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# Empowering Operators: Investigating Operational Challenges in Automated Power System Control Rooms using Applied Cognitive Task Analysis

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The growing electrification of society and the integration of intermittent energy sources are expected to transform the electric power system. In response to the rising unpredictability and the vast amount of available data, operations are becoming increasingly automated, which redefines grid operator responsibilities. The purpose of this paper is to investigate current and future procedural challenges encountered by grid operators in electric power system Control Rooms (CRs). Therefore, four experienced operators from a European Transmission System Operator were interviewed using the Applied Cognitive Task Analysis method. The results showed that grid operators make decisions by interpreting information from their tools, relying on experience, using pattern recognition, and team communication. The introduction of automation can increase task efficiency, but its implementation also brings challenges by redefining the roles of operators. Moreover, automation reduces training opportunities for novice operators, increasing the difficulty of understanding the system and the outcomes of their actions. The findings indicate that when introduced in the CR, automation needs to be carefully crafted with a properly defined role in the team. Tool developers should minimize black box effects and implement a suitable two-way communication between automation and humans. The introduction of automation also reduces the experience operators can get, potentially increasing the difficulty for operators to build their own practical knowledge that is needed to understand the grid and the outcomes of their actions. In conclusion, this paper suggests that automation risks 1) deskilling operators by removing opportunities for learning, 2) creating black box effects, 3) redefining the skill set necessary to operate the grid, 4) disrupting established communication structures. These risks should be mitigated by designing automation that can adapt its activity level to the cognitive load of the operator and enable two-way communication between humans and automation.

*Keywords*: Applied Cognitive Task Analysis, Automation, Control Room, Grid Operators, Power System, Team Communication

## 1. Introduction

Power grids around the world are transforming due to three coinciding factors: the electrification of the energy system, accumulated uncertainties from larger shares of volatile wind and solar power, and the deployment of data-driven technologies fueled by the multiplication of sensors, the increase in computing capabilities and the implementation of higher levels of automation. These developments significantly affect the work of control room (CR) operators responsible for monitoring and controlling the grid.

Research on future power system CRs often emphasizes technical developments, as seen in review papers (Peças Lopes et al., 2019) or prospects from Transmission System Operators (TSOs) (e.g.: (TenneT, nd)). Recently, some work emerged to discuss challenges from the perspective of the operators, such as by defining a framework for considering data access and representation, and interaction with the system in operations (G-PST, 2021; Marot et al., 2022). Additionally, previous works have been conducted to study situation awareness and automation in distribution

CR. For example, the Applied Cognitive Task Analysis (ACTA) interview method has been used to describe the crucial importance of communication between operators to maintain their situation awareness (Stevens-Adams et al., 2015). Similarly, a follow-up study revealed varying levels of trust in the automation among operators and highlighted risks related to error detection when working with automated systems (Stamber et al., 2016). The future role of CR operators with higher levels of automation has also been investigated by Prostejovsky et al. (2019). In that study, which bases its analysis on existing literature, the role of operators is described to evolve towards a "*disaster manager*" assisted by a decision support system, requiring preemptive training.

An early work identified automation as a mean to reduce human errors (Eliasson and Persson, 1996). However, as described by Bainbridge (1983), ironically, while automation aims to ease human work, it can bring new challenges to operators, especially during critical events when they need the most support. Hence, it is essential to ensure that emerging automation aligns with operator needs, supports effective decision-making in CRs, and ultimately ensures a safe and stable power grid. This means that with higher levels of automation, human operators still play an important role in safe power grid operations. While previous research has investigated technical solutions in power grids (e.g. (Peças Lopes et al., 2019)) and future operator roles (e.g. (Prostejovsky et al., 2019)), less is known about grid operators' own perspective on current and future tasks and challenges, especially in the context of TSOs.

Therefore, the purpose of this paper is to investigate current and future procedural challenges encountered by transmission grid operators in electric power system CRs. It specifically aims at discovering challenges and opportunities brought by automation. This work contributes to this body of literature by exploring the perspectives of grid operators to identify the risks brought by higher levels of automation, and conceptualizing how collaboration between human operators and automation should be designed.

The sections below first present the adaptation of the ACTA method that was used, then describe the findings of the qualitative analysis, and finally discuss design implications for real-time automation in this high stake environment.

