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Review:

Situational awareness architecture for smart grids developed in accordance with dispatcher's thought process: a review*

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Abstract: The operational environment of today's smart grids is becoming more complicated than ever before. A number of factors, including renewable penetration, marketization, cyber security, and hazards of nature, bring challenges and even threats to control centers. New techniques are anticipated to help dispatchers become aware of the accurate situations as they manipulate and navigate the situations as quickly as possible. To address the issues, we first introduce the background for this topic as well as the emerging technical demands of situational awareness in the dispatcher's environment. The general concepts and technical requirements of situational awareness are then summarized, aimed at offering an overview for readers to understand the state-of-the-art progress in this area. In addition, we discuss the importance of integrating the architecture of support tools in accordance with the dispatcher's thought process, which in fact guides correct and swift reactions in real-time operations. Finally, the prospects for situational awareness architecture are investigated with the goal of presenting situational awareness modules in an advanced and visualized manner.

Key words: Smart grid, Situational awareness, Dispatcher's thought process, Technical architecture
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1 Introduction

Smart grids nowadays integrate a vast number of new technologies including renewable generation, energy storage, electric vehicles, wide-area monitoring, and high voltage DC transmission systems, which benefit grid modernization, efficiency promotion, and emission reduction. However, these emerging integrations have challenged the traditionally defined secure and economic operation of power systems. For example, large-scale wind power penetration of the grid may cause voltage risks and high reserve costs (Ummels *et al*., 2007); accommodating distributed generations and flexible loads entails weather concerns for dispatchers (Evangelopoulos and Georgilakis, 2014; Olek and Wierzbowski, 2015); complicated hybrid interconnections with DC links increase the difficulties in dynamic security control (Wang *et al*., 2016).

Additionally, the errors caused by insufficient planning may lead to the potential vulnerability of power systems (Chompoobutrgool and Vanfretti, 2013). A cascading failure, the main phenomenon that induces blackouts, is another vital concern of control centers. Inadequate early alerts and inaccurate timely reactions are considered to lead to catastrophic results (de la Ree *et al*., 2005). It has been reported that if dispatchers had been reminded to keep in mind an accurate situational awareness of the power system situation, the blackout that occurred in 2003 in North America might have been avoided (Makarov *et al*.,

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2005). Extreme hazards in nature deteriorate the external environment of power system operations, resulting in a high level of risk for multiple contingences. Dispatchers need to manage the grid in consideration of the impact of weather in that case. Otherwise, the means to mitigate an outage risk becomes unrealistic (Chen *et al*., 2009). Furthermore, repairing power systems after severe disturbances, such as large load curtailment, generator tripping, and islanding, requires comprehensive analysis of state variation and the availability of controllable resources, to help dispatchers make restoration decisions (Sarmadi *et al*., 2011). Furthermore, an effective preparation for the load behavior of electric vehicle charging states and generation forecasting of grid-connected renewable energy (Wan *et al*., 2015) has proved to effectively assist dispatchers in facilitating smart grid energy management.

However, nearly none of conventional technical platforms in current use, the Energy Management System (EMS), for instance, integrate sufficient functions to enable efficient situational awareness in control centers. Although the EMS was developed over 30 years ago with an increasing number of modules having been integrated over time, it is widely acknowledged that there is a long way to go in enabling perfect situational awareness which can facilitate smart gird dispatching (Panteli *et al*., 2013). In recent decades, much attention has been paid to applying emerging technologies to facilitate the development of a new generation of support tools. These technologies basically include phasor measurement units (PMUs), information and communications technology (ICT), common information models (CIMs), data mining, cloud computing, and advanced visualization.

