Improved Multi-Criteria Distribution Network Reconfiguration with Information Fusion

Dario Masucci, Chiara Foglietta, Cosimo Palazzo, Stefano Panzieri
Engineering Department
University of "Roma TRE"
Via della Vasca Navale 79
00146, Rome, Italy
Email: {dario.masucci, chiara.foglietta, cosimo.palazzo, stefano.panzieri}@uniroma3.it

***Abstract*—Electrical grids are no more isolated infrastructures but they provide services towards other infrastructures and meanwhile water networks, telecommunications, gas pipelines and transport systems are mandatory in order to produce and deliver electricity. The reconfiguration algorithm determines the optimal tree configuration of the grid, after overloads or permanent faults. In literature, the reconfiguration algorithm takes into account feasibility, radiality, load balancing and energy losses.**

The aim of this paper is to consider the effects of interconnected infrastructures on the reconfiguration algorithm. In order to realise this aim, we must collect information coming from heterogeneous infrastructures and normalize it. CISIApro is an agent-based simulator which gathers data on equipment operability and evaluates the cascading effects of faults, cyber attacks and natural disasters. The short-term forecast provided by CISIApro is the input of the decision support system for electrical reconfiguration purpose. This decision support system is made of two parts: an off-line tool able to generate a large number of possible configurations and a multi-criteria decision making able to evaluate several criteria. The criteria are availability of the telecommunication network for closing the needed switches, availability of the generators to supply the downstream loads, load balancing and, eventually, the blackouts or the unfulfilled loads, in terms of population and importance.

The algorithm has been tested on a scenario made of three interconnected infrastructures: distribution grid, gas pipeline and telecommunication network. The electrical grid is the IEEE 14 busbar system, where one generator is a gas turbine, i.e., a load in the gas pipeline. Some results are explained for understanding how information fusion can improve decision support systems.

I. Introduction

Our lives are increasingly dependent on electricity and, therefore, attention to power grid resilience has increased in order to guarantee better and smarter decisions. The complexity of this problem is growing because power grids are no more a protected and isolated infrastructure, but they are interconnected with other critical infrastructures. Electricity supports the operations of other lifeline systems, such as communication networks, and key social systems, such as financial transactions. Other infrastructures provide services to power grids, such as SCADA (Supervisory Control and Data Acquisition) communication over a telecommunication network for remote control switches and fuel provided by gas pipelines for turbines.

Network reconfiguration is a very effective and efficient way to ensure load distribution of networks elements, to improve system reliability and voltage profile, and to reduce power losses. Taking into consideration a large number of switches in distribution network, whose on/off switching affects the network topology, reconfiguration problem can be defined as a complex combinatorial, non-differentiable, and constrained multi-objective optimization problem.

In literature, the problem considers only electrical aspects, such as voltage constraints or power losses. Electrical grid is also affected by external events, as failures in interconnected infrastructures or natural disasters, that are hard to include in the classical formulation. Therefore, fusion of heterogeneous data is mandatory in order to assess the current situation and increase operators' awareness helping them with improved decision support systems.

a) Contributions: In this paper, the authors describe how an interdependency model can be used in order to realize an intelligent distribution network reconfiguration algorithm. The interdependency model gathers unrelated data for several equipment providing normalized information to a downstream decision support system. In this paper the decision support system is for an electrical operator who wants to change the actual topology of the grid after a permanent failure in the grid itself, or after a natural disaster. The contribution of this paper is two-fold:

1) CISIApro is able to collect and fuse information for each modelled equipment. Each modelled entity within CISIApro produce an operative level, which is an aggregated risk metric, see [1] for further details on the model. Then, it also evaluates the quality of services towards other infrastructures and towards customers, as non-linear function of the single equipment involved in the service itself. CISIApro has been developed in order to understand how adverse events can be propagated and, therefore, it can be used to evaluate how equipment or services are affected by faults, disasters or cyber attacks.
2) The authors apply a multi-criteria decision making algorithm (ELECTRE II) for evaluating the optimal reconfiguration considering the interdependencies with the other infrastructures. In particular, we use an algorithm to develop a large number of possible configuration,

checking the radiality of each configuration, and considering the output of CISIApro in terms of available nodes and branches. Then, we run ELECTRE II with several criteria, considering the output of CISIApro: availability of the telecommunication network for closing the needed switches, availability of the generators to supply the downstream loads, load balancing and, eventually, reducing the blackouts or the unsupplied loads, in terms of population and importance. The results demonstrate how data fusion improves decision making.

b) Organization: The paper is structured as follows: related works are presented in Section II; the problem is formulated in Section III made of three main components: CISIApro simulator, the electrical distribution reconfiguration algorithm and the multi-criteria decision making; in Section IV the reference scenario is described in terms of main assumptions and considered dependencies between power grids and other infrastructures; then Section V presents the more significant simulation results; finally, some conclusions are in Section VI.

