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# The Future Role of Human Operators in Highly Automated Electric Power Systems

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**Abstract**

In the wake of the widespread deployment of Renewable Energy Sources (RESs) and the introduction of other distributed energy technologies, the grid exhibits faster and more intricate dynamics. A lot of attention is therefore being put on automated grid management systems, which entail a shift in the role and tasks of human operators in the Control Rooms (CRs). Given the rapid pace of development, the question ultimately arises if human guidance is necessary at all to safely operate the grid. This work investigates the prospective role of the human operators in CRs under consideration of cognitive challenges in highly automated power systems, aiming to maintain safe and efficient grid operation. A review on relevant literature casts light on the scope of influence of automated grid management systems, the operational states of power system that will still require human assistance, as well as activities and interactions. Finally, recommendations on the design of Decision Support Systems (DSS) supporting humans in their future role are provided.

*Keywords:* Control Room; Decision Support Systems; Human Computer Interaction; Human Operators; Power System Management; Situation Awareness

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## Acronyms

| | |
|---|---|
| **ACE** | Area Control Error |
| **AI** | Artificial Intelligence |
| **AMI** | Advanced Metering Infrastructure |
| **BESS** | Battery Energy Storage System |
| **CC** | Control Centre |
| **CR** | Control Room |
| **DER** | Distributed Energy Resource |
| **DMS** | Distribution Management System |
| **DR** | Demand Response |
| **DSA** | Dynamic Security Assessment |
| **DSO** | Distribution System Operator |
| **DSS** | Decision Support System |
| **EMS** | Energy Management System |
| **ES** | Expert System |
| **FACTS** | Flexible AC Transmission System |
| **GMS** | Grid Management Systems |
| **GUI** | Graphical User Interface |
| **HMI** | Human-Machine Interface |
| **ICT** | Information & Communication Technology |
| **LFC** | Load Frequency Control |
| **ML** | Machine Learning |
| **NPP** | Nuclear Power Plant |
| **PMU** | Phasor Measurement Unit |
| **RAS** | Remedial Action Scheme |
| **RES** | Renewable Energy Source |
| **RTU** | Remote Terminal Unit |
| **SA** | Situation Awareness |
| **SAGAT** | SA Global Assessment Technique |
| **SART** | SA Rating Technique |
| **SCADA** | Supervisory Control And Data Acquisition |
| **SE** | State Estimation |
| **SM** | Smart Meter |
| **SMI** | Smart Meter Infrastructure |
| **SO** | System Operator |
| **TSO** | Transmission System Operator |
| **UI** | User Interface |
| **VSC** | Voltage Source Converter |
| **WAMS** | Wide Area Monitoring System |
| **WDA** | Work Domain Analysis |

## 1. Introduction

*Turn the lights on, keep the lights on, and turn the lights back on when they go out.* This tongue-in-cheek job description by an electric utility's employee in [1] plainly sums up the task of utilities, and the way of achieving this remained basically unchanged in decades. Yet electric power grids are in a phase of rapid change, and so is the role of human operators in control rooms.

Before market liberalisation and the subsequent unbundling of the vertically integrated power system, control centres were manned with skilled dispatchers [2, 3]. They had broad knowledge of the whole power system and a deep understanding of the physical processes in all of the system in order to be able to manually intervene. However, in the wake of the widespread deployment of Renewable Energy Sources (RES) and the introduction of other new technologies, the grid exhibits faster and more intricate dynamics. A lot of attention is therefore being put on automated grid management systems, which entail a shift in the role and tasks of the human operators [4]. Given the rapid pace of development, the question ultimately arises if human guidance is necessary at all to safely operate the grid. For the most part, the possibilities emerging from Information & Communication Technology (ICT) and consecutive automated grid management tools in the next generation of Control Centres (CCs) are described, e. g., in [5, 6, 7, 8, 9, 10]. The operator role, on the other hand, is hardly ever discussed in the context of electric power systems.

This work investigates the prospective role of the human operator under consideration of cognitive challenges in highly automated power systems. Identifying and presenting relevant literature, the questions tackled in this work are:

- What is the expected scope and sphere of influence on the grid operation of automated control systems in future power systems?
- Which operational states of the power system will still require human assistance?
- How do tasks and interactions in the Control Room (CR) change in automated environments?
- How should a Decision Support System (DSS) be designed to assist human operators in their new roles?

In related works, the focus lies almost exclusively on control room functionality under the assumption of currently given operator roles. This paper contrasts with this common approach by also considering implications of changing automation technology on the possible future role and tasks of an operator. Automation functions in a highly automated power system are anticipated on the basis of the Web-of-Cells concept as proposed by the European research project ELECTRA [11].

The paper is structured as follows. In Section 2 we present a discussion starting with an overview of the tasks and roles associated with grid operation in present-day control centres. Section 3 focuses on psychological aspects in terms of Situation Awareness (SA) relevant to the energy sector and related industrial domains. The technical side of the subject is investigated in Section 4 by examining present Energy and Distribution Management Systems (EMS, DMS) used for power systems management and supervision. Advances in the automation and decentralisation of electric power systems are subsequently described in Section 5. Based on the findings up to this point, future demands on required expertise, tasks and requirements on operators and their environment are finally derived in Section 6. Section 7 concludes this paper. For the most part we will use the terms System Operator (SO) and Grid Management Systems (GMS) for Transmission System Operator (TSO)/Distribution System Operator (DSO) and EMS/DMS, respectively.