## 2. Method

This study utilized the ACTA method (Militello et al., 1997; Militello and Hutton, 1998) to investigate the procedural challenges encountered by grid operators working in a TSO organization. The ACTA method is a structured interview approach used to identify cognitively demanding aspects of the human work within safety critical domains, such as firefighting (Militello and Hutton, 1998), marine pilots (Berlin and Praetorius, 2023) or in the aviation sector (Seamster and Redding, 1997).

### 2.1. *Participants*

Four experienced operators were interviewed separately. The sample size was in accordance with recommendations for ACTA studies, ranging from 3 to 6 (Marshall and Finlayson, 2022; Militello and Hutton, 1998). The participants are coded from ID1 to ID4.

### 2.2. *Data collection*

The interview process spanned approximately 90 minutes and was audio recorded with the permission of each participant. Each interview involved two to three of the authors: one served as the primary interviewer, while the other assisted with probes and supplementary questions. A third author observed the proceedings and took notes.

Before the ACTA questions, the participant was informed about the interview procedure, their right to withdraw at any time, and that the collected data would be anonymized, used solely for this research study, and deleted after the study.

Following this introduction, the first ACTA data collection phase, the Task Diagram, was conducted to obtain a broad overview of the participant's work. To achieve this, the participant was asked: "*Draw an overview diagram of what you generally do when [selected task]. Focus on what you do and what order, rather than what you should think about.*". The selected task varied depending on the participant's role. The participants were instructed to break down the task into three to six main steps, use their own words to label each step, draw arrows to indicate the sequence, and '*think out loud*' as they described the process.

The objective of the second phase of the interview, the Knowledge audit, was to understand how expertise is applied in practice, using real examples. The participants were asked to choose one cognitively demanding task or subtask from the task diagram made in the first phase. The interviewer then asked a series of questions about the expertise required, the cues and strategies used, and why the task is cognitively challenging, in accordance with the method description.

The third phase of the ACTA, the Simulation Interview, was based on the presentation of a two-stage scenario designed to match relevant tasks of the participants. For the first stage, a challenging situation was presented. The second stage revealed an evolution of the scenario, in which initial corrective actions introduced new risks, potentially leading to a critical situation. For both stages, the participant was asked questions in accordance with the ACTA method (Militello and Hutton, 1998). These questions were aimed at identifying how the participant would conduct the analyses and react to the situation.

### 2.3. *Analysis*

The interviews were transcribed verbatim, and a cognitive demands table was used to categorize the data. Each interview was double-coded and analyzed independently before merging the results. All three authors categorized the cognitive demand tables together, and three overarching themes were identified: (1) A distributed system; (2) Technology and (3) Operator experience.

## 3. Results

The result is divided into three main parts: 3.1 A distributed system, 3.2 Technology, and 3.3 Operator Experience.

### 3.1. *A distributed system*

The transmission grid is spread over a very large area. Operators in the CR have no direct sensory contact with the equipment they are monitoring and manipulating. Therefore, results show that grid operators need support and communication from field technicians who perform maintenance operations and on-site monitoring. These technicians were described by one participant as "*the eyes [of the operator]*" (ID3), as they can convey sensory information indirectly over the phone. This spatial distribution means a decision about a substation could be shared between the CR and the on-field personnel. The correct time to perform a fix might depend on both the operation planning and resources, and the conditions in the station, of which the technician might be the better judge. The geographical distances also put the TSO at the crossroads between many different organizations. The synchronous grid ties multiple TSOs together as actions ripple throughout the network. Decisions on resource allocation to solve problems can be made over the phone or through other means of communication. TSOs are also connecting a set of power plants of various sizes and locations with distribution networks controlled by Distribution System Operators (DSOs). Major actors, such as nuclear power plant operators, can have a significant impact on power flows and therefore need to inform and collaborate with grid operators. Variations in consumption patterns, and more recently distributed renewable energy from prosumers or smaller-scale producers, will impact the power flows and can create problems for the stability of high-voltage transmissions. Finally, other organizations are occasionally collaborating with grid operators, like firefighters in case of a fire near or in a substation. It should be noted that all those organizations' goals do not necessarily align perfectly, and they might have to negotiate as part of the decision-making process.

Within the CR, operators are specialized in different roles, with access to specific tooling, various degrees of expertise in certain technology or analysis, and a set of responsibilities. The main functions in operations are the following: 1) balancing the production to match consumption, 2) preventing line overload, 3) ensuring no contingency can put the grid at risk ("N-1 criteria"), 4) performing switching operations to reroute power flows and de-energize equipment for maintenance,

5) ensuring voltage stability, 6) ensuring that the data infrastructure is functional. These functions are distributed among different operators, and an incident can involve multiple skills, leading to a collaborative decision-making process.

