A Healer Reinforcement Approach to Smart Distribution Grids by Improving Fault Location Function in FLISR

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Abstract— **In this paper, a conceptual framework for self-healing ability of Smart Grid is introduced, which includes three main layers; system, component, and healer healing (or healer reinforcement). An effective healer healing approach to accelerate the fault location function of the FLISR process is realized by optimal placement of fault indicators (FIs). A multiple objective function is formulated, and solved using multi-objective particle swarm optimization (MOPSO), to simultaneously minimize indispensable economic and technical objectives. To such aim, a summation of total customers' interruption costs during planning horizon and the FIs installation costs are considered as the economic objective function, and system interruption duration index (SAIDI) is assumed as technical objective function. Moreover, simulations are conducted with respect to uncertainties of automatic switching. The proposed healer reinforcement approach to improve overall Smart Grid reliability is examined on bus number four of the Roy Billinton test system (RBTS4), and results have shown that the algorithm can determine the set of optimal non-dominated solutions which allows planners to select one of the non-dominated solutions based on their professional point of view. Also, a max-min approach is employed to select the best result among the obtained Pareto optimal set of solutions.**

Keywords- distribution system reliability; fault indicator placement; healer reinforcement; MOPSO; Smart Grid; Self-Healing.

Nomenclature:

Sets:

Ω^{LP}	Set of network load points;
Ω^{LT}	Set of load types including residential, commercial, industrial, public, and critical;
$\Omega^{l}, \Omega^{t}, \Omega^{b}$	Set of network lines/transformers/buses;
Ω^{C}	Set of candidate locations of FIs;
Ω^{zone}	Set of zones associated with the distributed FIs.

Constants:

n_y	Planning horizon (year);
P_{ij}^{z}	Average demand of load type z at load point j within year i (kW);
λ_k	Failure rate of equipment k;
C_j^{FI}	Cost of installing an FI in candidate location j ($);
C^{m}	Annual maintenance costs of an FI per annual investment cost ($);
$Inf.R$	Inflation rate;
$Int.R$	Interest rate.

Function:

F_1, F_2	Economic/Technical objective function of the optimal FIs placement problem;
C^{IC}	Customers' interruption cost during planning horizon($);
C^{FI}	Cost associated with installed FIs ($);
RIR	Real interest rate;
$C_z^{o}(r_{jk})$	Interruption cost of load type z at load point j due to outage time r_{jk} ($).

Variables:

α_j	Binary decision variable suggested by optimization algorithm, which that is equal to 1 if an FI is installed at location j, and 0 otherwise;
r_{jk}	Interruption duration at load point j due to fault occurrence at k (hr/f);
r_{ij}^{z}	Restoration time associated with how the service can be restored (z) at load point i due to fault occurrence at i (hr/f);
$t_i^{f.l}$	Average fault detection time when zone j is faulted (hour);
L_i	Length of part i (km).

I. INTRODUCTION

In today's competitive electric market, following the changes in the power industry due to the deregulation and restructuring, reliability of distribution system can be regarded as the main goal of the distribution system planning [1]. Following the proliferation of customers' digital devices, unavailability and poor service reliability possess a significant impact on electric utilities' revenues. Thus, electric utilities are interested in finding ways to improve the reliability of their networks in a cost-effective manner [2]. The Smart Grid aims an effort to satisfy this requirement by making the grid self-healed.

Self-healing refers to the capability of system to identify and diagnose system disruptions, and minimize their adverse impacts with the objective of maximizing system availability, survivability, maintainability, and reliability [4-5]. In distribution systems, the self-healing can be performed in three levels; system level, component level or by reinforcing the healer system that is called as healer healing or healer reinforcement [6-7]. Operational functions of self-healing in system level consist of restoration process with reconfiguration, injection of distributed generation and energy storages, and load management applications. The component level includes mission oriented and continues operated devices such as circuit breakers, transformers, switches, and FIs, which should operate successfully. Smart Grid literature have chiefly focused on these two former approaches; while, the latter has gained less attention despite merit [7].

