CIPRNet Decision Support System: Modelling Electrical Distribution Grid Internal Dependencies

Keywords
natural hazards, risk analysis, interdependencies, power network, SCADA

Abstract
In this work, we present a peculiar application contained in a Decision Support System for Risk Analysis of (inter)dependent Critical Infrastructures under development within the EU FP7 CIPRNet Project. The application shows the efficacy and the benefits derived from a complete information of the multiple (inter)connected infrastructures (electrical and telecommunication) present in a Crisis Scenario. Electrical Distribution operators use SCADA systems to perform remote operations (tele-control) on the electrical grid such to ensure a constant and efficient energy supply to the consumers. Tele-control operations bi-directionally couple telecommunication and electrical networks: faults in one network produce effects, which then reverberate on the other. The work shows how the DSS, based on the damage estimate occurring on the two systems, may predict the correct tele-control operations needed for the restoring of the electrical grid based on topological properties of the electrical substations and the Telecom nodes.

1. Introduction
In 2009, hurricane Sandy brought high winds and coastal flooding in US, leaving nearly 8 million customers without power. In 2013, a 7.1 magnitude earthquake hit the Philippines causing severe damages to infrastructures. When a specific perturbation hit a system of Critical Infrastructures (CI), system’s dependencies propagate faults from one system to another producing cascading effects and thus amplifying impacts of the events. Prediction and/or a rapid assessment of Critical Scenarios can be thus a major breakthrough for increasing preparedness strategies, for activating mitigation actions by increasing systems resilience. To this end, a major goal could be represented by a correct prediction of the course of events, starting from the prediction of the occurrence of natural hazards and of their strengths, by the connection of event’s strength to the expected damages to assets, by the connection of the expected damages to the resulting impacts that they will produce in reducing or destroying supplied Services. If this analysis could also be accompanied by a thorough analysis of the Consequences that reduction or loss of Services might produce on relevant areas of societal life, this could represent an unique and valuable tools for supporting Emergency Managers, CI operators,
Public Administration Offices which strong commitment if Crisis Management (Civil Protection, Fire Brigades etc.). The realization of a similar object, cast in the form of a Decision Support System (DSS), is one of the objectives of the CIPRNet project. The designed DSS implementing the above mentioned risk assessment workflow other than predicting the extent of the expected crisis, can also be used to “weigh” the efficacy of the result of the proposed mitigation and healing actions.

The DSS can be logically represented in terms of five functional components (Bn) which leverage on a large Database containing GIS data of CI elements, assets, geographical, social, economic information of the area under control. These are:

- **Monitoring of natural phenomena (B1):** This functional block acquires geo-seismic, meteorological forecasts and nowcasting data, other than sensor field data when available.

- **Prediction of natural disasters and events detection (B2):** This block, based on information of B1, predicts, within an estimated temporal horizon, the strength of a limited set of natural phenomena occurring in the specified area.

- **Prediction of physical harm scenarios (B3):** This block evaluates the probability that each CI element can receive a damage if hit by the predicted natural events and the estimate of its loss of functionality. The association (Event Strength-Damage) of a physical component \( c_i \) of the \( x \)-th CI by a threat manifestation \( T_j \) is performed by considering the intrinsic vulnerability of \( c_i \) with respect to the intensity of \( T_j \) (output of B2). The outcome is a set of affected CI physical components and the extent of the estimated physical damages, the Physical Harms Scenario (PHS) defined as:

\[
PHS = (c^T, d^T)
\]  

where \( c^T \) is the set of CI components that are expected to receive an over-threshold probability to be damaged and \( d^T \) is the set of the extent of estimated damages for each CI component. The \( \text{PHS} \) can be provided to CI operators for alerting on the possible damages expected for the physical components of their CI.

- **Impact and Consequences estimate (B4):** This block estimates the Impact that Damages will produce on the Services delivered by the CI and the resulting Consequences, i.e. the effects on citizens, services, economy, and the environment (Criteria). European Council Directive 2008/114/EC [1] has, in fact, defined that the relevance of a given Crisis Scenario, produced by disruption or destruction of elements of European (or National) Critical Infrastructure shall be assessed in terms of cross-cutting Criteria weighting all the induced effects on the bases of their costs in terms of casualties other than in economic and other “public” costs.

