Distributed Energy Resource-Cognizant Upgrade Paths to the Traditional Restoration Strategy of Utilities for Improved Load Restoration

Preprint

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National Renewable Energy Laboratory

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Distributed Energy Resource-Cognizant Upgrade Paths to the Traditional Restoration Strategy of Utilities for Improved Load Restoration

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***Abstract*—Climate change has resulted in increasingly impactful and more frequent occurrences of extreme weather events. This trend poses a significant challenge for distribution utilities and system operators to ensure that there is uninterrupted power supply to critical loads in their networks under fault scenarios; however, currently, utilities deploying the automated fault location, isolation and restoration (FLISR) function in their advanced distribution management system (ADMS) do not take into account the available generation and load-modification capabilities of distributed energy resources present in the disconnected network due to an upstream isolated fault. This results in the network reconfiguration and restoration to result in sub-optimal load restoration. Therefore, this paper presents two approaches that can upgrade the existing FLISR capabilities of distribution utilities to significantly increase the restoration of critical loads. The performance of the proposed approaches is evaluated on a numerical model of a real distribution feeder in Georgia, USA.**

***Keywords*—DER, FLISR, network optimization, reconfiguration**

I. Introduction

Utilities are modernizing their distribution network solutions by replacing legacy distribution management system (DMS) with state-of-the-art grid automation solutions such as advanced distribution management system (ADMS) [1], which integrates various advanced functionalities, such as network analysis and optimization, with traditional DMS functions, such as outage management system and supervisory control and data acquisition system . With ADMS, the situational awareness and control of the distribution grid can be significantly improved, which helps the utilities optimize the system performance and outage costs much more efficiently [2].

Fault location, isolation, and service restoration (FLISR) [3] is an important application in the ADMS, and it helps in making the distribution system more reliable and resilient by identifying and isolating the faulty part of the system and enabling service restoration to the customers. This restoration is traditionally carried out through network reconfiguration [4] via tie-switches and sectionalizing switches so that customers in the disconnected section downstream from an isolated fault are connected back to the healthy circuit. However, traditional FLISR assumes that the only source of power supply is the distribution substation [5] and largely ignores the generation and load-modification capabilities of various distributed energy resources (DERs) in the network [6], [7]. Unlike traditional FLISR, the FLISR application of the near-future must be cognizant of such DERs [8] and integrate them efficiently in its calculations to benefit the customers by improving load restoration [9], [10].

Therefore, this paper proposes two upgrade paths to make traditional FLISR applications DER-cognizant and to help operators restore electricity to more customers in the event of one or more network faults. In the first upgrade scenario, the network reconfiguration is achieved – first, by considering load flexibility after incorporating DERs into the FLISR load calculations to restore as much of the disconnected network as possible; and second, by considering DER dispatch in the leftover isolated subnetworks which could not be connected back to the healthy circuit. In the second upgrade scenario, a holistic optimization is carried out to enable optimal network reconfiguration and DER dispatch in the disconnected network to maximize load served to the customers.

The paper is organized as follows. Section II provides a high-level description of the system considered in this paper, and Section III provides a description of the traditional FLISR application scenario and the two proposed upgrade scenarios. Section IV provides information about the numerical model of the test networkm while Section V details the numerical results. Finally, Section VI concludes the paper.

II. System Description

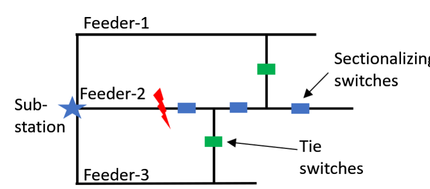


Figure 1: Simplified diagram of the system.

In this paper, a realistic distribution network is considered comprising of multiple feeders emanating out of the distribution substation (as shown in a simplified diagram in Figure 1). These feeders also have several sectionalizing switches to segment the feeder into multiple sections (or subnetworks) along with tie-switches to transfer load from one feeder to another. The system is also considered to have multiple utility-controlled DERs and aggregated behind-the-meter (BTM) DERs employing home energy management systems (HEMS). The BTM DERs consist of solar photovoltaic panel (PV), heating, ventilating and air conditioning appliance (HVAC), and electric water heater (EWH). Further, each load node in such a system is considered to have three components – critical, non-critical and a HEMS-controlled load. It is also assumed that the critical and non-critical loads can be curtailed on a real-valued scale, and the HEMS can take active/reactive power setpoints from the FLISR and dispatch their BTM DERs.