Finally, the analysis showed that operators are not the sole actors in the decision loop. Algorithms and computers perform multiple cognitive tasks that are essential to operations: collecting data throughout the network, predicting the future state of the grid, taking lightning-fast actions to protect equipment, following agreed-upon schedules, computing power flow analysis, and autonomously activating balancing reserves. Those are not strictly speaking forms of automation, but a broader set of computing tools that contribute to the team's performance. It is important to recognize that there are different forms of interactions between human operators and computer assistants, and that the relations might be dynamic. Machines can make errors, for instance, if the algorithms receive incomplete inputs, and operators might recognize such situations based on their experience and disagree with the machines' conclusions or actions. As described, CR operations extend well beyond the physical space, and decisions are not in the sole hands of the operators. They have a final responsibility to maintain the grid stability and the actors around it safe, but they rely on many people and technologies to perform at their best. That allows them to cover a large geographical area, to build deep domain knowledge, and to leverage powerful computing capabilities.

## 3.2. *Technology*

The analysis revealed that the system and tools that operators use are essential components to monitor, control, and evaluate the current and future state of the power grid. Functions they cover include real-time or pseudo-real-time data acquisition, data processing, remote control, simulation and computation, and automated control. This means that there is a bidirectional exchange of information between operators and the system through interfaces. In addition, operators should process the information quickly to build their own situation awareness. Although technological solutions are necessary to operate the grid, interview results identified the tools as a potential source of practical and cognitive challenges for grid operators.

### 3.2.1. *Tools interoperability*

To support the evolution of the power grid and improve CR operation, new tools and processes are progressively being added over time. As a result, similar to the distribution of tasks and roles between different grid operators, not all tools are integrated within the same system. The different parts of the system must communicate with each other to prevent a loss of information. The participants suggested that the interoperability between these may be imperfect. Hence, there can be a lag before the change of state of the grid, collected through measurements, is updated in all simulation tools. These imperfections bring an additional layer of complexity to operators' tasks; not only do they have to collect and process grid-related information, but they also need to be aware of such weaknesses to anticipate and eventually correct erroneous information.

### 3.2.2. *Human-machine interoperability*

The importance of human-machine communication adds to machine-to-machine communication. It is crucial for grid operators to get accustomed to the tools they are interacting with and understand automated processes that are out of their control. One participant explained: "*[some] tools are more like a black box. So we provide data to a tool, we're not sure exactly how the tool will actually use that kind of data*" (ID4). Incomplete knowledge about the way the system processes the data increases the difficulty of spotting errors in the results, and may lower the operator's trust in the system. This trust can also be challenged by system limitations that can create faulty data: "*you get an error, and you have a violation. The first thing you do is [...] you question the tool.*" (ID4). A lower trust may induce greater cognitive load as a CR operator will perform additional checks and use their own judgment to evaluate the coherence of the results.

Human-machine cooperation was also found to be impacted by the addition of automated actions. Operators need to be informed of the actions that are automatically triggered and to understand their own role in the process, as it can imply more monitoring and fewer control actions "*often, the best action is to do nothing*" (ID2). Poor communication can lead to bad synergies where an operator takes action as a response to a deviation that has already been addressed by the automated system.

#### 3.2.3. *Decision-support and visualization*

The study results showed that CR operators often face the challenge of dealing with vast amounts of data that look very similar and lack a clear hierarchy. An increased use of data amplifies the risk of information overload, as highlighted by a participant: "*now we are [...] going to more data-driven world with algorithms and AI and these buzzwords. But [...] too much information is no information, you have information overload*" (ID4). Another participant explained: "*you must be able to look at a lot of values and just pick out the things you need to see*" (ID1). A potential issue is that operators may overlook data because it is buried in a vast amount of numbers. To cope with a lack of intuitive interfaces and real-time feedback, the visualization of data, for instance, through maps, curves or graphs to replace raw numbers, was pointed out to be crucial to process the information. Although these strategies are already partially implemented, a better integration is expected in the future system: "*in our next system I want [...] a geographical schema, with [...] topology photos, like satellite photos[. . . ] It would be so easy and efficient*" (ID3). Another participant described building their own representation to increase data readability; "*I have built a map for myself, so I can just look at it better. Most of the operators have just a big screen [with] numbers*" (ID1). These visual aids can help to decrease the workload and make it easier to spot patterns and anomalies that would otherwise be hard to detect.