II. Related Works

The reconfiguration of the distribution network is an important part of power system operations. Distribution networks are normally operated as radial tree; however, during operations, configuration is changed by means of sectionalizing switches. The operating configuration is a radial network, where each sink node is supplied from exactly one generator node. Therefore, the distribution network reconfiguration (DNRC) problem is to find a radial operating structure that minimizes the system power loss while satisfying operating constraints, [2] [3].

Two are the possible motivations behind the reconfiguration of the power grid: load balancing and service restoration, [4]. In event of the overloads, changing the topology can relieve this particular situation. Service restoration is the reaction process in event of a permanent fault made of three steps: isolating the faulted area; supplying the non-faulted area and minimizing the load shedding [1].

According to the graph theory, a distribution network can be represented with a graph of $\mathcal{G}(N, B)$ that contains a set of nodes N and a set of branches B. Every node represents either a source node (supply transformer) or a sink node (customer load point), while a branch represents a feeder section that can either be loaded (switch closed) or unloaded (switch open). The reconfiguration algorithm determines an optimal tree of the given graph. The computational complexity of the optimal problem is very huge in large systems [5], [6] and, therefore, many heuristics have been developed in order to solve the reconfiguration problem [7].

The classical optimization problems consider the power losses of the electrical grid with two main constraints: feasibility and radiality. All nodes in the electrical grid must be connected by some branches to only one generator and the number of branches in the configuration must be smaller than the number of nodes by the number of generators. The simplest heuristic [2] is the branch exchange method, where the power losses are evaluated changing a pair of switches: close one and open another one at the same time. This method is easily understood but the solution is a local optima and depends on the initial network configuration.

In the last years, some researchers applied multi-criteria optimization algorithm to the reconfiguration problem. Usually, three objective functions are considered: minimization of power losses, minimization of deviation of node voltage and maximization of the branch capacity margin. Das in [8] evaluates these objectives through fuzzy sets considering their imprecise nature and solves it trough rule-based heuristic. An algorithm for reducing power losses and improving reliability on network reconfigurations is presented in [9] assessing the power losses on distribution and sub-transmission systems, promoting a global analysis on the impact of switching operations. In [10], the authors used a multi-criteria optimization algorithm for economic-related aspects: the cost of power losses and the cost of damages due to power supply interruption following some faults occurring into the distribution network.

One of the main challenge of the actual power grid is to face with the increasing amount of renewable resources. In [11], the authors propose a multi-period optimal power flow approach for assessing the improvement of distributed generation hosting capacity of distribution systems by applying static reconfiguration or dynamic reconfiguration, together with active network management schemes. In [12], the reconfiguration problem is analysed together with the optimal placement of renewable resources by means of a meta heuristic Harmony Search Algorithm.

The increasing use of remote controlled equipment in power systems leads the development of more efficient techniques for automatic reconfiguration of network, being particularly important in Smart Grid applications. In [13] presents a methodology and system for automatic reconfiguration of distribution network in real time. The optimization of the network performance is based on a heuristic method and multi-criterial analysis, based on the Analytic Hierarchic Process (AHP) method to define weights for the optimization criteria and to determine the best sequence of switching for the network.

In this paper, we consider an active network management for the electrical distribution grid, where each switch can be remotely telecontrolled from the SCADA control centre through a telecommunication network. In order to take into account the interdependencies among the electrical grid and other infrastructures (such as, telecommunication networks and gas pipelines, see [14] for further information), a framework able to collect and normalize all the information coming from heterogeneous fields is mandatory. CISIApro is an agent-based simulator for analysing the consequences of malfunctioning within interdependent critical infrastructures. In order to improve the situation awareness of distribution system operators, a smart decision support system is mandatory realised by means of a multi-criteria algorithm. We choose an improved ELECTRE II method [15]. ELECTRE II meets the required performance by introducing innovative aspects, such as the threshold values to model the uncertainty of available data. The choice fell upon these methods of resolution because it takes into account possible inaccuracies in CISIApro model and achieve the right balance between complexity of data to be processed and the time required to get the solution.

III. Problem Formulation

In this section, the electrical distribution network reconfiguration problem is explained, describing the three algorithms involved in the framework.

A. Data Integration using CISIApro

CISIApro platform is based on CISIApro engine, to calculate the cascading effects through the interdependency model, and on CISIApro GIS (Geographical Information Security) to geo-reference the critical infrastructures' elements of the case study.

CISIApro is a software platform based on a database-centric architecture in which the database plays a crucial role. This means a centralized asynchronous design that allows a good modularity and scalability where each element of the informatics infrastructure interfaces, independently, with the centralized database (DB) in order to get the last actualized data from the field, as in Fig. 1.

From this point of view, CISIApro engine does not only analyse actual situation and calculate the risk projected in the possible next future but, first of all, it plays the important role of Hybrid Risk Evaluation Tool. Hybrid because it is able to get information of different natures (sensor and data acquisition and complex event processing systems) and translating them in operational levels of resources, faults or services for the entities introduced in the critical infrastructure model.