## 2. The Human Operator

As any cyber-physical system, the electric grid needs humans for carrying out its purpose, the uninterrupted provision of electric energy [12]. From putting infrastructure and components into operation, maintaining their functionality, to bringing the system back on-line after blackouts, humans are involved to varying degrees at all stages. Whether we look at single assets or at the grid as a whole, supervision and control is conducted in the CR of the CC[1] as depicted in Fig. 1. While many processes are automated, it is ultimately the operators that keep the system running.

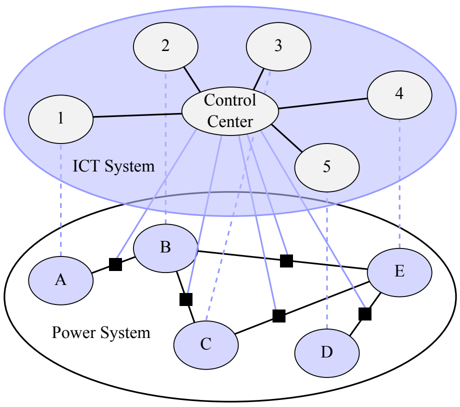


Figure 1: The electric grid viewed as a cyber-physical system as in [12]. The CR exchanges data with remote substation controllers (Arabic numerals) or directly with substation and network components (Latin letters).

### *2.1. Operator Roles*

Humans in electric power systems have operational responsibility complementary to automation [13]. Three types of roles are generally distinguished [14]:

1. Transmission/Distribution Operator (system operation)
2. Reliability Coordinator (supervision)

[1]Control Room and Control Centre are often used synonymously.

3. Balancing and Interchange Operator (market/ancillary services coordination)

We will focus predominantly on the first two categories in the frame of this work, as they are critical to resolving abnormal grid operation states.

*Transmission/Distribution Operators* monitor and control the grid from their workplaces inside the CR. Assisted remotely by field crews, they steer the system away from potentially dangerous operating states, develop contingency plans, and respond to emergencies. Each operator in the CR has specific tasks and gains awareness of the system operational state to act accordingly.

Coordination of all operators and tracking of work progress is done by control room *Reliability Coordinators*, who tracks and reviews activities [15, 16]. They supervise and direct the activities of assigned control room staff and coordinates scheduling of staff to ensure proper operational coverage. A supervisors job is to identify arising needs, to ensure compliance with regulations during daily business and coordinate operator training on the job as required. They also link company procedures and business objectives with the practical operational perspective, and introduce new policies and procedures.

### 2.2. *Tasks and Objectives*

Power system operators have to collectively cover a range of knowledge areas for maintaining power system operation under changing conditions: Resource and demand balancing , transmission system, emergency preparedness, emergency response, contingency analysis and reliability, and communications and data. They have to manually intervene when required, considering cost-effective and feasible solutions by first applying no-cost measures before taking more expensive solutions. The corresponding tasks as taken from the NERC operator training and certification process in [14] are listed in Table 1.

### 2.3. *Expertise Levels*

Several operator expertise levels can be differentiated based on time spent in the CR, task assignments, and gathered experience. As operators rise up in the hierarchy, they are expected to learn more complex tasks and complete them under decreasing amounts of supervision until reaching the top level, at which time they are able to operate independently. Two case studies were conducted in the Vermont utility described in [17, 18]. The identified operator expertise levels are summarised in the following.

Table 1: Tasks from the NERC power system operator training and certification process [14].

| Category | Tasks |
|---|---|
| Planning | Define system limitations such as operating limits and total transfer capabilities |
| | Define emergency procedures and system restoration plans |
| | Coordinate and revise generation and transmission maintenance plans as permitted |
| | Identification, communication, and direction of actions against threats and violations |
| | Implementation of interchange, emergency procedures and restoration plans |
| | Perform and interpret contingency analysis and dynamic security assessments |
| | Coordinate field crews and schedule asset maintenance |
| Monitoring | Calculate and monitor the area control error (ACE) |
| | Monitor interconnection reliability and limits to prevent instability and cascading |
| | Monitor and adjust reactive resources to maintain system voltage within limits |
| | Monitor and deploy emergency procedures, protective relaying systems and RAS |
| | Monitor and update telemetry and telecontrol parameters within the control area |
| Response | Adjust power flow and approve arranged interchange in the system |
| | Curtail confirmed power interchanges that adversely impact system reliability |
| | Deploy ancillary services for balancing generation and load considering reliability |
| | Direct emergency procedures incl. load shedding and coordinate system restoration |
| | Operate the control area to maintain load-interchange-generation balance |
| | Conduct switching and develop automated switching regimes |
| Reporting | Pursue operational planning and reliability evaluation |
| | Provide energy accounting and administer inadvertent energy paybacks |
| | Review generation commitments, dispatch, and load forecasts |

*1st Class (1C) operator.* First class operators possess a fast grasp of Supervisory Control And Data Acquisition (SCADA) data from which they infer other system states. Their good topological knowledge allows them to write and execute switching plans *ad hoc* independently of other operators. After five years they are considered *experts*.

*2nd, 3rd Class (2C/3C) operator.* Second and third class operators have various degrees of topological and SCADA data understanding, with which they support 1C operators.

*Novice.* New-hires with knowledge of electricity and system fundamentals are trained by senior operators. They execute basic operations under guidance and learn to interpret SCADA data, identify contingencies and prioritise alarms.

*Definition of an Expert.* Experts have a combination of strong academic or practical background and spent significant time in the control room. A CR expert is a 1C operator with additional five years of experience, which amounts to up to nine years in the CR in total [17]. Experts remain calm under stress, can efficiently multitask, process large amounts of data, while being tolerant to ambiguity. They are exposed to a multitude of events where they gain knowledge through experiential learning and practical work.

