A Tabu-search-based Algorithm for Distribution Network Restoration to Improve Reliability and Resiliency

Alessandro Bosisio, *Member*, *IEEE*, Alberto Berizzi, *Member*, *IEEE*, Daniele Lupis, Andrea Morotti, Gaetano Iannarelli, and Bartolomeo Greco

***Abstract*—Fault restoration techniques have always been crucial for distribution system operators (DSOs). In the last decade, it started to gain more and more importance due to the introduction of output-based regulations where DSO performances are evaluated according to frequency and duration of energy supply interruptions. The paper presents a tabu-search-based algorithm able to assist distribution network operational engineers in identifying solutions to restore the energy supply after permanent faults. According to the network property, two objective functions are considered to optimize either reliability or resiliency. The mathematical formulation includes the traditional feeders, number of switching operation limit, and radiality constraints. Thanks to the DSO of Milan, Unareti, the proposed algorithm has been tested on a real distribution network to investigate its effectiveness.**

***Index Terms*—Distribution system operators (DSOs), heuristic algorithms, power system reliability, power system restoration, resiliency.**

I. Introduction

RELIABILITY and resiliency represent two fundamental aspects for distribution networks (DNs). On the one hand, reliability measures the network's ability to ensure a safe and stable operation, reducing the amount of disservice procured to the connected users. On the other hand, resiliency measures the network's ability to withstand critical events such as heat waves, flooding, snow storm, etc., which can lead to multiple faults with the consequent disconnection of several users for very long time. In the last decade, DN reliability and resiliency received increasing attention from energy Authorities in Italy and worldwide [1]. As a result, energy Authorities have introduced performance indices to establish DN reliability, considering both the frequency and duration of interruptions, introducing a system of bonuses and penalties in an output-based paradigm [2].

In this scenario, fault restoration techniques have acquired new importance to reduce disservices to the users and penalties to the DSOs [3]. Restoration techniques for the medium-voltage (MV) network section located upstream of the faulted point are already well defined and implemented in literature [4]. Indeed, to achieve this goal, it is sufficient to identify and isolate the faulty element and then resupply the users connected upstream to the faulty point by reclosing the tripped circuit breaker located in the primary substation. Furthermore, with the implementation of communication systems and remote terminal units (RTUs), such operation could be achieved automatically using automation techniques, reducing further the time required to restore the energy supply [5]. On the other hand, restoring the network section downstream of the faulted point is still challenging. Historically, due to the smaller size and complexity of DNs, such operations were made by engineers who decided the restoration plan based on their experience. However, as the size of the power system and complexity increases, the problem has evolved from a relatively straightforward issue, mainly concerning the time minimization to perform such operations, to a multi-objective constrained problem, where traditional arrangement rarely provides fast optimum solutions. Nonetheless, to determine the best possible configuration, it would be necessary to analyze hundreds of thousands of combinations, requiring a massive amount of time.

Several problem formulations and optimization algorithms have been proposed concerning DN restoration [6]. Among the published papers, [7]-[11] include the DN reliability, while [12]-[16] focus on DN resiliency.

In [7], the advantages of using a two-stage restoration strategy rather than a single-stage restoration strategy following fault inception are shown. In the two-stage strategy presented, the first stage quickly restores the limited set of cus-

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A. Bosisio (corresponding author) and A. Berizzi are with the Energy Department of Politecnico di Milano, Milan, Italy (e-mail: alessandro.bosisio@polimi.it; alberto.berizzi@polimi.it).

D. Lupis was with the Energy Department of Politecnico di Milano, Milan, Italy, and he is now with E-distribuzione, Monza, Italy (e-mail: daniele.lupis@mail.polimi.it).

A. Morotti is with the Unareti Electrical Network Planning Department, Milan, Italy (e-mail: andrea.morotti@unareti.it).

G. Iannarelli is with the Department of Astronautics, Electrical and Energy Engineering of the Sapienza University, Rome, Italy, and he is also with the Technological Development Department of the DSO Unareti, Milan, Italy (e-mail: iannarelli.800040@studenti.uniroma1.it).

B. Greco is with the Unareti Market Development and Special Projects Department, Milan, Italy, and he is also with the Department of Astronautics, Electrical and Energy Engineering of the Sapienza University, Rome, Italy (e-mail: bartolomeo.greco@unareti.it).

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tomers using automated switches, while a later stage restores additional customers using manual switches. The two strategies are compared using a predictive reliability assessment algorithm capable of modeling each strategy. In [8], the reliability assessment of DNs embedded with renewable distributed generation (DG) sources has been carried out, emphasizing system uncertainties and optimal restoration strategies. The uncertainties associated with renewable resource power output, time-varying load demand, stochastic prediction errors, and random fault events have been accounted for in the formulation of restoration optimization for reliability evaluation. In [8], a parameter-free particle swarm optimization (PSO) technique is applied to address the complexity involved in the formulation. A novel DN reconfiguration (DSR) model to enhance the service reliability and the benefit of DNs with DGs and energy storage systems (ESSs) is proposed in [9]. First, the impact of sectionalizing switches and tie switches on reliability is considered. Second, the concept of "boundary switch" is introduced for quantifying the customer interruption duration. The DSR model is presented to minimize the customer interruption cost, the operation cost of switches, and the depreciation cost of DGs and ESSs. Reference [10] establishes a restoration model based on actual grid situation, which is more realistic for active distribution networks (ADNs), considering the user priority level, the load amounts restored, the counts of switch operations, the network loss after the power restoration, and the operation of power sources. In [11], an agent-based approach is proposed to optimize the reliability of a system in the restoration process, considering load balancing as a constraint. A modified restoration strategy based on reinforcement learning, namely the wolf pack algorithm (WPA), is proposed under the multi-agent framework and communication architecture. First, considering the network constraints and dynamic load, several types of agents are defined and abstracted to imitate physical entities. In addition, integrated with the WPA, the multi-agent system (MAS) is subsequently utilized to optimize the system reliability while considering the tradeoff of load balancing.

Regarding resiliency, [12] presents a novel modified Viterbi algorithm to identify the optimal DN restoration plan for improving grid resiliency. In the proposed algorithm, the switching operations performed for system restoration are the states with the minimum bus voltage seen as the cost metric for each state and the extent of load recovery as the observed event. Moreover, an improved flexible switching pair operation is employed to maintain the radial nature of the DN. Reference [13] proposes a resiliency-based methodology that uses microgrids (MGs) to restore critical loads on distribution feeders after a major disaster. By introducing the concepts of restoration tree and load group, restoring critical loads is transformed into a maximum coverage problem, which is a linear integer program (LIP). The restoration paths and actions are determined for critical loads by solving the LIP. Finally, the method is applied to Pullman's DN, resulting in the strategy that uses generators on the Washington State University campus to restore service to the Hospital and City Hall. Reference [14] proposes a new dynamic restoration strategy for DNs to enhance system resiliency against potential hazards. An efficient reconfiguration algorithm is developed to eliminate the use of integer variables to relieve the computational burden. Model predictive control is implemented to adjust the system topology and DER operation setpoints based on the updated fault information and DER forecasts. Reference [15] uses the concept of minimum spanning forest (MSF) to formulate the restoration problem, where each spanning tree in a forest is a self-sustained islanded grid (SSIG). Specifically, a weight is assigned to each edge in a DN based on several factors such as their exposure to vegetation, span length, location, and structures supporting them. Then, an MSF is obtained for the given network by switching off the edges with higher weights to form several optimal SSIGs. In [16], a novel networked MG-aided approach for service restoration in power DNs is presented. The uncertainty of the customer load demands and DG outputs are modeled in a scenario-based form. A stochastic mixed-integer linear program is formulated to maximize the served load while satisfying the operational constraints of the DN and MGs.