Once a fault occurs on a feeder of electrical distribution system without automation facilities, the fault management activities should be performed manually. In this situation, switching and repairing crews have to be sent to patrol the outage area that is determined based on the customers' outage calls [8-9]. Therefore, the fault location, isolation and restoration processes are surely time consuming, that finally results in

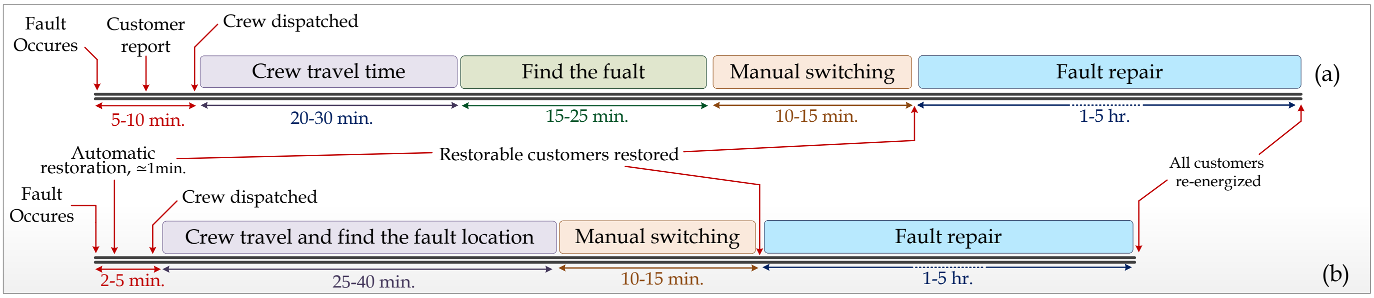

Fig. 1. Time required associated with each function of FLISR process, (a)/(b) with/without employing feeder automation facilities, respectively (adapted [28]).

poor service reliability and customers' dissatisfaction. However, with the network automation facilities such as remote control circuit breakers (RCCBs), remote control switches (RCSs), automatic reclosers, and FIs with remote access, the fault management activities are performed in much less time, which begets in lower customer outage time, high reliability and social welfare. Fig. 1 shows how fault activities in response to a fault proceed with and without the feeder automation facilities.

The self-healing ability leads to reliability improvement by automatic fault location, isolation and service restoration (FLISR) [7]. When a fault occurs, it is firstly detected by protective relays, and then the circuit breaker opens and de-energizes the faulted feeder. Afterwards, the exact or approximate location of the fault is determined by the fault location process which is conducted by employing FIs [10]. Thereupon, the faulted zone is isolated and restorable customers are re-energized by switching sequences, which are disposed by isolation and service restoration processes of the FLISR process. By doing so, restorable customers experience shorter interruption time; also by decreasing time associated with the fault detection, the customers in faulted zone are re-energized as soon as possible.

Healer healing accelerates routine applications of the FLISR function by either utilizing modern technologies or by improving the efficiency of existing technologies like expanding and relocating protective and control devices within distribution systems [7]. Moreover, expanding protective and control devices facilitates isolation and restoration applications, thus not only decreases interruption duration, but also decreases the number of the affected customers. Besides these, reinforcing the healer systems in component level improves component performances, which may be realized by components redundancy expansion. The discussed framework of self-healing and the impact of proposed healer healing approach on two other layers and overall Smart Grid reliability are summarized in Fig. 2.

The effects of protective and control devices on power distribution reliability are well studied; moreover, effects of redundancy expansion in both protective and control subsystems are investigated on the overall smart grids reliability in [7]. In this paper, we focus on the fault location process of the FLISR function and a proper healer healing approach is introduced by applying optimal placement of FIs. As Fig. 1 shows, crew travel time and fault detection process are decreased by employing FIs. Therefore, FIs expansion is a proper healer healing approach to accelerate fault detection process of the FLISR. Optimal placement of FIs enhances fault location function, thus decreasing customers' interruption duration.