## 3. Operator Situation Awareness

The term SA was coined in the attempt to create a construct of human decision making processes within complex, dynamic systems [19]. Defined as the primary basis for all decisions and actions taken by humans in the operation of complex and dynamic systems [19, 20], the concept of SA has since entered the mainstream of human factors research [21] and related domains that involve humans acting in challenging environments [22, 23, 24].

Operator SA of operators significantly impacts the probability of the system entering the cascading phase of a blackout [25]. Lack thereof is attributed to numerous power system incidents in the past as described in [17, 20, 23, 26, 27], highlighting the need for increased SA for both individuals and teams (e. g., operators in the same room or operator and field crew interactions [17]). This problem gets aggravated by automation, which entails the potential threat of reduced SA and increased risk of human errors [28, 29]. Important aspects of SA are therefore covered in the following in order to emphasise psychological considerations in the evaluation of the role of future operators. A generalised impact analysis of human factors on power system operation reliability is given in [30].

### *3.1. Models*

SA models aim to understand the relations and interactions between sensory inputs, cognitive processing of information and actions taken. They allow a systematic description of human performance for both routine tasks and abnormal working conditions [31]. A selection of widely adapted models is presented in the following.

*Three-Level Model.* Endsley's methodology models the cognitive process of dynamic decision making as a linear triadic relationship in a loop: Perception of elements in the current situation; Comprehension of their meanings and relations; and projection of future states with the given knowledge [19, 32]. External inputs, such as underlying system aspects, goals and expectations, as well as the subject's background and abilities, act on a mental model that eventually results in an action. Fig. 2 illustrates the complete model.

The three-level model is now the most widely used for describing SA, despite being frequently criticised for its disjunctive view on SA process and product [33].

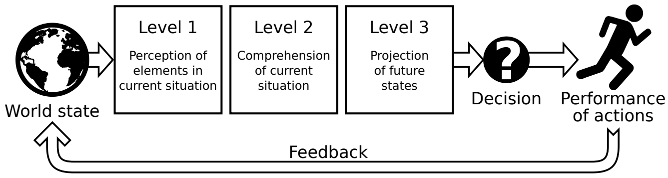


Figure 2: Endsley's three-level model of situation awareness based on [20].

*Perceptual Cycle.* As opposed to Endsley's three-level model, the perceptual cycle model [34] does not distinguish between the SA process and outcome [23]. Instead, it incorporates the impact of actions between the individual and the environment in a cyclical process (see Fig. 3). Interactions do not only modify the environment, but also internal schema that direct further explorations [33].

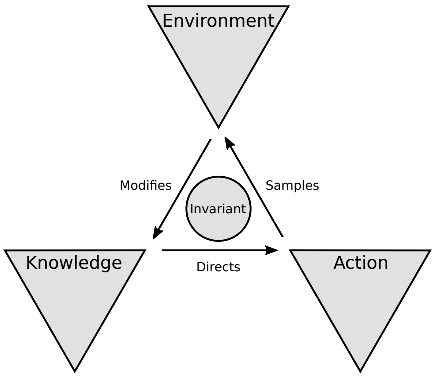


Figure 3: Perceptual cycle model based on [34].

*Work Domain Analysis.* Work Domain Analysis (WDA) helps to derive the domain-specific needs for the creation of economic interfaces supporting human performance and error recovery [35]. An overview about operator work domains has been derived from operator training and certification programmes [14]. The operator roles *Reliability Operator*, *Balancing and Interchange Operator* and *Transmission Operator* are designated by NERC to indicate the qualification credential. All of them describe roles in the technical domain, which requires specialised training. The operator training on a regular basis is examined in six different knowledge areas, which are shown in Fig. 4 and are further described in Table 1 of Section 2. In Fig. 4, it can be seen that the detail level of knowledge rises for each operator credential depending on the focus of the work domain. In general the activities of the operator can be decomposed into the two main fields of activity: power management and network management. While the examination of transmission operators focuses more on power transmission/distribution topics, the examination for a balancing and interchange operator exam emphasises power demand and balancing topics. The examination for reliability operators covers equally both areas. Knowledge in terms of communications and data, emergency preparedness and reliability is equally needed for all operator domains.

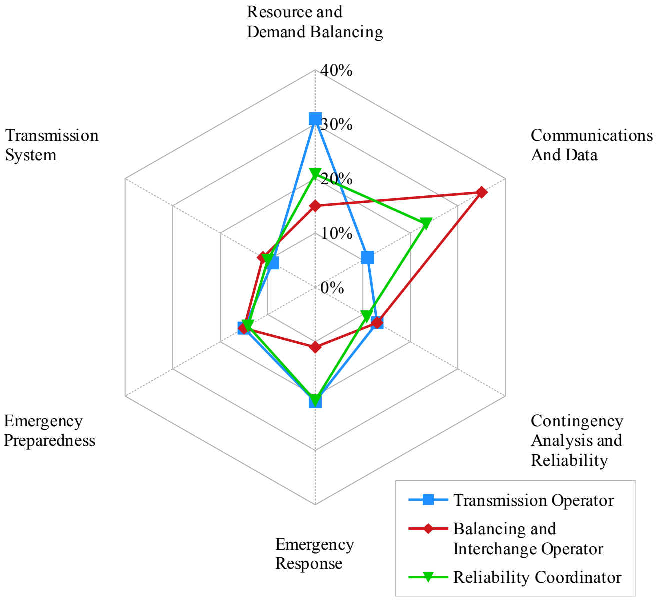


Figure 4: Operator Work Domain Analysis based on NERC training and certification programmes [14]. The percentage values are derived from the number of questions on specific topics divided by the total amount of questions within the certification exam for each credential.

