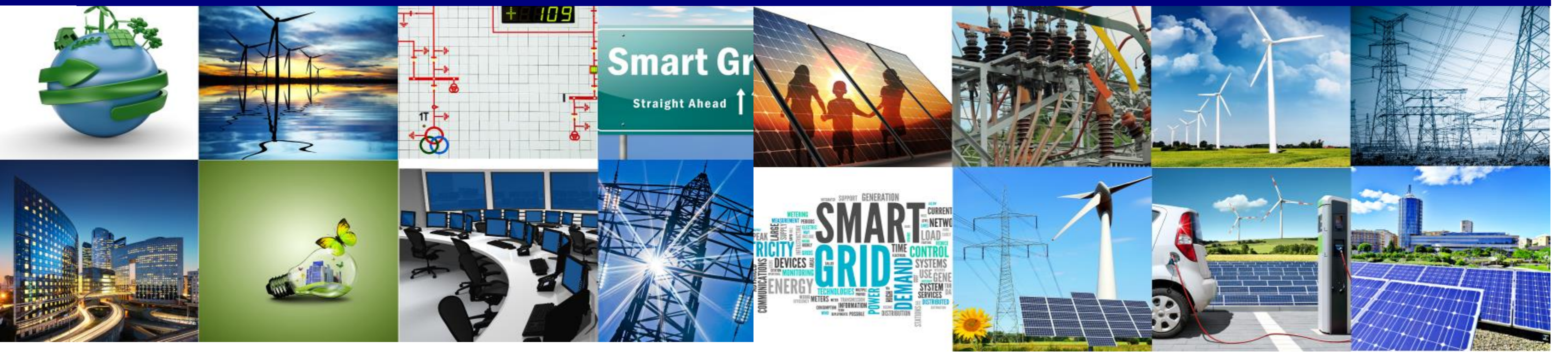
Project No. 609687

FP7-ENERGY-2013-IRP

# ELECTRA

## European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids



## WP 8

## Future Control Room Functionality

## Deliverable 8.3

## Recommendations on future development of decision support systems

20/02/2018

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|---|---|---|---|
| **ID&Title** | **D8.3**<br>Recommendations on future development of decisions support systems | **Number of pages:** | 33 |

**Short description (Max. 50 words):**

Deliverable 8.3 reports on the consolidation of experiences from visualisation, decision support prototypes experiments and recommendations on future developments of decision support systems.

| Version | Date | Modification’s nature |
|---|---|---|
| V0.1 | 26/10/2017 | First Draft |
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# Executive Summary

Task 8.4 aims to consolidate the outcomes from previous tasks in WP8 and detail the recommendations on future control room development. The work in Task 8.1 determined the future control room requirements, documented in the internal report R8.1. Task 8.2 built on this to design particular scenarios and develop new analytics and visualisations to assist human operators under the Web-of-Cells (WoC) architecture. These were reported in deliverable D8.1. Based on the scenarios in D8.1, Task 8.3 identified critical decisions that must be made during the operation within a cell, and how to automatically generate and rank potential solutions to help the human operator in making decisions quickly and correctly. This was reported in deliverable D8.2.

This document provides a condensed summary of key outcomes, deliverables and novelty from the research in WP8, including future control room requirements, visual analytics concepts, and decision support prototype experiments. From these findings, a high-level design of an overarching architecture for future control room functionality in a WoC context is developed. The key outcomes are:

- Design guidance for an advanced decision support system, which guides operators towards taking appropriate control actions by showing the expected outcomes;
- Enhanced situational awareness through visualisations embedded within the decision support to allow operators to quickly understand a situation;
- Defining an architecture that integrates the individual decision support algorithms within WP8 into an operator focused environment, defining the coordination between them.

Two decision support coordination scenarios are developed. One is decision support system coordination for frequency control. The other is coordination between transient stability preventive control and over/under voltage control.

# Terminologies

## Abbreviations

| | |
|---|---|
| AGC | Automatic Generation Control |
| BESS | Battery Energy Storage System |
| BRC | Balance Restoration Control |
| BSC | Balance Steering Control |
| CC | Cell Controller |
| CCT | Critical Clearing Time |
| CSO | Cell System Operator |
| CSP | Constraint Satisfaction Problem |
| DSO | Distribution System Operator |
| DSS | Decision Support System |
| ELECTRA | European Liaison On Electricity Committed Towards Long-Term Research Activity |
| EMS | Energy Management System |
| HVDC | High Voltage Direct Current |
| ICT | Information and Communication Technology |
| KB | Knowledge Base |
| LV | Low Voltage |
| PCC/GENCO | Production Control Centres |
| PMU | Phasor Measurement Unit |
| PPVC | Post-Primary Voltage Control |
| PV | Photovoltaic |
| SA | Situation Awareness |
| SCADA | Supervisory Control And Data Acquisition |
| SG | Synchronous Generator |
| SOC | State Of Charge |
| TS | Transient Stability |
| TSO | Transmission System Operator |
| VC | Voltage Control |
| OPC UA | Open Platform Communications Unified Architecture |
| WoC | Web-of-Cells |

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# 1 The Role of the Operator in the Web-of-Cells - Vision and Research Advances

## 1.1 Context and Background

The objective of WP8 is to develop and demonstrate decision support prototypes for system operator control room functions in the Web-of-Cells (WoC) framework. These need to show both the options for risk mitigation to the operator, and the consequences of each set of suggested preventive and corrective actions. In addition, they must recognise the increased level of complexity and autonomy within the WoC, leading to a new set of decision support and Situational Awareness (SA) tools that reflect the new operational environment.

Given the anticipated degree of automation, availability of market mechanisms and variety of contributing controls to voltage and frequency management, the decision support tools developed will need to be goal-oriented. That is, they are able to make independent assessments of the decisions that need to be taken in reaction to any control and information signals received. Decision support features will be created that are capable of exposing and characterising the threats to the power system and the vulnerabilities to which it is exposed. Advanced features that reveal congestion issues and reveal rising threat levels will be incorporated.

The operator will require access to mitigating actions that can reduce the risks to the system to a minimum with the resources available in real time. Compared with the current range of emerging tools, this work addresses the significant complication introduced by the increasing adoption of decentralised technologies and growing volumes of data. These software applications will be designed to show both the options for risk mitigation to the operator and also the consequences of each set of actions.

## 1.2 Role of the Human Operator

Before market liberalization and the subsequent unbundling of the vertically integrated power system, control centres were manned with skilled dispatchers who had a high-level technical understanding of the whole power system [1]. Their typical role was to monitor the performance of the power system and detect, predict and respond to any network violations. Human operators were required to have a deep understanding of the physical processes in all of the system. However, unbundling and the automation of the system entail new jobs with different levels of qualification, each specialised on particular aspects of Information and Communication Technology (ICT) driven power systems.

### 1.2.1 Change of Responsibilities

Operator responsibilities emerging from unbundling the energy system are illustrated in Figure 1.1. The classic dispatcher role is now exclusive to Production Control Centres (PCC or GENCO), whereas the Transmission System Operator (TSO) roles became significantly diversified. In a modern, market and ICT driven grid, new jobs requiring particular qualifications are created covering distinct tasks: secure and reliable operation of the grid, real-time balancing of the control area, system security, particularly with regard to the stochastic nature of renewable sources, and interfacing the physical grid with power system markets.

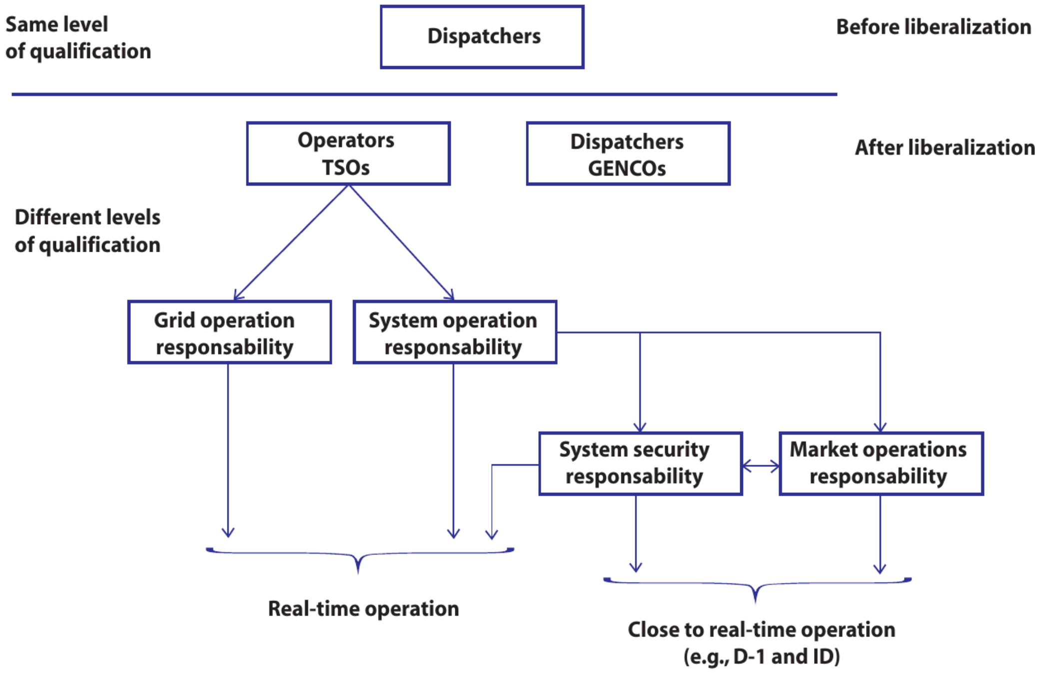


**Figure 1-1: Diversification of Responsibilities in a TSO Control Centre as taken from [1]**

As automation of tasks and increasing levels of autonomy and distributed intelligence improves the efficiency and safety of systems, it also removes the necessity or ability to undertake labour intensive monitoring and control of the network. Instead, relevant information needs to be extracted by the Supervisory Control And Data Acquisition (SCADA) systems for each operator role, enabling the operators to detect problematic or invalid conditions in the grid.

