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# Multi-Objective Evolutionary Algorithm for Service Restoration in the Presence of Distributed Generation

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**Abstract:** Distributed Generators (DGs) have been used to improve quality and reliability of service in Distribution Systems (DSs). They can be used to reduce faults impact on System Average Interruption Duration Index by allowing the minimization of healthy out-of-service (OFS) loads after the occurrence of permanent faults. IEEE also encourages power supply companies and customers to restore OFS loads by intentional islanding. This paper proposes a modification in recently proposed Multi-Objective Evolutionary Algorithm (MOEA) in subpopulation tables to combine intentional islanding of DGs with network reconfiguration to maximize restoration of OFS loads. The idea is to force intentional islanding whenever OFS heathy areas can be fully supplied by DGs. Simulation results (with a DS presented in the literature) have demonstrated the reliability of the MOEA new version to deal with service restoration problem in the presence of DGs.

*Keywords:* Service Restoration, Multi-Objective Evolutionary Algorithm, Distributed Generation, Distribution Systems.

## 1. INTRODUCTION

Power supply Interruptions in Distribution Systems (DSs) are inevitable and can be caused by either a network maintenance operation or the occurrence of permanent faults. Therefore, a fast and effective Service Restoration (SR) procedure is a critical way to increase customer satisfaction and reduce the impact of permanent faults on System Average Interruption Duration Index (SAIDI) by restoring out-of-service (OFS) loads. The SR problem is a complex and challenging problem, which involves several constraints, variables and conflicting objectives. Without considering Distributed Generators (DGs) the SR problem is regarded as a network reconfiguration problem. A solution is obtained by determining the minimal number of switching operations that results in a configuration with minimal number of healthy OFS loads without violating the operational and radiality constraints (Camillo et al., 2016). However, the complexity of this problem becomes higher when DGs are took into account.

The increased penetration of DGs in DSs has motivated studies addressing the planning and operation of microgrids. A microgrid is defined as a group of Distributed Energy Resources (DGs, energy storage systems, etc.) and loads in a well-delimited regions of a DS (Farrokhabadi et al., 2019). It can operate connected to the main feeder of a DS or in an isolated mode (disconnected from the main feeder), as a single controlled entity. To operate in an isolated mode a microgrid must keep voltage and frequency levels within the limits imposed by regulatory agencies and have injection capacities large enough to supply its loads (Hooshyar and Iravani, 2017).

Nowadays, DGs play an important role in DSs due to several factors, such as increased demand for energy, economic viability, minimization of environmental impacts, the need for more flexible electrical systems and significant technological advances. Hence, making use of DGs to restore OFS loads can improve reliability for customers. Traditionally, the utilities disconnect the DGs during contingencies (Zidan et al., 2017), which reduces their benefits. However, IEEE Standard 1547-2018 (IEEE, 2018) suggests the implementation of intentional islanding of OFS sectors [1] powered by DGs in case of power outages in DS and provides instructions for design, operation and integration.

Different approaches for solving the SR problem were analyzed in Zidan et al. (2017). The majority of them requires a simplified DS representation, which may resulting in getting deviating results from reality. Other methods calculate the optimal results without simplifications at cost of longer execution times, which is inappropriate for real time operation.

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[1] A sector is a set of buses and conductor connected by lines without switches.

Making use of the Node-Depth Encoding (NDE) (Delbem et al., 2004) to computationally represent the network topology, the Multi-Objective Evolutionary Algorithm (MOEA) in subpopulation-tables proposed in Marques (2018) is capable of dealing with practical aspects of the SR problem in large scale DSs, in an appropriate running time, without any simplification. However, it does not consider the existence of DGs.

This paper proposes a methodology that combines intentional islanding of DGs with network reconfiguration to solve the SR problem. The proposed methodology is based on the MOEA in subpopulation tables presented in Marques (2018) and makes use of the Local Search (LS) procedure developed in Fernandes (2019) to improve the search for solutions requiring operations only in switches in the healthy OFS sectors area. Unlike other methodologies, the proposed methodology considers first the possibility of intentional islanding. After that network reconfiguration, based on LS procedure and MOEA in subpopulation-tables, is performed. A test system proposed in the literature is used to validate the proposed methodology.