In order to solve the optimal placement of FIs, many mathematical models and algorithms have been developed in the literature [11-19]. In [11], reliability modeling of FIs is intro-

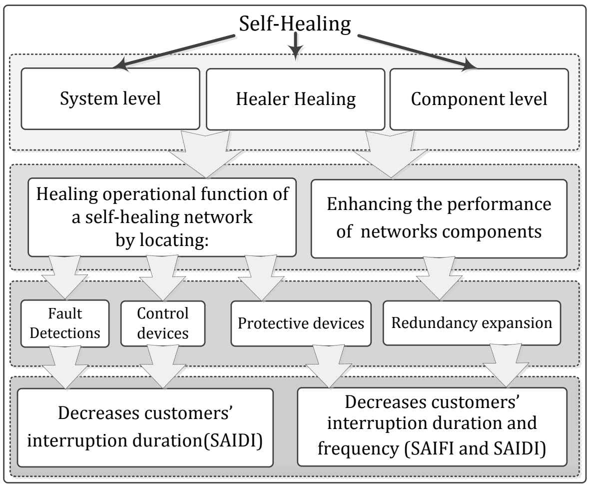

Fig. 2. Self-healing framework and the healer healing operational functions

duced; also effects of different locations and numbers of the FIs are evaluated. However, economic issues have not assumed in the proposed model. In [12], IBSFLA and BSFLA algorithms have been suggested for placement of FIs in distribution networks. Although economic issues are considered within the proposed model, the technical objectives and reliability indices are ignored. A genetic based algorithm and artificial immune algorithm are conducted in [13] and [14] for simulation process of the optimal location and number of FIs with special economic combined objective function, respectively. However, the probabilities of successful operation of control devices are rarely referred. A genetic based algorithm is used in [15] to determine the optimal position of FIs in an actual distribution network. Nevertheless, the candidate locations of FIs are limited to the main branches. In [16], the immune algorithm is adopted to solve the optimal FIs placement problem. Besides the mentioned studies, more efforts are conducted in [17-19].

Based on the above mentioned studies, it can be seen that a multi-objective approach is scarcely applied in previous studies yet; moreover, the probabilities of successful operation of devices are rarely referred.

In this paper, the optimal placement of FIs is introduced as an effective approach to accelerate the fault location process of the FLISR; also the impact of FIs on overall Smart Grid reliability is investigated. To such aim, Particle Swarm Optimization (PSO) algorithm has been employed to minimized economic and technical functions. Moreover, a planning approach has been employed via Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to simultaneously minimize the indispensable economic and the technical objective functions. The multi-objective optimization obtains a set of compromised solutions of different objectives which are known as Pareto optimal set of solutions or non-dominated solutions. Furthermore, a max-min approach is used to select the best result among the obtained Pareto optimal set based on the decision maker viewpoints. To demonstrate the effectiveness of proposed healer healing approach, bus four of the Roy Billinton test system (RBTS4) is employed for simulation.

II. PROBLEM FORMULATION

From the reliability stand points, the proposed healer healing approach by expanding FIs within the smart distribution networks is a proper solution to minimize the fault detection and restoration time. However, it is neither economical nor necessary to install an FI at each upstream and downstream of the main feeder and laterals of a distribution network; thus it is imperative to determine their optimal placements. Accordingly, the aim of the optimal FIs placement problem is to define decision parameters including locations among candidate places, while objective function(s) to be simultaneously minimized with respect to the following installation rules [11, 14]:

- The candidate locations are the beginning of each lateral and both upstream and downstream of the main feeders, except for normally open tie nodes.
- It is assumed that RCSs and RCCBs contain fault detection and related communication interface. Therefore, the FIs could not be installed on these devices.

In the following subsections, the modeling of FIs, economic and technical objective functions are defined.