### 1.2.2 Operator Roles Within a WoC Framework

Within the European Liaison on Electricity Committed Towards Long-Term Research Activity (ELECTRA) WoC framework, each cell is managed by an automated Cell Controller (CC), which is constituted of a set of algorithms for voltage and frequency control. The CC is under the responsibility of a Cell System Operator (CSO) that supervises its operation and, if required, overrides it. A CSO oversees one or multiple CCs, whose corresponding cells do not necessarily need to be adjacent [2]. This allows control to be undertaken remotely at times in order to increase flexibility and redundancy [3].

Operators are released to focus on more strategic decisions within an increasingly complex control environment. Their role is to maintain their SA in terms of the overall stability and operation of the network. When corrective actions are automatically undertaken, they need to ensure that the predicted final state of operation is acceptable and stable. As a result, management system needs to be integrated with new functionality to provide effective support for the operators [4]. If the automated and autonomous systems are unable to coordinate to ensure a stable system then the operators need the tools to alert them to this, and to intervene to solve it. They also need tools to reduce their workload, given the complexity of the WoC, particularly in emergency situations. With regard to Figure 1.1, system security will increasingly gain significance with higher levels of real-time operation automation as implied by WoC.

The operators are responsible for online supervision of the network. Highly automated systems bear the risk of the “out-of-the-loop” syndrome, where the operators are detached from the state of the system and are unable to grasp the decision making process [5]. Hence, Decision Support

Systems (DSSs) need to provide condensed SA of the operational conditions and control trajectories in real time, as the automatic systems will take the majority of control decisions. The operator will be alerted to situations when the automatic systems cannot manage the contingencies/deviations. The operator will intervene and take control using their knowledge obtained by training and experience, as well as the recommendations from decision support functions. Improved decision support can guarantee timely operator intervention and flexibility towards rapid recovery of the power system. If a decision needs to be made by the operator, the DSS will prioritise alternative solutions to a problem. This allows a control decision to be taken quickly. Moreover, the DSS is able to apply the optimal solution if there is no response from the human operator within a certain time.

## 1.3 WP8 Future Control Room Requirements and Visualisation Features

Within WP8, future control room requirements have been identified and visualisation features have been discussed in [6] [7]. The summary of future control room requirements and visualisation features are provided below.

### 1.3.1 Control Room Requirements

The increasing complexity of power system requires the human operator to cope with more control tasks in the control centre. As a result, a set of requirements for future control rooms need to be identified to reduce the burden on the operator. The requirements drawn from Task 8.1 are summarised below:

- Considering a scenario characterized by a high level of distributed controls, each local controller and the corresponding portion of the managed network is mapped onto the grid topology and the local controllers' statuses (stopped/running/warning/alert) are monitored.
- The status of each local controller displayed to the control room operator includes simple summary indicators related to the status of health of the associated ICT infrastructure, including cyber security. Simple real time indicators are provided by the ICT department and will be based on real time data from the ICT monitoring managed by the ICT experts.
- In the case of controllers with different operational modes, automatic adaptive behaviour depending on the ICT status can be implemented. The control room operator has to be informed of the currently active mode and is able to override the automatic operational mode.
- Context aware visualisation screens show only "need to know" information to the operator during their different activities.
- In the case of alerts, the Control Room system provides guidance including the root cause with suggestions of corrective actions and decisions that can be taken automatically proposed to the operator.

### 1.3.2 Visualisation Features

A high-level view of the controlled system shows the operator all the cells in the control domain and the neighbouring cells, including their status. Only for the cells under their responsibility can the operator access a detailed view.

For the high-level view of the WoC, the required mandatory information is:

- The geographical map of the controlled network;
- Cells' current status (actual load and generation, frequency and its rate of change);
- Status of cells' reserves (generation and storage);
- Tie lines power exchange.

In a detailed view of each cell, the following information is considered as mandatory:

- Single line diagram of the network;
- Line currents and power flows, and bus voltages;
- Tie lines currents and power exchange;
- Current status and reserves of neighbouring cells;
- ICT network topology, the status of ICT components and of communication services.

## 1.4 WP8 Control Room Decision Support Advances and Achievements

Through the research undertaken in WP8, a range of scenarios where improved control room functionality is required were tackled. These led to new ways of tackling these issues in the context of the WoC operation and view on cell operators.

### 1.4.1 Dynamic Visualisations

The control of a power system starts with an effective visualisation strategy of the most important states of the system. Due to the complexity of modern power systems however, an enormous amount of information is required in order to properly observe and derive system values. It is necessary to display at a glance all information, while trying to keep the decision process as smooth and simple as possible due to the fact that humans are bad multi-taskers. The main point is therefore defining how much information does the cell operator need to know. Is there the need to continuously view all the details of what is going in the cell or just the general status is sufficient (e.g. the n-1 is verified, frequency and all voltages are within limits) in case nothing is wrong, and only “need to know” information in case something is not right [8]?

The developed control room visualisation concepts provide network overviews, where the topology and state are dynamically queried based on the current view and level of detail chosen by the operator. Moreover, significant reduction of the binary connectivity information of electric distribution grid is required [9]. An example taken from Deliverable 8.1 is shown in Figure 1.2 [8].

Purpose:

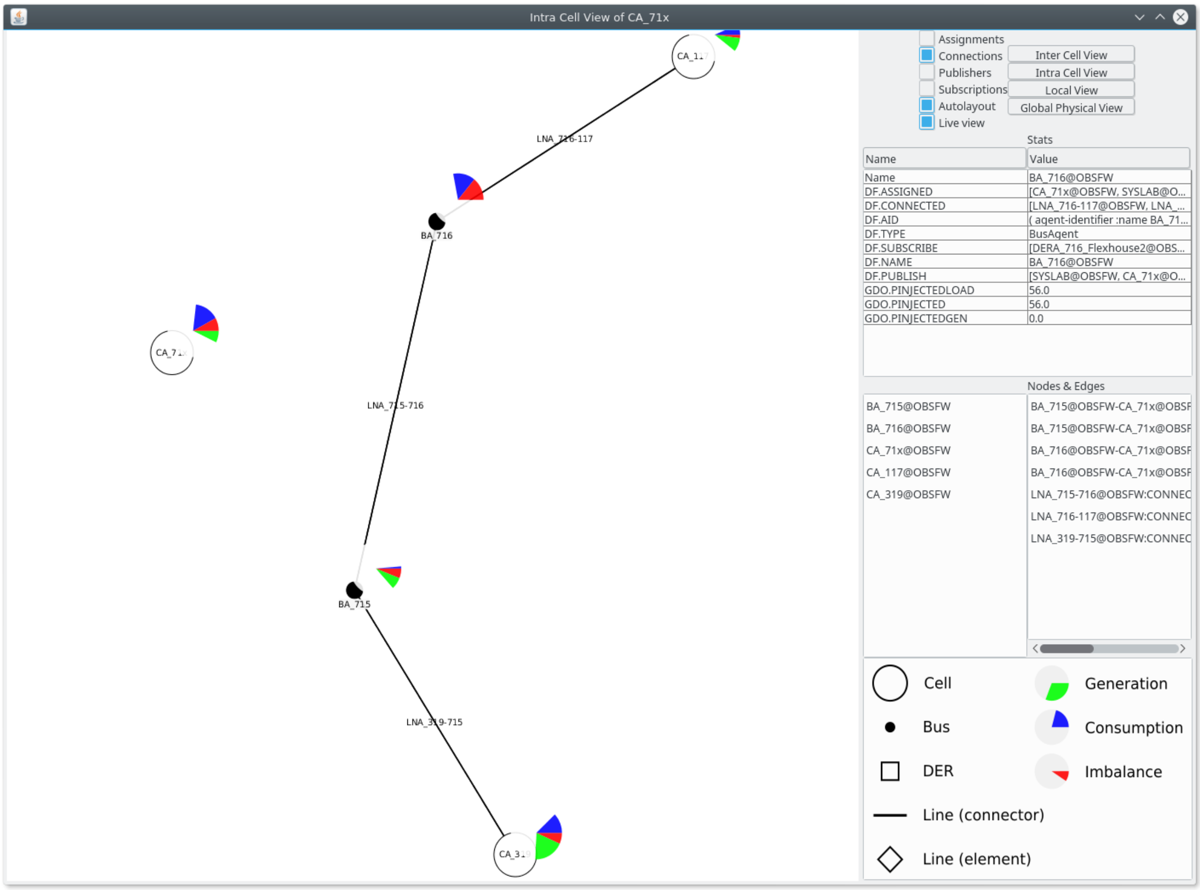
- Dashboard overview of the power system
- Provide topology and state information in a single-line diagram
- Alternative concept to current static SCADA concepts to cope with the increasing amount of data in Smart Grids

Features:

- Dynamic topology querying without central topology storage
- On-demand data acquisition by dynamically establishing and closing communication links
- Interactive interface that presents arbitrary levels of detail (from a top-level cell and tie-line overview down to single buses with connected devices)
- Various overlays:
    - Only topology
    - Live state feeds
    - Communication links including data flow direction
- Graphical state visualisation
    - Line loading
    - Power balances
- Additional text-based state overview for cell/line/bus properties (e.g. voltages)

Accomplishments:

- Development of a multi-agent system-based platform for designing and testing the visualisation concepts
- Flexible physical layer to interface with various data sources. Two have been implemented:
    - Text reader for historical data
    - Open Platform Communications Unified Architecture (OPC UA) for live data
- Tested on two different network models:
    - Power Networks Demonstration Centre using simulated data to indicate faults and line overloads
    - SYSLAB at DTU for a live simulation, where a separate market-optimization tool managed the grid



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| DF.CONNECTED | [LNA_716-117@OBSFW, LNA_... |
| DF.AID | ( agent-identifier :name BA_71... |
| DF.TYPE | BusAgent |
| DF.SUBSCRIBE | [DERA_716_Flexhouse2@OBS... |
| DF.NAME | BA_716@OBSFW |
| DF.PUBLISH | [SYSLAB@OBSFW, CA_71x@O... |
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| GDO.PINJECTED | 56.0 |
| GDO.PINJECTEDGEN | 0.0 |

Nodes & Edges

BA_715@OBSFW
BA_716@OBSFW
CA_71x@OBSFW
CA_117@OBSFW
CA_319@OBSFW

BA_715@OBSFW-CA_71x@OBSF
BA_715@OBSFW-CA_71x@OBSF
BA_716@OBSFW-CA_71x@OBSF
BA_716@OBSFW-CA_71x@OBSF
LNA_715-716@OBSFW:CONNEC
LNA_716-117@OBSFW:CONNEC
LNA_319-715@OBSFW:CONNEC

**Figure 1-2: Intra-Cell view taken from the dynamic visualisation concepts in Deliverable 8.1[8]**

### 1.4.2 Transient Stability

In order to operate the power system with sufficient Transient Stability (TS) margins in terms of Critical Clearing Time (CCT), it is important to analyse the current grid state for critical contingencies. Preventive actions are suggested to the control room operator by the decision support tool if contingencies that violate the pre-defined stability limit are identified.