The issues of how to assemble these technical blocks and how to seamlessly establish integrated application platforms for a dispatcher's routine use have been a strong area of interest in recent years. To address these issues, some earlier research from the literature is presented. Giri *et al*. (2012) provided a detailed overview of emerging trends in control centers including situation analysis methods, visualization, and alternative solution recommendations. Some researchers presented the theories, challenges, and applications for situation awareness in power systems, especially as regards individual and team operation consciousness (Panteli and Kirschen, 2015). The importance of highly flexible visualization was highlighted in Schneiders *et al*. (2012), which used a man-machine interface (MMI) to enable global state observation. A group of researchers (Makarov *et al*., 2012) investigated the concept, method, and implementation of PMU-based security awareness technology. An optimal model was proposed for PMU placement aimed at achieving the best situational awareness effectiveness (Sodhi and Sharieff, 2015). Considering wide-area aspects, data stream mining algorithms have been applied by using synchronous data to satisfy the requirement of quick decision making for situational awareness applications (Dahal *et al*., 2015). Novel synchronous baseline data and mining methods have been studied to obtain dynamic security constrained limits which suffer from a computation burden in EMS but are of particular concern to dispatchers (Kaci *et al*., 2014). With the goal of achieving better equivalence conditions for dynamic behavior awareness of external systems, PMU-based parameter identification techniques have been proposed in recent decades (Zhao *et al*., 2015). Furthermore, to enable seamless integration and flexible access for advanced awareness applications in the presence of several different device objects, a highly scalable CIM and interoperable data exchange mechanism are urgently needed (Britton *et al*., 2016).

In this paper, we first briefly introduce the widely accepted concepts of situational awareness, and then address the emerging trends in technology and a comprehensive comparision and investigation of the situational awareness tools applied in smart grids. Subsequently, based on our industrial software development experience and research on smart grid energy dispatching, a closed-loop technical architecture which adapts to the dispatcher thought process is presented to suggest a developing principle for efficient situational awareness support systems for control centers of the future.

2 General concepts of situation awareness

The term 'situation awareness' (SA) has specific meanings in different engineering fields. The most widely accepted definition is stated as "continuous extraction of systemic information along with integration of this information with previous knowledge to form coherent mental pictures, and use of those pictures in directing further perception and anticipating future need" (Vidulich *et al*., 1994). Basically, the aim of efficient situational awareness is to keep operators tightly coupled to the dynamic evolution of a particular environment (Moray *et al*., 2004).

In recent years, many different domains, such as cyber networks, information communication, social networks, transportation systems, and even financial services networks, have implemented SA for their specific purposes. For example, a dynamic monitoring method for traffic flow was studied from the aspect of the driver's situational awareness (Zheng *et al*., 2004). Likewise, SA technology for financial network security has been addressed in the literature (Hauss and Eyferth, 2003). The methods that can enhance emergency situational awareness using wide area social media have been further investigated (Yin *et al*., 2012). The methodology proposed in Yin *et al*. (2012) is quite inspiring for non-centralized big data analytics, and is a useful supplement for specific industrial measurements, such as video monitoring, supervisory control and data acquisition (SCADA), and the Geographic Information System (GIS).

From a technical point of view, the application of situational awareness has three critical levels: perception, comprehension, and projection. Specifically, perception refers to the monitoring of current states and detection of ambient conditions. The term comprehension primarily lies in interpreting the reasons that cause the changes or evolution of status to the given objects. The level of projection emphasizes extrapolating future actions regarding the given boundary conditions and targets. Obviously, the phenomenon of awareness acts to naturally correspond to the questions of what, why, and how. Fig. 1 illustrates the classical three-level structure of the phases of situational awareness (Endsley, 1995).

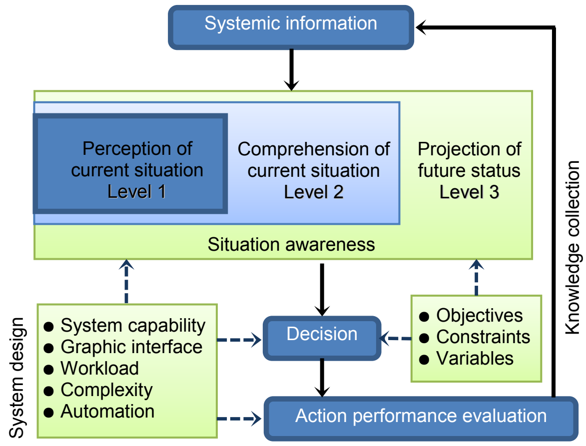


Fig. 1 A three-level illustration of situational awareness

3 Dispatcher thought process oriented situational awareness architecture

3.1 Dispatcher's thought process

As previously discussed, dispatchers are now challenged by increasingly more complicated operational situations than ever before. Therefore, besides personal engineering experience and regular support such as state estimation, *N*-1 analysis, and conventional security assessments, it is important to recognize what dispatchers need for in-depth perception of operational security. According to our study, the following aspects can be regarded as the most significant concerns of control centers.