## 2. PROBLEM FORMULATION

Energy Not Supplied (ENS) corresponds to the amount of energy not supplied by consumers due to service interruptions. As ENS combines the information of power not supplied and time required to perform switch maneuvers, it is more important for SAIDI than final number of OFS loads or Power Not Supplied (PNS), as proposed by Mohammadi and Afrakhte (2012). Therefore, SR problem can be formulated as a multi-objective problem in order to minimize ENS and number of switching operations, considering operational constraints of DSs (Shin et al., 2004).

Some considerations are taken into account to include DGs in the proposed formulation of the SR problem: DGs are dispatchable and with ability to black start; in the occurrence of outages in sectors with DG (microgrids), this sector is turned off; and sectors with DGs can operate in both grid-connected or isolated forms.

The SR problem can be formulated as Equation 1 (Marques, 2018).

$$\begin{aligned} Min.\ ENS(G),\ \psi(G) \\ s.t.:\ A(G^e)x(G^e) = c(G^e) \\ A(G^e)Y_x(G^e)A(G^e)^t v(G^e) = c(G^e) \\ X(G^e) \leq 1 \\ B(G^e) \leq 1 \\ V(G^e) \leq \delta \\ G\, must\, be\, a\, graph\, forest \\ G = G^e \cup G^{ne} \end{aligned} \quad (1)$$

where G is a radial configuration of the DS represented by a graph forest, $G^e$ is the energized portion of the system, $G^{ne}$ is the restorable OFS portion of the system, $ENS(G)$ is the ENS during the time interval necessary to execute the switching operations to obtain the final configuration after the fault isolation, $\psi(G)$ is the number of switching operations necessary for the obtaining of $G$ from the configuration with the faulted sectors isolated, $A(G^e)$ is the pseudo-oriented node-edge incidence matrix, $x(G^e)$ is the complex currents' vector in the lines in $G$, $c(G^e)$ is the vector containing the load complex currents at the buses ($c \leq 0$) or the injected complex currents at the substation or in buses with DGs($c > 0$) in $G$, $Y_x(G^e)$ is the network admittance's diagonal matrix in $G$, $v(G^e)$ is the complex voltages' vector in $G$, $X(G^e)$ represents the maximum network loading observed in a configuration $G^e$, $B(G^e)$ is the maximum substation loading for a configuration $G^e$, $V(G^e)$ is the maximum relative voltage drop found for $G^e$, and $\delta$ is the maximum permissible voltage drop..

Equation 2 guarantee that DGs' power will be within its operation limits(Pereira et al., 2014).

$$\begin{aligned} P^g_{DG\,min} \leq P^g_{DG} \leq P^g_{DG\,max}\ \forall g \in nDG \\ Q^g_{DG\,min} \leq Q^g_{DG} \leq Q^g_{DG\,max}\ \forall g \in nDG \end{aligned} \quad (2)$$

$P^g_{DG\,min}$, $P^g_{DG\,max}$, $Q^g_{DG\,min}$ and $Q^g_{DG\,max}$ are, respectively, minimum active power, maximum active power, minimum reactive power and maximum reactive power of a DG unit installed at bus g; $P^g_{DG}$ and $Q^g_{DG}$ are active and reactive power injected by DG unit installed at bus g; and $nDG$ is the numbers of DG in DSs.

Another important aspect for computational and efficiently representation of DSs is the use of NDE, which is a graph structure proposed by Delbem et al. (2004). In this paper, NDE is used to computationally represent both energized and non-energized (restorable OFS) portion of DS. NDE has, additionally, two genetic operators that generate only graph forest. Consequently, the usage o NDE naturally ensures the last but one constraint.

## 3. METHODOLOGY

### *3.1 Base Methodology*

The base methodology (Marques, 2018) consists of a MOEA that mixes features from MOEAs in Subpopulation Tables (Santos et al., 2010) and Non-Dominated Sorting Genetic Algorithm - II (NSGA-II) (Deb et al., 2002). Besides, it is able to deal with practical aspects of the SR problem, such as, providing a switching sequence, prioritizing special customers (or priority consumers) and others. This methodology have been successfully evaluated in real DSs by the research group, as in Camillo et al. (2016); Marques et al. (2018); Marques (2018); Marques et al. (2019) and Fernandes (2019).