*Activity Theory.* Like the perceptual cycle model, the activity theory model [36] considers SA as an intertwined process of all components. Dynamic reflection over past, present, and future, as well as on situational features enables individuals to form and modify mental models of their environment.

### *3.2. Metrics*

Metrics allow to quantify the level of SA and are crucial to design of operator DSS as presented later. A comprehensive overview of metrics is provided by the Single European Sky ATM Research (SESAR) project in [37]. Two distinctive categories can be identified, subjective and objective [38], from which the following methods are deemed to be the most useful for modern ICT-driven systems [39].

*SA Global Assessment Technique (SAGAT).* Developed along with Endsley's Three-Level model presented in Section 3.1, SA Global Assessment Technique (SAGAT) probes test subjects at random times in the simulated scenario about their perceived SA [19, 26]. While not free from criticism, it is now a *de facto* standard instrument [21].

*SA Rating Technique (SART).* This post-trial method uses ten dimensions of SA that can be rated and weighed by the participants [37, 19]. Its highly subjective character raises suspicion about the results' validity, however, SA Rating Technique (SART)'s applicability in environments that lack simulations makes it a viable tool [39].

### *3.3. Human-Machine Interfaces*

Introduction of full graphics replacing the mimic board for SCADA systems in CCs and the development of digitised ICT significantly expanded the possibilities for power system monitoring and remote operation. Human-Machine Interfaces (HMIs) or Human-System Interfaces, as they are sometimes called, are the medium between human operators and the system under control [29], and are designed with respect to usability, simplicity, and ergonomics. Interactive visual interfaces play a major role in HMIs, as they provide a more intuitive overview on the system's state than purely computational analyses [40].

### *3.4. SA in Electric Power System*

The complexity of power systems is continuously rising, raising the risk of human operators being unable to manage the grid in all situations unless their cognitive capabilities are assisted by appropriate tools. As the quantity and the rate of gathered data in the CR, as well as the requirement for quicker diagnosis and decision making by operators rises, the so-called human cognitive barrier is reached [41] and information cannot be further processed. Enlarging SA means to deal with the cognitive barrier by appropriate tools and visualisations. Several factors influence SA in CRs: the design of Graphical User Interfaces (GUIs), operator stress and workload, automated decision support, application complexity and operator training. If all these factors get aligned with the tasks, critical situations will get acknowledged sooner and can get mitigated successfully, effectively contributing to stability and lowering the risk of blackouts. Therefore, the necessary data and information has to be collected from the available information sources and subsequently filtered, organised, condensed and evaluated.

The three-level model described in Section 3.1 is typically adapted for evaluating power system SA. Applications of the model include hierarchical visualisation concepts amongst others [42, 27]. Fig. 5 combines the three-level model with the findings of an SA indicator system described in [43]. In addition to those works, we identify a *model state-space* layer on which both the SA and communications layers map their data, which will later be used for recommendations regarding the design of future DSS.

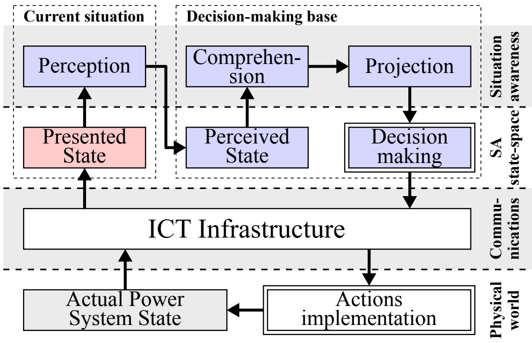


Figure 5: Power systems SA based on the three-level model in [19] and the SA indicator system of [43].

### 3.5. *Electric Power System Operating States*

SA allows to classify separated operating states of the electric grid, and in turn, the state determines which aspects of SA are important for the operator. Normal and abnormal operating states of a power system according to [44, 45, 46] are described in the following, supported by a summary in Table 2 and their temporal dependency in Fig. 6.

*Normal.* In normal operation state, all constraints are satisfied and existing reserve margins are sufficient. Generation matches the existing load demand, while equipment utilisation is within its limits. Possibly occurring disturbances can be handled without restriction.

*Alert.* The alert state is entered when the probability of a disturbance increases. Security constraints are satisfied, but a disturbance could result in a limit violation (e.g., equipment overload). In alert state, preventive measures can restore normal state.

*Emergency.* If a serious disturbance occurs before preventive measures can be taken, the system enters the emergency state. Now security constraints are being violated. The power system would still operate, but curative control actions need to be initiated in order to restore at least the alert state.

*In Extremis.* If system constraints are heavily violated and the measures in emergency state are not sufficient, further initial or subsequent disturbances lead to disintegration and the power system is *in extremis*. Emergency control actions are needed to save the system from total collapse.

*Restorative.* The system enters the restorative state, when control is taken reconnect load and resynchronise islanded system parts. Depending on circumstances, the system transits to either to the alert or to the normal state.

*Black Out.* A black out is the system state in which the operation of a part or the entire transmission system is no longer possible.

Table 2: Definition of Operational States [45, 46].

| **State** | **Definition of Condition** | **Control Methods** |
|---|---|---|
| Normal | Boundary conditions fulfilled | No intervention required |
| Alert | Safety-level below limit, boundary conditions still fulfilled | Preventive measures to restore adequate reserve margins needed (e. g., security dispatch, increased reserves, tie-line rescheduling) |
| Emergency | Boundary conditions violated, countermeasures of *alert* state insufficient or too slow | Immediate intervention needed (e. g., fault clearing, fast redispatch, load shifting) |
| In Extremis | Boundary conditions violated and system balance disturbed | Drastic measures to contain disruption of the entire system (e. g., load shedding or islanding) |
| Restorative | System equipment available for restoration | Reestablish sustainable system state (i. e., restart and synchronisation of generation units, load restoration, synchronisation of areas) |
| Blackout | (Parts of the) System down | Post-mortem analysis, preparing black start-capable units |

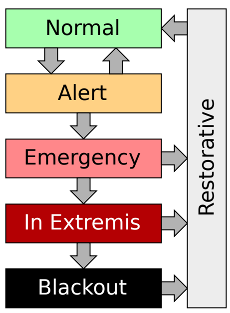


Figure 6: Power system operating states based on [45] and [47].