For example, we can image an information system where we have not only data acquisition from common sensors but also data regarding malfunctions reported by users. This means different kinds of data to assess the risk of actual ongoing situation.

As we can see, in Fig. 1, we have a schematic representation of CISIApro platform architecture where we appreciate the modular design and the DSS (Decision Support System) data processing structure.

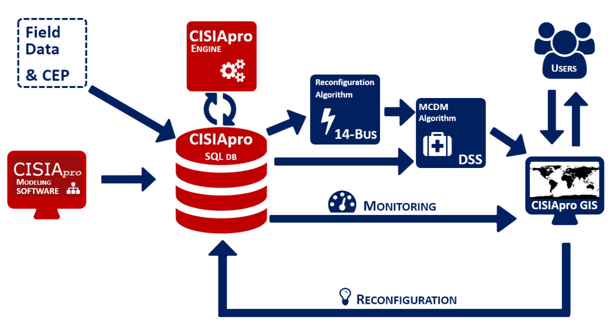


Fig. 1. CISIApro Architecture.

At the same time, with this architecture, we are able through CISIApro modelling software to dynamically change the interdependencies model and plug-in other modules (like Decision Support System modules) in order to have a real-time scalable and flexible system which can be changed at any time.

The data stored in the database comes from the field and from, eventually, a Complex Event Processing (CEP) algorithm to track and analyse streams of information about events that are happening, in Fig. 1. Once the state variables are modified, CISIApro Engine automatically detects the change of system state and runs a simulation instance to calculate the cascading effect. Afterwards CISIApro stores produced data associating a unique run id, see Fig. 2. Then, the network reconfiguration algorithm is executed and the possible reconfiguration are sorted thanks to the Multi-Criteria Decision Making and visualized to the electrical operator. Eventually, the reconfiguration can be applied into the reference scenario for evaluating the consequences in the system.

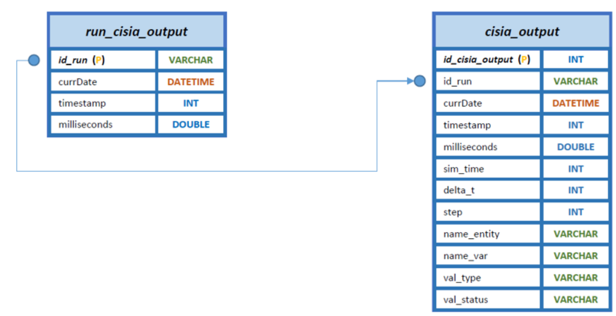


Fig. 2. CISIApro data output structure.

In this way, any downstream module can get data regarding the latest critical situation in the modelled scenario. On the same scenario, the electrical distribution network reconfiguration algorithm is capable to recognize the power grid configuration in order to produce and communicate all possible network reconfigurations to the DSS module. Only subsequently, the DSS will be able to exploit all possible reconfigurations through the assignment of the risk levels calculated in real-time by CISIApro.

The data flow ends with the output in CISIApro GIS where all critical infrastructures are displayed through an intuitive interface along with the ranking of possible configurations and with some suggestions for the operator for increasing the operative levels of involved entities. It is also made available a button to simulate the effects of suggested reconfiguration by decision support system.

B. Electrical Distribution Network Reconfiguration Algorithm

The reconfiguration algorithm is an off-line tool able to generate all the possible configurations for the electrical distribution network in the considered scenario, see Section IV.

This algorithm takes as input the electrical topology, expressed as a graph $\mathcal{G} = (N, B)$ containing a set of nodes N and a set of branches B. The nodes contain a subset of generators that are NG. The algorithm generates all configurations respecting two constraints:

- Feasibility: all nodes are connected to a generator (i.e., no isolated node are possible);
- Radiality: only one generator can feed a load.

The resulting configurations are a forest, i.e., a set of trees starting from a generator. In other words, we consider only configurations with not more than $N - NG$ branches. In event of a load failure, the feasible configurations contains exactly $N - NG - NF$, where NF are the number of faults at load level.

C. Multi-Criteria Decision Making: ELECTRE II

Single criteria optimization was the approach adopted for managerial decision problems for years. It is a mathematical method used to search the optimal solution (maximum or minimum) of a decision problem when the pursued aim is unique and it is subject to multiple constraints. If we want solve complex problems, with more objectives and constraints, the single criteria optimization approach is too simple and the model can not match with problem to be solved.

In this context, multi-criteria analysis methods allow us to compare and sort the alternatives according to the problem's objectives, that are often at odds with each other. These methods, in contrast with the classical techniques of operational research, don't provide solutions objectively good, but they provide a support to the decision-maker to achieve an acceptable compromise between the various objectives pursued.