Operators could also get greater assistance from the tools in the decision-making process: "*you just need to think of every possibility if you will take the decisions, take action*" (ID2). They often heavily rely on their own understanding of the system to navigate through the set of options they have when exploring potential actions and their consequences. Tools with solution space exploration could reduce the complexity of the task from their perspective.

### 3.3. *Operator experience*

The results from the analysis suggest that operators largely rely on experience when managing events and anomalies, when making decisions, and in stressful situations.

#### 3.3.1. *Managing events and anomalies*

Several different events can affect a power grid (e.g., equipment failure, weather events, or unexpected demand spikes) and thus be managed by the operators. The analysis of the interviews indicated that novice operators sometimes struggle when preparing for events due to the complexity and scale of the grid. While the situations may be familiar, each instance requires a fresh evaluation. It was also described that novice operators sometimes want to focus on the reason for a disturbance, but should develop an ability to 'inhibit' analytical thinking in favor of rapid, consequence-focused action under time pressure. One participant described this: "*As we have noticed in the educational steps, [...] people are mainly focusing on trying to find a reason [...] for what happened, but that's not your responsibility. The responsibility is to solve the actual consequences right now and not try to find out the reason.*" (ID4). The same participant described that "*We don't need to know exactly why it's happened. [...] We need to know [what] in our grid model is wrong in the future.*" (ID4). Furthermore, the participants emphasized that effective event management relies on experience; hence, experienced operators use pattern recognition and expertise to interpret symptoms and pinpoint underlying issues. This knowledge, which is gained through hands-on work or training, greatly improves fault resolution efficiency. However, this reliance on experiential knowledge presents a challenge for novice operators, who may lack the contextual understanding necessary to interpret complex situations accurately. Communication with other crew members was therefore described by the participants as important for novices to handle those situations, thus relying on the experience of colleagues.

In addition to understanding the grid, another important part of making sense of the grid is that grid operators must understand the data infrastructure and recognize potential anomalies. Assessing a tool's reliability depends on understanding how input quality affects its accuracy. If the input data is flawed, the output will also be wrong, as illustrated by challenges in maintaining accurate system parameters and forecasts. These results indicate that to be able to spot data anomalies or assess tool reliability, experience is key.

#### 3.3.2. *Decision-making and anomalies*

Operators in grid control environments must continuously make decisions in a dynamic and evolving context, where actions taken in the present can have significant implications for the near future. This requires the ability to anticipate system behavior, assess risks, and manage cascading effects across interconnected components. For example, the participants described that operators must address events not only as they occur but also with consideration for their potential future consequences. A fault that appears minor in the present may escalate into a critical issue later in the day, such as during peak evening demand. One respondent described: "*we need to look ahead on what is the upcoming issues in the upcoming hours and make calculations on these cases*" (ID4). This necessitates continuous decision-making based on both current and predicted system states, where uncertainty is inherent and timing is crucial. In addition, actions taken to resolve one violation can affect other parts of the system. Operators must therefore consider the broader implications of their decisions, which involves complex cognitive processing, including scenario evaluation and risk assessment. This interconnectedness increases the difficulty of decision-making and demands a holistic understanding of system dynamics. The analysis also showed that operators must learn to prioritize and decide which perturbations should be addressed first. "*If we fix this [overload], probably the other ones will also be fixed at the same time.*" (ID4).

#### 3.3.3. *Handling stressful situations*

The results revealed that novice operators often feel compelled to act quickly when unexpected events occur, largely due to stress and uncertainty. However, experienced operators emphasized that immediate action is not always the best response. With experience comes the ability to recognize when inaction is the most effective strategy, especially in situations where the system is likely to self-correct. This ability to remain calm and avoid unnecessary interventions is closely tied to conducting a careful risk assessment before acting. Experienced operators described how, under stress, it is easy to react impulsively, but effective decision-making requires pausing to analyze the current system's state and consider the potential consequences of any intervention. For instance, one participant described a situation where a transformer triggered a gas alarm, indicating internal damage. If the operator fails to assess the situation, does not consider the inter-connectiveness of the system and simply reconnects the transformer because it is needed, this could lead to a more severe fault. This example highlights that while novices may focus on immediate action to resolve symptoms, experts rely on their understanding of system dynamics and risk assessment to determine when intervention is truly necessary. This expertise is developed over time, through hands-on experience and learning from past incidents.