3.1.1 Multidimensional security awareness

To evaluate comprehensive operational status, the multidimensional concepts shown in Fig. 2 including the associated indices and methods have been proposed in the literature. Specifically, security (Shetty *et al*., 2012), stability (Morison *et al*., 2004), and reliability (Kundur *et al*., 2004) already have widely recognized definitions. The term 'vulnerability' (Tesseron, 2008) has already benefited from extensive investigation in the last decade, as it refers to phenomena involving criticality, weak links, unreasonable topology, low ability for survival from successive attacks, and operational bottlenecks constrained by compulsive margins.

Despite the fact that the aforementioned terms have distinguishably highlighted features, there usually exists some overlapping application in the assessment model and engineering explanation. However, the goal of achieving an accurate evaluation in all aspects for a smart grid necessitates providing packages of effective indices based on diverse analytics, which enable dispatchers to infer the operational margin domain and consequently determine reasonably secure boundaries for any control strategy.

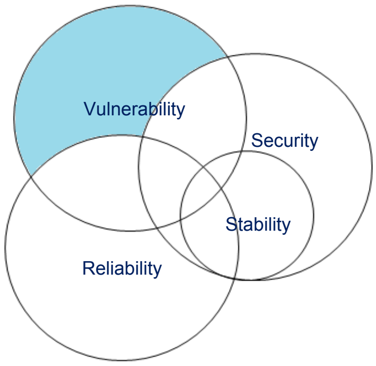


Fig. 2 Overlapping content within security situation evaluations for a smart grid

3.1.2 Awareness: looking ahead

New technical challenges have emerged for smart grids. For example, the rapid variation of power flow balance conditions due to large-scale renewable penetration has caused difficulty for control centers to obtain adequate operational knowledge of the power system through currently implemented applications. In addition, emergencies like accidental faults and relay operation errors probably lead to topology change and critical parameter variations, requiring dispatchers to track a rapidly changing situation as accurately as possible.

Therefore, situational analytics based on future security is necessary for tracking a rapidly changing operational status and predicting the probabilistic risk of on-going operation scenarios as well as pre-set contingencies in pursuance of facilitating trend-based security perception for dispatchers. Fig. 3 illustrates a part of the procedure. However, appropriate modeling methods and advanced computing schemes are requested for addressing this forthcoming challenge.

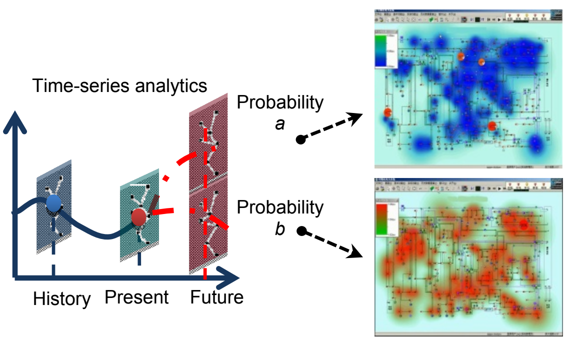


Fig. 3 Graphical illustration of tracking future operational situations

3.1.3 Event-driven strategy assistance

In addition to regular security assessment and margin alarms based on evaluating multiple performance indices, event-driven countermeasure assistance for abnormal conditions according to computationally modeled solutions is desired by dispatchers. Abnormal conditions refer to the major failures or faults and operating scenarios for which the monitored status is outside the secure boundaries.

Basically, strategy assistance, such as suggestions for load shedding, generation re-dispatching, and substation wire switching, must be quickly updated along with operational condition changes. This assistance can be very useful for dispatchers especially when facing cascading failures because some critical experiential knowledge, sensitivity, and voltage controllability, for example, may be less effective due to substantial variations in power system operation modes. In this area, a high-performance computing scheme is necessary to help dispatchers make accurate online decisions (Tian *et al*., 2016).

3.1.4 Experience collection and knowledge mining

Using historical data, we can significantly enhance the ability of the operational personnel to perform event analysis on an as-needed basis (Kezunovic, 2011). For example, successful solutions, such as mitigating operational risk, reducing contingency impacts, and solving major faults, can be expected to aid dispatchers when they face similar conditions. This approach may enable considerable improvement in the comprehension and projection of ideal online situational awareness. However, two technical challenges exist in the field. The first is the method that models experience or detects operational rules, which should be reflected in the intended visualization presented in a control center. Such a visualization should offer a clear snapshot to dispatchers. The second is how to identify similarities between stored cases and real-time scenarios. However, few cases in the literature have focused on these studies thus far.