The ELECTRE methods family stems from the idea that the rigorous mathematical axioms cannot describe a complex reality such as the decision-making process, which is characterized by many contradictions. Their purpose is to develop a method that faithfully adheres to reality. They follow the decision irrationality and they reject the completeness theorem, expressed as "*the decision maker, faced with two alternatives, must be always able to express his preference or indifference*". The ELECTRE II ranks the alternatives from the best to the worst, using the outranking relation whose meaning is "at least as good as", see also [15].

We consider a situation with one decision maker, with m alternatives and n criteria or attributes, where the alternatives are explicitly listed using the notation $A_1, A_2, \ldots, A_m$. The ELECTRE II method is defined by a $m \times n$ matrix, called decision matrix and denoted with C, where each element c_{ij} evaluates the alternatives i according the the j criterion. In general, not all the attributes are numerical, but it is mandatory to map the qualitative attribute into an arbitrary numeric value maintaining the same ranking of the alternatives.

Two kind of analyses allow the verification of outranking relationships between two alternatives:

1) Concordance analysis consists in an analysis of those factors and criteria which do not oppose to the fact that one alternative might be preferred to another;
2) Discordance analysis defines the regret to choose an alternative instead of another

The ELECTRE II method creates an outranking relationship among the alternatives, using also a weight w_j for each criterion j, representing its relative importance respect to the other criteria. The key concept is that A_h *is preferable to* A_k if:

- Great satisfaction is achieved preferring A_h to A_k;
- No great dissatisfaction is obtained in preferring A_h to A_k

Let us consider the definition of preference P_j.

Definition 1: Given two different alternatives, A_h and A_k, A_h is preferable to A_k according to the j criterion, denoted as $A_h P_j A_k$, if $c_{hj} \geq c_{kj}$.

Definition 2: Given two different alternatives A_h and A_k, A_h dominates A_k, in symbols $A_h \geq A_k$, if $c_{hj} \geq ckj$ for each criterion $j = 1, \ldots, n$.

ELECTRE II method is usually divided into three stages.

Stage I: In this stage, the method evaluates the concordance matrix C_{hk} and the discordance matrix D_{hk}, for every couple of alternatives $(A_h, A_k), h \neq k$.

The concordance matrix takes into account the weight of the criteria according to which h is preferable to k:

$$c_{hk} = \frac{\sum_{j:A_h P_j A_k} w_j}{\sum_j w_j} \tag{1}$$

The discordance matrix takes into account the criterion most opposing to the preference of h to k:

$$d_{hk} = \max_{j:A_k P_j A_h} \left\{ \frac{c_{kj} - c_{hj}}{diffMax_j} \right\} \tag{2}$$

where $diffMax_j = \max_j\{c_{hj} - c_{kj}\}, h = 1, \ldots, n, k = 1, \ldots, n$.

Stage II: Let us introduce some veto thresholds, strong f and weak d, to assess the alternatives outranking. Two concordance thresholds S_C^d and S_C^f are introduced such that $0 < S_C^d < S_C^f < 1$. If $S_c \to 1$ then only one concordance value exists and no conflict is generated where choose one alternative with respect to another one. Two discordance thresholds S_D^d and S_D^f are introduced such that $0 < S_D^f < S_D^d < 1$. If $S_D \to 0$, then it means that we can choose with no regret one alternative with respect to another one.

Therefore, two outranking relationships can be defined: weak and strong outranking.

Let us define *weak outranking* $A_h S_D A_k$ between two alternatives A_h and A_k if and only if $c_{hk} \geq S_C^d$ and $d_{h,k} \leq S_D^d$.

Let us define *strong outranking* $A_h S_F A_k$ between two alternatives A_h and A_k if and only if $c_{hk} \geq S_C^f$ and $d_{h,k} \leq S_D^f$.

We obtain two graphs, one weak and one strong, enhancing the level of available information and making the choices more accurate. The strong graph is more rigid and strict, with few outranking relations and many incomparability relations.The weak graft is less restrictive and richer in outranking and presents fewer incomparability relations.

Stage III: Using two different order algorithms, one ascending and one descending, it is possible to obtain the final alternatives' classification. In this stage in particular, the algorithm elaborated during the research and tested several times during the simulation stage includes the following sequential operations:

1) Calculate the aggregated weak dominance matrix E^d as node/node incidence matrix of the weak outranking graph
2) Calculate the aggregate strong dominance matrix E^f as node/node incidence matrix of the strong outranking graph
3) Calculate the aggregate dominance matrix $E = \{e_{hk}\} = E^d + 2E^f$
4) Calculate the alternatives' score in accordance with two orders: the sum in each column e_h^c of the matrix E is calculated for each alternatives h, and the sum in each row e_h^r of the matrix E is evaluated.
5) Calculate the alternatives' classification: for each alternative h we obtain $e_h = e_h^c - e_h^r$ and then the alternatives are ordered according to e_h values.

The final classification of the alternatives is given by the arithmetical sum of the scores obtained from the described orders. The alternatives' classification is obtained using a matrix approach instead of a graphic one, as proposed in the original version of the ELECTRE II algorithm.