## 4. Discussion

The purpose of this paper was to investigate current and future procedural challenges encountered by grid operators in electric power system CRs. The overall results indicate that grid operators make decisions by interpreting information from their tools, relying on experience, using pattern recognition, and team communication. They work in a complex, interconnected system, where actions affect the system in real time as well as in the future. Both operational decisions and learning happen when operators interact with each other and the system. However, with the advent of more complex automation, disruptive changes are expected in the coming years, as TSOs will try to deploy these in real-time operations to handle an increasingly volatile power system. As described in Bainbridge's seminal work (1983), while automation aims to reduce human workload, it paradoxically increases the cognitive demands on operators during rare but critical interventions. Therefore, the following paragraphs describe considerations for the deployment of automation that can help preserve the benefits of existing teamwork in the CR.

### 4.1. *Exposing learning opportunities*

The results revealed that real-time events in CRs represent key opportunities for operators to learn about the system and build experience to face further challenges. Therefore, the distribution of tasks between grid operators and automation should be flexible in order to match their skills and training needs, and balance the cognitive load of each situation. If a situation turns out to be stressful, automation should step in and react quickly to known problems to relieve the cognitive load and allow operators to focus on the bigger task at hand. In calmer situations, the automated system could delegate interesting cases. The operator could compare their own solution with the automated response. Alternatively, a less experienced operator could take a larger share of tasks to increase their learning. This aligns with Prostejovsky et al. (2019) who argue that "*meaningful activities during idle times need to be part of the operators' duties*". However, Prostejovsky et al. (2019) advise passive monitoring of automation, while the findings here suggest that during normal conditions, operators should not only analyze decisions taken by the automated system, but also actively and autonomously solve problems to build experience in preparation for crises.

### 4.2. *Enabling two-way communication*

The study showed that in a CR, efficient teamwork is enabled by two-way communication between every entity involved. The results constitute good evidence that the standard for communicating between human operators is not matched by human-tool nor by tool-tool interfaces. To support the learning objectives outlined above, automation should have the capability to share the logic: from the inputs to the conclusions, including decisions, assumptions, and part of the process. This exchange could happen in a dialogue between operators and the information systems, or by passive visual and audio communications, as it exists in collaborative human decision-making. It would allow the operators to better understand and build trust in the automated system (Marot et al., 2022). In addition, tools should allow information to flow freely between them of their own initiative or at the operator's request. Tool interoperability is essential to reduce friction in tool usage and ensure the system is coherent, as decisions are based on shared signals in the data.

### 4.3. *Methodological considerations*

As experienced when applying ACTA in other domains (Berlin and Praetorius, 2023), during the first phase of the interview, the participants had difficulties in creating the linear task diagram that was expected. It turned out that grid operators face a dynamic and iterative decision-making process with multiple branches and different cycles during the analysis. This resulted in confusion when selecting a task to investigate in phase two. An adaptation of the method could be to further investigate several steps that constitute an iterative loop. One element that was underexplored in these interviews, and limited the scope of the analysis, is the interaction and collaboration between operators, for which adaptations of the ACTA method may be needed. Finally, it should be noted that the ACTA method focuses on current procedural challenges experienced by grid operators. Hence, although they may have conveyed some of their thoughts about potential evolutions, to resonate about the future system, the discussion is elaborated by combining results from the study with existing works, models, and theories.

## 5. Conclusion

The analysis of the four ACTA interviews that were conducted for this study first identified key elements in the decision-making process of grid operators. Their decisions are influenced by the interpretation of information from tools, their experience, pattern recognition and team communication within a highly interconnected system. Both operational decisions and learning occur through interaction with the team and technology, but increasing automation will reshape these dynamics. Implemented automation in power system control processes aims to enable efficient operation in an increasingly complex and volatile power grid, yet its implementation must be carefully balanced to maintain operator engagement and expertise. This study highlights that automation risks should be mitigated by designing automation in an operator-centric way:

(1) allowing automation to adapt its activity level to the cognitive load of the operator, avoiding boredom and cognitive overloads
(2) enabling two-way communication between humans and automation to facilitate teaming and collaborative decision making

Future research should define design guidelines for novel intelligent tools, training strategies, and fallback procedures to enable the potential of automation and ensure reliable grid operation while keeping the operators in the loop.

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