In this framework, the paper presents a tabu-search-based algorithm for DN restoration able to identify reasonable solutions to back-feeding faulty MV feeders. Such solutions are determined in a two-step approach: the first step consists of back-feeding the out-of-service area, while the second performs a series of load shifting operations to ensure the best possible network reliability or resiliency. The flexibility of choosing reliability or resiliency goals can be exploited according to seasonal periods or based on unexpected critical events. Moreover, traditional topological and electrical constraints are included. In the algorithm, solutions are found acting on tie switches (TSs), constituted by normally open switches at the end of MV feeders, and sectionalizer switches, constituted by normally closed switches located along with MV feeders. The proposed algorithm has been tested on a 15 kV real DN located in Rozzano (Milan), owned by the DSO Unareti. The proposed algorithm has its main benefits in translating the Italian regulation regarding DN reliability and resiliency into an optimization approach. Therefore, it allows considering two objective functions related to reliability and resiliency to give the operational engineers more flexibility in improving the DN security. Moreover, the objective functions model the practical approach used by Unareti engineers in the daily network operation and consider network data that are easily and readily available in the company databases, instead of being complex and most often unavailable for computing the traditional reliability and resiliency indexes such as system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), etc.

The remainder of the paper is organized as follows. In Section II, the problem formulation is given. Section III describes the tabu-search-based algorithm. In Section IV, case study is presented, while concluding remarks are given in Section V.

II. Problem Formulation

The restoration problem can be treated as a temporary reconfiguration problem where the system returns to its original configuration once the fault has been fixed. The transitory topology has to work in safe conditions, minimizing the customers affected by the service interruption. It is worth noticing that the back-feeding feeders used for network restoration face a transitory increase in power, which gives a potentially dangerous over-stress to the electrical components.

DN restoration problems can be expressed using optimization models. The objective function selected depends on the DSO goal. This paper considers two objective functions inspired by the Italian output-based regulation defined by the Regulatory Authority for Energy, Networks, and Environment (ARERA). The current rules and metrics to evaluate the reliability and resiliency of DSOs are described in the technical report "Integrated text of the quality of the distribution services 2016-2023" (TIQE) [17]. The reliability of the DSO network is evaluated based on the yearly SAIFI and SAIDI. The Authority applies bonuses or penalties comparing the DSO indexes with a pre-defined threshold. In addition, the regulation lets the DSOs exclude, from the reliability computation, the faults which would happen in the so-called "perturbated conditions period (PCP)", which are defined as periods with an anomalous number of faults. Particularly for urban DNs, this situation is usually caused by heat waves. Combining the high temperature in summer with the increasing air conditioner load can enormously increase the number of outages, bringing the DNs to work under stressed conditions. These phenomena and the ability of the network to face hazardous events fall into the term of resiliency [18].

After conducting an in-depth analysis of the location of the faults in the last 5 years, it is observed that the MV feeders are, as shown in Fig. 1, the part of the DN of Milan most affected by failures [19].

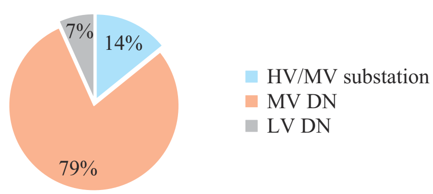

Fig. 1. 5-year failure data recorded and its location in DN of Milan.

Almost all the recorded faults affect the MV cables. Only a few faults have been related to high-voltage (HV)/MV substations, e. g., short circuit on bus-bar, triggering of transformer protection devices, and the low-voltage (LV) DN.

A. Reliability Objective Function

This subsection presents the proposed reliability objective function. Considering the failure statistic shown in Fig. 1, we define a risk index for MV feeders called feeder risk index (FRI), which estimates the feeder reliability. The FRI of a generic feeder i is computed as:

$$FRI_i = L_{fi} C_{LVfi} \tag{1}$$

where L_{fi} is the length of the MV feeder i; and C_{LVfi} is the number of LV customers supplied by the feeder i.

For each feeder, the reliability is estimated by multiplying the feeder extension L_{fi}, assumed to be proportional to the failure probability, by the number of LV customers supplied C_{LVfi}, assumed to be proportional to the impact of faults. For clarity, Fig. 2 shows a simplified layout of two MV feeders, where PS is the primary substation; SS is the secondary substation; L is the MV branch length; and C_{LV} is the number of LV customers supplied by the SS. For example, the feeder risk index of Feeder 1 is $FRI_1 = (L_1 + L_2 + L_3 + L_4)(C_{LV1} + C_{LV2} + C_{LV3} + C_{LV4})$, while for Feeder 2, $FRI_2 = (L_5 + L_6 + L_7)(C_{LV5} + C_{LV6} + C_{LV7})$.

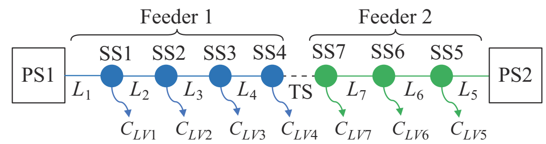

Fig. 2. Simplified layout of two MV feeders.

Since the objective function has to measure the reliability of the whole DN, the index reported in (2), which is referred to as the network risk index (NRI), is also defined as:

$$NRI = \sum_{i=1}^{F} FRI_i \tag{2}$$

where F is the number of feeders.

Referring to Fig. 2, the pre-fault NRI is $NRI_{pre\text{-}fault} = FRI_1 + FRI_2$.

In order to provide a yardstick as immediate and understandable as possible, the ratio of the NRI after ($NRI_{restored\text{-}net}$) and before ($NRI_{pre\text{-}fault}$) the reconfiguration is computed. The objective function is therefore to minimize the following expression (3):

$$\min \frac{NRI_{restored\text{-}net}}{NRI_{pre\text{-}fault}} \tag{3}$$

Considering Fig. 2 and assuming a fault on the first branch of Feeder 2, the only way to restore energy to the three SSs in green is closing the TS. Thus, the NRI changes as: $NRI_{restored\text{-}net} = (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7)(C_{LV1} + C_{LV2} + C_{LV3} + C_{LV4} + C_{LV5} + C_{LV6} + C_{LV7})$.