In the reconfiguration problem, the alternatives are the feasible reconfigurations, as a list of closed/opened switches. The criteria represent the alternatives sort algorithm, according to electrical operator preferences. We consider eight criteria:

1) Active healthy switches: we consider the average value of the closed switches' operative level, where a "healthy" switch means an electrical breaker that can be remotely telecontrolled;
2) Active healthy generators: we consider the average value of active generators' operative level, where a "healthy" generator means a generator with low risk of producing power;
3) Number of active generators: we prefer configurations with more active generators, in this way the grid is balanced among the generators;
4) Healthy changing switches: we consider the average value of the changing switches' operative level, where a "healthy" switch means an electrical breaker that can be remotely telecontrolled;
5) Hops number: each hop represents a switch status change, starting from the actual configuration to obtain the particular configuration. We prefer configuration with low hops, according to a low energy profile;
6) Configuration strategic value, implemented as the average value of the active switches' strategic value. Each switch has a value based on its strategic importance;
7) Black-out dimension: we consider the amount of loads not feed by the grid;
8) Population involved, as the population negatively affected by the black-out obtained by particular configuration.

IV. Reference Scenario

This paragraph describes the case study used to validate the overall system. The aim is to understand how data fusion can improve the distribution network reconfiguration in an interdependent scenario. We consider three main infrastructures: a distribution electrical grid and a gas pipeline which guarantees the fuel for one turbine generator of the electrical grid; both the electrical and the gas grids are controlled by two distinct SCADA control centres by means of an Ethernet-based telecommunication network.

The power grid has a mesh topology and it has five generators, where one of them is a gas turbine unit and the others are solar and wind farm and two substations from the electrical transmission grid.

The distribution gas pipelines have a radial topology from the regulator connected to the gas transmission network. The model considers a set of pumping stations maintaining constant the gas pressure by means of compressors. If a leakage happens or if a compressor is out of order, the storage supplies the gas pipelines to fed customers. The natural gas is also used as fuel for an electric generator connected to circuit breakers. Electricity is needed for pumping stations and regulators within the gas pipelines.

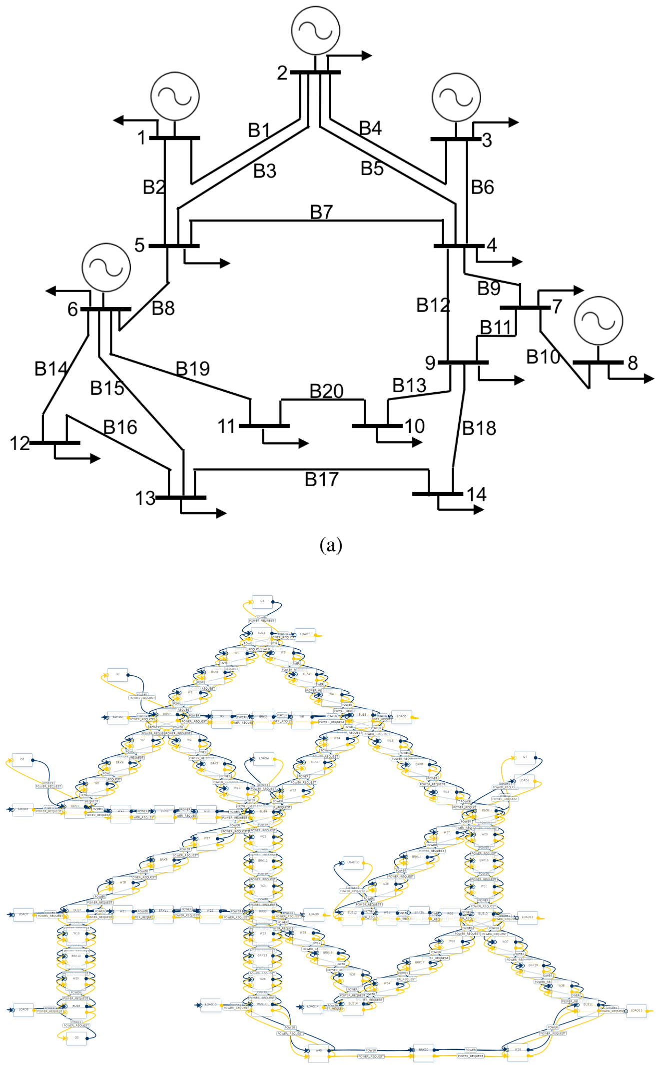
Both those two infrastructures have a SCADA control centre, able to collect data from sensors and change pre-defined threshold for generators. Those SCADA control centres make use of an Ethernet-based telecommunication network.

The telecommunication network has a mesh structure and is made of optical fibre. We model it for land-line and mobile services, for understanding how coordinate crises. Telecommunication network is actually used among electric and gas SCADA control centre and field sensors. Telecommunication routers and switches need electricity to proper work.