A. Modeling of FIs

As shown in Fig.1, existences of FIs reduces the time associated with the fault location process, which cause reduction in interruption time of both restorable customers and customers in faulted zone, consequently increase the system reliability. The FIs limit the area where crew should patrol to find the fault, thus searching zone and time associated to find the fault depends on location and number of FIs. The zones are defined as an area of a feeder which is either exists between one FI (or RCS, RCCB) and the end of lateral (or tie point), or exists between two installed FIs (or RCSs). Thus, the FIs are modeled in (1), where τ represents average fault location time [11-13].

$$t_i^{f.l} = \tau \cdot \frac{L_i}{\sum_{j \in \Omega^z} L_j} \quad (1)$$

B. Economic Objective Function

In this paper, the economic objective function of optimal FI placement problem is formulated as a mixed integer non-linear programming problem through (2)-(5):

$$Min\ F_1 = C^{IC} + C^{FI} \quad (2)$$

$$C^{IC} = \sum_{i=1}^{n_y} \left[(1+RIR)^i . \sum_{j \in \Omega^{LP}} \sum_{z \in \Omega^{LT}} \sum_{k \in \{\Omega^l \cup \Omega^t \cup \Omega^b\}} \left[P_{ij}^z . \lambda_k . r_{jk} . C_z^O(r_{jk}) \right] \right] \quad (3)$$

$$C^{FI} = \sum_{j \in \Omega^C} \alpha_j . C_j^{FI} \left[1 + C^m \sum_{i=1}^{n_y} (1+RIR)^i \right] \quad (4)$$

$$RIR = \frac{1+Inf.R}{1+Int.R} - 1 \quad (5)$$

The economic objective function of the optimal FIs placement problem is represented in (2) which should be minimized. The customers' interruption cost (C^{IC}) throughout the planning horizon is considered in the first term of (2) and modeled via (3) in which, the annual customers' interruption cost of each load point is calculated by presuming possible contingencies occurred in the network. Customers' interruption cost function (C_z^o) is utilized in (3) which depends on weight coefficient of customer types and interruption duration. Also, the RIR refers to real interest rate that discounted present value of the customers' outage time and formulated as (5).

The second term of (2) accumulates costs associated with installation and maintenance of the selected fault indicators and calculates through (4). The installation cost and maintenance cost during the planning horizon of each selected FI are assumed in the first and second terms of (4), respectively.

C. Technical Objective Function

In this study, system average interruption duration index ($SAIDI$) is considered as technical function. It is determined by dividing the sum of all customer interruption durations by the number of customers served during a year, as follows [2]:

$$Min\ F_2 = SAIDI = \frac{\sum_{i \in \Omega^{LP}} \sum_{k \in \{\Omega^l \cup \Omega^t \cup \Omega^b\}} \lambda_k . r_{ik} . n_i}{|\Omega^{LP}|} \quad (6)$$

III. SOLUTION APPROACH

A. Multi-objective Particle Swarm Optimization (MOPSO)

In this study, the PSO and MOPSO algorithms are applied to the proposed healer reinforcement approach by determining the number and location of FIs through Smart distribution Grid. PSO method is developed in 1995 by Kennedy and Eberhart which is a swarm intelligence method that roughly models the social behavior of swarms for the optimization of continuous non-linear functions. To such aim, it is considered that the particle vectors suggest the FIs places to install, accordingly the value of considered objective functions are calculated for each generated particles using (1) and (5). The PSO and MOPSO algorithm are well explained in [20-23].

B. Max-Min Approach

Each solution obtained in the Pareto optimal set could be selected as the final layout, according to the planner's point of view. There are several approaches to select the best solution among Pareto set of solutions. In this study, max-min approach is employed to reach this aim. If the minimum of objective function is desired, the objective functions are normalized using (7). Afterwards, minimum of each normalized objective function is selected as a max-min value. Then maximum value of these max-min values is selected as the final solution [24].

$$\mu_i^k = \frac{f_i^{max} - f_i^k}{f_i^{max} - f_i^{min}} \quad (7)$$

where f_i^{min} and f_i^{max} are the absolute minimum and maximum values of the i^{th} objective function, respectively. Also, f_i^k is the value of the i^{th} objective function of k^{th} non-dominated solution.

