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Implementation of ENTSO-E emergency & restoration procedure in a real-time environment

Igor Bundalo
Institute "Mihajlo Pupin", University of Belgrade
Belgrade, Serbia
igor.bundalo@pupin.rs
https://orcid.org0000-0003-1690-1738

Goran Jakupović
Institute "Mihajlo Pupin", University of Belgrade
Belgrade, Serbia
goran.jakupovic@pupin.rs
https://orcid.org/0000-0003-0223-118X

Marija Popović
Institute "Mihajlo Pupin", University of Belgrade
Belgrade, Serbia
marija.popovic@pupin.rs

Srđan Subotić
Elektromreža Srbije JSC
Belgrade, Serbia
srdjan.subotic@ems.rs

Dušan Prešić
Security Coordination Centre SCC Ltd. Belgrade
Belgrade, Serbia
dusan.presic@scc-rsci.com
https://orcid.org/0000-0001-6198-9404

***Abstract*— This paper describes one implementation of the ENTSO-E emergency & restoration procedure in a real-time environment. The initial system, featuring this procedure, was developed as part of the Horizon 2020 Trinity project. The system was implemented in a study environment and tested on a network model that simulates the behavior of the power system model of Serbia and the zone observability of neighboring Transmission System Operators (TSOs). Within the framework of the R^2D^2 project, improvements to this system are underway. While in the initial system version, the identification of islanding events relied solely on topological analysis, in this iteration, the algorithm will be expanded with additional verification based on precise frequency measurements obtained through Phasor Measurement Unit (PMU) devices.**

Keywords— Resilience, system split, topology

I. Introduction

The strategic goal of the European Union is to improve the resilience and reliability of current Electrical Power and Energy Systems (EPES) against a growing number of threats and vulnerabilities that may affect such a critical infrastructure, exposing weaknesses with harmful and damaging effects on different stakeholders and final customers. Horizon Europe project called R^2D^2 deploys four products dedicated to preventing, protecting, and restoring EPES in two different and independent but complementary scenarios in the energy value chain from regional coordination between TSOs, to privacy of LV customers. The project will build on top of strong energy coordination actions in South-East Europe (SEE), following EU legislation and in alignment with the recent activities promoted by ENTSO-E on cyber-security in transmission systems. R^2D^2 will deliver a palette of complementary solutions synthesized into four products:

1. Multi-risk assessment framework for power system (C3PO)
   -Goal: contributing to a systematic, disciplined, and repeatable approach for evaluating an energy system security strategy.
   - Beneficiaries: System Operators.
2. Resilience suite for TSO & DSO (IRIS)
   -Goal: intervenes when coordination between system operators is needed for security reasons.
   -Beneficiaries: System Operators and Regional Coordination Centres (RCC).
3. Prevention Systems for Energy Infrastructures Security (PRECOG)
   -Goal: To provide a cybersecurity framework to OT and IT.
   -Beneficiaries: System Operators, IT consultants, electric industries and manufacturers.
4. Enhanced Assets Maintenance and Management Toolkit (EMMA)
   -Goal: To contribute to the reliability of the physical assets and to expedite a faster grid recovery.
   -Beneficiaries: System Operators, contractors, electric industries, and manufacturers.

The IRIS tools will help System Operators to handle these new challenges to improve the resilience of the EPES. This paper describes one of IRIS tools called Emergency & Restoration - System Split module. The main purpose of this module is to detect a system split of the power system based on measurements in the SCADA system, and then to initiate guided communication at the SEE regional level. This communication should follow certain predefined system split scenario and guide dispatchers through all the steps provided by applicable rules and procedures, as well as help them make operational decisions based on the characteristics of the system split. Detecting system split typically relies on precise frequency measurements acquired through Wide Area Measurement Systems (WAMS). However, this method lacks the ability to determine the exact boundary of system split.[1]To address this limitation, the presented algorithm utilizes the topology processor, enabling accurate delineation of boundaries between newly formed islands. Furthermore, frequency measurements from WAMS systems are utilized for additional verification purposes.