Purpose:

- Maintain the power system in a secure state by preventively re-dispatching the generators to be able to withstand possible contingencies.
- Identification of critical generators that do not satisfy the pre-defined stability limit in terms of CCT.

- Determination of the required re-dispatch of generators to return the system in a secure state with respect to TS.

Features:

- Reduction of the computational burden of the assessment by pre-filtering the contingencies so that only critical contingencies are considered.
- Consideration of full system dynamics - no simplifications of power system model.
- A fast procedure to determine the dispatch is proposed by harnessing the virtually linear relationship between the CCT and the active power output of the generator.
- Control room operator is presented with a comprehensive but condensed form of the results of the assessment.
- Possibility to interact with the tool, e.g. change the availability of Synchronous Generators (SGs) for re-dispatch.

Accomplishments:

- Approach tested successfully on two reference systems:
    - Nine-bus system
    - New England system (39 buses)
- Achieving a near-optimal re-dispatch solution for SGs which satisfies the pre-defined stability limit in reasonable computation time.
- Evaluation of execution time of the assessment showed that the calculation of CCTs during the dispatch procedure has the largest impact on the overall execution time. This gives important insights for improving the performance of the approach in terms of execution time when developing it further for application in a control room.

### 1.4.3 Loop Flows

Within ELECTRA, we target an automated control system that realises the best possible solution for the scheduled flows under the given physical constraints. Details can be found in [8] [10] and scenarios example of inter-cell loop flows can be found in [11]. Real-time monitoring of all production and consumption together with topological information allows the control system to react immediately to changing conditions and steer the grid back to its optimal operating point using available flexibility resources. Deviations from scheduled flows are therefore minimized. The remaining permanent deviations should ideally be fed back into the market and reflected in the price signals in order to mitigate unwanted flows after the next market clearing. From a control room operator’s point of view, significant deviations from the scheduled flows that will not cease to exist after balancing actions indicate problems in the automated control system. These problems may have different causes, such as poor grid models the control is operating on, corrupted live data streams within and from other cells, falsely reported operational states of generators/breakers/etc., among many others that are outside of the normal operational state.

Purpose:

- Detect potential problems in the automated control system or participating units.

Method:

- Monitor tie-line flows;
- Check for deviations of tie-line flows from their scheduled values;
- If deviations exceed threshold, inform human operator to investigate the cause.

### 1.4.4 Post-Primary Voltage Control

Under the framework of WP8, the Post Primary Voltage Control (PPVC) approach developed in Task 6.2 was integrated in an operating tool for cell operators. The scenarios example of PPVC can be found in [11]. This PPVC runs a proactive algorithm every 15 minutes to calculate the optimal set points of the reserves, and a corrective mechanism to overcome unexpected grid events or load/generation forecasting errors. The integration of PPVC in the operating tool provides an enhanced grid observability to cell operators, as they will have easy access to all relevant data in a straightforward manner. The tool also enables cell operators to control the flexible resources available in the cell remotely and to modify the solution provided by the PPVC algorithm with the guarantee that no technical problem will occur in the cell. Although the voltage control algorithm was set to minimize losses, the cell operator may use the remote control functionality to reduce costs by using cheaper flexible resources. The performance of the tool was evaluated through simulation and proved to be an effective asset to manage cell operation in an efficient way.

Purpose:

- Assistance with the voltage control designed for the Web-of-Cells;
- Enhance grid observability and provide all the relevant data in a friendly way to the cell operators.

Features:

- Highlight voltage violations;
- Visualise information about the range of voltages in the cell, the total flexibility that is being used by each type of resource and its costs, and the global cell status indicating the total load, generation, PV generation, losses and energy imports/exports of the cell;
- Visualise information about buses voltage, branch loading, the load profile, the PV profile, the losses profile, the imports/exports profiles and the state of the flexible resources;
- Stop or resume the utilisation of the flexibility provided by an individual resource;
- Stop or resume the utilisation of the flexibility provided by an aggregated set of resources (flexible load, PV or storage).

Accomplishments:

- Development of a fully operational tool;
- Tested with different scenarios including a forecasting error scenario.

### 1.4.5 Decision Support during Frequency Events

A prototype DSS was developed that gathers cell information and provides the knowledge and optimisation tools to support proactive decision making [10]. It has knowledge about decision points and what data is required for each decision point. Once a decision point is identified, it provides the option(s) based on its knowledge or optimised solutions by interacting with its optimisation tool. The selected optimisation method is constraint programming, which is applied to the frequency problem being cast as a Constraint Satisfaction Problem (CSP). Therefore, the system is composed of a Knowledge Base (KB) and a CSP solver. For some cases, the KB has the knowledge to directly provide the decision plan based on its knowledge without using the CSP solver. For many problems, there may be more than one set of variable assignments that satisfy all declared constraints. In such cases, the CSP solver can be configured to return either a user-defined number of solutions in a best-first manner or to search for all possible solutions. A full user interface prototype was also created for the DSS.

Purpose:

- Identify decision support required for frequency control;

- Design novel functions and approaches to delivering this;
- Test against scenarios.

Features:

- Knowledge based and CSP algorithms provide a mechanism for configurable decision support;
- Provides decision support under various network conditions, including:
    - Restore frequency for a single frequency event [10];
    - Bring state of charge of battery energy storage system into safety energy range after a frequency event [10];
    - Restore frequency during two simultaneous frequency events [10];
    - Restore frequency due to loss of a tie-line [10];
- Multiple ranked solutions can be delivered to various decisions;
- The user interface provides useful advice to engineers.

Accomplishments:

- Full working prototype constructed;
- Tested on a range of cases studies for two scenarios [12]: single frequency deviation event and two frequency deviation events.

## 1.5 Alignment with Stakeholder View of Future Control Room Functionalities

With the rapidly changing environment and drivers around today's power systems, the control room of the future may look significantly different. As more data are being generated and collected by wide area measurement systems, automated control systems and other "smart" applications the operator will need additional support to sift and prioritise key information. As a result, identifying the needs and establishing the functionalities of future control rooms is important and is being considered by many key players within the industry. It was critically important that the work of WP8 took account of stakeholder views and supported (and challenged, where appropriate) the options being considered. To this end, Cigré Study Committees and Working Groups have reported on the requirements within a future control room. Two key reports have been published which describe the future requirements in the 21st century control room. These were assessed in terms of the research within WP8. The reports are:

1. Challenge in the Control Centre (EMS) Due to Distributed Generation and Renewables [13]
2. Capabilities and Requirements of a Control Centre in the 21st Century: Functional and Human Resources View [1]

WP8 focuses on future control room functionality within a WoC environment. These reports provide industry evidence of the challenges and needs that need to be addressed within WP8. They clearly point to the need to develop control room decision support with visualisation and SA to help the human operator to make a decision quickly and correctly. The state-of-the-art of future control room functionality can be summarized into three key areas that align with WP8, T8.3 and T8.4: decision support, SA (visualisation) and forecasting. Both reports highlight these areas, and their comments are summarised in the subsections below.

### 1.5.1 Challenge in the Control Centre (EMS) Due to Distributed Generation and Renewables [13]

This report introduces several countries' control centres and shows how they deal with the increasing penetration of renewable and distributed generation by using different tools and techniques. It summarised the future challenges system operators will face or need to consider. It proposed solutions, including tools and process changes. In terms of specific evidence for this deliverable, the report stated:

- *Decision Support:*
    1. "Data and analytics will provide key enablers to manage the network differently [13]".
    2. There needs to be transformation of an increasing amount of data into useful information for the operator.
    3. Regional and cross-regional interdependencies need to be considered.
    4. There is a move from static to dynamic grid status analysis, e.g. using Phasor Measurements (PMUs).
    5. Monitoring and decision support tools move closer to real-time.
    6. An integrated solution for decision support tools is of high importance.
- *Situational Awareness (Visualisation):*
    1. "Future innovations of control center user interface need to focus on how data can be turned into useful information for increasing situational awareness of operators [13]".
    2. "The visualization can be optimized to highlight significant deviations from normal state [13]".
    3. "Visual analytics will make it possible to integrate data from different sources (PMU, weather forecast, asset management, SCADA, network analysis) into a single holistic view. This view will allow the operator to analyse data in a broader context, identify underlying dependencies and understand the dynamics of the grid [13]".
    4. More integration between TSOs and DSOs will be needed as the majority of distributed energy resources are connected at DSO level.
- *Forecasting:*
    1. "New applications including advanced forecasting tools, the use of synchrophasor measurements and upgraded control centres are also a necessity for certain power systems [13]".
    2. "Control centres will need new tools such as the next generation of Automatic Generation Control (AGC) which will be able to concurrently take account of renewable generation forecasts, demand forecasts, storage facilities, market schedules and internal and external High Voltage Direct Current (HVDC) exchanges, in order to automate the physical dispatch process [13]".
    3. "Operators will also need information on future network states (look ahead) for taking preventive actions ahead of time [13]".

These requirements clearly align with the research results of WP8 and T8.4.

### 1.5.2 Capabilities and Requirements of a Control Centre in the 21st Century: Functional and Human Resources View [1]

This report presents future control centre requirements and capabilities based on analysis ranging from jobs and tasks within the control centre to the knowledge required by control centre operators. For each analysis, it states the challenges and proposes what needs to be undertaken, such as risk management, situational awareness of system dynamic phenomena and new training and knowledge requirements for control centre operators.