IV. CASE STUDY AND NUMERICAL RESULTS

A. *Case study*

In this paper, effectiveness of proposed healer healing approach by optimal placement of FIs is studied in several scenarios and simulated on bus number four of Roy Billinton test system (RBTS). Fig. 3 shows single-line diagram of the RBTS4 which includes three supply points, seven feeders, 38 load points and 4770 customers [25]. Five types of customers including residential, commercial, industrial, public customers, and critical public customers are considered as discussed in [26]. In this study, the repairing time is set equal to three hours, additionally, lines length and failure rates are given in [25]. Considering extended period of repair time for a faulted transformer (50 to 200 hours), it is assumed that spare transformer is available for each individual transformer; thus replacement time is considered instead of the repair time [27].

As Fig.3 shows, the problem is solved with regard to available remote control devices within the network. Moreover, it is assumed that the probability of successful operation of remote control switches, fuses, RTUs, control center, communication interface and feeder protection relays are 0.985, 0.90, 0.98, 0.98, 0.996 and 0.995, respectively [1].

To evaluate economic objective function through (2)-(5), the investment cost of the FIs with remote access is assumed US$ 1000 [16]. The life horizon of the FIs, inflation rate and interest rates are considered 10 years, 6% and 7%, respectively. Besides, the C_z^o of different type of customers are considered as discussed in [26]. According to the discussed installation rules, there are 72 candidate locations for the FIs installation in the under study network.

B. *Numerical Result*

The proposed healer reinforcement approach is conducted on the RBTS4 using PSO/MOPSO to solve single-/multi-objective problems. The single-objective problem is simulated in two scenarios; considering economic or technical objective functions and the multi-objective problem is conducted by considering both objective functions.

1) *First Scenario*

In this scenario, the problem is solved via single objective optimization by considering economic objective function with respect to maximum investment which is set equal to US k$ 40. Fig. 4 depicts the convergence rate of the proposed algorithm. The optimal value of the considered objective function is US k$ 630.84, which achieves by installing 22 FIs in the suggested optimum locations, as presented in Table 1.

Table 2 illustrates reliability indices of Smart Grid before and after applying the proposed healer reinforcement approach. As expected, optimal placement of FIs results in almost 15 % reduction in both SAIDI and CAIDI. The decrease in customers' interruption cost is about 12 % during the planning horizon, which not only compensates the installation and maintenance costs, but also brings almost US k$ 62 benefit. Thus, the proposed healer reinforcement approach is economically justifiable.

According to the obtained results, Table 1 illustrates that the economic objective function (F_1) can be minimized by placing four FIs within the long feeders of studying network, and two or three ones within the short feeders. To demonstrate this installation fact, the economic function for feeder number

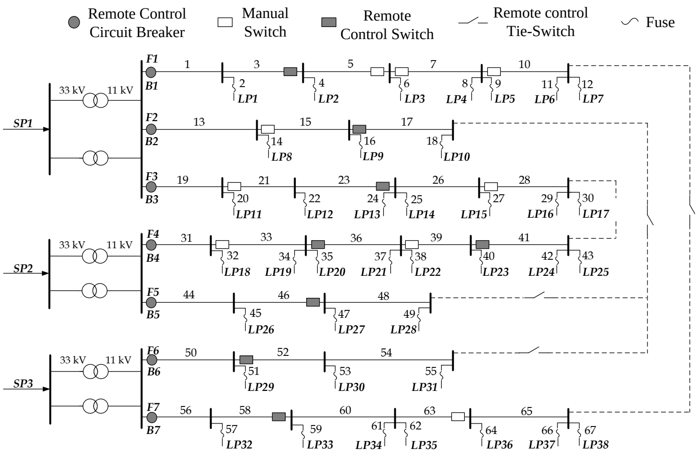

Fig. 3. Studying network configuration (RBTS4) [41]

three of studying network by installing different number of FIs is solved and illustrated in Fig. 5. As expected, in the studying feeder, minimum value of economic function is achieved by installing four FIs.