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The motivation for creating this tool arose from a major system split that happened on November 4, 2006, which proved that coordination among TSOs is necessary. The similar disturbance happened on January 8, 2021, after work on the ER module had begun. Analysis of this disturbance showed that the rules for resynchronizing the system are very complex, and that the dispatchers of the national control centers failed to fully apply them, so we can now confidently say that the idea for such Emergency & Restoration application development was justified. It has also been shown that the current tool for exchanging global system status information (European Awareness System – EAS) is not sufficient in such disturbances. On the other hand, it should be noted that disturbance from January 8, 2021 was successfully resolved, despite all detected problems, as assessed by ENTSO-E experts.

II. System Architecture

Fig. 1 illustrates the Emergency & Restoration-System split application's architecture. Network Topology Processor (NTP) determines the network topology and identifies electrical islands based on static equipment connectivity and switching equipment statuses. The NTP generates a bus-branch equivalent network model with branch parameters determined from actual equipment parameters. Measurements from the SCADA system are further associated with this bus-branch model. Real-time application database (ADB) is implemented as a relational database and serves as a central repository of data on the power system elements (generators, transmission lines, transformers, loads), as well as all necessary data for determining the static topology of the network (element connectivity, bus structure, busbar field descriptions, circuit breaker descriptions...). The static connectivity of the power system elements is described by their terminal connections to the nodes. In addition to static, relatively unchanging data, the application database contains dynamic data on analog measurement values and the status of switchgear obtained from the SCADA system. The application database also contains system parameters necessary for the operation of network applications, as well as corresponding data required for the connection with the SCADA system.

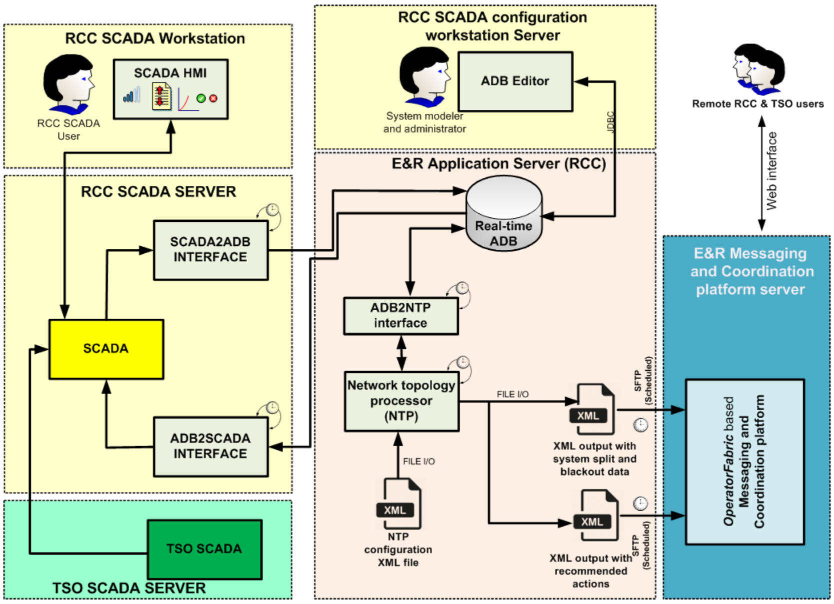

Fig. 1. Architecture of Emergency & Restoration-System split application

The ADB Editor is a tool for viewing and editing ADB content. The network model is visually represented as a hierarchical tree. The hierarchical levels are: company, area, substation, and voltage level.

The content of the ADB can be saved as a study case on which various analyses can be performed, such as switching on/off breakers, which could result in the network being split into multiple islands.

SCADA HMI, the main user interface to the SCADA system, provides real-time data presentation using dynamic pictures with vector graphics, user-defined graphs, or alarm lists. Execution of complex control functions is done easily using specialized dialogs directly from dynamic pictures.

Coordination platform serves as the centralized component for communication between TSOs and RCC in the system restoration process and for coordinating TSOs actions. It is based on the OperatorFabric platform which is a modular, extensible, industrial-strength platform for use in electricity, water, and other utility operations. This platform is developed by the Linux Foundation and features publicly available code. Communication through the coordination platform is based on a notification system in the form of cards that are displayed to users. Cards can be in a simple form of free text, or enriched with different forms, pictures, graphs, maps, etc. There are four types of cards, each one used for describing different types and severities of processes:

1. Informative cards notify the operator of an event or convey a message from other participants in the system, without requiring a response from the operator.