This MOEA includes multiple steps, from fault isolation to system's final configuration for the operator. It can be divided, in a simplified way, into the following major steps: reading data, obtain configuration after the isolation of the sectors in fault, performing a modified version of the local Exhaustive Search (ES) propoded in Camillo et al. (2016) [2], generation of initial population, searching for SR solutions through an evolutionary process of MOEA and, finally, proving a set of feasible and appropriate SR solutions.

[2] The original ES proposed in Camillo et al. (2016) is performed considering only the normally open switches that connect OFS sectors to energized sectors.

Its evolutionary process uses the principle of subpopulation tables, which divides the population in subpopulations and stores them in tables. Each table represents an important aspect of the SR problem. This principle has the advantage of addressing several objectives simultaneously without requiring penalty or weighting criteria. Furthermore, base methodology uses a efficient Forward-Backward Sweep Power Flow (Shirmohammadi et al., 1988) with the ability to handle large DSs.

### *3.2 Proposed Methodology*

The proposed methodology replaces the ES proposed in Camillo et al. (2016) by the LS procedure developed in Fernandes (2019), which expands the ES and allows different results during the evolutionary stage while preserving the consolidated structure of the base methodology. Initially, the LS is performed to guarantee the generation and feasibility analysis of all possible radial configurations requiring: (i) operations only in normally open (NO) switches incident to the healthy OFS sectors, like ES; and also (ii) operations in both NO and normally closed (NC) switches incident to the healthy OFS sectors. Therefore, the LS is able to perform the same operations of ES and still tries all possible combinations considering only maneuvers with deenergized sectors by operating NC switches. Thus, a new population will be generated and serve as initial population for the evolutionary stage.

In the context of SR problem considering the presence of DG, solution procedure should consider different situations, depending on where the fault occurred, location and type of DGs. In order to perform power flow analysis the DGs were modelled considering PQ control mode. Depending on the location of the fault, the solution procedure considering the presence of DGs should consider the following possibilities:

- Situation 1: DGs are located in the faulted sectors (if faults occurred inside microgrids);
- Situation 2: DGs are located on sectors that were not directly affected by the fault. That is, absence of DGs in faulted and in healthy OFS sectors.
- Situation 3: DGs are located in healthy OFS sectors (i.e., those that were disconnected due to faulted sectors' isolation).

Each of such possibilities requires a different treatment to solve the SR problem. For situation 1, DGs will be shut down and remain so throughout the failure recovery period. In situation 2, DGs may continue normally operating. In situation 3, some standards do not allow DGs to function in an isolated mode. Thus, as in situation 1, these DGs will be shut down and remain so for the entire period of fault recovery (Zidan et al., 2017). However, the IEEE Standard 1547-2018 (IEEE, 2018) encourages the use of intentional islanding, that is, portions of the power grid, which have DGs, can operate in isolated form from the utility grid.

When considering the possibility of intentional islading (Situation 3), there are two possible scenarios:

(i) DG is capable to supply the loads present in its sector (microgrid loads). In other words, DG's total power is greater than or equal to the power demand of its microgrid (loads and losses);
(ii) DG is not able to supply its microgrid loads.

In scenario (i), it is considered that island formation will occur in less than two seconds by protection devices, so DGs can be kept in operation according to IEEE (2018). Therefore, the sectors with DGs are isolated by protection maneuvers, and the resulting configuration is consider as the first individual of the proposed methodology. After LS tries to reconnect the rest of healthy OFS sectors. Figure 1 shows an example of a DS with a microgrid (sector 8). In Figure 1, circles represent substation, squares are sectors, each feeder is represented with a different color, dashed lines represent NO switches and full lines NC switches. Figure 2 shows an example of situation (i) in which the microgrid is isolated when a fault occurs in sector 4, so the NC switch that connects sector 7 to 8 is opened by protection devices responsible for the isolation of the microgrid (color grey represents the OFS sectors).