## 4. The Power System Control Room

The CR constitutes the focal operational point and the nerve centre of the power system [48]. CRs have evolved from hardwired analogue systems with manual controls into integrated, modular, digital systems [49, 5], providing a wide range of functionalities.

### *4.1. Organisation & Processes*

A modern control room comprises a User Interface (UI) to access software modules in the EMS or DMS. It brings together the various operators, the SCADA system backed by ICT infrastructure for collecting, processing and storing data, and HMIs for operators to observe and control the system.

The alternation between idling and routine activities under low stress level, and dynamic, non-predictable, high stress situations, which require action under time pressure, is characteristic for the power system operator in the CR [48]. As illustrated in Fig. 7, both power system operation and operational planning in terms of technical processes and market rules are conducted in the CR. While the operational long term and day-ahead planning (today for tomorrow) is often practised in the back office, the intra-day actions are moving more and more into the CR, closer to real time [50] (see also Fig. 8).

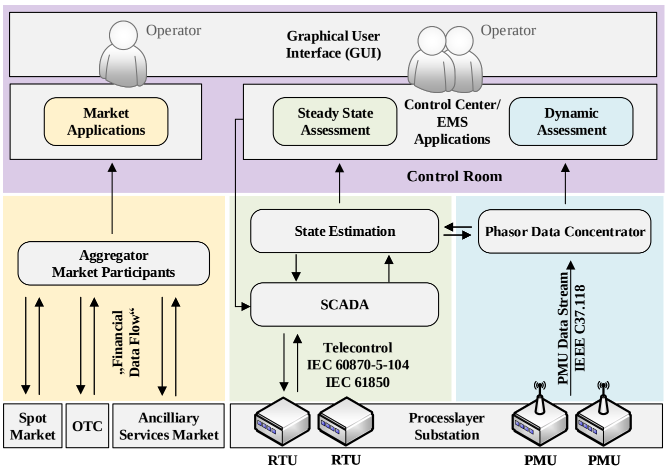


Figure 7: Overview of essential processes in a power system control center.

Both system operation in the close to real-time domain and operational planning-ahead make use of static and dynamic tools as illustrated in Fig. 7. They require data acquisition through communication channels to substations in the controlled area. The operational planning deals with long-, medium- and short term scheduling and planning for the future real-time operation (e. g., week-ahead planning, day-ahead and intra-day congestion forecast). The procedures of operational planning and system operation are shown in Fig. 8 [51, 52].

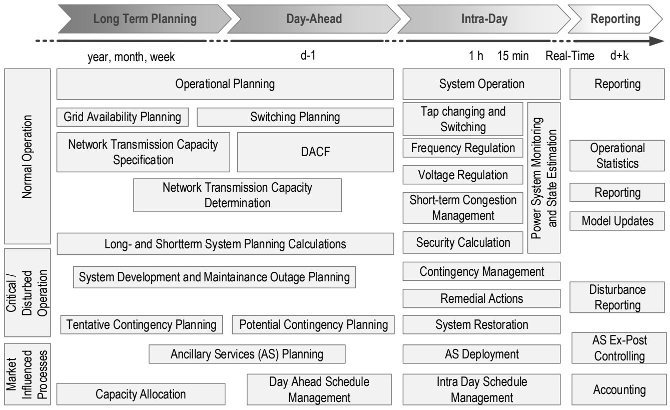


Figure 8: Processes of Operational Planning and System Operation [51, 52].

### 4.2. *Features of Modern Grid Management Systems*

Acquiring state information has been a necessity since the early days of interconnected power systems. In electric power systems, EMS and DMS are assistant systems for supervision and estimation of the grid state, frequency control, economic dispatch after load events, contingency analyses, and stability assessments [5]. They are highly-integrated software suites customised to the needs of individual TSOs and DSOs [53].

Operator tasks in power system CR operation as discussed in Section 2 are aided by several toolboxes built into the EMS/DMS. Some are capable of system operation support in the real-time domain, such as state estimation, monitoring, and control (e. g., circuit switching). Others help maintaining power quality (voltage and frequency), aid preventive or corrective security evaluation, or remedial activities and decision support. Management systems typically consist of separate productive and training environments, the latter using historical data from the archive and synthetic data to train specific situations.

Current SCADA systems combine most of the aforementioned functionalities in an HMI that provides operator workplaces and wallboard visualisations [54, 55]. The visualisation and decision support functionalities provided by SCADA systems are equally static and often require manual modifications (e. g., switch status state tracking). SCADA systems are tailored to the needs of SOs and the individual human operators, who can remotely access the SOs' substations, assets [53, 56] and other functionalities [57]. Data is acquired from various sources of different vendors, which requires a broad knowledge about implemented technologies. Communication links between SCADA and remote sensors or tele-control actuators are typically static links in central databases maintained by asset operators themselves. Changes in device configurations or the topological grid structure and corresponding database entries thus at times need manual modifications.