2) *Second Scenario*

In this scenario, the problem is solved through a single-objective optimization by considering the system average interruption duration index ($SAIDI$) as an objective function. The restoring service of each load point might be conducted automatically, manually or even after repairing the faulted zone, as shown in Fig. 1. Therefore, $SAIDI$ depends on how the service can be restored and categorized into three main categories. Hence, $SAIDI$ is calculated by presuming possible contingencies with respect to uncertainties of the automatic switching. Moreover, as the first scenario, maximum investment cost is set equal to US k$ 40. The convergence rate of the proposed algorithm is presented in Fig. 6. As it can be seen in this figure, the optimal value of the best solution is 0.30671, which is obtained by installing 40 FIs in the suggested optimum locations, as presented in Table 1.

Table 2 gives the reliability indices of healer healed system; it illustrates that CAIDI is decreased about 31 %. Also, as expected, reliability indices in this scenario are more improved in comparison with those reported in the first scenario. From an economic standpoint, the C^{IC} is reduced from US k$ 692.53 to US k$ 604.21 that recoups the planning investment and the maintenance cost. Furthermore, the cost benefit of the optimum placement is about US k$ 47.56.

Table 1 illustrates that $SAIDI$ can be minimized by placing four and seven FIs within each short and long feeders, respectively. To demonstrate this fact, by installing different number of FIs in the feeder number three of studying network $SAIDI$ is calculated and illustrated in Fig. 7. As it can be seen, by increasing the number of FIs, reduction rate of $SAIDI$ is decreased, and when the number of FIs exceeds more than 10, increasing in FIs numbers has no impact on amount of $SAIDI$.

The obtained results from the single objective optimizations indicate that the proposed healer healing approach extremely depends on the assumed objective function. The obtained layout in the first scenario is more economical in comparison with those obtained from the second one, while the obtained layout in the second scenario is more technically justifiable. Accordingly, it seems that a compromise between the technical

TABLE I. OPTIMAL NUMBER AND LOCATIONS OF FIS IN THE SECOND SCENARIO

Case	Optimum FI locations	Number of FIs	C^{FI} (US k$)
Minimizing Economic Function	7D,8D,10D,13U,16D,21U,26D,27D,28U,33U, 38D,39D,40D,44U,48D,50U,52U,54D,60U, 63D,63U,65U	22	22.418
Minimizing Technical Function	3D,4D,5U,7D,7U,10D,10U,15D,15U,17U,20D,21U,23D,26D,27D,28D,28U,33D,33U,34D,36 U,37D,39D,39U,41U,44U,45D,47D,48U,50U,52U,54D,54U,58D,60U,61D,62D,63U,64D,65U	40	40.760
Minimizing Economic and Technical function	3D,5D,7D,7U,10D,11D,13U,15U,17U,21D,22D,26D,28D,28U,30D,33D, 33U,35D,36U,38D,40D,41U,46D,48D,50U,53D,54U,58D,59D,61D,63D,63U,65U	33	33.620

TABLEI II. RELIABILITY INDICES ASSOCIATED TO THE OPTIMAL LAYOUTS

Objective Functions	Cost Function	SAIDI	CAIDI	AENS	ASAI	C^{IC}
Existing system	692.53	0.44889	0.99731	1.98787	0.999949	692.53
Min. Cost	630.84	0.37981	0.84383	1.67162	0.999957	608.42
Min. SAIDI	644.97	0.30671	0.68140	1.61532	0.999963	604.21
Min. Cost and SAIDI	640.94	0.34522	0.76698	1.65809	0.999961	606.30