In terms of specific evidence for this deliverable, the report stated:

- *Decision Support:*
    1. “Decision support tools including optimization of remedial actions are required [1]”.
    2. “Development of decision support tools to facilitate coordination, common security analysis and optimization of remedial actions [1]”.
    3. “Decision support tool, possibly artificial intelligence software and more integration between TSOs and DSOs is about to happen [1]”.
- Situational Awareness (Visualisation):
    1. “A vast portion of the operator’s job is involved in developing situation awareness (SA) and keeping it up to date in a rapidly changing environment. SA can be thought of as an internalized mental model of the current state of the operator’s environment [1]”.
- *Forecasting:*
    1. “As the majority of decentralized generation is connected to DSO systems, the requirements for data exchange with DSOs have significantly increased due to their active networks, especially regarding more detailed representation of the connected DSO systems, forecast information and possibility of participation in ancillary services that have an impact in the operational network scenario and in the security assessment [1]”.

These requirements clearly align with the research results of WP8 and T8.4.

### 1.5.3 Summary

All of the above provide evidence that three key facets are required for future control room functionality:

- *Decision Support:*
  Decision support can guide the operator to the actions that are available, and their expected outcomes, hence reducing the burden on operators. In addition, decision support can automatically implement its plan if no response has been received from a human operator, expediting control decisions.
- *Situational Awareness (Visualisation):*
  To support the human operator to make decisions, the right information needs to be provided at the right time. Also, this allows human operators to see where the process is in relation to current and future limits and targets.
- *Forecasting:*
  The human operator needs to be able to see a future state of the system. Forecasting can be used to do that. If there will be a violation, the violation can be resolved ahead of time. Forecasting could include control behaviours, generation output, demand, weather and congestion/violation.

The research in Tasks T8.2 and T8.3 have demonstrated that decision support developed for particular scenarios are useful to assist operation in resolving the situation. Moreover, the new analytics and visualisations designed with these two tasks show our work is consistent with the SA (visualisation) of key information mentioned above. However, the forecasting will be considered as a future work of WP8.

# 2 Overview of Decision Support Tools Created through WP8

In ELECTRA D5.3, the role and responsibility of operator have been sated as shown below.

- "Each cell is managed by a so-called Cell Controller (CC). The CC is under the responsibility of a Cell System Operator (CSO) role that supervise its operation and, if needed, is able to override it. A Cell System Operator (present DSO/TSO) can operate multiple CC and therefore operate more cells also non-adjacent [2]."
- "As a physical entity, a Cell System Operator can be responsible for many cells respectively cell controllers on the basis of providing more optimal (financially and technically) solutions to the integrated grid. This does not change the real physical structure of cells and its physical constituents. Each CSO is responsible for establishing and maintaining automatic control mechanisms as well as procuring sufficient reserves, contributing to a stable and secure system operation [2]."
- "A CSO has the role of monitoring the system and its interconnections, to initiate control actions in response to critical events in order to maintain secure and stable operation. Further, it is the CSO's responsibility to coordinate with neighbouring operators regarding control actions that affect them as well [2]."

As a result, each cell is managed by a CSO and a CSO can manage more than one cell. The scenario for an operator could be either a CSO is responsible for only one cell or a CSO is responsible for multiple cells. For simplicity, the operator scenario is selected within this report is one CSO per cell. The role responsibility of the CSO is to monitor and initiate control actions as necessary within the cell. If the CSO needs neighbouring cell support, the CSO will coordinate with the neighbouring CSO.

In Task 8.3, several decision support functions have been designed, based on different control room scenarios, to assist operators in mitigating critical issues. The decision support scenarios and tools developed are listed below. Each decision support scenario and tool is described in detail in Section 3.

- Frequency Control Coordination (USTRATH; ENEA; RSE)
    - **USTRATH_DSS_1**: Procurement of new BRC reserves after a frequency event;
    - **USTRATH_DSS_2**: Response to a frequency event larger than the Balance Restoration Control (BRC) reserves can handle;
    - **USTRATH_DSS_3**: Response to an emergency request from a neighbouring cell for BRC support;
    - **USTRATH_DSS_4**: BSC replacement of BRC deployed reserves;
    - **ENEA_DSS**: BESS energy restoration after a frequency deviation event;
    - **RSE_DSS**: Response to a frequency event due to the loss of a tie-line
- Transient Stability Preventive Control and Over/Under Voltage Control Coordination (DTU; SINTEF)
    - **DTU_DSS**: Transient stability preventive control approach;
    - **INESC_P_DSS**: Decision support for over/under voltage.
- Inter-Cell Loop Flow Management (SINTEF)
    - **DTU_SINTEF_DSS**: Decision support for management of inter-cell loop flows.

The work reported in this deliverable considers how these can all be combined effectively within a control room within the WoC. This directly builds on all of the novel outcomes and accomplishments from WP8.

# 3 Decision Support Scenarios

Building on the research outlined in Section 2, a design exercise has been undertaken to specify how the decision support systems will be integrated, combined and coordinated to allow the operator to improve their decision making. The high-level integration of the developed decision support systems is illustrated in Figure 3.1, and this includes support for transient stability (TS), voltage control (VC) and frequency control. Each decision support system operates independently based on the network situation and provides available actions associated with outcomes. Moreover, the decision support functions may need to interact with each other in order to mitigate any conflict that may occur, such as TS decision support and VC decision support (details of the interaction between these are described in 3.2.4). Once decision options are relayed to the user interface, the operator can either take the best action or override the action and finally control signals are sent to the network environment. If there is no response from the operator within the defined time period, the decision support can automatically send the best action to the network environment. The coordination between the different developed decision support systems is presented in the following subsections.

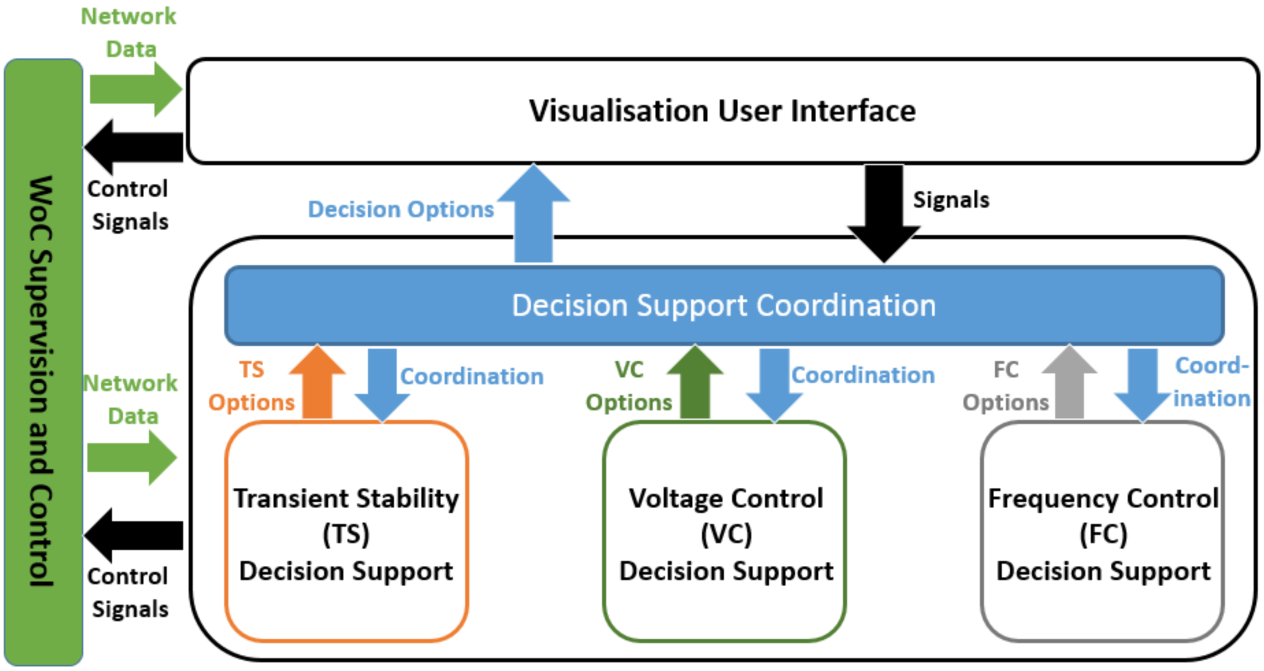


Figure 3-1: Integration of Different Decision Support Functions

## 3.1 Coordination of Frequency Control Decision Support Functions

From T8.3 (D8.2), there are six different decision support functions (USTRATH_DSS_1, USTRATH_DSS_2, USTRATH_DSS_3, USTRATH_DSS_4, RSE_DSS and ENEA_DSS) for frequency control. These can be classified into two different scenarios based on two different frequency events (single frequency event or two frequency event). The details of how each decision support function coordinates with the others are described below.

### 3.1.1 Coordination between Decision Support Functions in a Single Frequency Event

Three decision support functions are involved within a single frequency event; ENEA_DSS, USTRATH_DSS_1 and USTRATH_DSS_4. These three functions are all considered after the frequency is restored:

- ENEA_DSS brings the State Of Charge (SOC) of a Battery Energy Storage System (BESS) into its *safety energy range* by setting charging/discharging current, and evaluates the energy restoration time.
- USTRATH_DSS_1 aims to procure new reserves for BRC to mitigate against a further frequency deviation that might happen within a short timescale [14].
- USTRATH_DSS_4 replaces the deployed BRC reserves with less expensive options [14].

As a result, ENEA_DSS can provide the status of BESS with available capacity for USTRATH_DSS_1. Then, USTRATH_DSS_1 can use available BESS capacities as a part of the calculation for procuring BRC reserves. Therefore, the order to trigger these three DSS is shown in Figure 3.2 below:

1. ENEA_DSS (①) is triggered first bringing SOC of BESS into safety energy range and also provides available capacity of BESS for USTRATH_DSS_1. While ① is undertaking its processing and analysis, ② can start in parallel with all the resources not involved in process ① (for each cell, the list of the BESSs not involved in the “safety energy band” process and thus available for the process ②)
2. Then, USTRATH_DSS_1 (②) procures available reserves for BRC as soon as possible based on available BESS capacities received from ENEA_DSS and other available reserves.
3. Finally, USTRATH_DSS_4 (③) is triggered to replace BRC deployed reserves with less expensive options.