### *4.3. Monitoring*

Originally gathered via hard-wired sensors, data is now acquired by means of ICT from Remote Terminal Units (RTUs) in substations [58], small-scale producers and consumers in the field using Advanced Metering and Smart Meter (SM) Infrastructures (AMI, SMI) [59, 60, 61], up to Wide Area Monitoring Systems (WAMS) using Phasor Measurement Units (PMUs) [33, 62]. Additionally, communication to different internal processes, company subsections or 3rd parties leads to an increasing number of interfaces which require a strong knowledge about the performed operational tasks of the own and the connected 3rd party EMS/DMS. Relevant power system automation and communication protocols are mentioned in [12, 10]. The large-scale roll out of SMs, PMUs, and a rising number of Distributed Energy Resources (DERs) push established centralised SCADA designs to their limits [57, 54, 63].

Dynamic Security Assessment (DSA) tools play a growing role in modern EMS [64, 65]. Changes in the power domain lead to structural changes in the CR EMS. Besides classical SCADA and management functionalities, novel security analyses, monitoring and decision support tools are entering the control room, based on statistics, machine learning and optimisation [66]. Following such developments in the underlying technology of CRs, operators have to adapt to this changing environment.

### *4.4. CR in Related Areas*

Power system operators are naturally cautious towards new technologies and admitting paradigm shifts for the vital importance of the grid, because changes bear the risk of failure. Other application domains and industries facing similar challenges have been less conservative, and can therefore provide best-practice examples for future CRs. Control rooms of Nuclear Power Plants (NPPs) are closely related to power system operation and have been studied extensively due to their safety-critical nature [24, 67, 68, 69]. Industrial automation in manufacturing and the process industry are perhaps the most advanced in terms of automation because of their long history [70, 71, 72, 22, 38]. Experiences and developments on SA in the automotive and aviation sectors also hold important findings [73, 74, 75]. Case studies on SA in control rooms provide insight on workflows in the mentioned domains as documented in [76, 20, 24, 77, 69, 17, 18, 35, 78, 79].

## 5. Automation of the Electric Power System

The first step towards power system automation was already undertaken in the 1970s, when Load Frequency Control (LFC) was incorporated into EMSs [23]. Since then, automated closed-feedback controllers were incorporated in other parts of the system, especially reaction times beyond human capabilities as in fault and anti-islanding protection are needed [80, 81]. Management and operation of the system, however, have largely remained unchanged so far. But in view of rapid technological progress and changing demands, the question raises why electric power grids and the energy sector as a whole wouldn't move towards full automation just like the related manufacturing and process industries (see Section 4.4).

Acknowledging the need for new solutions, the ELECTRA Integrated Research Programme [11] investigated the what-if scenario of a highly automated electric system. Focus was put on real-time frequency and voltage control, as well as DSS [82, 83]. In the following, the views of ELECTRA about ongoing and expected changes of the state-of-the-art electric power grid are described.

### *5.1. A Changing Environment*

Where in the past a few big bulk generators were used to control the system within a well-defined hierarchy, a multitude of heterogeneous resources now needs to be coordinated on much shorter timescales for various reasons: High intermittency of generation from volatile sources such as solar and wind decrease the predictability of the system [84]; inverter-coupled devices in place of synchronous machines reduce the total inertia, which speeds up response times and is detrimental to the grid's resilience to disturbances [85]. Active distribution networks therefore gain much attention both from academia and industry following the advent of small-scale generators and other DERs distributed throughout the low- and medium-voltage grid [86].

The progress in measurement systems as described in Section 4.2 provides the required state observability to tackle these challenges together with new control hierarchies. As DSOs turn from pure network maintainers into active system coordinators [87], new data management schemes for and between TSOs and DSOs are being worked out in order enable active collaboration and to avoid control conflicts [88]. This is further necessitated by the recent trend towards consumer-centric markets, which contribute to the decentralisation of power system management [89].

Data exchange between SCADA systems and distributed resources, the different control regimes, and involved market players is only made possible by computer systems, which are able to handle the incoming amounts of data within the required time frame. While parts of system management, such as unit commitment, load dispatch, and voltage control, were aided by DSS since the 1970s, other aspects like topology and fault restoration are still performed manually. In view of the increasing number of controllable resources and complexity of the grid, human operators struggle with their supervision and control tasks. Automated grid management systems therefore need to take over more responsibilities, which will be elaborated in the subsequent sections.

### *5.2. Degrees of Automation*

Automation means a system's ability to operate, act or self-regulate independently without human intervention [90]. Various degrees of automation exist between its two poles, manual control and full automation, as given in Table 3.

Table 3: Levels of Automation based on [90].

| **Level of Automation** | **Description** |
|---|---|
| Manual control | Human performs all tasks |
| Gathering and filtering | System gathers, filters and highlights key information |
| Batch processing | System aids in action as instructed by human |
| Shared control | System and human generate decision options, human decides and carries out with support |
| Consensual decision making | System recommends options, human decides, system carries out |
| Automated control and decision support | System recommends options, selects best and system carries out, human can intervene if desired |
| Full automation | System carries out all tasks |

Following the definition of automation and the corresponding classification, a *highly automated* system…

- handles normal operating conditions without manual intervention by humans;
- offers decision support to human operators in alert and critical conditions;
- reduces human workload considerably.

At present, GMS exhibit levels of automation that mostly correspond to the *Shared Control* and *Decision Support* categories. Most tasks during normal operation mode are automatised, and alert modes are well covered by DSS. Handling of more severe states is left to the operators, who follow emergency procedures and carry out remedial tasks as described in Section 2.3.