It is worth noticing that the NRI demonstrates to be correlated and to measure the SAIFI index with a good approximation, which, as mentioned, is used in the Italian reliability and resiliency regulation with the advantage of being easily computed [19]. Therefore, the reliability objective function aims to make the number of users and length of feeders as uniform as possible, even in the post-failure topology. In fact, the more the feeders are uniform, statistically, the less the impact of a potential failure that could occur when the network has not yet returned to the initial configuration will be.

B. Resiliency Objective Function

Among the extreme weather events, heat waves are the most critical experience for the urban DN of Milan [20]. A heat wave is a period of extremely hot weather, and climate change makes heat waves more intense and frequent, stressing underground cables. The increase of power demand, caused by massive and contemporary use of air conditioners, and a reduction of the heat transfer from cables to the soil, affect feeder's temperature [21]. Therefore, the weakest parts of the feeder chain, i.e., the electric power cable joints, experience an increasing number of failures [22]. Heat waves are located in the summertime, mainly in June and July.

Although the DN is well designed for normal operational conditions, many faults could affect it during heat waves. As shown in Fig. 3, a simultaneous fault could cause a prolonged interruption with no possibility of restoration from another feeder. The Unareti experience says that most faults affect the first part of the feeder, the one close to the PS busbars, which carries the total power delivered to the users by the feeder itself, e.g., the branch between PS1 and SS1 in Fig. 3. In case of an outage on this branch, the power has to come from an alternative path, for instance, branch SS4-SS7 by closing TS_1. Feeder 2 now also has to carry the full power of Feeder 1, potentially resulting in a simultaneous fault. If a double-fault happens on branches PS2-SS5 and SS7-SS4, all the SSs in red remain unsupplied until one of the two outages is restored. This situation is even more critical in underground cables because finding and repairing the outage could last up to 12 hours.

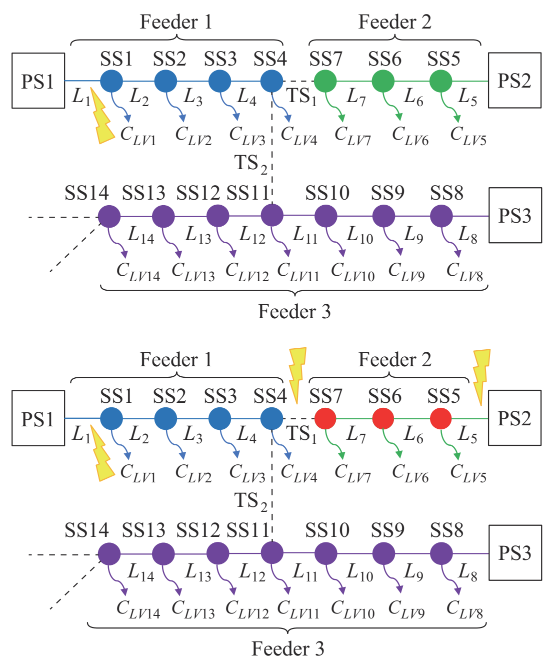

Fig. 3. Simultaneous fault and its consequence on energy supply.

Following the same approach of the *FRI*, for any of the sections that could suffer from a simultaneous fault, we define a section risk index (SRI) as a measure of resiliency. The sections are the network portions comprised of two SSs with at least three incident branches or between a PS and the first SS with at least three incident branches. Referring to Fig. 3, the sections are PS1-SS1-SS2-SS3-SS4, PS2-SS5-SS6-SS7, PS3-SS8-SS9-SS10-SS11, and SS11-SS12-SS13-SS14. Once again, the SRI of a generic section i can be defined as the product of the failure probability and its impact:

$$SRI_i = L_{si} C_{LVsi} \tag{4}$$

where L_{si} is the length of the section i; and C_{LVsi} is the number of LV customers of the section i.

Failure probability is still proportional to the length of the section L_{si}: longer sections have a higher probability of failure than shorter ones. On the other hand, the failure impact is associated with the number of LV customers C_{LVsi} potentially interrupted in case of a simultaneous fault. Considering the layout in Fig. 3, $SRI_1 = (L_1 + L_2 + L_3 + L_4)(C_{LV1} + C_{LV2} + C_{LV3})$; $SRI_2 = (L_5 + L_6 + L_7)(C_{LV5} + C_{LV6} + C_{LV7})$; $SRI_3 = (L_8 + L_9 + L_{10} + L_{11})(C_{LV8} + C_{LV9} + C_{LV10})$; and $SRI_4 = (L_{12} + L_{13} + L_{14}) \cdot (C_{LV12} + C_{LV13} + C_{LV14})$. The LV customers C_{LV4} and C_{LV11} are excluded from the computations, since the triple connection with other secondary substations protects SS4 and SS11 from the impact of potential simultaneous faults.

Similar to the NRI, for a generic feeder j, we define the index reported in (5), which is referred to as the feeder sections risk index (FSRI):

$$FSRI_j = \sum_{i=1}^{S} SRI_i \tag{5}$$

where S is the number of sections subject to increased power whenever feeder j is used for back-feeding an outage feeder. Considering the layout of Fig. 3, and supposing to back-feed Feeder 1 using Feeder 3, the section SS11-SS12-SS13-SS14 is not included in the computation of the FSRI of Feeder 3, since an increased power is observed only in the section PS3-SS8-SS9-SS10-SS11 when Feeder 3 back-feeds Feeder 1.

The resiliency objective function has been defined to reduce the cascade fault probability. Therefore, the objective function is defined to minimize the FSRI of the feeders used to back-feed the outage feeder. As already mentioned, unlike the reliability objective function, only the length and LV customers of the sections belonging to the back-feeding feeders subject to increased power flow are computed. Moreover, the FSRI is weighted by the power measured at the beginning of the feeder, assuming that higher power increases the probability of faults [23], ending up with the expression in (6):

$$\min \frac{\sum_{j=1}^{F_{bf}} FSRI_j \cdot P_j}{\sum_{j=1}^{F_{bf}} P_j} \tag{6}$$

where F_{bf} is the number of back-feeding feeders that carry the increased power flow P_j. Thus, the resiliency objective function aims to choose the least risky back-feeding feeders from the point of view of possible multiple failures, which would lead to the disconnection of end-users for a long time. Therefore, the most resilient routes are preferred, i.e., the feeders that expose the shortest routes and with the lowest number of users that cannot be counter-powered.

C. Operational Constraints

In order to ensure a safe operation of the network even after the restoration process, the algorithm has to consider the constraints related to the network topology and its operation, including nodes and line limits. The constraints considered are reported below.

1) Radial structure. DNs are operated radially to avoid difficulties in fault detection, isolation, and feeder protection coordination. Thus, the radiality of the network shall be maintained during the switching operation and at the end of the restoration process.