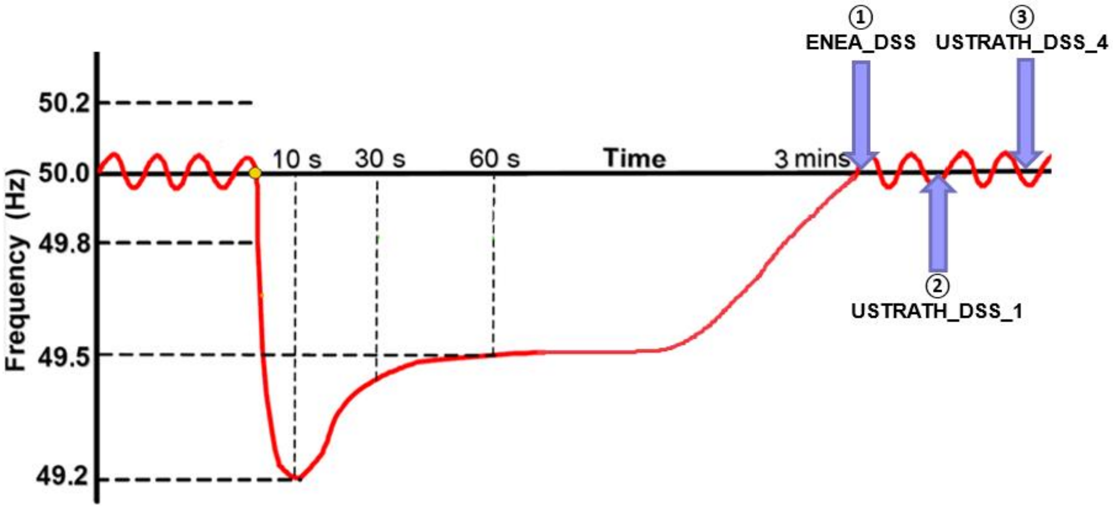


**Figure 3-2: Decision Support Coordination Scenario with ENEA_DSS, USTRATH_DSS_1 and USTRAT_DSS_4**

The decision supports coordination diagram for single frequency event is shown in Figure 3.3 below.

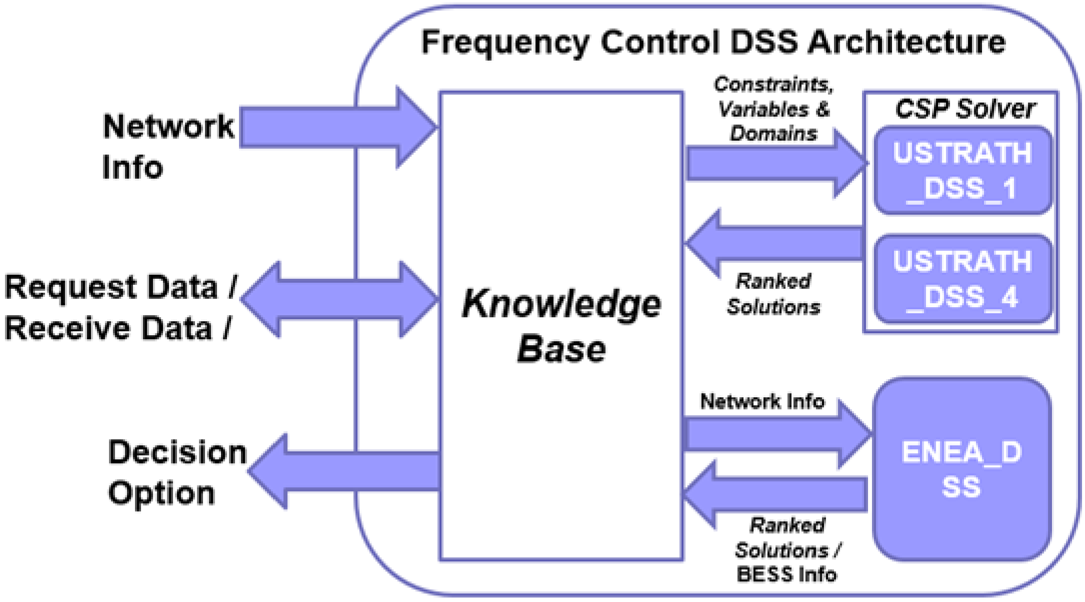


Figure 3-3: Single Frequency Event Decision Support Coordination Diagram

As shown in the diagram, it can be noted that the information regarding BESS, provided by ENEA_DSS, is one of the inputs to the knowledge base within frequency control decision support architecture developed in Task 8.3 (D8.2) [10]. Then, the knowledge base provides the required input for USTRATH_DSS_1 and USTRATH_DSS_4 within the CSP solver.

### 3.1.2 Coordination between Decision Support in a Two Frequency Event

For a two frequency event, there are three decision support functions involved; RSE_DSS, USTRATH_DSS_2 and USTRATH_DSS_3. These three decision support functions trigger based on different types of frequency deviation.

- RSE_DSS is triggered if a frequency deviation occurs due to loss of a tie-line between cells.
- USTRATH_DSS is triggered if a frequency deviation occurs due to loss of generation larger than the BRC reserves can handle [14].

RSE_DSS and USTRATH_DSS are both used to restore the frequency to the operational limit. However, RSE_DSS and USTRATH_DSS operate in different ways.

- RSE_DSS: cells which lose a tie-line connection are responsible for restoring frequency by operating different levers, such as grid reconfiguration; storage; power plant support, distribution generation contribution and load modulation.
- USTRATH_DSS: only the problem cell (frequency deviation occurring within the cell) takes the responsibility to restore frequency and neighbouring cells need to respond if a problem cell requires support from them.

As a result, RSE_DSS and USTRATH_DSS are running and operating independently and a possible scenario diagram is shown in Figure 3.4 below. If the frequency deviation occurred due to loss of a tie-line, RSE_DSS (①) is triggered to respond and restore frequency. The triggering of the RSE_DSS is performed when specific protection functions are able to properly identify and isolate a faulty section. When this protection detects a fault on the tie-lines the RSE_DSS is triggered.

If the frequency deviation occurred due to loss of generation larger than the BRC reserves can handle, it needs USTRATH_DSS (❶, ❷) to restore frequency by its own available reserves or through negotiation with neighbouring cells.

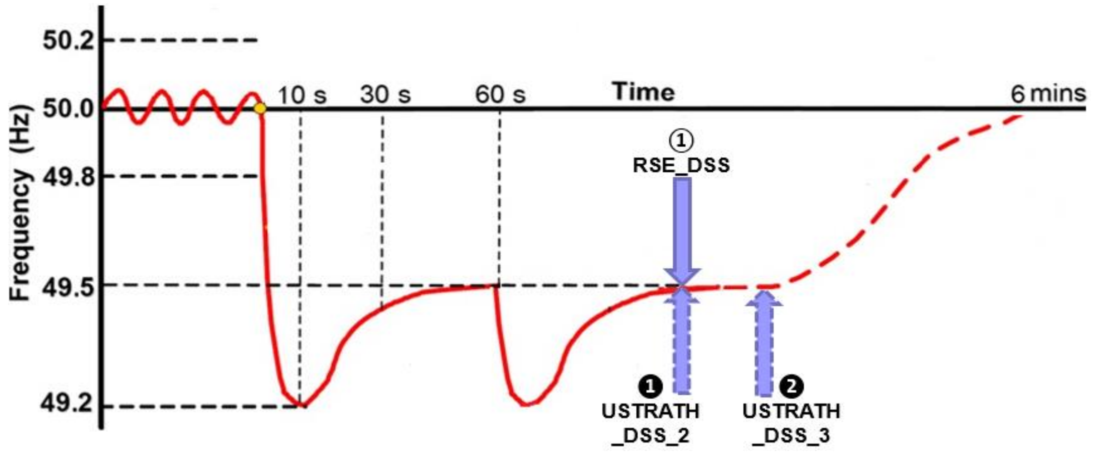


Figure 3-4: Decision Support Coordination Scenario with RSE_DSS, USTRATH_DSS_2 and USTRATH_DSS_3

The decision support coordination diagram for a two frequency event is shown in Figure 3.5 below.

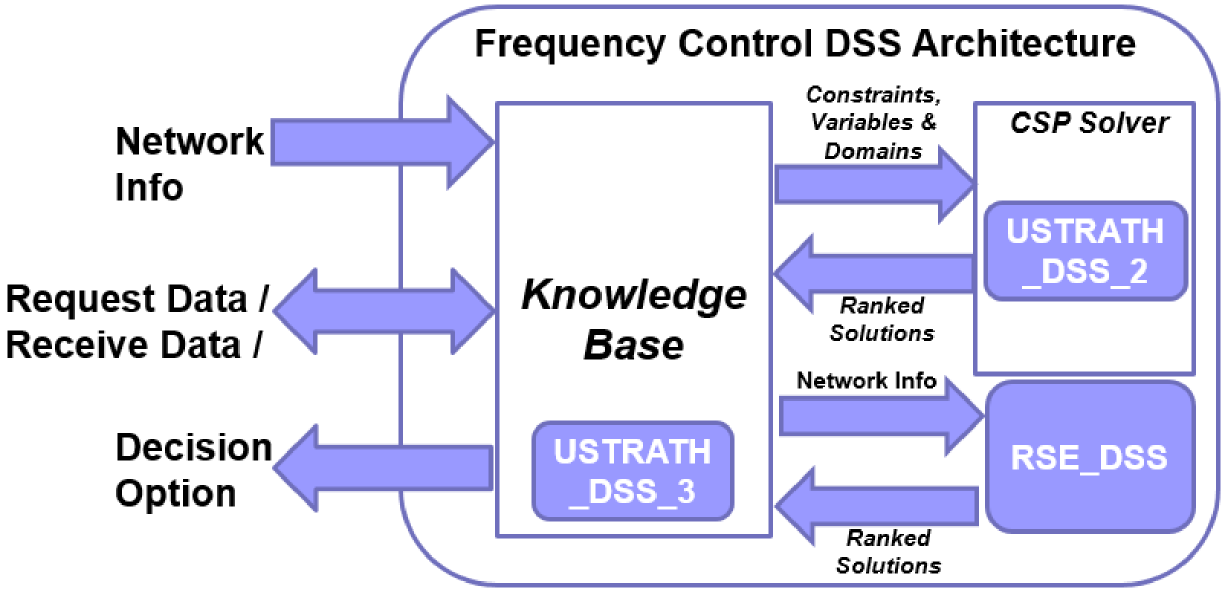


Figure 3-5: Two Frequency Event Decision Support Coordination Diagram

As shown in the architecture above, the knowledge base decides which decision (USTRATH_DSS_2, USTRATH_DSS_3, and RSE_DSS) to trigger under the various situations and provides the required input.