III. Description of FLISR Scenarios

A. Baseline Scenario: Traditional FLISR

This scenario is modelled based on the operation logic of traditional FLISR applications of most utilities. In this scenario, once a fault is located and isolated, availability of tie-switches is checked which can connect the healthy circuit to the disconnected network downstream of the isolated fault. If a tie-switch is available, it is turned ON if the healthy circuit on the other side of the tie-switch can pick up the rated capacity of all the loads in the disconnected network. If there are sectionalizing switches available to segment the disconnected network into multiple subnetworks, then the tie-switch will be turned ON only if it can pick up at least the load in the first adjacent subnetwork. The sectionalizing switches are then operated to transfer as many subnetworks as possible to the healthy circuit. As is the case with traditional FLISR operation of utilities, it is further assumed that all the utility-controlled and BTM DERs are not utilized and remain offline.

B. DER-Cognizant FLISR Upgrade Scenario - 1: Integrating DER Felxibility

In this scenario, FLISR considers the presence of DERs in the disconnected network downstream of an isolated fault. The operation logic to close the tie-switches so as to connect the disconnected network to the healthy circuit is similar to the Baseline scenario in Section III-A; however, when the load calculations are done to evaluate whether to close the tie-switch, instead of considering rated load values and no DERs as in the Baseline scenario, load flexibility is evaluated by considering dispatch of DERs and the lower bound value of the loads is considered. This approach results in a lower available-capacity threshold needed for the healthy circuit to be able to pick up the loads in the disconnected network. Also, for the subnetworks which can not be connected back to the healthy circuit, the DERs (with some behaving as grid-forming while others as grid-following) present in those subnetworks are dispatched to pick up as many loads as possible by enabling load-shedding.

C. DER-Cognizant FLISR Upgrade Scenario - 2: Full Scale Network Optimization

In this scenario, DER availability is fully leveraged and FLISR determines the optimal statuses of all available tie-switches connecting to the healthy circuit and all sectionalizing switches, that can make segmentations, in order to maximize restored loads in the entire disconnected network while maintaining radiality. Unlike the Baseline scenario and Scenario-1, in this scenario, the tie-switches with the healthy circuit can be closed even if the healthy circuit can only partially meet the rated load or the lower-bound load requirement of the disconnected network, by shedding loads and dispatching DERs optimally.

D. Optimal Utilization of DERs and Load-Shedding

For the isolated subnetworks in Scenario-1 and for all the subnetworks in Scenario-2, the optimal dispatch of utility-controlled DERs and BTM DERs using HEMS and the optimal load-shedding of critical and non-critical loads is performed using the optimization model developed in a prior work [11]. The optimization model essentially minimizes critical and non-critical load-shedding considering an unbalanced three-phase distribution system model. Also, the HEMS model is considered to implement the setpoints dispatched by FLISR and aims to keep the indoor temperature and water heater temperature of the home within limits. The reader is referred to [11] for the detailed formulation, which has not been included in this paper for brevity.

IV. Test System

The aforementioned three scenarios (i.e., Baseline, Scenario-1 and Scenario-2) are implemented on a numerical model of a real distribution feeder, as shown in Figure 2a, in Georgia, USA. This feeder consists of more than 1000 load nodes overall with three normally-closed sectionalizing switches (labelled as SS1, SS2 and SS3), and three faults are assumed to have occurred at times t = 00:00, 04:00 and 07:00. It can be observed from the locations of these faults and the sectionalizing switches that the faulty area in the entire feeder can be divided into multiple subnetworks (labelled as SN1, SN2, SN3 and SN4). Further, two normally-open tie-switches (TS1 and TS2) are shown in Figure 2a, and they can be used to connect the faulty subnetworks to the healthy circuit (shown as comprising of dark blue nodes). Finally, Figure 2a shows that there are multiple utility-controlled DERs in the faulty area subnetworks, and the results in Section V will demonstrate usage of these utility-controlled as well as BTM DERs located at the load nodes and managed by HEMS to improve the FLISR operation and help it restore more critical loads.