**Support of efficient strategies to cope with crisis scenarios (B5):** This block provides Crisis Managers with a decision list of actions in those cases where the DSS can provide further information needed to support a crisis solution.

In Section 2 we describe the objective of this contribution which reports on a specific task for supporting electrical operators in assessing the correct Impact Scenario expected from a \( \text{PHS} \). This task constitutes the initial stage of the B4 functional block and accounts for the prediction of the short time scale Impacts on the electrical infrastructure, considered to have a major role in crisis management scenarios [3]. Section 3 describes the architecture implemented within the CIPRNet DSS for the B4 functional block. Section 4 describes the electrical distribution grid reconfiguration algorithm. The algorithm plays a central role in the prediction of the short time scale impacts of a \( \text{PHS} \) on the electrical infrastructure. Section 5 describes a test case for the proposed platform and how the prediction of the short time scale impacts (in particular for large crisis) is useful to improve possible mitigation strategies of crisis due to natural events. The Section 6 draws some conclusions.

### 2. Assessment of short time scale impacts

In this work, we present how the DSS performs the impacts assessment. In particular, we will focus on the short time scale impacts assessment. Starting from the predicted damages in a test case involving a distribution power network and the relative SCADA system, the proposed module computes the reduction of QoS of the electrical network due to the predicted damage scenario. The Impact evaluation module has been dived into two different phases: in the first, strongly coupled infrastructures (such as the electrical and the telecommunication ones) are considered. Their strong coupling activates dependency mechanisms holding in the short time scale (from a few minutes up to one hour). Coupling of these infrastructures to other CI establishes with a larger latency: during very short times scales, other CI could be considered as “decoupled” from the previously cited infrastructures, in a sort of adiabatic approximation [5]. For this reason, the DSS has divided the Impact evaluation in two stages: for the short time scale the Impacts assessment module resolves the electrical reconfiguration problem described in Figure 1 as the top of the three steps of Impacts and Consequences estimate.
Modelling the dynamic of a power network and its dependencies with the other systems such as its SCADA system requires a deep knowledge of the electric network model and this task can be extremely complex using mathematical approaches. Then, we present how our DSS implements an approach to tackle this issue based on simulation of the network topology of the two systems and using forecast results relative to the possible outages of specific substations. We present a procedure that, based on the estimated damages, is able to predict, within a limited time horizon, those substations that, with high probability, may be disconnected from the network due to the possible occurrence of natural threats. In addition, by exploiting the knowledge of the (inter)dependencies between the electrical network and the SCADA system, it detects the electrical substations that can be operated remotely and those that, in turn, would require a manual intervention. The difference in time of the automatic and manual recovery operations required to re-energize specific electrical loads, is used to predict the outage durations of specific substations and ultimately the Consequences of the predicted Crisis Scenario.

The outcome of the impact evaluation is called Impact Scenario (IS), defined by a vector containing the set of the variations \( \Delta Q_i \) of the Quality of Service (QoS) associated to each CI. The IS can be generically represented as:

\[
IS = \Delta Q_1, ..., \Delta Q_N
\]

Based on census data and metrics measuring the vulnerability of the society to the degradation of CI services expressed by the IS, the DSS will estimates the consequences grouped by specific criteria. The outcome of the consequence estimation is called Consequence Estimate (CE). From the electrical grid operator point of view, the CE information can be used in different situations:
1) small crisis scenario,
2) large crisis scenario and
3) electrical grid performance optimization.

A Crisis Scenario can be considered light if the available resources to restore the normal network QoS are sufficient and/or the CE values are small. During a light scenario the knowledge of the QoS of the other CI networks and in particular of the other CI components providing services to the electrical infrastructure (as for instance, the fixed and mobile telecommunication network for the electrical infrastructure SCADA system) can be used to further improve the restoration procedures in order to minimize the disconnection time of users and critical loads. During a severe crisis scenario, characterized by high values of CE values and/or inadequate available resources for restoration, the DSS output is used to optimize the available resources in order to mitigate the consequences of the crisis. Indeed, in this case, it will not be possible to restore (as in light crisis situation) all users and critical loads in an acceptable time. In these cases, the Pre Impact assessment and DSS output in general support the decision-making process. In the end, the CIPRNet DSS can be used as a what-if analysis tool and, in general, CI operators can use the DSS output to drive future network development programs. In this work,
we focus on the Pre-Impact Assessment which deals with the short time scale electrical-telecom interaction.