2. Action cards require some action from the operator, such as confirming or rejecting a proposed Frequency Leader nomination, requesting a frequency control actions, and so on. Action cards are also used when coordinating multiple users (here TSOs) to align the plan of action, such as the system split,

multiple participants in the power system need to coordinate their actions to safely restore the system to a stable state.

3. Alarm cards are similar to active cards, but additionally indicate that an urgent response from the operator is required.

4. Alignment cards indicate that some coordination has been completed and send the results of that coordination.

By using the aforementioned cards, all necessary information is exchanged between participants, enabling sending and receiving updates in real-time, which is of the uttermost significance in the processes that require prompt synchronization between participants and monitoring of their actions, as is the case in the system split restoration process. In addition, all executed actions are stored on the platform and can be checked by users, enabling transparency of performed processes in the coordination platform.

In addition to the core application modules, there are supplementary modules designed to facilitate the primary function of data conversion: SCADA2ADB interface, ADB2SCADA interface and ADB2NTP interface.

III. System Split Detection Algorithm

Based on static equipment connectivity and switching equipment statuses, the NTP determines network topology and identifies electrical islands. The NTP generates a bus-branch equivalent network model with branch parameters determined from actual equipment parameters. Measurements from the SCADA system are further associated to this bus-branch model. The NTP model is entirely bus-branch oriented, so all equipment must be represented with no more than two terminals. In cases where equipment has more than two terminals, such as three-winding transformers, a single-branch representation is no longer possible, resulting in more than one equivalent branch. Three-winding transformers must be decomposed into three two-winding transformers in order to represent them with no more than two terminals.

Topology is processed in two stages: identification of the buses and identification of the islands. First stage identifies buses through processing of switching equipment statuses. Determination of energized electrical islands is performed after measurements allocation. An electrical island is energized if there is at least one voltage measurement above a certain threshold [2][3][4].

In every execution cycle, NTP generates an XML file with a temporary list of islands. Each island is assigned a temporary ID that corresponds only to that cycle of the topology processor. Each island has an energization status indicating whether it is energized and a list of nodes. At any given time, there may be islands in the network that have been split or have become de-energized. Any changes in the energization status of islands are detected, and some may be declared as split or in a blackout state. The algorithm considers only 220 kV and 400 kV nodes by default for input data. Users have the possibility to define voltage levels of interest for analysis.

1. In each processing cycle, topology processor data from the current and previous cycle are used. There are theoretically three situations: Pure system split – an energized island is split into two or more smaller islands that are still energized;
2. System splitting with blackout – an energized island is split into two or more smaller islands, where some of the smaller islands are de-energized;
3. System blackout – the previously energized island becomes completely de-energized.

Frequency measurements are used for additional verification of topological analysis in the following way:

1. If frequency measurements are close in two newly formed islands, it is necessary to display a message indicating that there may not have been a network split, but rather that the topological analysis is inadequate due to incompleteness of the model on the 110 kV side

2. If the topological analysis shows the existence of only one island but frequencies within it differ, then a message should be displayed indicating that it is necessary to find an error in telemetry.

IV. Coordination Steps in the System Split Scenario

The coordination part starts when report.xml file is received in the specific location on the server where the coordination application is deployed. The application listens for appearance of new files on a defined location and when the file is delivered by the business part of a module, the first step in the coordination is started automatically.

The coordination steps are based on the rules of the regional group ENTSO-E continental Europe for emergency and restoration. However, these rules are very complex and it is very difficult for operators to follow them completely. Therefore, the coordination steps, according to the checklist principle, are predefined based on the most likely scenario in the case of a system split for the region of Southeast Europe (which happened or almost happened in the near past).

All involved TSOs and RCC receive the notification informing them that a system split has occurred, and islands have been detected. Subsequently, all TSOs in the region acknowledge the detection of the system split.

Next, E&R application displays all directly affected TSOs in the region (bordering the system split line), while TSOs confirm that they are directly affected. After that, the RCC sends a warning to all TSOs in the region to:

1. Switch Frequency Restoration Controllers to Frozen Control Mode.
2. Manually or automatically accelerate the stabilization of the system by overriding Frozen Control Mode if appropriate.
3. Adjust the system state on EAS according to transmission system conditions.