### 3.1.3 Visualisation for Frequency Control

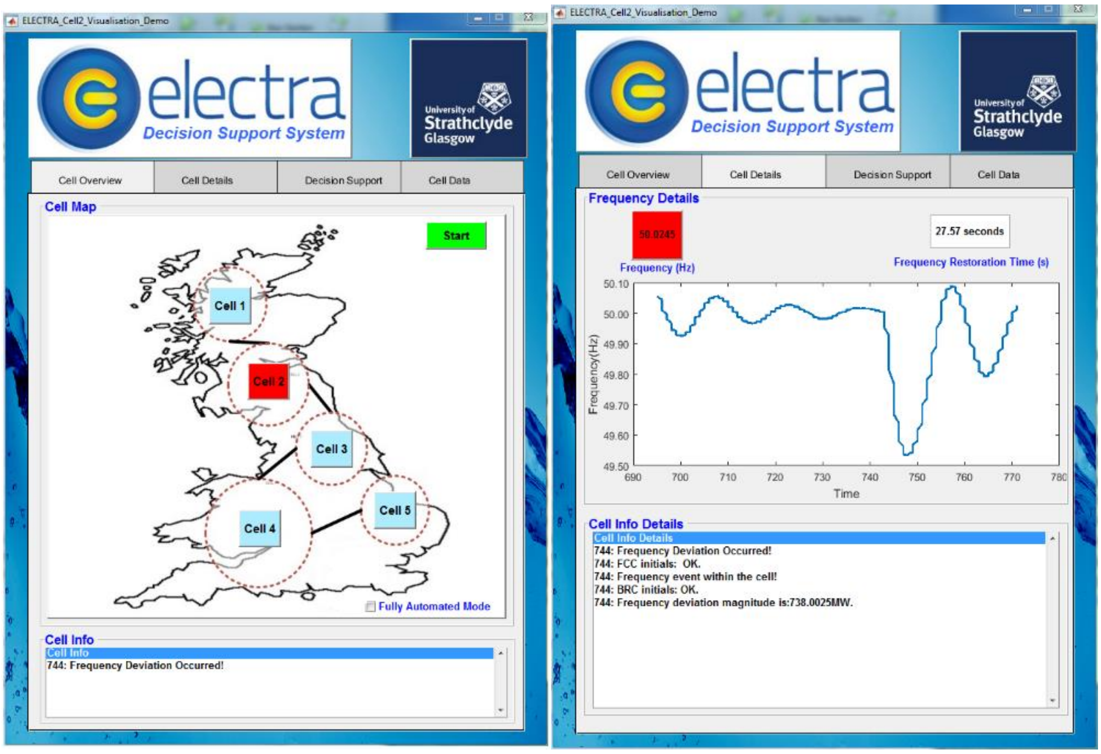
In order for the operator to engage with the decision support effectively, prototype visualisations have been designed. These are shown in Figure 3.6 and aim to provide enhanced situational awareness. The user interface allows the operator to observe the system state at a glance and understand the situation quickly. As a result, the user interface provides four different functions for the operator to interact with, including Cell Overview, Cell Details, Decision Support, and Cell Data:

- Cell Overview (Figure 3.6(a)): This provides a high-level view of the controlled system with a geographical map that contains all cells. The operator can click the cell to see the cell information, including, generation, demand and available reserves. The cell flashes to alert the operator when an event within the cell causes a frequency deviation.
- Cell Details (Figure 3.6(b)): The cell details view provides frequency status, including a frequency diagram and frequency value combined with a coloured indicator (green means

normal condition and red means frequency deviation). When a frequency deviation occurs, it shows the time it will take to restore the frequency.

- Decision Support (Figure 3.6(c)): The integrated decision support system will list the suggested actions to take and their expected outcomes. The decision support system will give the operator a certain window of time to override the suggested priority action after which, if no response has been received, it automatically applies the best option. In addition, it provides available reserves in its own cell and reserves of neighbouring cells.
- Cell Data (Figure 3.6(d)): The operator can access other information within the cell in Cell Data, such as area control error, and power control error. They can save all the data for future analysis.

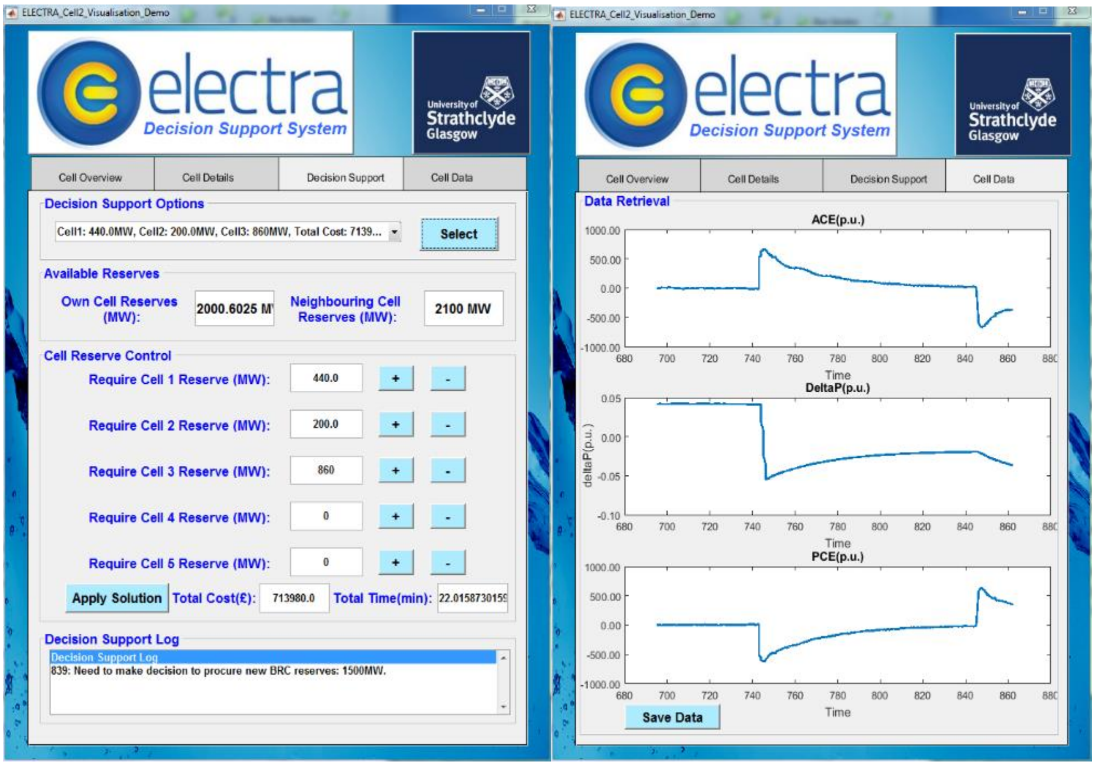
In addition, there are cell logs to record network activities in order to make the operator aware of what is happening in the controlled system.



```
Cell Info
744: Frequency Deviation Occurred!
```

```
Cell Info Details
744: Frequency Deviation Occurred!
744: FCC initials:  OK.
744: Frequency event within the cell!
744: BRC initials: OK.
744: Frequency deviation magnitude is:738.0025MW.
```

**(a) Cell Overview** **(b) Cell Details**



**Decision Support Options**

Cell1: 440.0MW, Cell2: 200.0MW, Cell3: 860MW, Total Cost: 7139...

**Available Reserves**

Own Cell Reserves (MW): 2000.6025 M

Neighbouring Cell Reserves (MW): 2100 MW

**Cell Reserve Control**

Require Cell 1 Reserve (MW): 440.0

Require Cell 2 Reserve (MW): 200.0

Require Cell 3 Reserve (MW): 860

Require Cell 4 Reserve (MW): 0

Require Cell 5 Reserve (MW): 0

Total Cost(£): 713980.0

Total Time(min): 22.015873015

**Decision Support Log**

```
Decision Support Log
839: Need to make decision to procure new BRC reserves: 1500MW.
```

**(c) Decision Support** **(d) Cell Data**

**Figure 3-6: Visualisation User Interface for Frequency Control**

## 3.2 Coordination of Transient Stability Preventive Control and Over/Under Voltage Control DSSs

In T8.3 (D8.2), a transient stability preventive control decision support scenario (DTU_DSS_1) and an over/under voltage decision support scenario (INESC_P_DSS_1) are described. Based on the previous findings, the necessary information and its presentation to understand the current grid state from an operator perspective is discussed. Furthermore, the links and potential conflicts between the DSS objectives are described.

### 3.2.1 Background and Objective of the Transient Stability DSS

The Transient Stability DSS analyses the current grid state and determines if sufficient transient stability margins in terms of CCT are given [15]. In this case, the CCT for severe contingencies (i.e. three-phase faults) is assessed in an online fashion. The stability margins are predefined as a certain minimum CCT that has to be fulfilled. If the analysis determines CCTs which are lower than the predefined limit, preventive actions are determined. Several preventive actions to restore the stability margins are possible, e.g. the temporary increase of voltage set point. However, here, a re-dispatch of active power set points of SGs is used to re-establish the transient stability margins as this is an effective approach. As the control is of preventive nature, the re-dispatch must be determined in the most economical way due to the additional costs imposed by the re-dispatch. Operators would refuse to take expensive counteractions if not necessary. Besides the economical aspect, fulfilment of technical constraints such as, active/reactive power capabilities of generators, maximum line flows and voltage levels must be satisfied. On top of this, the determined countermeasures to re-establish the transient stability margins should not interfere with operational constraints or jeopardize other stability aspects. Therefore, possible conflicts with other decision support functions need to be analysed.