2) Bus voltage limits. Bus voltages must be kept within the operating limits, standardly suggested to be within ±5% of the nominal voltage value. The algorithm, therefore, considers inequality (7).

$$V_{\min} \leq V_k \leq V_{\max} \tag{7}$$

where V_k is the voltage at the bus k; and $V_{\min}$ and $V_{\max}$ are the minimum and maximum voltage values allowed at the node k, considered as $0.95V_k$ and $1.05V_k$, respectively.

3) Branch current limit. Branch current must be maintained within the operating limit to avoid overheating. Since the repair of the outage components could take time, particularly in underground cables, inequality (8) is considered. Therefore, the current flowing on branch i, i.e., I_i, has to be lower than the rated current $I_{i,Rated}$.

$$I_i < I_{i,Rated} \tag{8}$$

4) Switching operations. The number of switching operations must be limited in order to reduce both switching costs and restoration time. Thus, as depicted in (8), a maximum number of five switching operations is allowed.

$$N_{switch,\max} \leq 5 \tag{9}$$

III. Tabu-search-based Algorithm

The algorithm developed is based on tabu search [24], which is a meta-heuristic algorithm used to solve optimization problems. The main advantage of TS with respect to conventional genetic algorithm and simulation annealing lies in the intelligent use of the past history of the search to influence its future search procedures. TS can be viewed as an iterative technique that explores a set of problem solutions by repeatedly moving from one solution x_0 to another solution x_1 located in the neighborhood $N(x_0)$ of x_0. Thus, starting from an initial solution x_0, the tabu search procedure iteratively finds a neighborhood of the current solution $N(x_0)$ made of a set of candidate solutions. Each candidate's objective function is evaluated, and the one with the best value is selected to be the current solution. The procedure is repeated starting from the new solution until a stopping criterion is satisfied. Tabu search is based on the concept of "tabu" as actions that could lead to a counter-productive path towards obtaining better solutions, or specifically, actions that could lead to already visited solutions. A peculiar characteristic of such an algorithm is that it allows the actions that deteriorate the current objective function value to avoid being stuck in a local optimum point, which may cause the algorithm to get trapped in cycles. To overcome this issue, memory is used to store a list of attributes that characterize the chosen solution and classify such attributes as "tabu". Thus, a candidate of the neighborhood can be selected as a successive solution only if it has attributes not contained in the memory, which, for this reason, is also named as "tabu list".

In the following text, an overview of the implemented algorithm is presented. Referring to the layout of Fig. 4, given the DN data and the faulty branch, the algorithm builds a virtual version of the network topology and identifies the unsupplied area, e.g., the two SSs shown in red. Then, it identifies the open branches available for back-feeding the unsupplied area, the TSs. In the case of Fig. 4, those switches are named as TS_1 and TS_2. Each TS corresponds to a possible starting solution, which is stored in the long-term memory (LTM). Finally, the algorithm computes the objective function of each solution either by (3) or (6). Moreover, the following current and voltage violations and dangers are computed.

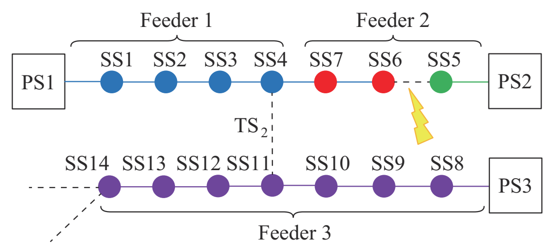

Fig. 4. Example of starting solution related to TS_1.

1) Current violation: when the current of the branch i I_i is greater than its rated current $I_{i,Rated}$.

$$I_i > I_{i,Rated} \tag{10}$$

2) Current danger: when I_i is greater than 75% of its rated current $I_{i,Rated}$ but smaller than its rated current $I_{i,Rated}$.

$$0.75 I_{i,Rated} < I_i < I_{i,Rated} \tag{11}$$

3) Voltage violation: when the voltage of the node k V_k exceeds the limits of ±5% of the rated voltage $V_{k,Rated}$.

$$V_k < 0.95 V_{k,Rated} \tag{12}$$

$$V_k > 1.05 V_{k,Rated} \tag{13}$$

4) Voltage danger: when V_k is between the limits of ±5% and ±2.5% of the rated voltage $V_{k,Rated}$.

$$0.95 V_{k,Rated} < V_k < 0.975 V_{k,Rated} \tag{14}$$

$$1.025 V_{k,Rated} < V_k < 1.05 V_{k,Rated} \tag{15}$$

According to the objective function and the eventual violations and dangers, the most fitting solution, i.e., the one with the best objective function and the lowest number of violations and dangers, will be selected as the starting solution x_0. For example, TS_1 in Fig. 4 is selected as the starting solution while the other option remains in the LTM, available for later investigation. The radiality constraint is always satisfied since the algorithm closes a single TS towards an unsupplied and isolated network section.

From the starting solution x_0, the algorithm finds the neighborhood $N(x_0)$. The neighborhood is made by the possible solutions that can be obtained from the current solution throughout a single action. Considering action of changing the network topology throughout the opening and closure of a couple of tie-sectionalizer switches, if such switches were chosen randomly, the neighborhoods would be made by several unfeasible solutions. In fact, all the solutions always have to fulfill the radiality constraint to give a feasible DN operating layout. Therefore, considering Feeder 1 shown in Fig. 4 as the back-feeding feeder, a neighborhood radial solution can be obtained by performing the following operations: opening the sectionalizer switch SS_{F1} making a portion of Feeder 1 temporary out-of-service, and resupplying the out-of-service portion of Feeder 1 by closing the tie switch TS_2 to connect the unsupplied portion to Feeder 3, as shown in Fig. 5. It is worth noticing that to guarantee the radiality constraint and restore the energy supply to all the customers, the closed TS must always be located downstream of the open SS. The selected neighborhood considers the feeder subject to the highest number of violations and subsequently dangers. In fact, the goal of the algorithm is to perform a load shifting from the feeder characterized by violations and/or dangers to another feeder, balancing the feeder's extension and load.

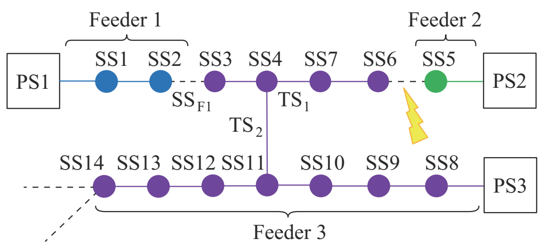

Fig. 5. Example of neighborhood related to switches SS_{F1}-TS_2.

Whenever a new feasible solution that fulfills all the operational constraints is found, its objective function is compared with the available best solution and eventually marked as the new best one if the objective function is improved. The neighborhood solutions are stored in the STM used to keep track of the solutions already checked to avoid visiting the same solution multiple times. Every time a better solution is found, the network constraints are also evaluated considering the load data of the next 24 hours to ensure that the proposed solution can guarantee a safe operation for a time long enough to repair the outage component; otherwise, the solution is rejected. The procedure is repeated for a given number of iterations: if no feasible solution is obtained, the algorithm takes the second-best initial solution from the LTM and repeats the whole process. The pseudocode of the proposed algorithm is reported in Appendix A.