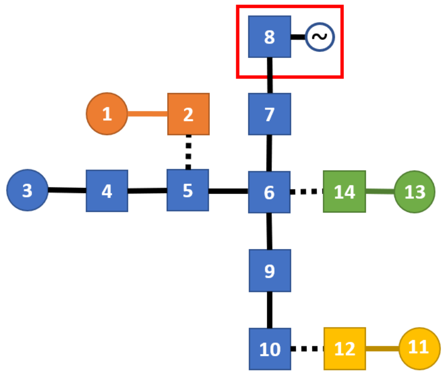


Figure 1. Example of a DS with four feeders and one microgrid.

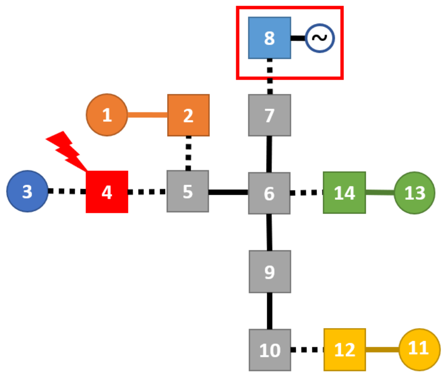


Figure 2. Example of a DS with the microgrid on isolated mode and faulted sector isolated

In scenario (ii), where DG is not capable to supply all loads, SR methodology continues normally, DG is turned off and DG's sector is considered in the restoration problem. Figure 3 represents scenario (ii).

During its evolutionary stage the proposed methodology performs switching operations (via the application of the NDE's reproduction operators) that can cause temporary power supply cuts at sectors, without DGs, that were not affected by the fault because of the need to relief or transfer load between feeders.

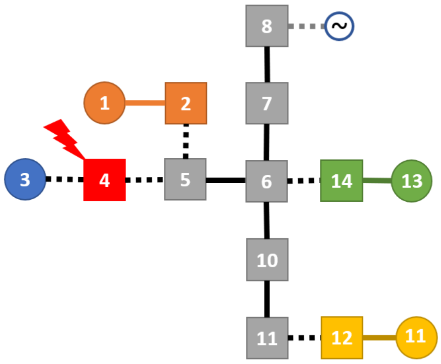


Figure 3. Example DS with DG disconnected and faulted sector isolated

The proposed methodology is divided in six main stages:

(1) Data read to obtain information of prefault configuration and fault location;
(2) Obtainment of the configuration after fault isolation;
(3) Verification of DGs locations;
  (a) If there is any DG in the restorable OFS sectors, verify microgrid's power;
  (b) If there is any DG in the faulted sectors, disconnect it;
(4) Obtainment of a configuration with all possible intentional islanding;
(5) Local Search;
(6) Evolutionary process.

## 4. RESULTS

In order to assess the proposed methodology, simple fault situations were considered in the DS illustrated in Figure 4, where numbers identify sectors. This system, already used by Romero et al. (2016), Marques (2018) and Fernandes (2019), is composed of 53 sectors, 3 substations, 6 feeders, 53 bus and 61 manual switches. In the prefault configuration the DS is under a maximum network loading of 75.2%, maximum relative voltage drop of 2.8% and maximum substation loading of 76.7%.

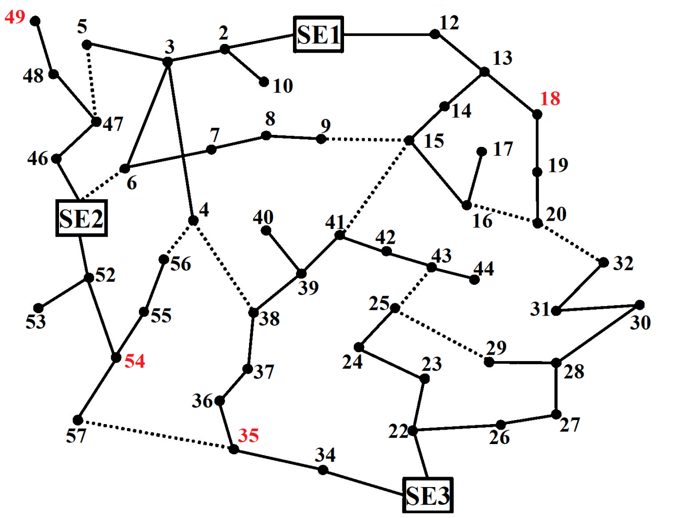


Figure 4. Test distribution system (Adapted from Peralta et al. (2019)).