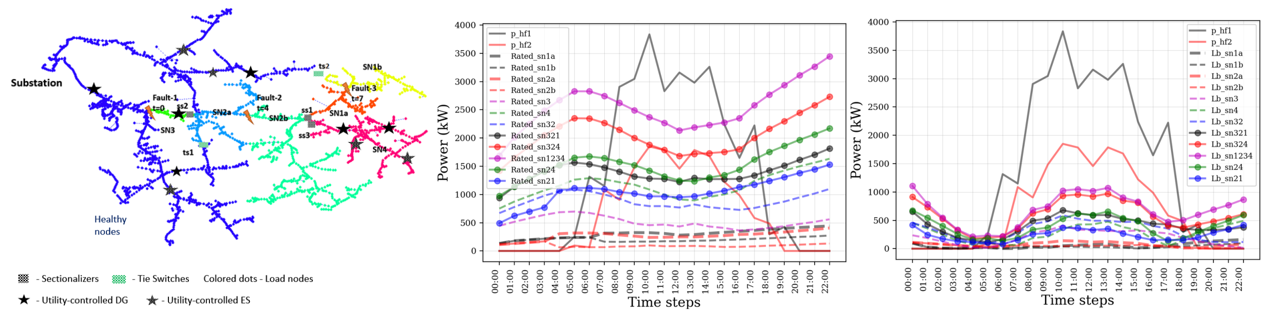
Further, Figure 2b presents time-series plots of power availability of the two healthy circuit connections (labelled as *hf1*, for the healthy circuit connection via TS1, and *hf2*, for the healthy circuit connection via TS2), as well as the sum of rated load requirement of the loads in each combination of possible subnetwork configurations. Also, Figure 2c presents time-series plots of power availability of the two healthy circuit connections as well as the sum of lower-bound load requirement of the loads in each combination of possible subnetwork configurations after considering DER availability in the subnetworks.

V. Simulation Results

A. Baseline Scenario: Traditional FLISR logic

Results for the Baseline scenario imitating the traditional FLISR logic of most distribution utilities are presented in this section. The switching actions over time of the tie-switches and the sectionalizing switches are shown in Figure 3a, with red meaning the switch is OFF and green meaning the switch is ON. Referring to Figure 2b and the network topology, it can be observed that the tie-switch TS1 turns ON from 06:00 to 18:00 only when *hf1* has sufficient power availability to support loads in at least the subnetwork SN2a. Similarly, the tie-switch TS2 turns ON from 07:00 to 19:00 only when *hf2* has sufficient power availability to support loads in at least SN1b (due to Fault 3). All the sectionalizing switches (SS1, SS2 and SS3) remain in the same normally ON state from before the fault because the occurrence of faults prevents the need for any segmentation requirement as the healthy circuit powers are sufficient for the remaining connected subnetworks.

Figure 3b and Figure 3c show that the utility-controlled DG and ES assets, respectively, remain unutilized, and Figure 3d shows that the HEMS are only able to consume power when their respective subnetworks are connected back to the healthy circuit. Finally, the critical load served is shown in Figure 3e,

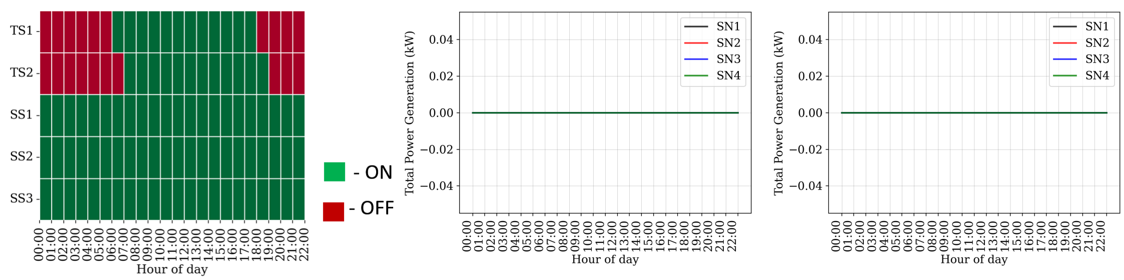


(a) Feeder topology with fault locations, switches and DERs

(b) Available healthy circuit powers and required rated powers for the subnetworks

(c) Available healthy circuit powers and required lower bound powers for the subnetworks.