### 3.2.2 Background and Objective of the Over/Under Voltage DSS

The PPVC approach developed in Task 6.2 was integrated in an operating tool for cell operators. The operating tool allows for an enhancement of observability and provides all the relevant data in a user-friendly way to the cell operators, which makes it a good complement to visualise the voltage control strategy in the cells.

This PPVC runs a proactive algorithm every 15 minutes to calculate the optimal set points of the reserves and a corrective mechanism to overcome unexpected grid events or load/generation forecasting errors that would ultimately lead to voltage limits' violations.

The visualisation tool for cell operators is described in 3.2.5.

### 3.2.3 Interfaces between the two DSS

The transient stability and over/under voltage DSS aim to fulfil different objectives by controlling active power and reactive power of controllable units. As a change in one electric variable also affects other variables, the parallel operation of the two DSSs needs to be coordinated as they interface with each other.

In the following, the circumstances under which the two DSSs need to be treated separately or together are described.

> **Radial cell configuration, Voltage Control (VC) only applied in the Low Voltage (LV) grid:** Each low- and medium voltage cell is connected at exactly one point to the transmission network, and can itself handle voltage issues at the LV-MV coupling points. As SGs are almost exclusively connected to the HV grid, the DSSs for Voltage Control (VC) and Transient Stability (TS) can derive their recommendations independently from each other, because the corresponding control actions are decoupled.
>
> **Radial cell configuration, VC includes low to high voltage networks:** The optimisation is performed over all voltage levels of the grid, therefore coordination between the two DSSs needs to be carried out. The prioritisation over one another is described in Section 3.2.4.
>
> **Meshed cell configuration:** In a meshed grid operation scenario as envisaged by the ELECTRA project, a fully integrated solution of automatic control and decision support systems is required. Individual grid segments can no longer be considered as decoupled, thus conflicting operation modes could arise as a consequence of uncoordinated control and DSS actions [16].

For the situations where the DSSs need to be coordinated, a common interface for the cell operator should be developed. This interface may change depending on the conditions and circumstances of the cell. Therefore, the interfaces of the VC-DSS and TS-DSS should be considered separately or combined, depending if they influence each other or not:

- If a cell does not have any SG, TS-DSS is not relevant for its operation and only the VC-DSS interface should be presented to the operator;
- Otherwise, in the presence of SGs, the TS-DSS may influence the operation of the VC-DSS and, in this case, the interface needs to be adapted as buses with SGs are particularly critical to ensure cell stability.

As the transient stability problem is only relevant after a fault or other unexpected disturbance, the combined interface should only appear to the operator when such situations occur. Thus, in normal state, the interface presented to the operator would only be the VC-DSS, as shown in the following flowchart in Figure 3.7.

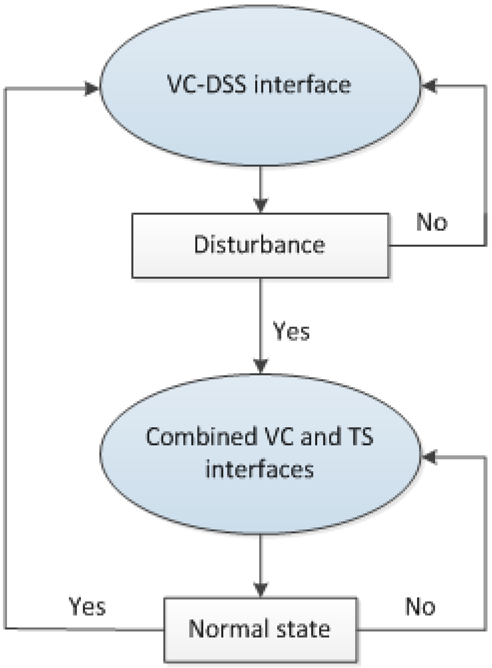


**Figure 3-7: Adaptable User Interface Depending on the Grid State**

The potential conflicts between the DSS and the information presented to the cell operator are discussed in the following sections.

### 3.2.4 Interaction between the Transient Stability and Over/Under Voltage DSS

If the two DSSs are integrated in the same tool, they need to interact with each other in order to mitigate any conflict that may occur. Some conflicts that may occur are when the TS-DSS sends a set point to a SG and it creates voltage problems in the buses surrounding the SG or if the VC-DSS sends a power set-point to a SG that will decrease the CCT below the predefined limits. If any conflict occurs, one DSS should take priority over the other and the possible cases are the following:

a) VC-DSS with priority – it should be provided reactive power set points and/or voltage set points as input for the TS-DSS. These set points need to be respected in the assessment from the TS-DSS.
b) TS-DSS with priority – it should be provided a minimum voltage limit which the VC-DSS needs to respect in the PPVC algorithm. Only a minimum voltage limit needs to be provided from the TS-DSS, as higher voltage set points are generally improving transient stability.

In case of no conflicts, both DSSs have the same priority and they cooperate with each other so that both objectives are fulfilled. The operator can also decide that some actions need to be taken in order to assure that sufficient flexibility is available in case any problem occurs. In order to increase the flexibility of SGs, necessary to the TS-DSS, the operator can reduce their active power set points by replacing/re-dispatching with non-conventional reserves and thus, it is necessary to run the voltage control algorithm with new restrictions. In view of the consequences of not complying with the limits/stability constraints, transient stability is seen as more problematic due to the fact that an outage of one or more generators could affect a large portion of the grid, if not the whole grid, while voltage violations rather have a local impact. Therefore, transient stability might also require prioritization in case of emergency.

### 3.2.5 Presentation of the Information to the Cell Operator

In D8.2, two different visualisation tools were developed, one for each DSS. The information presented to cell operators of each tool is the following:

- TS-DSS:
    - Highlight critical buses to human operators through visualisation (e.g. different colours), where CCT approaches minimal threshold; and
    - Overlay of voltage thresholds/constraints imposed by TS-DSS.

In the following, it is shown how the results of the TS-DSS is presented to the control room operator. The amount of presented information is kept low such that the attention of the operator is focused on the most important parts without overloading them with too much information. In addition to the visualisation, acoustic warning signals could be generated when the CCT is below a specified limit, e.g. 200 ms. Different levels of severity can then be added depending on the size of the critical unit. If there is a need for in-depth information, the control room operator should be given the possibility to access the underlying data, e.g. reactive power set points.

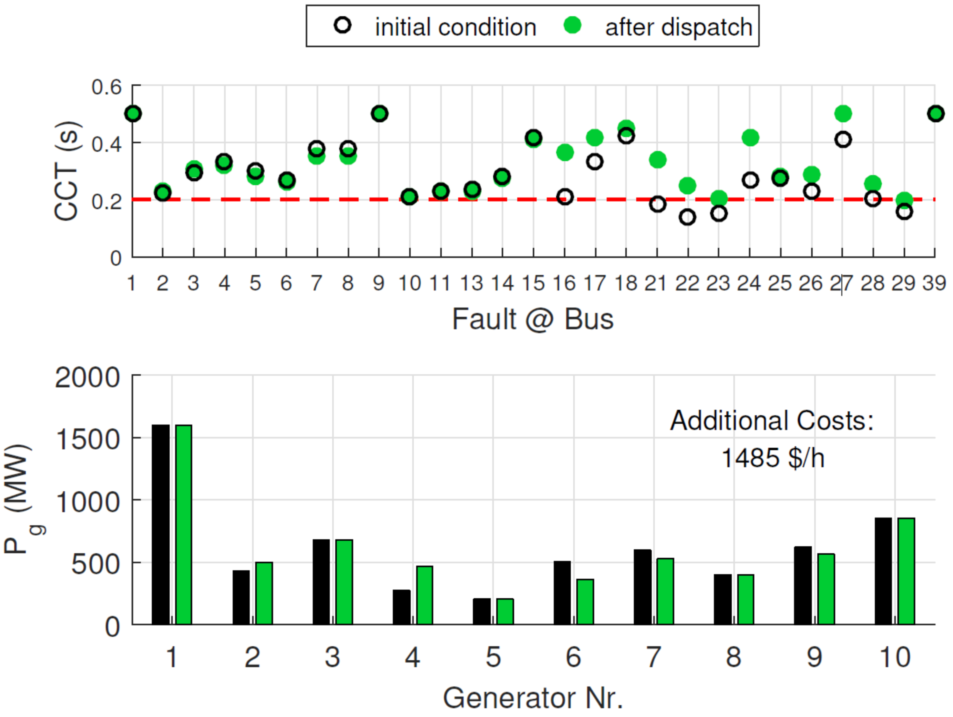


**Figure 3-8: Visualisation of CCT Following Re-Dispatch**

Figure 3.8 shows and example of results from the New England system of a successful re-dispatch that are being presented to the control room operator. The upper plot shows the critical clearing times at all buses before (black circles) and after (green circles) the re-dispatch. The red line shows the user-specified threshold for the minimum CCT which is set to 200 ms. The lower plot shows the active power setpoints of the generators before and after the dispatch in corresponding colours. Moreover, the additional costs imposed are shown [17].

- VC-DSS:
    - Highlight voltage violations;
    - Present operator solutions from optimal power flow (D8.2, Fig. 3.18) -> Possibly by colouring affected buses according to the expected voltage levels;
    - The information provided in the “Global information” section is the number of buses that are in each range of voltage (“emergency situation”, “abnormal situation”, “normal situation”), the total flexibility that it is being used by each type of resource

and its costs and the global cell status indicating the total load, generation, PV generation, losses and energy imports/exports of the cell; and,

- ○ The information provided in the “Detailed information” section is the buses voltage, the branches loading, the load profile, the PV profile, the losses profile, the imports/exports profiles and the state of the flexible resources.