### *5.3. Machine Learning*

Expert Systems (ESs) and DSS assist humans in executing real-time process control decisions in complex systems [91] and have been part of power system management for a long time. [41] defines an expert system as a software paradigm where knowledge concerning a problem is encoded into a computer program. Strengths and weaknesses of expert systems when compared to human involvement have been discussed in [92]. As expected, humans excel at creative tasks, whereas ES are better at repetitive, predictable tasks using pre-programmed rules and heuristics. In [93] a few minor conceptual differences between ESs and DSS are pointed out (e. g., the usage of data models and shells), but most differences lie in the nomenclature. The two terms are often used interchangeably and we therefore favour the use of DSS for its higher frequency in recent literature.

Contrary to static DSS implementations, Machine Learning (ML) enables computers to directly learn from data. With the wide availability of measurement and other information in electric power grids, data-based learning is the logical continuation to classical rule-based knowledge inference in power system management. Artificial Intelligence (AI) techniques provide power system engineers with tools to augment numeric programs with their experience and heuristic knowledge [94]. Results interpretation, however, is difficult, particularly in so-called deep neural networks. Methods for understanding and explaining their predictions are discussed in [95].

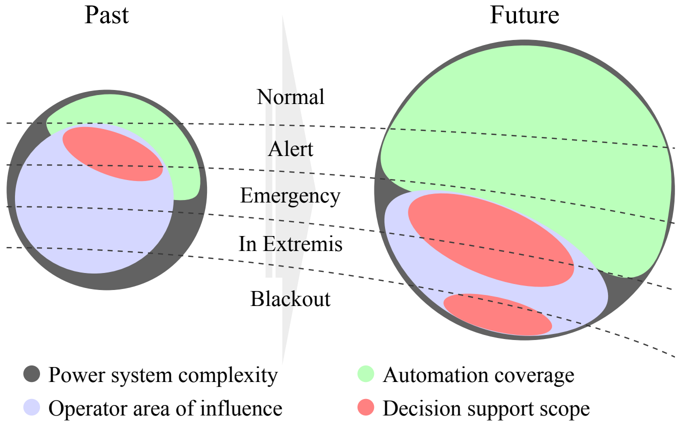


Figure 9: Qualitative illustration of the shift in the areas of influence of human operators, automated control systems and DSS on the increasingly complex electric power system. The dashed lines split the areas into operating states according to Fig. 6.

The potential applications of ML in power system CRs have been investigated in the last three decades [96, 41], but it is only now that these concepts become feasible. A number of tasks of ML are identified for application in modern power system CRs, such as automatic fault diagnosis and evaluation [97], alarm prioritisation, fault switching schedules, safety checking, routine switching schedules, fault diagnosis and isolation, automatic switching and network optimisation [98, 99].

### *5.4. The Highly-Automated Power System*

Intermittent energy provision from renewables, faster grid dynamics due to reduced inertia, a significantly higher number of active participants and market players, among others, increase the uncertainty in current and forecasted grid states [100]. Hence, the admissible set of normal and alert grid states handled by the automated control loops will grow. Machine learning may enable the system to handle normal and alert situations because of their frequent occurrences. Fig. 9 qualitatively illustrates this shift in the area of influence from human operators to automated systems over time. Table 4 provides an overview of the technical characteristics of future power systems.

## 6. Operators and Decision Support Systems in Future Power Systems

The characteristics of a highly automated power system following the changing composition of the grid was layed out in Section 5. Computers will conduct many of the tasks formerly belonging to human operators in order to keep the grid operating. Considering

Table 4: Characteristics of future power systems.

| Aspect | Description |
|---|---|
| Observability | WAMS, PMUs, SMs, SE contribute to nearly 100% observability |
| Controllability | Complete ICT coverage and therefore means for remote control, DR, flexibility from small-scale generators, VSC and FACTS devices |
| Hierarchy | Decentralised, energy communities acting as utilities [101, 102, 103] |
| Inertia | Low inertia (constant) due to high share of inverter-coupled generators, fast dynamics, high transients due to reduced ability to smooth out events [104, 85] |
| Composition | Mostly renewables supported by BESS, few bulk generators with synchronous machines to cover essential base load |
| Uncertainty | High uncertainty of volatile energy resources, unpredictable weather conditions and disasters will become more frequent [105, 106, 107] |
| Resilience | Power system operating conditions will be relaxed to increase ability to withstand changing conditions [106, 108] |
| Black-Start | Automated using BESS [109, 110, 111, 112] |

the employment of AI in operation and decision support, a naive assumption would be that all possible grid states could be managed by the automated system as time progresses. But the composition of the grid itself is not static, and with the continuous introduction of new technologies human operators will nevertheless remain an integral part in the future [23].

### *6.1. A Shift In Responsibility*

As automation of tasks, increasing levels of autonomy, and distributed intelligence improve the efficiency and safety of the grid, they also remove the necessity and even ability to undertake labour-intensive monitoring and control of the network during normal and alert operating states (see Fig. 9). Human intervention will be necessary in emergency and *in extremis* situations, which typically would go beyond scenarios ML-based systems are trained on because of lack of data. Human intuition and the expertise of senior CR staff (see Section 2.3) in conjunction with sophisticated DSS will fill the gaps in the set of training scenarios.

For most of the time, however, the human operator would spend the time idling. This bears the risk of the out-of-the-loop syndrome as discussed in Section 3, which negatively affects the operator's ability to reason and constitutes a serious threat to the safety of the grid. Drawing from experiences gained in related safety-critical areas (see Section 4), meaningful activities during idle times need to be part of the operators' duties:

- Operational adjustments (e. g., topology, setpoints) that improve the long-term stability of the system have to be evaluated in the CR and between utilities;

- Audit and analyse inputs and outputs of automatic control tools;
- Weighing of AI estimates and recommended actions by experience and intuition;
- Frequent training in simulators, both for individual operators as well as the whole team including field crews.