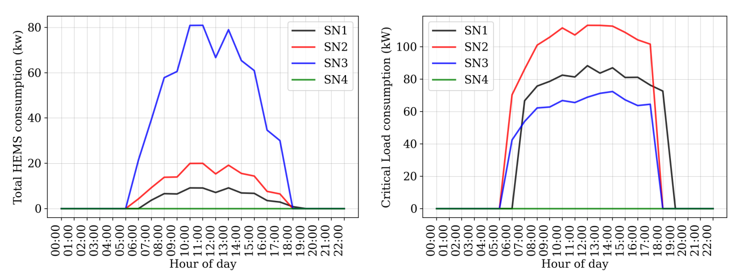
Figure 2: Feeder topology, and available healthy circuit powers and load requirements of the subnetworks.



(a) Switch Positions

(b) Utility-controlled DG

(c) Utility-controlled ES



(d) HEMS

(e) Critical Load

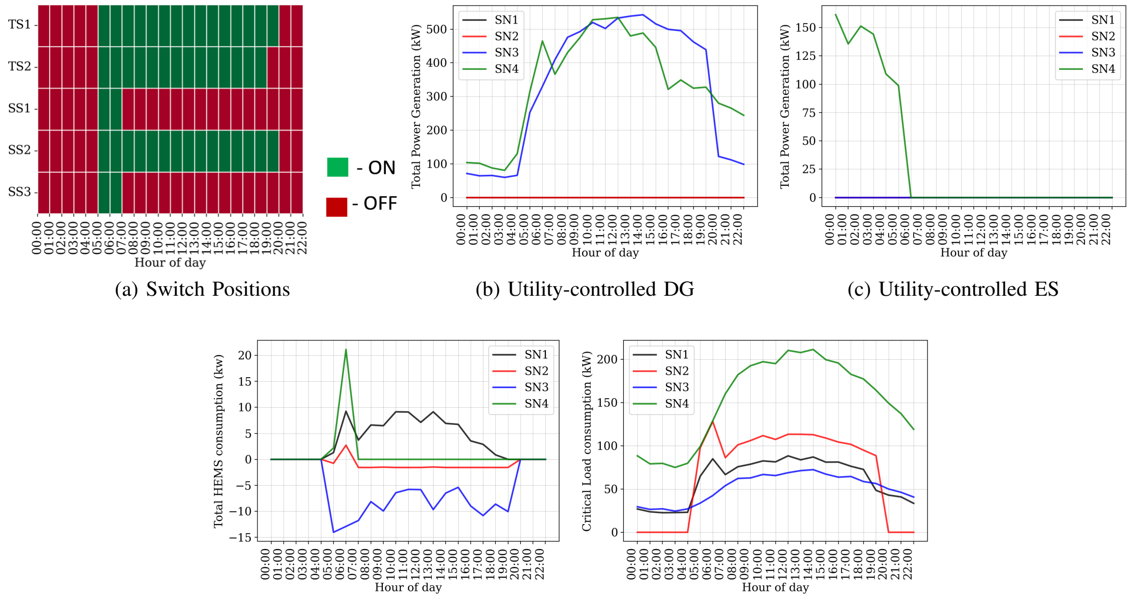
Figure 3: Plots for the Baseline scenario.

and it can be observed that the critical loads can be supplied only when their subnetworks are connected to the healthy circuit. For SN4, since there are faults on either of its sides, the healthy circuit cannot connect to SN4, which results in zero load to be served in that subnetwork.

