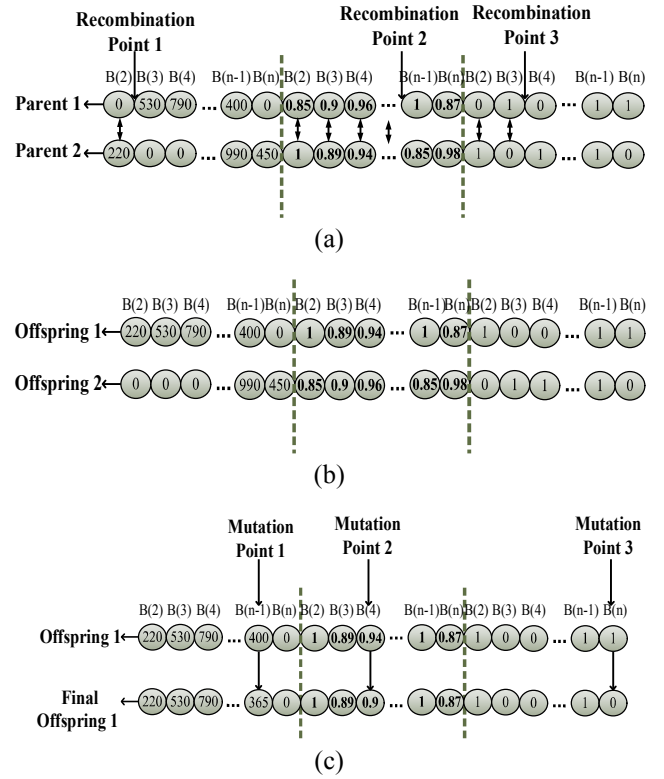


Fig. 2. (a) Selected parents, (b) Recombination process, (c) Mutation process.

accounts for optimal site and size of DGs, the second string is for adaptive power factor of DGs and finally the third string determines the optimal site for smart meters.

3.2 Recombination and mutation

Recombination stage refers to a stochastic process in which some of the chromosomes are randomly selected, and from stochastically determined crossover points (CPs), are combined together to create new offspring. Therefore, each offspring would possess a portion of its parent's coding. Afterwards, some of the genes in the produced offspring are exposed to random mutations to remain the stochastic temper of reproduction process. Fig. 2(a), (b) and (c) demonstrate the multi-point recombination and mutation process for the proposed chromosome.

4. Numerical Results and Discussion

4.1 Test system specifications

To investigate the validity and outperformance of the proposed methodology, the well-known 69-bus test system has been considered as the test bed here. Figs. 3 demonstrate the single line diagram for this system. At this system, bus 1 is connected to the sub-transmission network and is assumed as the substation. The fundamental network

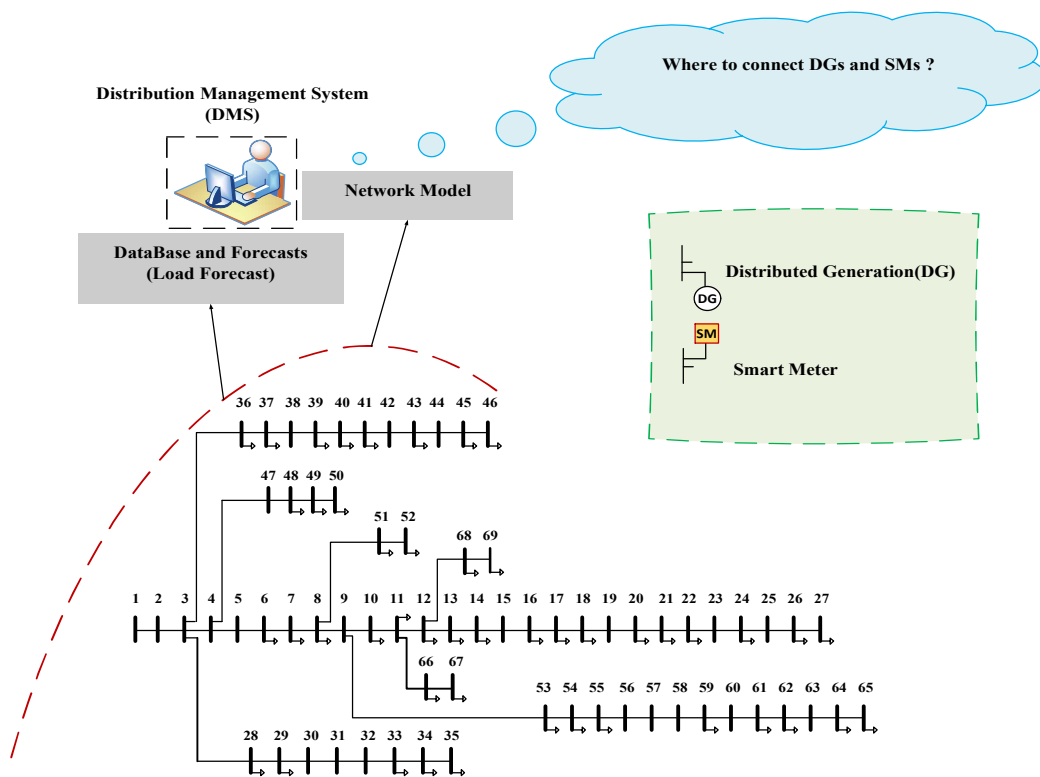


Fig. 3. Single line diagram for IEEE 69-bus test system.