IV. Case Study

This section reports the results of applying the proposed algorithm to a real DN located in the north of Italy. The considered DN, whose layout is shown in Fig. 6, supplies 127 SSs, represented by oval shapes, using the eighth MV feeders arising from a couple of PSs, drawn as red squares. The open branches are highlighted in yellow; those in yellow are also the 36 SSs remotely controlled, while the others, drawn in blue, can only be operated manually. The network serves 11000 LV customers and consists of 70 km of MV underground cables. The simulations were performed considering a total power of 24 MW which corresponds to the peak hour of June 2019.

The restoration algorithm performance has been verified simulating several faulty branches. For simplicity, only the results of a fault on the branch in red in Fig. 6 is reported in the paper. The algorithm coding has been done in Python and run on a personal computer with AMD Ryzen 5 2500U processor and 8 GB of RAM (6.90 GB usable). As stopping criterion, a maximum number of 30 iterations has been selected.

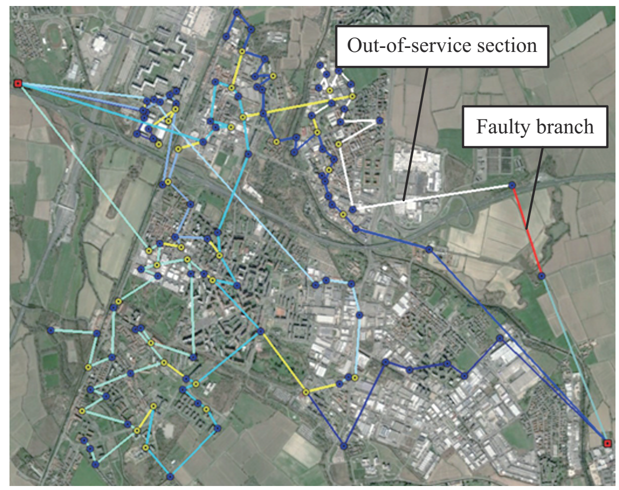

Fig. 6. Layout of 15 kV DN taken as a study case.

As already mentioned in Section III, one of the main constraints in the restoration problem always has a radial structure. Starting from the faulty branch, such constraint is always satisfied since the algorithm will close a single TS towards an unsupplied and isolated network section. For the load shifting instead, to guarantee the radiality constraint and restore the energy supply to all the customers, the closed TS must always be located downstream of the SS open.

A. Reliability Objective Function

In the reliability objective function approach, the goal of the algorithm is to minimize (3). As shown in Fig. 7, the restoration starts closing the tie switch TS_1, to back-feed the out-of-service section, which is highlighted in white in Fig. 6. However, the new network layout violates some operational constraints. Therefore, the algorithm starts performing load shifting: the couple TS_2-SS_2 reduces the extension of the back-feeding feeder, and the operation of the DN shows only two dangers. The algorithm performs operations of three switches, and the objective function is 1.17 (therefore, the $NRI_{restored-net}$ is 18% worst than the $NRI_{pre-fault}$). The network layout of the first feasible solution is shown in Fig. 7. The green color indicates the closure of a previously open switch (TS); and the orange color indicates the opening of a previously closed switch (SS). Figure 8 shows the value of the objective function in each iteration and the minimum objective function. For the sake of clarity, only the first fourteen iterations are shown. As shown in Fig. 8, the best feasible solution is obtained after fourteen iterations and the algorithm suggested the switches operations represented in Fig. 9. Concerning the first solution shown in Fig. 7, the initial back-feeding feeder, the one related to TS_1, changes, and five switch operations are suggested. Thanks to the STM, the algorithm autonomously changes the back-feeding feeder to obtain a better solution. As a result, the objective function decreases to 1.08, corresponding to an $NRI_{restored-net}$ 8% worse than the $NRI_{pre-fault}$, which is a good result considering that the network is working in $N-1$ contingency operation. Table I reports the comparison of feeder risk indexes for pre-fault layout, the first and the best feasible solutions. The faulty line is originally on feeder OP1204, which obviously improves its FRI. The algorithm shares its LV customers and extension among feeders AS00151, AS00152, and OP1201. Feeder AS00151 has slightly reduced its extension and customers, which are shared, together with the extension and customers of the faulty feeder, with feeders AS00152 and OP1201 that increase their FRI by 115% and 380%, respectively.

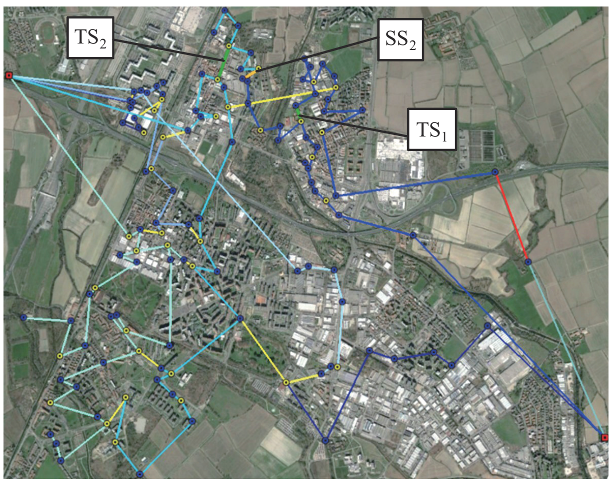

Fig. 7. Network layout of the first feasible solution.

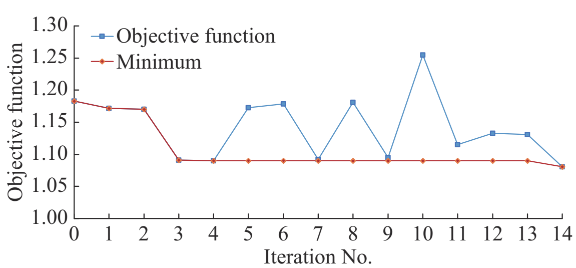

Fig. 8. Objective function values through iterations.

B. Resiliency Objective Function

In the resiliency objective function approach, the goal of the algorithm is to minimize (6). As shown in Fig. 10, two are the TSs available to select the initial solution. The first one, TS$_1$, is located in the middle of the out-of-service area, leading to an FSRI of 618, which is the sum of three SRIs of feeder AS00151 sections (Fig. 10). The second one, TS$_2$, is at the end of the out-of-service area and is characterized by an FSRI equal to 2474. In the second case, the back-feeding is made through a more extended section belonging to feeder OP1203. Thus, the algorithm starts selecting the back-feeding related to TS$_1$, whose objective function is computed as $OF = \frac{FSRI_{AS00151} \cdot P_{AS00151}}{P_{AS00151}} = \frac{618 \times 5.53}{5.53} = 618$.