The operating tool for cell operators, which has a user interface (Figure 3.9 below), presents updated cell information divided into two parts: the global information and the detailed information. The global information is always visible for the operator and represents information of the cells under the responsibility of the Cell Operator and neighbouring cells, while the detailed information is only visible when the operator decides to have an in depth visualization of a given cell.

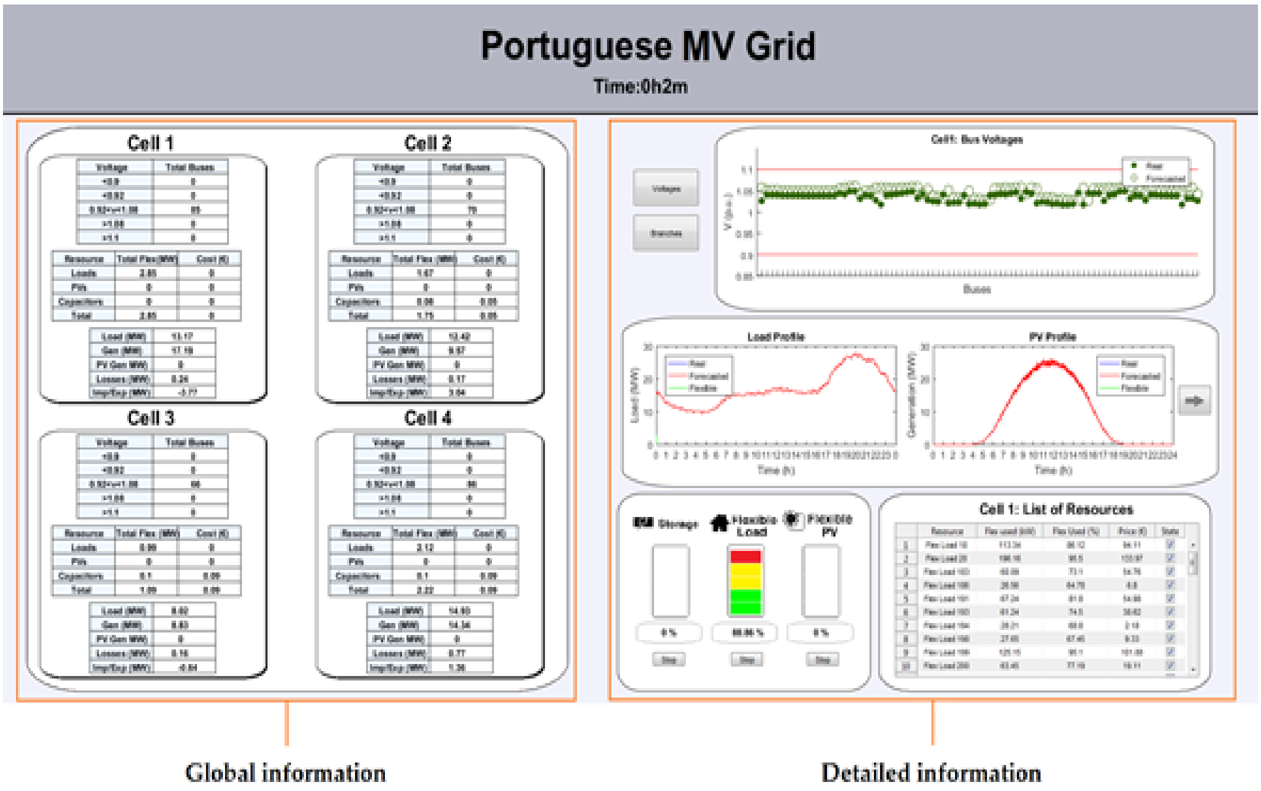


Figure 3-9: User Interface for Cell Operators

The operating tool presented in the figure above also enables cell operators to control the flexible resources available in the cell remotely and to modify the solution provided by the PPVC algorithm with the guarantee that no technical problem will occur in the cell.

The optimal set points defined by the PPVC algorithm and sent by the cell operator to the flexible resources available will change their operating state and may interfere with other decision support functions, such as the transient stability DSS described in the previous section.

All the information presented in both tools can be combined in a single one. Nonetheless, it is important to highlight the locations where some potential conflicts may occur between the two DSSs. In these locations, it is important to know if the voltage in the buses or the power deployed by SG are reaching their limits and thus, this information should always be visible to the cell operator. In addition, when a fault occurs, the CCT information should always appear to the cell operator.

A possible way of implementation is overlays in the dynamic visualisation concept described in Deliverable 8.1 and Section 1.3.2. In the same vein of the presented on-demand peer-to-peer data acquisition for live state and topology monitoring and topology, SCADA systems will be dynamically linked to the various DSSs. DSS and/or pieces of information can be added or removed to and from the SCADA system without any manual reconfiguration needs, allowing the system to adapt to future needs.

# 4 Conclusions

This deliverable summarises the learning and major achievements within WP8 and provides detailed recommendations on future control room development. These include the highlighted requirements of the future control room from Task 8.1, and an overview of key outcomes from control room scenarios development and decision support system experiments from tasks T8.2 and T8.3. As a result, we can conclude that an environment with advanced decision support system, enhanced situational awareness (visualisation) and forecasting are critical to allowing the human operator to quickly understand a situation and carry out the best decision efficiently.

WP8 has developed several scenarios within a control room based on the WoC architecture. These cover control requirements including transient stability preventive control, loop flow management, pro-active voltage control and frequency management. One or more decision points within these scenarios have been identified and implemented through the research tools and prototypes created. In order to demonstrate an integrated decision support system, a design for the combination and co-ordination of the developed decision support tools has been created, including how they react to decision points and events. This decision support system blueprint for different control functionalities can fully support the control of the WoC concept, and allows the human operator to benefit from improved information and automated decision making under complex WoC scenarios.

In addition, a number of visualisation prototypes have been developed for different decision support control functions. These provide operators with key information, and provide situational awareness during events. They also allow operators to access network data and to alter or add control actions if necessary.

# 5 References

[1] U. Spanel et. al., “Capabilities and requirements of a control centre in the 21st century-functional and human resources view,” Cigré, 2016.

[2] ELECTRA IRP, “D5.3 The Web-of-Cells Control Architecture for Operating Future Power Systems,” 2018.

[3] Alexander M. Prostejovsky, “Increased Observability in Electric Distribution Grids: Emerging Applications Promoting the Active Role of Distribution System Operators.” PhD Thesis, 2017. 284 p.

[4] M. Rezkalla, K. Heussen, M. Marinelli, J. Hu, and H.W. Bindner, “Identification of Requirements for Distribution Management Systems in the Smart Grid Context,” Universities Power Engineering Conference (UPEC), 2015 Proceedings of the 50th International, pp. 1-6, Staffordshire, 1-4 Sep. 2015.

[5] M. Panteli, D. S. Kirschen, “Situation awareness in power systems: Theory, challenges and applications,” Electric Power Systems Research, vol. 122, pp. 140-151, 2015.

[6] ELECTRA IRP, “Internal Report R8.1 Key Requirements for Future Control Room Functionality,” 2015.

[7] C. Tornelli, R. Zuelli, M. Marinelli, A. Z. Morch, and L. Cornez, “Requirements for future control room and visualization features in the Web-of-Cells framework defined in the ELECTRA project,” CIRED, Open Access Proc. J., vol. 2017, Iss. 1, pp. 1425-1428, 2017.

[8] ELECTRA IRP, “D8.1 Demonstration of Visualization techniques for the control room engineer in 2030,” 2016.

[9] A. Prostejovsky, O. Gehrke, M. Marinelli, M. Uslar, “Reduction of Topological Connectivity Information in Electric Power Grids,” Universities Power Engineering Conference (UPEC), 2016 Proceedings of the 51st International, pp. 1-6, Coimbra, 6-9 Sep. 2016.

[10] ELECTRA IRP, “D8.2 Demonstration of decision support for real time operation,” 2017.

[11] M. Marinelli, K. Heussen, A. M. Prostejovsky, H. W. Bindner, V. M. Catterson, J. Merino, and C. Tornelli, “Scenario-based approach adopted in the ELECTRA project for deriving innovate control room functionality,” CIRED, Open Access Proc. J., vol. 2017, Iss. 1, pp. 1450-1453, 2017.

[12] A. S. Zaher, V. M. Catterson, M. H. Syed, S.D.J. McArthur, G. M. Burt, M. Marinelli, and A. Prostejovsky, “Enhanced Situational Awareness and Decision Support for Operators of Future Distributed Power Network Architectures,” Innovative Smart Grid Technologies (ISGT Europe), 2016 6th IEEE PES International Conference and Exhibition on, pp.1-6, Ljubljana, 9-12 Oct. 2016.

[13] M. Power et al., “Challenge in the control centre (EMS) due to distributed generation and renewables,” Cigré, 2016.

[14] M. Chen, V. M. Catterson, M. Syed, S. D. J. McArthur, G. M. Burt, M. Marinelli, A. M. Prostejovsky, and K. Heussen, “Supporting Control Room Operators in Highly Automated Future Power Networks,” CIRED, Open Access Proc. J., vol. 2017, Iss. 1, pp. 1492-1495, 2017.

[15] M. Pertl, M. Rezkalla, M. Marinelli, “A Novel Grid-Wide Transient Stability Assessment and Visualization Method for Increasing Situation Awareness of Control Room Operators,” Innovative Smart Grid Technologies (ISGT Asia), 2016 IEEE PES International Conference and Exhibition on, pp.1-6, Melbourne, 28 Nov - 01 Dec 2016.

[16] F. Marten et al., "Analysis of a reactive power exchange between distribution and transmission grids," 2013 IEEE International Workshop on Intelligent Energy Systems (IWIES), Vienna, 2013, pp. 52-57. doi: 10.1109/IWIES.2013.6698561

[17] Michael Pertl, Tilman Weckesser, Michel Rezkalla, Kai Heussen, and Mattia Marinelli, “A decision support tool for transient stability preventive control,” Electr. Power Syst. Res., vol. 147, pp. 88–96, 2017.

# 6 Disclaimer

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