The time considered for manual switch operation was 25 minutes, with a total estimated time of 4 hours for the fault to be fully corrected, as proposed by Romero et al. (2016) and Zidan and El-Saadany (2012). The voltage drop limit considered was 10%. Number of generations to be processed by the evolutionary stage combined to LS was 30,000. All simple fault cases were simulated 35 times, with the proposed methodology evaluating intentional islanding for capable DGs and comparing with forcing DGs in OFS sectors to shut down during the restoration process.

Four sectors with different aspects were chosen to consider the presence of DGs (identified by red numbers in Figure 4): Sector 18 - this sector is located in the middle of a feeder and has a heavy load; Sector 35 - which is near a substation; Sector 49 - it is located at the end of a feeder, and Sector 54 - which is located in the middle of a feeder. All DGs have the same active and reactive powers as the power demands of their sectors. So, in case of intentional islanding, all DGs are capable of supplying the corresponding sectors. Five different location of faults were tested to analyze the impact of intentional islanding compared to cases without considering the possibility of islanding.

### *4.1 Case 1 - Fault in sector 12*

The isolation of the faulted sector 12 causes power outage of all sectors supplied by its feeder. When considering the possibility of intentional islanding (case 1.b), sector 18 is isolated and DG continues to supply sector's loads, leaving sectors 19 and 20 only two options for service restoration through NO switches. Table 1 presents the results obtained by the proposed methodology in this situation.

If no islanding is done (case 1.a), the DG in sector 18 is forced to shut down and considered as a common sector in the system reconfiguration process, obtaining the results presented in Table 1. Comparing both situations, intentional islanding reduced both the number of switching operations and the ENS. Table 1 shows the recurrence of each result obtained throughout 35 simulations, ENS per phase, PNS per phase and total number of maneuvers.

Table 1. Summarization of test results for Case 1.

| Case | Recurrence | ENS(G) (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| 1.a | 35 of 35 | 20957.47 | 6098.40 | 5 |
| | 35 of 35 | 19790.92 | 5128.2 | 7 |
| 1.b | 35 of 35 | 15107.40 | 4643.10 | 3 |
| | 35 of 35 | 13132.35 | 3326.40 | 6 |

### *4.2 Case 2 - Fault in sector 34*

The fault in sector 34 also causes power outage of all feeder's sectors. The DG in sector 35 is located near the faulted sector causing reduction of available NO switches for reconfiguration in intentional islading cases, affecting the possibilities of restoring the OFS loads. The number of individuals generated through LS was 361, when intentional islanding is performed (case 2.b), compared to 1,328 individuals when DG is switched off (case 2.a). Table 2 presents the results obtained in both cases.

Table 2. Summarization of test results for Case 2.

| Case | Recurrence | ENS(G) (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| 2.a | 35 of 35 | 18520.43 | 3742.20 | 5 |
| | 35 of 35 | 15413.48 | 207.90 | 8 |
| 2.b | 35 of 35 | 14570.33 | 2494.80 | 5 |
| | 35 of 35 | 11139.98 | 207.90 | 6 |

Even with reduced restoration possibilities, ENS is lower when intentional islanding is applied. There are also improvements in both restoration problem objectives when comparing the solutions with the lowest switching operations.

### *4.3 Case 3 - Fault in sector 52*

Faults in sector 52 cut power supply of all feeder's sectors, similar to fault in sector 12. However, in this case the DG islanding does not have a great impact in LS reconfiguration possibilities, since there is already a low amount of individuals (Ds configurations) possible to be generated (14 without islanding and 5 with islanding). Table 3 presents the results with intentional islanding (case 3.b) and without islanding (case 3.a). Intentional islanding once again improves results compared to no islanding.