On the other hand, data mining based awareness tools for potential operational rules for smart grids are effective supplements for decision making on the part of dispatchers. There exist quite a few algorithms in the literature that focus on power system operation rule detection, many of which enable dispatchers to obtain helpful information. For example, a typical application of support vector machine (SVM) for transient stability awareness was presented to help dispatchers understand the nature of vulnerability (Moulin *et al*., 2004). To implement online contingency screening and ranking, a supervised learning approach was proposed with several static security indices as input features (Verma and Niazi, 2012). Furthermore, a composited classifier incorporating static and transient features was established to recognize security patterns (Kalyani and Swarup, 2013). Besides adaptive operating status prediction, the preventive control scheme and optimal power flow (OPF) can also be integrated with data-driven modeling, for instance, by means of a neural-network and decision tree (Gutierrez-Martinez *et al*., 2011). In addition, a novel electric power knowledge theory model was proposed to solve the problem of normalized modeling of electric power expertise for a particular management and analysis of smart grid big data (Huang and Zhou, 2015).

3.1.5 Flowchart of dispatcher's thought processes related to technical requirements

The preferable SA framework applied in a control center should organize the relevant functionalities according to dispatchers' cognitive procedures. This cognition generally refers to a kind of inferential ability for predicting, recognizing, analyzing, and solving operational problems. Meanwhile, it is commonly agreed that the SA framework should be capable of enhancing interactive integration of dispatchers' cognition and the associated applications. Fig. 4 illustrates a generalized flowchart for dispatcher cognition associated with SA functionalities.

As shown in Fig. 4, a dispatcher's thought process can be divided into six blocks, each of which needs a suite of appropriate SA functionalities to improve individual performance. Generally, when a fault occurs, rather than manually examining SCADA, it is more efficient for control centers to visualize the contingency situation by means of visible trajectories and the contouring of critical parameters (Fig. 3). In such a case, the variation in dynamic security indicators for the fault area and more global aspects can be monitored at the same time. After observing the on- and post-fault evolution of events, it is quite natural for dispatchers to logically infer which details were out of sync, including the fault event process and eventually the system-wide impacts. There is no doubt that a precise graphical demonstration of the sequence of event (SOE) and tripping analysis would greatly contribute to more comprehensive judgment in the control center.

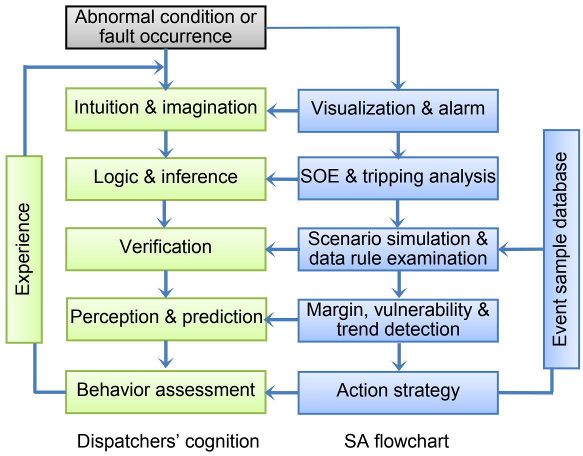


Fig. 4 An illustrative diagram of the relationship between a dispatcher's thought process and the situational awareness workflow

However, based on initial understandings, dispatchers need to be aware of the possible evolution of future operations, considering the probabilistic time-varying features of a power system. Online simulation and verification depending on rapid systemic modeling and data mining analytics are thus particularly necessary. With the support of exploratory multidimensional security computation, the perception of a current situation and the near future state can be enabled, providing evidence for further control strategies. Once the dispatch actions are executed, the assessment program should be launched with the aim of quantifying the effects of SA procedures and producing feedback for dispatchers. From the point of view of gaining experience, the strategy assessment is conducive to quantifying the resulting performance as well as effectiveness of the specific reactions. With regard to the SA aspect, the recorded operational scenarios involving human intervention can be used as offline training and online reference samples for dispatchers.

To clarify the primary gap between the currently applied EMS and the expected SA framework, Table 1 lists the basic features and required characteristics.