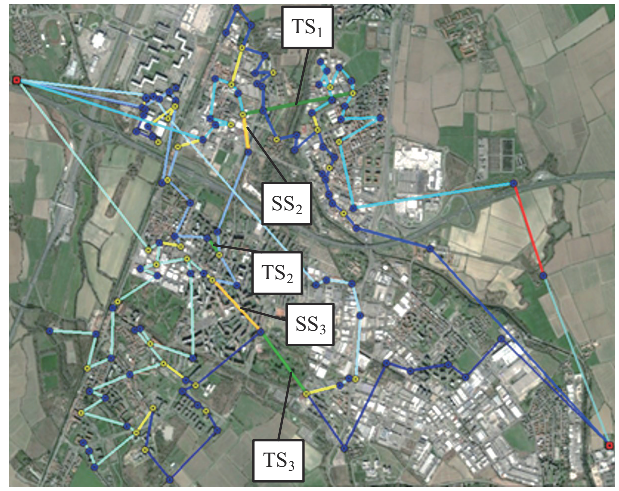

Fig. 9 Best feasible solution.

TABLE I
COMPARISON OF FEEDER RISK INDEXES

Feeder	FRI		
	Pre-fault layout	First feasible solution	Best feasible solution
OP1201	4170	4170	20130
OP1203	13463	35427	13463
OP1204	13770	5	5
AS00151	25373	35460	24966
AS00152	5967	5967	12747
AS00153	26	26	26
AS00163	511	511	511
AS70154	43143	43143	43143
Total NRI	106423	124709	114991

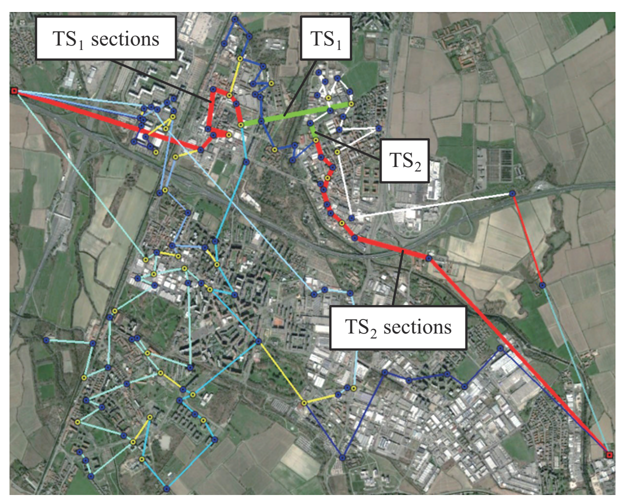

Fig. 10. Feeder's section (in red) and related TSs (in green).

It is worth noticing that the power flow on the feeder AS00151 increases from 3.14 MW in the pre-fault layout to 5.53 MW. Since the initial solution is unfeasible, the algorithm shifts load to find a solution that fulfills the operational constraints. The FSRI and power flowing on related feeder for the initial solution, the first feasible and the best feasible solutions are shown in Fig. 11. At first, the load of the feeder AS00151 is shared with feeder AS00152, decreasing from about 5.5 MW to less than 4 MW, ending up with the first feasible solution. The objective function becomes $OF = \frac{1}{P_{AS00151}+P_{AS00152}}(FSRI_{AS00151} \cdot P_{AS00151} + FSRI_{AS00152} \cdot P_{AS00152}) = \frac{1}{5.53+3.96} \times (618 \times 5.53 + 676 \times 3.96) = 647$.

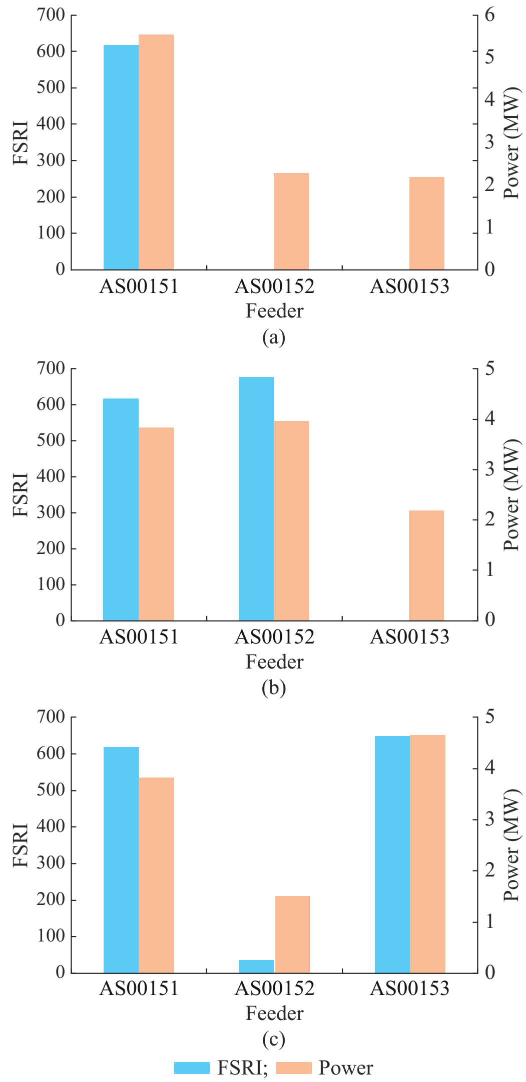

Fig. 11. FSRI and power flowing on related feeder for initial solution, the first feasible and the best feasible solutions. (a) Initial solution. (b) The first feasible solution. (c) The best feasible solution.

Moreover, the algorithm performs further load shifting, moving load from feeder AS00152 to feeder AS00153. The resulting objective function is $OF = \frac{1}{P_{AS00151}+P_{AS00153}} \cdot (FSRI_{AS00151} \cdot P_{AS00151} + FSRI_{AS00153} \cdot P_{AS00153}) = \frac{1}{5.53+4.65} \times (618 \times 5.53 + 649 \times 4.65) = 635$.

Feeder AS00152 is no longer included in the objective function because its power is reduced concerning the pre-fault condition (1.51 MW < 2.28 MW).

Therefore, the objective function changes from 618 in the initial unfeasible solution to 647 (first feasible solution) and 635 (best feasible solution). Figure 12 shows the network layout of the best feasible solution, where the five operated switches are highlighted in green and orange. At first, the TS_1 is closed to resupply the out-of-service section by the feeder AS00151. Later, the switching couple TS_2-SS_2 shifts part of the load from the feeder AS00151 to AS00152. Finally, using the switching couple TS_3-SS_3, the algorithm shifts some of the load from the feeder AS00152 to AS00153.

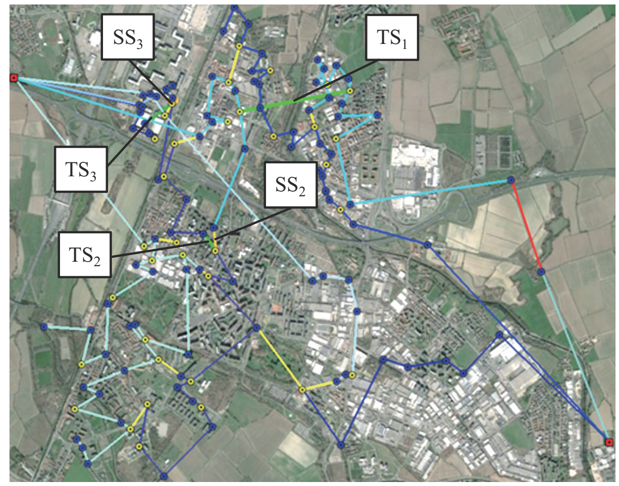

Fig. 12. Network layout of the best feasible solution.