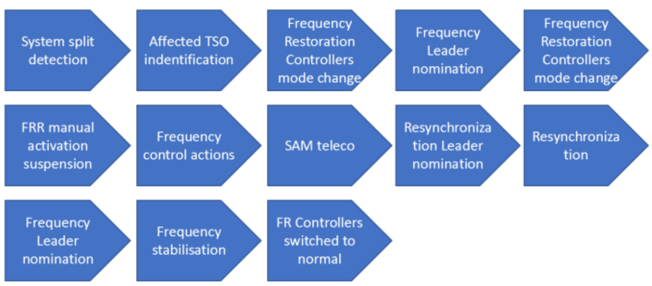

Fig. 2. Coordination steps in the system split scenario

Once all TSOs in the region confirm the specified actions, the RCC sends them a proposal for Frequency Leader nomination based on available FRR reserve. Once the Frequency Leader is confirmed, Frequency Deviation Management after Frequency Leader nomination begins for each subsystem. The RCC sends a warning to all TSOs in the region to:

1. Switch/keep the Frequency Restoration Controller in Frozen Control Mode if the TSO is not the Frequency Leader.
2. Switch the Frequency Restoration Controller to Frequency Control Mode if the TSO is the Frequency Leader.
3. Additionally, announce its status as Frequency Leader on EAS.

Next, RCC sends warning to all TSOs in the region, with the exception of the Frequency Leader, to suspend the manual activation of frequency restoration reserves and replacement reserves activation (i.e. manual Frequency Restoration Process – mFRP and Replacement Process – RP). After successful frequency control actions Synchronous Area Monitor (SAM) starts a telephone conference with the directly affected TSOs, RCC and nominated Frequency Leaders to determine Resynchronization Leader. All TSOs are informed about selected Resynchronization Leader. Also, RCC warns the Resynchronization Leader to announce its status on EAS.

Before resynchronization, the Frequency Leader of the region warns RCC and all TSOs in the region about upcoming resynchronization. After resynchronization, Frequency Leader of the region informs RCC and all TSOs in the region about executed resynchronization. In addition, RCC warns the Resynchronization Leader to deactivate its status as Resynchronization Leader on EAS. Next, Frequency Leaders of reconnected areas decide who should be the Frequency Leader after resynchronization. After that, RCC warns Frequency Leader to confirm or to deactivate its Frequency Leader status on EAS. In the next step, RCC sends warning to all TSOs in the region to switch Frequency Restoration Controller to:

1. Frozen Control Mode (for those TSOs which are not Frequency Leader)
2. Frequency Control Mode (if TSO is Frequency Leader after resynchronization)

After frequency stabilization, Frequency Leader informs other TSOs to switch Frequency Restoration Controllers to Normal Operation Mode. Finally, Frequency Leader switches Frequency Restoration Controller to Normal Operation Mode and deactivates Frequency leader status on EAS.

The above described steps represent just the most likely scenario for a system split. In case the real system state deviates from this sequence of steps, the RCC operator, after consultations with TSOs, can manually go to the step of the scenario that corresponds to the real state in the system (RCC has a coordinating role in the system restoration process and therefore controls the coordination platform). It is also important to note that the Emergency & Restoration application has the ability to initiate a regional teleconference between all TSOs and RCC in case there is confusion during the implementation of the steps, or if any TSO opposes the proposed coordinated actions.

V. Conclusion

This paper provides an insight into a practical implementation of the Emergency and Restoration rules of the ENTSO-E Regional Group Continental Europe for the case of a system split. The proposed solution is in line with the European trend of extending the mandate of RCCs, which includes coordination activities in real time, as defined in the EU Clean Energy Package. The described Emergency and Restoration application is designed to work in a real environment and is planned for installation in the RCC that is responsible for non-EU TSOs in Southeast Europe (SCC, Belgrade). This integration promises to significantly improve the coordination of TSO activities, especially in scenarios involving system split or blackout events. Such enhancements are essential for ensuring the resilience and reliability of the European electricity grid, thereby safeguarding against potential disturbances and bolstering the continent's power grid security. Therefore, the planned installation of this system represents a significant step forward in fortifying the energy infrastructure and mitigating risks associated with system instability. Further research and practical applications in this field are necessary to fully realize the potential benefits of improved coordination and real-time control in safeguarding the European power grid.

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