The electrical grid is the IEEE 14 busbar test system [16], in Fig. 3a, and its implementation within CISIApro is depicted in Fig. 3b. The electrical grid is an active network where each switch can be opened or closed from the control centre, changing the actual topology in event of overloads or permanent fault. Each branch has a sectional switch that can be telecontrolled. In Fig. 3a, the busbars are numbered from 1 to 14, and the switches on each branch are enumerated with the symbols $Bi, i = 1, \ldots, 20$. For example, $B1$ is the switches number 1 between busbar 1 and 2, and so on.

In this scenario, we consider the following situations as meaningful:

- Fault on a compressor within the gas distribution network. The compressor in the pumping station maintains constant the gas pressure and, in event of failure, the loads and also the gas turbine of the power grid (specifically, the generator connected to busbar 2, see Fig. 3a) can be without the right amount of fuel and the risk of the generator is increased due to possible fuel unavailability;



(a)

(b)

Fig. 3. The electrical distribution network: in (a), the IEEE 14 busbar test system scheme and in (b) the implementation within CISIApro.

- Cyber attack on the telecommunication network, such as a Denial of Service (DoS), see also [1]. In this case, the partial unavailability of telecommunication network causes problems on the controllability of the electrical switches.
- A fire occurring near load 13, causing a permanent fault at the bus level. Firstly, the bus is isolated, opening automatically the switches (in particular switch 16 and 17 in Fig. 3), and then another configuration can be chosen in order to increase the reliability of the network

The initial configuration of the electrical grid is the following one: the switches $\{B2, B5, B9, B12, B13, B14, B15, B18, B19\}$ are closed and the others $(\{B1, B3, B4, B6, B7, B8, B10, B11, B16, B17, B20\})$ are opened. We observe that two generators just feed the loads connected the same busbar: considering the initial configuration, generators on busbar 3 and on busbar 8 are islands (or eventually micro-grids) feeding the loads connected to the respectively busbars. In Fig. 3a, the loads are represented by arrows coming out from the busbars.

V. Results

In this paragraph, we comments the results obtained from the framework and how data integration improves decisions. As already described in the previous paragraph, we consider three different situations. Nevertheless, real situations could also include several adverse events in a subsequent order.

ELECTRE II is an almost automated approach that involves minimal intervention by the decision maker, which, apart from having a crucial role in the final choice, is also the main actor in the definition of an important magnitude value, represented by the criteria weights. They must be attributed to each basic criterion according to operator' judgements and opinions. The variation of these magnitudes can lead to different results, maintaining unaltered all the other conditions. Obviously there is a default configuration where we consider the weights perfectly balanced but a particular configuration of the criteria weights can be set, depending on the scenario and the events that the operator is to manage. A weight equals to zero does not mean that the criterion is not considered but its valued less than the others.

Situation 1. Fault within the gas distribution network: In this situation, CISIApro evaluates the cascading effect of a fault at the compressor within the pumping station in a gas pipeline. The generator number 2 (connected to busbar 2 in Fig. 3) is a gas turbine fed with natural gas provided by the pipelines. In CISIApro the operative level of the generator is equals to 0, corresponding to a high risk.

After CISIApro execution, a first step in the decision making process is the definition of the list of all the feasible configurations. After this step, the ELECTRE II algorithm is executed with weight w_j for each criterion. The weights in this situation are described following the list provided in the final part of Section III-C:

$$W = \{w_j\} = \{0, 0, 1, 0, 0, 0, 0, 0\} \quad (3)$$

where the electrical operator prefers a configuration with a high number of generators, i.e., the third criterion.

In TABLE I, the five better configurations are listed in descending order from the preferred one, with the evaluation of each criterion. We include just six of the eight criteria, because the last two, related to the blackouts, do not discriminate the alternatives. The symbols in TABLE I $\{C1, C2, C3, C4, C5, C6\}$ denote the criteria in the same order as in Section III-C, for example $C1$ is the mean vale of the operative level of the closed switches, and so on.

Situation 2. Cyber attack on the telecommunication network: In this case, CISIApro evaluates the consequences of a Denial of Service within the telecommunication and its effects on the physical system, see also [1] for more detailed information. The consequences of this cyber attack is a high risk for a set of switches, i.e., switches number 8,

TABLE I

SORTED RESULTS IN DESCENDING ORDER FOR SITUATION 1, WHEN THE GAS TURBINE IS AT HIGH RISK: THE FIRST CONFIGURATION IS THE BEST ONE. THE CONFIGURATION IS EXPRESSED AS A LIST OF CLOSED SWITCHES.

Configuration	C1	C2	C3	C4	C5	C6
$\{2, 6, 10, 13, 15, 16, 17, 18, 20\}$	0.98	1	4	0.97	0.33	1
$\{2, 6, 10, 12, 13, 15, 16, 18, 20\}$	0.97	1	4	0.98	0.47	1
$\{2, 6, 10, 12, 13, 14, 15, 18, 19\}$	0.97	1	4	0.95	0.73	1
$\{6, 8, 10, 11, 15, 16, 17, 19, 20\}$	0.99	1	3	0.96	0.07	1
$\{2, 5, 10, 13, 14, 15, 17, 18, 20\}$	0.97	0.75	4	0.97	0.6	1

TABLE II

SORTED RESULTS IN DESCENDING ORDER FOR SITUATION 2, CAUSED BY A DENIAL OF SERVICE. THE CONFIGURATION IS EXPRESSED AS A LIST OF CLOSED SWITCHES.