Even during normal operation, operators need to step in and assist in rare cases:

- Undefined situations and unclear problem classifications whose solutions cannot be inferred from past scenarios;
- Ambiguous or contradictory information from faulty measurements;
- Severe implications of possible solutions, such as shedding of crucial loads;
- Jurisdictional conflicts that require a real person as responsible party.

*6.2. Operator Interactions*

Successful transfer of essential information between operators in the CR and the field crew is imperative to maintain proper grid function (see Section 4). Carrying out collaborative tasks in increasingly complex systems as described in Section 5.4 therefore requires more efficient interactions for humans to keep up with the faster dynamics.

As a study on computer-supported collaborative learning found out [113], direct interaction between collaborators is actually not the most efficient way to solve complex tasks. Instead, individuals that have access to representations of their collaborators' knowledge perform better than groups which are genuinely collaborating. Applying this finding to human interactions in the CR entails shared SA between operators on the fly as in [90]. Where today sharing of information and laying out emergency plans are performed almost exclusively orally either face-to-face or via telephone, DSS can take a considerable share of the communication load.

Future DSS will not only feed information to each operator individually, but also assess their SA and subsequent actions in order to distribute it to other operators. Each operator will thus be instantaneously aware of their collaborators' views, which are intelligently incorporated in the presented DSS feed. As a consequence we will find a much quieter CR during emergency situations, effectively improving the operators' ability to focus.

DSS facilitate the decision making process of the human operator. When designing DSS, knowledge of psychological mechanisms of information processing allows to prepare and present the system state in such a manner, that the different mental processing stages are actively assisted. Taking the three-level model applied to power systems in Fig. 5 as an example, the ultimate goal is to "short-circuit" the path between *presented state* and *decision making*. Incorporation of SA models and metrics, like the ones in Section 3, is therefore imperative.

Fig. 10 demonstrates this concept for one operator by extending Fig. 5. Raw data from the SCADA system is first mapped onto an internal world model, from which a classification of the current situation is derived. The DSS then infers implications of the current situation if no actions are taken. Classification and implications are presented to both the operator and their collaborators to help them with situation perception and comprehension. Exclusively for the operator at hand is the evaluation of scenarios emerging from feasible actions, granting him an automated and filtered projection of the situation to make a fast but substantiated decision.

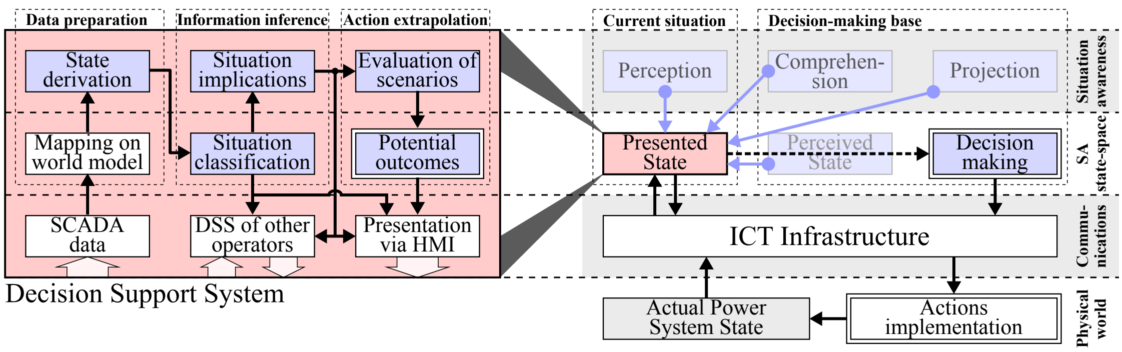


Figure 10: Incorporating human SA models in the design of future DSS.

Collaborative DSS extend the concept of individual SA to shared SA. By including situation information of other operators and field crews, each operator workplace becomes an immersive environment, effectively enhancing human task-solving ability as described in Section 6.2. Consideration of SA metrics is particularly important in such a case: While a human operator can reasonably judge the validity of information provided by the DSS in his area of expertise, they may be incapable to rate situations in other areas. What is more, operators must not have any reason to doubt external SA inputs in order to facilitate efficient decision-making. Online evaluation of SA validity using applicable SA metrics is therefore paramount for guaranteeing safe operation of the future grid.

## 7. Conclusions

The necessity of human involvement in system control in presence of automation is questioned at times, ranging back to the first widespread usage of computers up to most recent developments in ML and AI. However, a closer look on the extent and aspects of automation reveal the indispensable nature of human intuition when dealing with abnormal situations, as demonstrated in this work on the future role of human operators in highly automated power systems.

An inevitable consequence of technological progress is the shift in responsibility. In the face of ML, common and frequent tasks where lots of data are available will be automatised, which will free operators of this duty. This is both an opportunity and a challenge. Human operators can focus exclusively on handling abnormal grid states, such as *in extremis* and blackout scenarios, supported by collaborative DSS for shared SA. On the other hand, the complexity of the grid, out-of-the-loop syndrome, and non-transparent AI decision making may overwhelm humans when facing real threats.

We therefore foresee the future role of operators to resemble that of a *disaster manager* with its three principles: Preparedness, response, and recovery [114, 115]. As such, the new role implies training for, and collaborative identification of potential threats to the power grid while the system is operating normally. The actual threat is then decidedly met with the support of advanced DSS that provide shared SA across all humans involved in the mitigation process. These conclusions are intended to serve as a starting point for future development on CR aspects. By highlighting the mutual benefits for the operator and the grid, related research is encouraged to take our findings into consideration.

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