Table 3. Summarization of test results for Case 3.

| Case | Recurrence | ENS(G) (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| 3.a | 35 of 35 | 4134.9 | 485.1 | 4 |
| | 35 of 35 | 3205.13 | 0 | 5 |
| 3.b | 35 of 35 | 3222.45 | 762.3 | 3 |
| | 35 of 35 | 1443.75 | 0 | 4 |

### *4.4 Case 4 - Fault in sector 2*

Unlike previous cases, a fault in sector 2 does not allow any kind of islanding, because there is no DG in OFS sectors. This case is considered to evaluate the impact of DGs outside OFS sectors and the effectiveness of restricted NDE operators (no maneuvers with DG sectors can be done, as DGs' shoutdown are undesired). Although the sector in faulted is next to a substation, similar to cases 1 and 3, restriction in switching operations did not have any negative impact. Actually, DGs effect is more noticeable, as results obtained when combining DGs presence (case 4.b) and restricted switching operations are better than results without considering the presence of any DG in the test system (case 4.a). Table 4 presents the results obtained in each situation by the proposed methodology.

The switching sequence of this solution obtained by proposed methodology (in terms of ENS) without considering the presence of any DG in the test system is illustrated

Table 4. Summarization of test results for Case 4.

| Case | Recurrence | ENS(G) (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| 4.a | 35 of 35 | 8674.05 | 1663.20 | 4 |
| | 35 of 35 | 5486.25 | 0 | 5 |
| 4.b | 35 of 35 | 5925.15 | 485.1 | 4 |
| | 35 of 35 | 4995.38 | 0 | 5 |

in Table 5. Table 6 presents the switching sequence of the best solution obtained by proposed methodology (in terms of ENS) considering the presence of DGs illustrated in Figure 4. In both cases the best solution allows service restoration for all OFS healthy sectors having possibility of restoration (sectors 3, 4, 5, 6, 7, and 9). However, the solution obtained considering the GDs is better in terms of ENS.

Table 5. Example of switching operations of a solution generated for Case 4 without DGs.

| Open | Close | $ENS(G)$ (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| SE1 - 2 | - | - | - | - |
| 2 - 3 | - | 18214.35 | 5751.9 | 2 |
| 6 - 7 | - | 18214.35 | 5751.9 | 3 |
| - | SE2 - 6 | 8674.05 | 1663.2 | 4 |
| - | 15 - 9 | 5486.25 | 0 | 5 |

Table 6. Example of switching operations of a solution generated for Case 4 with DGs.

| Open | Close | $ENS(G)$ (kWh/phase) | PNS(G) (kW/phase) | $\psi(G)$ |
|---|---|---|---|---|
| SE1 - 2 | - | - | - | - |
| 2 - 3 | - | 18214.35 | 5751.9 | 2 |
| 3 - 5 | - | 18214.35 | 5751.9 | 3 |
| - | SE2 - 6 | 5925.15 | 485.1 | 4 |
| - | 47 - 5 | 4995.38 | 0 | 5 |

All simulations were performed with a computer with 32GB of RAM and a Core i7 4770 processor running Ubuntu 18.04, Table 7 shows the average simulation time of all cases occurred in less than 8 seconds, each.

Table 7. Average simulation time.

| Case | Time (s) | Case | Time (s) |
|---|---|---|---|
| 1.a | 6.368 | 1.b | 6.000 |
| 2.a | 6.469 | 2.b | 6.784 |
| 3.a | 6.279 | 3.b | 7.508 |
| 4.a | 6.959 | 4.b | 6.961 |

## 5. CONCLUSION

This paper has proposed a MOEA in subpopulation tables for solving service restoration problem in the presence of DGs. The proposed MOEA combines intentional islanding of DGs with network reconfiguration to maximize restoration of OFS healthy loads. Tests performed in a DS presented in literature proved the main contributions of this proposed methodology and showed that intentional islanding is advantageous in most situations (even if it reduces the amount of possible switching operations affecting both LS and evolutionary process of the proposed methodology).

Advantages of intentional islanding depend on the correct planning of DS, because it is necessary to properly set protection devices, and, if the DGs are not allocated in adequate sectors, islanding events may be impossible to occur or restoration of healthy OFS sectors can be affected (if the islanding isolates sectors with no possibility of reestablishment by other means). The test results also indicated advantageous even when the DGs are not located in healthy OFS sectors, since they relieve the feeders where they are located.

Future works comprise the validation of the proposed methodology on a large real DS.

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