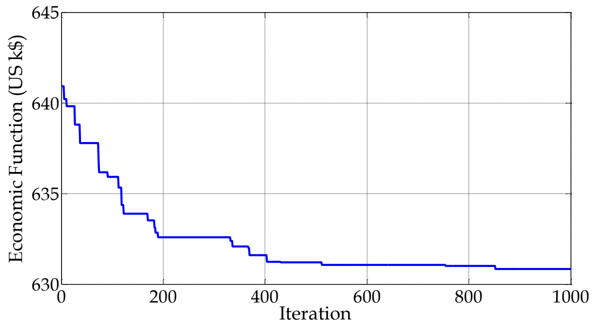

Fig. 4. The convergence rate of the proposed algorithm

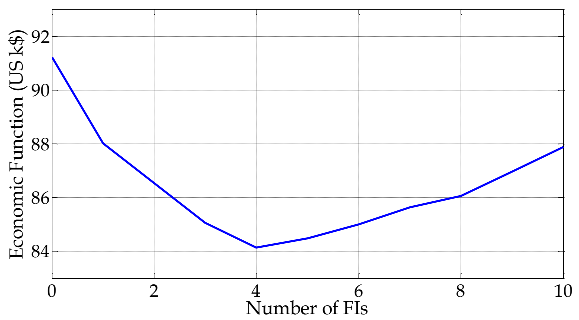

Fig. 5. Economic objective function versus various numbers of FIs

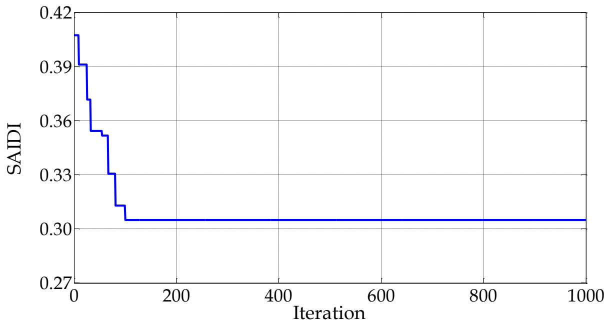

Fig. 6. The convergence rate of the proposed algorithm

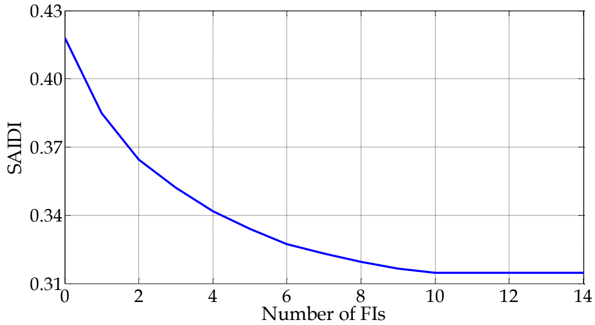

Fig. 7. Technical objective function versus various numbers of FIs

an economic objectives might be helpful to find the optimal FIs arrangement.

3) Third scenario

In this scenario, a multi-objective approach is applied to the FIs placement problem using particle swarm optimization to simultaneously minimize both economic and technical objectives. Fig. 8 shows the obtained Pareto optimal set of solutions. The best compromised solution among obtained Pareto set of solutions is achieved by applying the max-min method. The economic and technical objective function values of the best solution are US k$ 640.94 and 0.34522, respectively; which is achieved by placing 33 FIs as presented in Table I.

Table II presents reliability indices of this case. As expected, the economic function of the multi-objective optimization is approximately larger than which obtained from single objective in minimizing the economic function; however, the technical objective function is more improved. As represented in Table II, the highest reliability level is achieved by the proposed healer reinforcement approach by considering technical objective function in optimal FIs placement problem, however, this case is not as economical as two other ones. Accordingly, applying a multi-objective optimization to the FIs placement problem makes an interaction between technical and economic issues. Furthermore, the results illustrate the advantage of the multi-objective optimization above the single objective optimization.