3. Architecture

The aim of the Pre Impact Assessment phase of the risk assessment workflow implemented within the CIPRNet DSS is to obtain the most realistic impacts assessment of a specific PHS on the electrical distribution grid. To this end, it foresees the involvement in the loop of electrical and telecommunication networks operators. This is beneficial for different reasons:

- CI operators have contingency plans to reconfigure their network after failures on one or more CI components;
- Contingency procedures depend on the current configuration of the CI network. Only CI operators have access to the current configuration of their networks;
- Contingency plans and CI network details are considered sensitive data that CI operators would not share and/or distribute.

The proposed platform for the Pre Impact Assessment phase has been implemented leveraging the experience gained in the DIESIS [4] project where a federated simulation environment was proposed. In the present work, a simplified version of the isolation and reconfiguration procedures adopted in ACEA and implemented within the ACEA module of Figure 2 will be described.

4. Implementation

The isolation and reconfiguration algorithm implemented within the electrical module has been developed in collaboration with ACEA. The electrical distribution grid of Rome can be modelled as showed in Figure 3.

The network is composed of a number of Primary Substations (PS). Each PS originates one (or more) Medium Tension (MT) semi-backbone(s) ending into a further PS. The term “semi” is used as the MT line is cut at a certain stage by a switch which decouples the line into two halves, each of them supplied by one of the two overlooking PS. Each semi-backbone connects a number of Secondary Substations (SS), some of them being remotely controlled. SS on a specific semi-backbone are fed, in the normal configuration, by a specific PS. The network can be configured (using the switches showed in Figure 3) in a way that the SS on a semi-backbone (or a subset of these substations) are fed by the closest PS (in Figure 3, the PS P1 can be considered the closest primary substation for P1 and vice versa). Each SS is modelled as a Finite State Machine as showed in Figure 4. In normal condition the SS is in the initial “FUNCTIONING” state.

Starting from this state, the secondary substation can move into two different states:

- **FAILURE STATE**: when a failure in the SS occurs, the transition 1 is activated. The SS remains in this state for the expected failure duration (the failure duration is contained in the PHS).
- **NOT FUNCTIONING STATE**: a SS can be in this state after the activation of protection devices. For example, when a SS moves into the FAILURE STATE all SS on the same semi-backbone move into their NOT FUNCTIONING STATE.
Figure 4. Secondary Substation Finite State model

Figure 5 shows cases that the algorithm needs to consider to compute the SS restoration time (the presented cases are not exhaustive).

A SS remains in this state waiting for restoration. The duration of the restoration can be of a few minutes (about 3-5 minutes) if the SS can be tele-controlled or much longer (50-55 minutes to few hours) depending on several factors (e.g., time required by emergency crews to reach the faulted substation and to restore it).

Let us assume that a \( t=t_1 \) the electrical substation SS3 is in FAILURE STATE. All SS on the same semi-backbone will move into their NOT FUNCTIONING STATE starting from \( t=t_1 \).

In Case a) SS1 and SS2 can be restored in a few minutes (e.g., 5 minutes): SS2 can be remotely restored.

In Case b) remote control cannot be used so that SS1 and SS2 restoration requires a manual procedure performed by emergency crews. The manual restoration of a SS would take 50-55 minutes (for real cases, this time can be estimated by historical data of the electric operator), as it could imply the reach of the faulted SS (in a complex urban scenario). The other two cases of Figure 5 - Case c) and Case d) - require the closest PS to restore SS on the semi-backbone after the SS in failure state. In Case c) SS3 can be restored using the next PS; in addition, considering that as SS3 is remotely controlled, restoration would take few minutes (e.g., 5). In Case d), the SS3 cannot be restored using the next primary substation and the restoration duration would depend on the failure duration of the two failures on the backbone.

The implemented algorithm takes into account all possible restoration cases. A simplified sketch of the simulation algorithm of the ACEA restoration procedures is shown in Figure 6.