B. Scenario-1: Integrating DER Flexibility

For Scenario-1 with DER flexibility integrated, the switching actions over time of the tie-switches and the sectionalizing switches are shown in Figure 4a. Referring to Figure 2c and the network topology, it can be observed that the tie-switches TS1 and TS2 now turn ON at 05:00 because both *hf1* and *hf2* have sufficient power availability to support the lower-bound of load requirement after considering DER availability, in at least the subnetworks SN2a and SN1b, respectively. All the sectionalizing switches (SS1, SS2 and SS3) also turn ON at 05:00 because the healthy circuit powers are sufficient for the lower-bound of the connected subnetworks after Fault-2 happened at 04:00; however, at 07:00 when Fault-3 happens, there is no possible connection path between the healthy circuit and subnetworks SN1a, SN2b and SN4, so the sectionalizing switches SS1 and SS3 turn OFF. The tie-switches TS1 and TS2 turn OFF at 20:00 and 19:00, respectively, once their power availability is insufficient with respect to lower-bound load requirements of their closest subnetworks.

Since in this scenario, the FLISR can also employ DERs to support the critical loads, Figure 4b and Figure 4c show that the utility-controlled DG and ES assets, respectively, are being dispatched as grid-forming resources even before the tie-switches are turned ON at 05:00 to support critical loads in their own subnetworks (because the asset capacities are sufficient to support the lower-bound load requirement of their own subnetworks). This is also the reason why the HEMS are also disconnected until 05:00. After the tie-switches are turned ON, the HEMS in the subnetworks connected to the healthy circuit are asked to be at their lower-bound powers, while the HEMS in isolated subnetworks (i.e., SN4 after 07:00) are disconnected. Finally, the critical load served is



(a) Switch Positions (b) Utility-controlled DG (c) Utility-controlled ES

(d) HEMS (e) Critical Load

Figure 4: Plots for Scenario-1.

shown in Figure 4e, and it can be observed that, compared to the Baseline scenario, the critical loads can now be supplied even when their subnetworks are not connected to the healthy circuit. For SN2, since it does not have any utility-controlled DERs, its loads can be served only when the sectionalizing switches on either of its sides are ON.

C. Scenario-2: Full-scale Network Optimization

For Scenario-2 with full-scale network optimization, Figure 5a shows the switching actions over time of the tie-switches and the sectionalizing switches. It can be observed that the tie-switches TS1 and TS2 turn ON whenever the respective connection point, i.e., *hf1* or *hf2*, has a non-zero power availability. The sectionalizing switches (SS1, SS2 and SS3) now turn ON or OFF based on the availability of resources and network radiality constraints.

In this scenario, the FLISR employs DERs to the fullest extenet to support the critical loads, as can be seen in Figure 5b and Figure 5c for the utility-controlled DG and ES assets, respectively, and in Figure 5d where the HEMS are observed to be actively consuming/generating power throughout the day. Finally, the critical load served is shown in Figure 5e, and it can be observed that, compared to the Baseline and Scenario-1, significantly more critical loads are now being supplied.

D. Key Differences

The overall comparison results for the three scenarios are presented in this section. First, Figure 6a presents the critical load shed time-series for the three scenarios. It can be observed that the Baseline scenario has the worst load-shedding (approx. 7837 kWh) because it does not employ existing DERs and relies on connecting the healthy circuit to the downstream disconnected network only if the rated load in that network can be fully supported after checking for segmentation via sectionalizing switches. Scenario-1 with DER flexibility integrated has a smaller load-shedding (approx. 2973 kWh) than the Baseline scenario because it does employ DERs to support loads; however, because the decision to close the sectionalizing switches is still made based on whether the healthy circuit power is sufficient to take on loads (albeit lower-bound values) for one or more adjacent subnetworks, it results in some subnetworks to be left isolated and they have to then rely on their own resources to support their loads. Scenario-2 with full-scale network optimization alleviates this shortcoming by considering the healthy circuit power availability as well as all DERs together in a holistic optimization to support as much of load requirement as possible. This approach results in the smallest load-shedding (approx. 421 kWh) out of all the three scenarios. Further, Figure 6b and Figure 6c show average indoor temperature and water heater temperature of the homes, and it can be observed that Scenario-2 with full-scale network optimization is able to maintain more comfortable temperatures throughout the day than the other two scenarios.