Fig. 9 also displays a comparison between different scenarios for the interruption duration of each load point. As expected, by implementing the proposed healer healing approach the interruption duration of all customers decreased. However, the improvement percentage varies for each load point which these variations are due to existing restoration time and load types.

V. CONCLUSIONS

In this paper, a conceptual framework for self-healing ability of Smart Grid is introduced, including system, component, and healer healing (or healer reinforcement) layers. Also, the effects of the healer healing layer on two others were briefly mentioned. Moreover, the interactions between healer healing and the FLISR process in fault occurrences state were discussed. By focusing on the fault location process of the FLISR, FIs expansion was introduced as a proper approach to accelerate the fault location function and reinforce the self-healing ability of Smart Grid. To such aim, the optimal placement of the FIs problem was simulated on the RBTS4 and studied in several scenarios considering different objective functions. The problem was solved through a single objective PSO by consi-

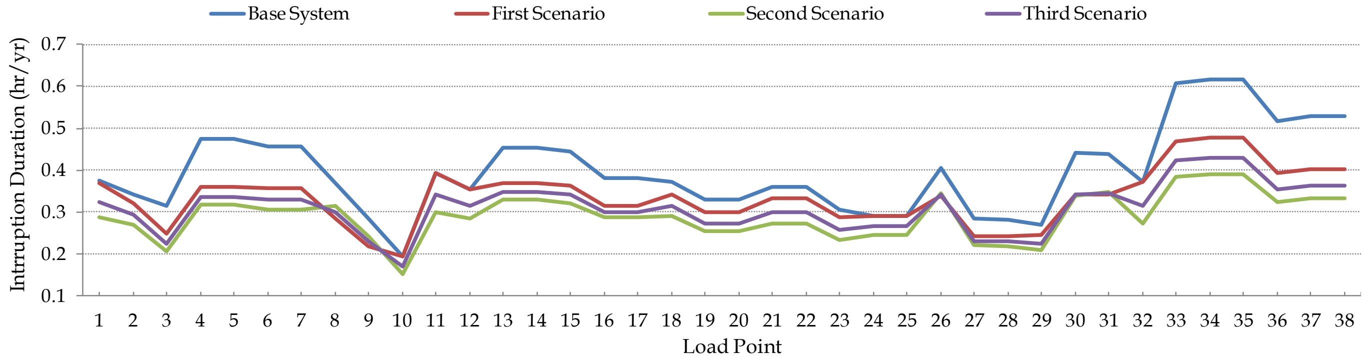

Fig. 9. Customers' interruption duration in different scenarios

dering technical and economic objective functions. The results illustrated that proposed healer healing approach extremely depended on the assumed objective function. Thus, in order to incorporate both economic and technical issues in optimization, the problem was solved using MOPSO algorithm to simultaneously minimize indispensable economic and technical objectives. The result obtained by the MOPSO illustrated that the multi-objective optimization makes an interaction between reliability level of Smart Grid and the economic issues.

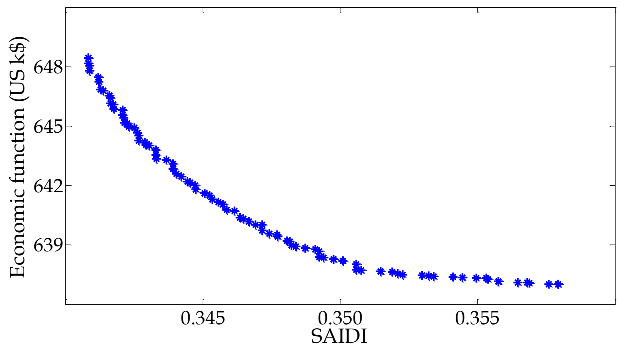

Fig. 8. Pareto-optimal set of solutions

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