V. Conclusion

The paper presents a tabu-search-based algorithm able to assist operational engineers in identifying solutions to restoring the energy supply after permanent faults. To optimize reliability or resiliency, the algorithm can consider two objective functions according to the network property. The proposed algorithm suggests the most valuable tie switch and the load switching operations that improve the considered objective function. Thanks to the collaboration with the DSO of Milan, Unareti, the proposed algorithm has been tested on a real DN to investigate its effectiveness. The results demonstrates that the algorithm can suggest a robust, fast, and feasible restoration plan. Moreover, since the switching operations are different considering the reliability or the resiliency approach, the simulation outputs confirm the validity of considering two distinct objective functions. The proposed algorithm could potentially be the basis of an automatic real-time tool to support the control room operators in restoring energy supply after a permanent fault, maximizing the DN reliability or resiliency.

Appendix A

Algorithm 1: pseudocode

1. Load input data
2. Create network graph
3. Function *determine out-of-service area (faulted line)*
4. Initialize *long term memory*
5. Function *generate starting solutions (out-of-service area)*
6. Set *current solution* = *best initial solution* and $k = 0$
7. Function *compute OF(network configuration, reliability or resiliency, TS, SS)*
8. Check *best solution*

9. Initialize *short term memory*
10. **While not** *stopping criterion*
11. $k=k+1$
12. Function *determine feeder for load shifting (network configuration)*
13. Function *generate neighbourhood (selected feeder)*
14. Set *current solution = most fitting neighbourhood solution*
15. Update *short term memory*
16. Check *best solution*

Function *generate starting solutions (out-of-service area)*

1. **For** each *node* **in** *out-of-service area*
2. Determine *edges* of *node n*
3. **For** each *edge e*
4. **If** *edge* **is open**
5. *edge = tie switch*
6. Close *tie switch*
7. Determine the new network layout
8. Function *compute OF(network configuration, reliability or resiliency, TS, SS)*
9. Update *long term memory*
10. Restore initial layout

Function *generate neighbourhood (selected feeder)*

1. **For** each *node* **in** *load-shifting feeder*
2. Determine *edges* of *node n*
3. **For** each *edge e*
4. **If** *edge* **is open**
5. *edge = tie switch*
6. **For** *edge* **in** *ordered edges in load-shifting feeder*
7. **If** *edge* **is not** *tie switch*
8. *edge = Sectionalizer*
9. Close *tie switch* and open *sectionalizer*
10. Determine new network layout
11. **If** configuration already analysed
12. Go back to 7
13. **Else**
14. Function *compute OF(network configuration, reliability or resiliency, TS, SS)*
15. Restore initial layout
16. **Else**
17. Stop

Function *determine out-of-service area (faulted line)*

1. Find *faulted feeder*
2. **For** each edge in *faulted feeder*
3. **If** exist closed path from edge to source
4. Edge status = "*in service*"
5. Node_1 status and node_2 status = "*in service*"
6. **Else**
7. Edge status = "*out-of-service*"
8. Node_1 status and node_2 status = "*out-of-service*"

Function *determine feeder for load shifting (network configuration)*

1. **For** each *feeder* **in** network layout
2. Set *voltage violations at feeder* = 0, *current violations at feeder* = 0
3. Set *voltage dangers at feeder* = 0, *current violations at feeder* = 0
4. **For** each *node* **in** *feeder*
5. **If** voltage violation
6. *voltage violations at feeder* + 1
7. **If** voltage danger
8. *voltage dangers at feeder* + 1
9. **For** each *edge* **in** *feeder*
10. **If** current violation
11. *current violations at feeder* + 1
12. **If** current danger
13. *current dangers at feeder* + 1
14. Sort feeders by higher number of violations and dangers
15. Select first *feeder* in list

Function *compute OF(network configuration, reliability, tie switches, sectionalizer switches)*

1. **for** each *feeder* **in** network layout
2. Set *FRI* of *feeder* = 0
3. Set *length* = 0, *LV_users* = 0
4. **for** each *edge* **in** *feeder*
5. *length = length + edge_length*
6. **for** each *node* **in** *feeder*
7. *LV_users = LV_users + node_LV_users*
8. *FRI_feeder = length · LV_users*
9. Compute *NRI*
10. Calculate *OF* value

Function *compute OF(network configuration, resiliency, tie switches, sectionalizer switches)*

1. **If** *sectionalizer switch* **is** null
2. Set *length* = 0, *LV_users* = 0
3. **For** *edge* **in** ordered edges of back-feeding feeder
4. **If** *edge* **is not** *tie switch*
5. *length = length + edge_length*
6. **Else**
7. Stop
8. **For** *node* **in** ordered nodes of back-feeding feeder
9. **If** node **is not in** *tie switch nodes*
10. *LV_users = LV_users + node_LV_users*
11. **Else**
12. Stop
13. *SRI = length · LV_Users*
14. *Power* = power at feeder source node
15. Calculate *OF* value
16. **If** *sectionalizer switch* **is not** null
17. **For** each *feeder* **in** network layout
18. **If** power at feeder source node > power at feeder source node of starting solution
19. Set *length* = 0, *LV_users* = 0
20. **For** *edge* **in** ordered edges of back-feeding feeder
21. **If** edge **is not** *selected tie switch or sectionalizer switch*
22. *length = length + edge_length*
23. **Else**
24. Stop
25. **For** *node* **in** ordered nodes of back-feeding-feeder

```
        If node is not in selected tie switch or sectionalizer switch nodes
            LV_users = LV_users + node_LV_users
        Else
            Stop
    SRI_feeder = length · LV_Users
    Power_feeder = power at feeder source node
Calculate OF value
```

References

[1] C. Cambini, A. Croce, and E. Fumagalli, "Output-based incentive regulation in electricity distribution: evidence from Italy," *Energy Economics*, vol. 45, pp. 205-216, Sept. 2014.

[2] E. Fumagalli, L. Lo Schiavo, S. Salvati *et al.*, "Statistical identification of major event days: an application to continuity of supply regulation in Italy," *IEEE Transactions on Power Delivery*, vol. 21, no. 2, pp. 761-767, Apr. 2006.

[3] F. Shen, Q. Wu, and Y. Xue, "Review of Service Restoration for Distribution Networks," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 1, pp. 1-14, Jan. 2020.

[4] Y. Liu, R. Fan, and V. Terzija, "Power system restoration: a literature review from 2006 to 2016," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 3, pp. 332-341, Jul. 2016.