VI. Conclusion

This paper proposed two approaches to upgrade the traditional FLISR application used in the ADMS solution employed by most utilities, by making the FLISR aware of DERs in the distribution network. The proposed approaches were evaluated on a numerical model of a real distribution network in Georgia, USA, and the service restoration results were compared with a baseline, imitating the traditional FLISR logic. The results showed that both the proposed approaches resulted in a significantly reduced load-shedding compared to the baseline, and the utilities can employ one or the other approach based on their desired restoration improvement needs and the required efforts.

Acknowledgment

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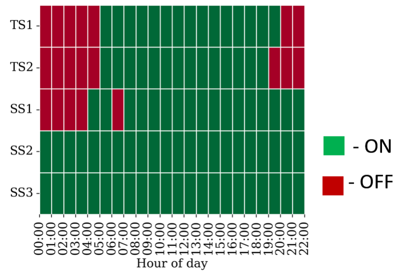
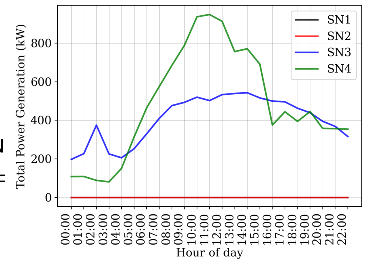
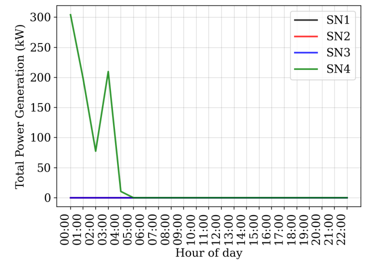


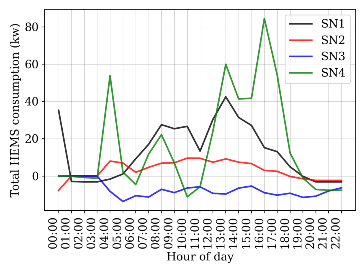
(a) Switch Positions



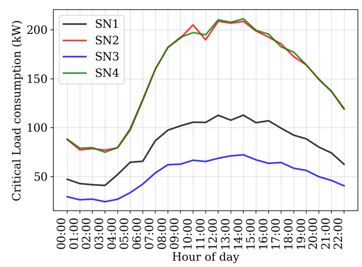
(b) Utility-controlled DG



(c) Utility-controlled ES

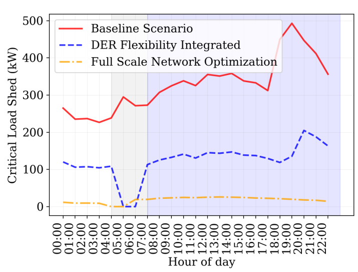


(d) HEMS

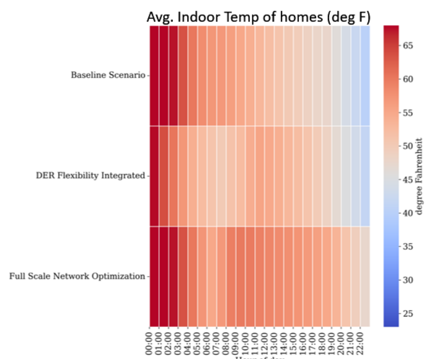


(e) Critical Load

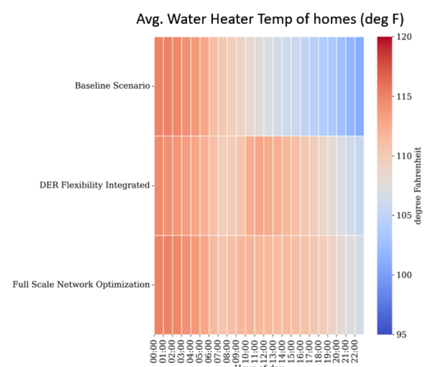
Figure 5: Plots for Scenario-2.



(a) Critical load shed for all the scenarios.



(b) Avg. indoor temperature of the homes



(c) Avg. water heater temperature of the homes.

Figure 6: Comparison plots for the three scenarios.

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