Configuration	C1	C2	C3	C4	C5	C6
$\{2, 5, 11, 13, 14, 15, 17, 18, 20\}$	1	1	3	0.83	0.6	0.64
$\{2, 6, 9, 13, 14, 15, 17, 18, 20\}$	1	1	3	0.83	0.6	0.63
$\{2, 6, 10, 13, 14, 15, 17, 18, 20\}$	0.89	1	4	0.75	0.47	0.64
$\{6, 7, 10, 13, 14, 15, 17, 18, 20\}$	0.89	1	3	0.8	0.33	0.67
$\{2, 6, 10, 11, 13, 14, 17, 18, 20\}$	0.89	1	4	0.8	0.33	0.62

10, 16 and 19 in Fig. 3 have operative level equals to 0. The criteria weights $\{1, 0, 1, 0, 0, 0, 0, 0\}$ prefer configurations with a greater number generators and "healthy" switches involved in the reconfiguration. In normal situation for the power grid, the loss of controllability can be a minor problem, but in event of overloads the operator may change the topology and could not do it due to problems on the telecommunication network.

We also change the strategic value of each switch:

- Switch 01 = 0.05
- Switch 02 = 0.10
- Switch 03 = 0.15
- Switch 04 = 0.20
- Switch 05 = 0.25
- Switch 06 = 0.30
- Switch 07 = 0.35
- Switch 08 = 0.40
- Switch 09 = 0.45
- Switch 10 = 0.50
- Switch 11 = 0.55
- Switch 12 = 0.60
- Switch 13 = 0.65
- Switch 14 = 0.70
- Switch 15 = 0.75
- Switch 16 = 0.80
- Switch 17 = 0.85
- Switch 18 = 0.90
- Switch 19 = 0.95
- Switch 20 = 1.00

where 1.00 means very important switch.

The results are summarized in TABLE II in descending order. Among the feasible configurations, there are also three configuration where the switch 10 is telecontrolled from opened to closed status, in any case. The results of the multi-criteria decision making are not easily to understand due to the large amount of criteria, weights, thresholds and parameters.

TABLE III

SORTED RESULTS IN DESCENDING ORDER FOR SITUATION 3, CAUSED BY A FIRE AROUND BUSBAR 13. THE CONFIGURATION IS EXPRESSED AS A LIST OF CLOSED SWITCHES.

Configuration	C1	C2	C3	C4	C5	C6
$\{2, 5, 6, 10, 13, 14, 18, 19\}$	1	1	5	1	0.67	1
$\{2, 3, 6, 10, 13, 14, 18, 19\}$	1	1	5	1	0.53	1
$\{2, 3, 5, 6, 9, 10, 14, 18\}$	1	1	5	1	0.53	1
$\{2, 3, 6, 7, 10, 13, 14, 18\}$	1	1	5	1	0.4	1
$\{2, 3, 5, 6, 7, 10, 14, 18\}$	1	1	5	1	0.4	1

Situation 3. A fire occurring at load 13: CISIApro evaluates the consequences based on a geographic propagation of the fire event: near the fire, all the equipment are at danger. The electric grid must isolate the fault opening the sectional switches around the busbar 13.

The feasible reconfigurations obtaining closing one switch less than before are more than 6.000. In the previous situations, the number of feasible configurations was around 2500.

The criteria weights prefer a configuration with a major number of generators, as in situation 1.

The results for the five better configurations are presented in TABLE III, without considering the number and the population involved in blackout, that are at busbar 13.

VI. CONCLUSION

The distribution reconfiguration problem is an example of decisions that an electric operator must make every day during his work. This decision is usually made considering only the information related to the electrical grid itself. Nowadays, the electrical grid has a web of interconnection with other critical infrastructures, such as telecommunications and gas pipelines. Those interconnections make even harder every decision. Fusing information improves the operator awareness.

This paper demonstrates how information integration, realised using CISIApro, enables multi criteria decision making. CISIApro is an agent-based simulator for forecasting the consequences of adverse events in a scenario made of interconnected infrastructures. In this way, CISIApro can be also considered as an integration platform of heterogeneous signals coming from the field.

CISIApro results are used as input of a decision support system. ELECTRE II is a method of the multi-criteria decision making, which simulated the operator process in decision but in automatic way. ELECTRE II is devoted to rank the alternatives, i.e., the feasible configuration, following several criteria. Those criteria can also be very different between each other.