[5] D. P. Le, D. M. Bui, C. C. Ngo *et al.*, "FLISR approach for smart distribution networks using E-Terra software – a case study," *Energies*, vol. 11, no. 12, p. 3333, Nov. 2018.

[6] A. E. B. Abu-Elanien, M. M. A. Salama, and K. B. Shaban, "Modern network reconfiguration techniques for service restoration in distribution systems: a step to a smarter grid," *Alexandria Engineering Journal*, vol. 57, no. 4, pp. 3959-3967, Dec. 2018.

[7] R. E. Brown and A. P. Hanson, "Impact of two-stage service restoration on distribution reliability," *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 624-629, Nov. 2001.

[8] K. Zou, G. Mohy-Ud-Din, A. P. Agalgaonkar *et al.*, "Distribution system restoration with renewable resources for reliability improvement under system uncertainties," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 10, pp. 8438-8449, Oct. 2020.

[9] S. Guo, J. Lin, Y. Zhao *et al.*, "A reliability-based network reconfiguration model in distribution system with DGs and ESSs using mixed-integer programming," *Energies*, vol. 13, p. 1219, Mar. 2020.

[10] X. Hong, M. Xia, and Y. Hua, "A service restoration method for active distribution network," *Energy Procedia*, vol. 61, pp. 339-344, Jan. 2014.

[11] Y. Ren, D. Fan, Q. Feng *et al.*, "Agent-based restoration approach for reliability with load balancing on smart grids," *Applied Energy*, vol. 249, pp. 46-57, Sept. 2019.

[12] C. Yuan, M. S. Illindala, and A. S. Khalsa, "Modified Viterbi algorithm based distribution system restoration strategy for grid resiliency," *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 310-319, Feb. 2017.

[13] Y. Xu, C. C. Liu, K. P. Schneider *et al.*, "Microgrids for service restoration to critical load in a resilient distribution system," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 426-437, Jan. 2018.

[14] W. Liu, F. Ding, and C. Zhao, "Dynamic restoration strategy for distribution system resilience enhancement," in *Proceedigns of 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington DC, USA, Feb. 2020, pp. 1-5.

[15] S. Poudel, H. Sun, D. Nikovski *et al.*, "Resilient restoration of power distribution system based on minimum spanning forest," in *Proceedigns of IEEE PES General Meeting*, Atlanta, USA, Aug. 2019, pp. 1-5.

[16] A. Arif and Z. Wang, "Networked microgrids for service restoration in resilient distribution systems," *IET Generation, Transmission & Distribution*, vol. 11, no. 14, pp. 3612-3619, Sept. 2017.

[17] ARERA. (2015, Dec.). Delibera 646/2015/R/eel – Testo integrato della regolazione output-based dei servizi di distribuzione e misura dell'energia elettrica, per il periodo di regolazione 2016-2023. [Online]. Available: https://www.arera.it/it/docs/15/646-15.htm#

[18] R. Moreno, M. Panteli, P. Mancarella *et al.*, "From reliability to resilience: planning the grid against the extremes," *IEEE Power & Energy Magazine*, vol. 18, no. 4, pp. 41-53, Jul. 2020.

[19] UNARETI S.p.A.. (2021, Jun.). Piano di Sviluppo e Incremento resilienza. [Online]. Available: https://www.unareti.it/unr/unareti/elettricita/cittadini/piano-di-sviluppo-e-incremento-resilienza//

[20] L. Bellani, M. Compare, R. Mascherona *et al.*, "A supervised classification method based on logistic regression with elastic-net penalization for heat waves identification to enhance resilience planning in electrical power distribution grids," in *Proceedigns of ESREL 2020 PSAM 15*, Milano, Italy, Sept. 2020, pp. 3853-3860.

[21] D. Falabretti, L. Lo Schiavo, S. Liotta *et al.*, "A novel method for evaluating the resilience of distribution networks during heat waves," *International Journal of Electrical and Electronic Engineering and Telecommunications*, vol. 9, no. 2, pp. 73-79, Mar. 2020.

[22] A. Ghaderi, A. Mingotti, F. Lama *et al.*, "Effects of temperature on mv cable joints tan delta measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 10, pp. 3892-3898, Oct. 2019.

[23] L. Bellani, M. Compare, E. Zio *et al.*, "A reliability-centered methodology for identifying renovation actions for improving resilience against heat waves in power distribution grids," *International Journal of Electrical Power & Energy Systems*, vol. 137, p. 107813, May 2022.

[24] F. Glover, E. Taillard, and E. Taillard, "A user's guide to tabu search," *Annals of Operations Research*, vol. 41, no. 1, pp. 1-28, Mar. 1993.

Alessandro Bosisio received the M.S. and the Ph.D. degrees in electrical engineering from Politecnico di Milano, Milan, Italy, in 2011 and 2015, respectively. He is currently a Researcher in the Energy Department at the same University. His main research interests include distribution network (DN) operation and planning, electric power system optimization, operation of renewable in MV/LV DNs and smart grids.

Alberto Berizzi received the Ph.D. degree in electrical engineering from Politecnico di Milano, Milan, Italy, in 1994. He was an Assistant Professor at Politecnico di Milano from 1992 to 1998, and since 2006, he has been a Full Professor of electric power systems. His main research interests include security of power systems, power system operation and planning, electricity market operation, dynamic perturbations of large-scale power system, and operation of renewablein HV/MV/LV DNs.

Daniele Lupis received the M.S. degree in electrical engineering from Politecnico di Milano, Milan, Italy, in 2021. He is currently a Junior Infrastructure & Network Engineer in a local DSO, E-distribuzione, Monza, Italy. His main research interests include DN operation and planning, network reliability, network resiliency, network protection and automation, distributed energy sources, and smart grids.

Andrea Morotti received the M.S. degree in electrical engineering in 2013 from Politecnico di Milano, Milan, Italy. He is currently head of the Electrical Network Planning Department (HV, MV, and LV) of the DSO Unareti, after a few years of experience in designing, constructing, and commissioning primary substations. His main research interests include network planning, smart grids, distributed and flexible resources, storage, sustainability, network resiliency, protection and automation.

Gaetano Iannarelli received the M.S. degree in electrical engineering in 2016 from the Sapienza University of Rome, Rome, Italy. He is currently a Ph.D. student in the same University within the Department of Astronautics, Electrical, and Energy Engineering. In the meantime, he works as a smart grids specialist in the Technological Development Department of the DSO Unareti, Milan, Italy. His main research interests include DNs, smart grids, distributed and flexible resources, storage, sustainability.

Bartolomeo Greco received the M.S. in electrical engineering from Politecnico di Milano, Milan, Italy, in 2018, and he is currently a Ph.D. student in the Sapienza University of Rome, Rome, Italy, within the Department of Astronautics, Electrical, and Energy Engineering. He works in the DSO Unareti since 2018. His main research interests include DN planning, smart grids, network reliability, optimization, distributed energy resource dispatching, multi-energy systems, network resiliency, protection and automation.