data including impedance of branches and the active and reactive loads for all buses could be found in [25]. The permissible range for voltage magnitudes in all buses has been determined to be between 0.95 p.u and 1.05 p.u respectively. The maximum possible investment capital, available for DNO, limits the maximum penetration of DGs up to $PER_{DG} = 50\%$ of the peak load of the network with a maximum number of 3 DGs.

The minimum and maximum accessible size for DGs has been assumed as 200 and 2000 kW. With respect to APF mode, DGs are allowable to operate with power factors between 0.85 and 1. Also, the maximum number of buses that DNO initiates to install the SMs is taken to be equal with 5 to establish DLC demand response contracts with consumers to reduce their loads up to 10%, say $PER_{DLC} = 10\%$. GA has been executed in several runs with different values for crossover and mutation rates. Even though there were not so remarkable differences, the best results are obtained with population size of 50, recombination rate equal with 0.5 and mutation factor adjusted at 0.01 respectively.

4.2 Multi-Scenario Optimal Sizing and Siting of DGs and SMs

To present a comprehensive investigation, four different scenarios have been devised as the following:

- Scenario 1: Base plan;
- Scenario 2: Optimal placing of only 1 DG and SMs;

- Scenario 3: Optimal placing of 2 DGs and SMs;
- Scenario 4: Optimal placing of 3 DGs and SMs.

Base plan represents the basic structure of the test cases without any DGs and SMs. For each of the second, third and fourth scenarios there have been designated three different cases including:

- Placing DGs operated in unity power factor (UPF) mode and without placing SMs, designated with Case-I;
- Placing DGs operated in APF mode and without placing SMs, designated with Case-II;
- Placing both DGs in APF mode and SMs to perform DLC demand response, designated with Case-III.

In the following subsections, simulation results are obtained for each scenario and discussed in depth.

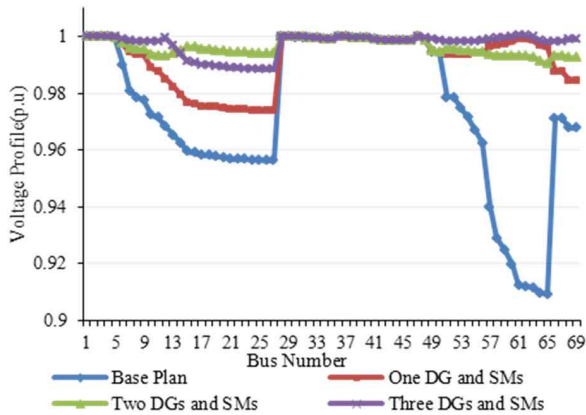
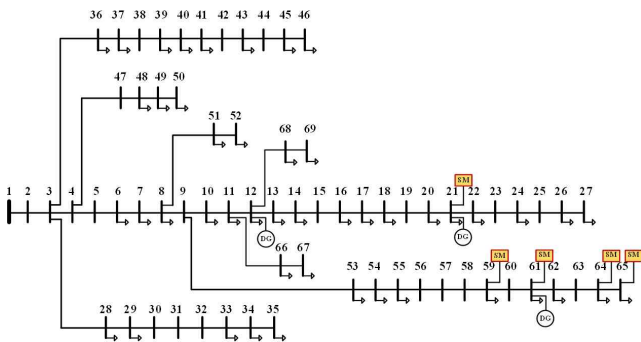
4.3 Numerical results for IEEE 69-bus test system

For test system and in its base structure, the total load of the network is equal with 3.8019 MW and 2.6941 MVar. The power losses without any installation of DGs and SMs is attained as 224.95 kW. The minimum voltage value is 0.9092 which occurs at bus 65.

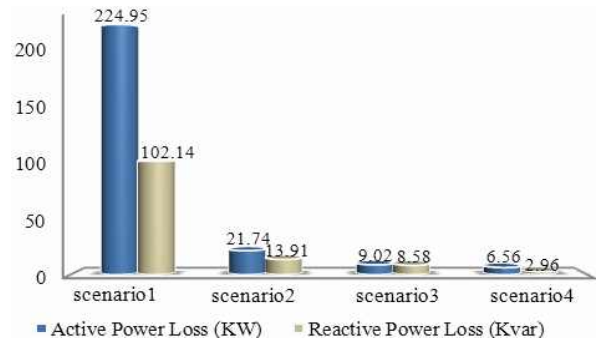
Table 1 provides the obtained numerical results for test system in different scenarios where the optimal site and size of DGs and also the optimal installation sites for SMs have been determined. For the case of second scenario,