In this paper, the criteria represent how the other infrastructures affect the reconfiguration problem, a well known problem. The results show how the proposed framework is flexible and can handle also large amount of alternatives, but with good performances in terms of computational time. The case study presented is an example of how this framework can be exploited.

This framework can suffer of out-of-memory due to the number of feasible configurations. This problem can be solved reducing the number of configurations, considering explicitly one or more criteria, within the selection algorithm, see Section III-B. Another possibility is to reduce the matrices dimensions of ELECTRE II (that are usually causing the out-of-memory problem) in the following way: dividing the problem into sub-problems of 1000 alternatives, choosing the better configuration respect to the others, and finally executing an ELECTRE II method among the optimal configurations of each sub-problem. With this approach, we can eventually improve the computational time using parallel programming, without precision loss.

Ongoing work is related to the inclusion of electrical criteria within ELECTRE II, such as the power losses, and eventually the comparison between the standard formulation and the results of this paper.

Acknowledgement

The research paper is partially supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 700581 (ATENA - Advanced Tools to Assess and Mitigate the Criticality of ICT Components and Their Dependencies over Critical Infrastructures) www.atena-h2020.eu

References

[1] C. Foglietta, C. Palazzo, R. Santini, and S. Panzieri, "Assessing Cyber Risk Using the CISIApro Simulator," in *Critical Infrastructure Protection IX*, ser. IFIP Advances in Information and Communication Technology, M. Rice and S. Shenoi, Eds. Springer International Publishing, Mar. 2015, no. 466, pp. 315–331, dOI: 10.1007/978-3-319-26567-4_19. [Online]. Available: http://link.springer.com/chapter/10.1007/978-3-319-26567-4_19

[2] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[3] D. Shirmohammadi and H. W. Hong, "Reconfiguration of electric distribution networks for resistive line losses reduction," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1492–1498, Apr. 1989.

[4] Q. Zhou, D. Shirmohammadi, and W. H. E. Liu, "Distribution feeder reconfiguration for service restoration and load balancing," *IEEE Transactions on Power Systems*, vol. 12, no. 2, pp. 724–729, May 1997.

[5] E. M. Carreno, R. Romero, and A. Padilha-Feltrin, "An Efficient Codification to Solve Distribution Network Reconfiguration for Loss Reduction Problem," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1542–1551, Nov. 2008.

[6] A. B. Morton and I. M. Y. Mareels, "An efficient brute-force solution to the network reconfiguration problem," *IEEE Transactions on Power Delivery*, vol. 15, no. 3, pp. 996–1000, Jul. 2000.

[7] R. Sarfi, M. Salama, and A. Chikhani, "A survey of the state of the art in distribution system reconfiguration for system loss reduction," *Electric Power Systems Research*, vol. 31, no. 1, pp. 61–70, Oct. 1994. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/0378779694900299

[8] D. Das, "Reconfiguration of distribution system using fuzzy multi-objective approach," *International Journal of Electrical Power & Energy Systems*, vol. 28, no. 5, pp. 331–338, Jun. 2006. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0142061506000184

[9] D. P. Bernardon, V. J. Garcia, A. S. Q. Ferreira, and L. N. Canha, "Multicriteria Distribution Network Reconfiguration Considering Subtransmission Analysis," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2684–2691, Oct. 2010.

[10] I. Tristiu, M. Eremia, C. Bulac, and L. Toma, "Multi-criteria Reconfiguration of Distribution Electrical Networks for Minimization of Power Losses and Damage Cost due to Power Supply Interruption," in *Power Tech, 2007 IEEE Lausanne*, Jul. 2007, pp. 385–390.

[11] F. Capitanescu, L. F. Ochoa, H. Margossian, and N. D. Hatziargyriou, "Assessing the Potential of Network Reconfiguration to Improve Distributed Generation Hosting Capacity in Active Distribution Systems," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 346–356, Jan. 2015.

[12] R. S. Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham, "Power Loss Minimization in Distribution System Using Network Reconfiguration in the Presence of Distributed Generation," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 317–325, Feb. 2013.

[13] L. Pfitscher, D. Bernardon, L. Canha, V. Montagner, V. Garcia, and A. Abaide, "Intelligent system for automatic reconfiguration of distribution network in real time," *Electric Power Systems Research*, vol. 97, pp. 84–92, Apr. 2013. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378779612003598

[14] S. M. Rinaldi, J. P. Peerenboom, and T. K. Kelly, "Identifying, understanding, and analyzing critical infrastructure interdependencies," *IEEE Control Systems*, vol. 21, no. 6, pp. 11–25, Dec. 2001.

[15] J. Figueira, S. Greco, M. Ehrgott, and C. Henggeler-Antunes, Eds., *Multiple criteria decision analysis: state of the art surveys*, ser. International series in operations research & management science. New York, NY: Springer, 2005, no. 78.

[16] R. Christie. Power systems test case archive. University of Washington, Electrical Engineering (UWEE). [Online]. Available: http://www.ee.washington.edu/research/pstca/