1. Read data from DB (Electrical Distribution Grid topology, failures)
2. Initialize grid topology data structure
3. Initialize electrical and telco failures data structures
4. Initialize simulation constants //start, end simulation time, simulation step
5. for (time=0; time<END_SIMULATION_TIME; time+=SIMULATION_STEP){
   a. check_telco_failures(time) //check if at \( t=time \) there are telco components entering in the failure state
   b. check_electrical_failure(time) //check if at \( t=time \) there are electrical components entering in the failure state
   c. update_tlc_status(time)//set tlc status = NOT WORKING for those secondary substations remotely controlled using a BTS that is not functioning (its functioning status = NOT WORKING)
   d. update_net(time)//this procedure update the state of each secondary substations
6. }

Figure 6. The main simulation loop

The input for the algorithm is constituted by the electrical grid topology, the telecommunication components providing services to the electrical grid SCADA system, mainly Base Transceiver System (BTS) and the PHS data. The BTS provides telecommunication services required by the SCADA system of the power distribution stations.

The output is represented by the power profile of the SS during the simulated time slot. After the initialization phase, where the electrical grid topology is loaded from the CIPRNet DB as well as the PHS data, the main simulation loop starts. The simulation algorithm introduces a check order of incoming events (i.e. failures).

First, the algorithm checks the state of the BTS. Each BTS is modelled using the model shown in Figure 7. In particular a BTS, the procedure check_telco_failures(time) (step 5a of Figure 6) loops through all BTSs and updates their state accordingly (a BTS in failure moves its status from
FUNCTIONING to FAILURE). The status of the BTs will influence the functioning status of the electrical grid SCADA system (procedure update_tlc_status(time)). Then, (step 5.b of Figure 6) the algorithm updates the failure status of the SS. If a SS moves its state from FUNCTIONING to FAILURE the functioning state of the components (e.g. a BTS) powered by the SS will be updated as well.

After the update of the status of the SCADA components (step 5.c of Figure 6) the simulation loop calls the update_net(time) procedure (step 5.d of Figure 6). This procedure updates the status of each SS. In particular, the procedure checks if it is possible to restore (i.e. shifts their status to the FUNCTIONING state) all SS that are in the NOT FUNCTIONING state. The update_net(time) procedure takes into account the different possible cases some of them showed in Figure 5.

**Figure 7. BTS Finite State model**

5. The Rome electrical distribution grid test case

A real case study is shown in Figure 8 where we represented a section of the power distribution grid of an area of the Rome City, consisting of: (i) 9 HT/MT substations (PS); (ii) 154 MT/LT substations (SS); (iii) 6 Telecom BTS and (iv) 3 hospitals. Each PS has a number of backbones consisting of several SS. Some of these may feed Telecom BTS or hospitals in addition to generic users (e.g., households).

The figure shows a possible PHS (all the SS shown in red) i.e., the set of SS estimated to be in failure based on predicted Damages due to the natural events manifestation. Based on the presented reconfiguration procedure, the pre-impact assessment module estimates the IS i.e., the possible evolution of the power network (Figure 10) considering the assumption that all the BTS are working properly.

**Figure 9. Estimated substations in failure state**
Figure 8. Representation of a section of a power distribution grid of Rome. Rome scenario at time $t=t_1$

Figure 10. Rome scenario at time $t=t_2$ (hypothesis: BTS are working properly)
The expected outage duration of the electrical secondary substations is provided to the Comprehensive Impact Assessment module based on I2Sim that subsequently evaluates the resulting impacts on the other infrastructures present in the scenario. This outcome, i.e., the Impact Scenario together with census data available for the city of Rome, feeds specific metrics able to estimate the effects on the different societal Criteria to the predicted reduction or loss of Services. These information may be useful for decision makers to know, during crisis scenarios that in a specific area there might be a high concentration of citizens (e.g., old aged people, disabled people) that may be severely affected by the different outages of primary services (e.g., water, gas) resulting as cascading effects of the unavailability of electric power.

6. Conclusion

This work shows how the DSS, currently under development within the EU FP 7 CIPRNet project, attempts to solve the full risk analysis workflow, from events prediction to impacts and consequences estimation of a Critical Scenario. In this work, we described a core component of this system i.e., the pre-impact assessment module able to estimate the possible effects of specific natural threats to the electrical infrastructure. Indeed, the reduction of the quality of services of the electrical infrastructure may produce negative effects on all human activities and the societal life in general. This module constitutes the bases for a comprehensive impacts and consequences assessment. Moreover, we showed, using a test case, how the electrical grid operators can benefit from the outcome provided by this approach which considers, among others, (inter)dependencies among the electric and SCADA networks. Future works will focus on the application of this approach to estimate the best strategies that minimize the consequences of a crisis.

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