Table 1. Optimal results for IEEE 69-bus test system

Scenario	Cases	Power losses (kW)	Loss reduction (%)	Minimum voltage (p.u.)	DGs optimal size (MW) and site	Optimal power factor	Buses for installing SMs
Scenario 1	Base Case	224.95	–	0.9092(B65)	–	–	–
Scenario 2	Case-I	83.192	63.02	0.9683(B27)	1.873(B61)	1.00	–
	Case-II	23.88	89.38	0.9723(B27)	1.873(B61)	0.85	–
	Case-III	21.74	90.24	0.9738(B27)	1.733(B61)	0.85	B11, B12, B18, B21, B61
Scenario 3	Case-I	73.83	67.18	0.9729(B65)	0.363(B18), 1.637(B61)	1.00(B18), 1.00(B61)	–
	Case-II	12.13	94.61	0.9865(B65)	0.425(B18), 1.569(B61)	0.88(B18), 0.85(B61)	–
	Case-III	9.02	96.00	0.9900(B65)	0.501(B16), 1.480(B61)	0.87(B16), 0.85(B61)	B12, B49, B59, B61, B64
Scenario 4	Case-I	73.59	67.28	0.9734(B65)	0.441(B18), 1.11(B61), 0.449(B64)	1.00(B18), 1.00(B61), 1.00(B64)	–
	Case-II	11.58	94.85	0.9884(B27)	0.377(B17), 1.373(B61), 0.247(B64)	0.88(B17), 0.85(B61), 0.86(B64)	–
	Case-III	6.56	97.08	0.9920(B27)	0.777(B12), 0.827(B21), 1.596(B61)	0.87(B12), 0.90(B21), 0.85(B61)	B21, B59, B61, B64, B65

**Fig. 4.** Voltage profile for IEEE 69-bus test system in different scenarios.**Fig. 5.** The optimal size and site of DGs and SMs in IEEE 69-bus test system.

the minimum power losses corresponds to Case-III with 90.24% reduction in total power losses. Also, as it is obvious with respect to Table 1, considering DLC demand response program through installation of SMs, would affect both the optimal site and size of DGs to be installed. In the third scenario, considering two DG units with APF to be installed, has resulted to 96.00% reduction in total power losses. Although the total size of DGs has only increased by 0.0355 MW from 2.9144 MW to 2.9499 MW, but power

**Fig. 6.** Total active and reactive power losses for IEEE 69-bus test system in different scenarios.

losses have decreased an extra 5.76% in its total value. Meanwhile, the worst bus voltage value has increased from 0.9738 to 0.9905 p.u. which signifies a very influential improvement in voltage profile too. These notable triumphs are due to applying DGs in APF mode and affecting more than one DG units in the most influential parts of the network. By concurrent placement of DGs and SMs in the fourth scenario, there has been an extra loss reduction by 1.08% and also voltage profile improvement with respect to second and third scenarios. But, as the fourth scenario reports in Table 1, comparing Case-II and Case-III, the most important effect of DLC demand response through SMs comes back to the change in optimal site and size of DGs to be installed. Also, Fig. 4 depicts the voltage profile for the Case-III in three different scenarios. As it is seen, the best voltage profile is obtained for the Case-III in fourth scenario wherein DGs are in APF mode and through optimal placement of SMs, the DNO has contracted DLC demand response with the most suitable consumers. The optimal PFs for the three DGs has been achieved as 0.87, 0.90 and 0.85. It is worth noting that the concurrent placement of SMs with DGs not only affects the installation buses of DGs, but also change the placement regime of SMs too. The optimal results obtained for the test system in the fourth scenario has been illustrated in Fig.

5 visually. Also Fig. 6 demonstrates the reduction in both active and reactive power losses in different scenarios. It is clear that the maximum reduction corresponds to Case-III in scenario 4.

5. Conclusion

The presence of well promising DRPs such as DLC demand response interactions in the future ADNs has been tailored in the problem of optimal siting and sizing of DG units. By presenting a comprehensive mathematical formulation for the non-linear problem, concurrent allocation of SMs and DGs has been modeled and tackled based on GA. Different scenarios has been put under investigation on IEEE standard 69-bus test system. It was shown that applying DG units in APF mode which results in higher reactive power support, would have a considerable effect on power loss minimization and voltage profile improvement too. By this way, the optimal value of PF for each DG unit has been assigned as well. In the sequel, the effect of DLC demand response between large consumers, has been investigated by optimal placing of SMs in the network. By reducing up to 10 percent of optimally determined consumers through SMs, the regime of optimal siting and sizing of DG units has been altered. Performing DLC demand response has resulted in the change of both size and site of DGs to be installed. There has been extra power loss reduction and voltage profile improvement as well. Thus, it is necessary for DNOs to consider the DRPs in the expansion planning problems as well as siting and sizing issues in the future ADNs.

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