Table 1 The basic performance comparison between the current Energy Management System (EMS) and advanced situation awareness (SA)

Awareness stage	Conventional EMS	Advanced SA
Intuition & imagination	Traditional visualization Artificial roaming Steady showcase	Multi-level visualization Smart focusing Dynamic tracing
Logic & inference	Simple judgment Determinative analysis Threshold alarm	Composite criterion Probabilistic analysis Sequence monitoring
Cognition verification	Parallel computing Modeling-driven Passive configuration	Cloud-based computing Data-driven Knowledge discovery Proactive evolution
Perception & prediction	Limited indicators Load prediction Information island Impact estimation	Comprehensive security Trend identification Integrated implementation Risk evaluation
Behavior assessment	Post-fault evaluation Simple strategy Adaptivity to simple attack	Multi-impact evaluation Strategy suggestion with risk ranking Cascading failure alerts
Experience acquisition	Not available	Scenario storage Similarity based analysis Fault feature extraction Smart expert diagnosis

3.2 Tiered technology components

Technically, smart grids necessitate specific modules to reinforce the dispatchers' ability to draw precise inferences and consequently plan correct strategies. Unlike social networks and ecological systems, deploying SA in a smart grid can partly be based on existing real-time data acquisition systems. Despite the fact that these monitoring systems are capable of measuring operating snapshots and transferring data to a control center, due to the lack of sufficient awareness-oriented analytics, e.g., stability margins and transmission limits, it is hard to support operation decisions unless complicated calculations are carried out. In addition, any deficiency or inaccuracy in the technical factors, including mathematical models, algorithms, and information collection, probably causes highly misguided results in security perception, which instead endangers secure operations. Therefore, it is important to investigate the technological components that may contribute to establishing high-performance SA for a smart grid.

3.2.1 Architecture layer

Acquiring adequate SA requires a novel architecture to organize overall security perception routines. Although the traditional SCADA-based EMS, the most important decision support infrastructure currently in use, has been upgraded for several decades, it is still considered to lack sufficient compatibility and scalability for future SA functionality. Consequently, the demand for these features by dispatchers now and in the years ahead is not completely satisfied. Fig. 5 simply illustrates the flowchart of a conventional state estimation (SE) based on EMS states with some extra scenarios that are requested.

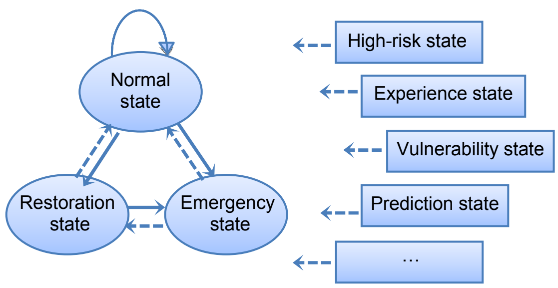


Fig. 5 Current Energy Management System (EMS) architecture and awareness demands on dispatchers

Obviously, the current EMS can hardly cover all the expected functions. The primary reasons we suppose is that, to date, there has been little research focused on the details of a dispatcher's thought process and the dispatcher's need to make inferences.

However, as the proactive brain of the smart grid, the dispatcher's decision procedures should be emphasized as a critical part of the top-level design for an SA architecture.

3.2.2 ICT layer

In the last decades, an expanding implementation of ICT, which represents a fundamental element in the growth of smart grids, has been evidenced (Kezunovic and Bose, 2013). Technically, ICT used in smart grids is categorized as a small set of layers, consisting of component, communication, information, function, and business layers (Albano *et al.*, 2015). The CIM defined by the IEC 61970 and IEC 61968 series of standards, for example, is widely known as the prevailing Unified Modeling Language (UML) based modeling method for the component layer representing the physical entities of smart grids in software models, as well as exchange protocols. Smart Energy Profile (SEP) 2.0 (ZigBee Alliance, 2013), a part of the ZigBee suite, is another novel ICT approach focusing on the modeling of demand response, load control, metering, and billing behaviors. In the communication layer of an ICT for a smart grid, infrastructures such as WiMax, HAN, RF Mesh, and Fiber/DSL/PLC have been investigated (Gungor *et al.*, 2013), a number of which have been demonstrated in practice in systems. There is no doubt that a well-deployed ICT architecture is the prerequisite for facilitating SA with high efficiency and performance. On the other hand, due to the increasing importance of ICT technology support, the performance of cyber-physical electrical energy systems is becoming an essential concern in dispatching centers (Shi *et al.*, 2015).

3.2.3 Data layer

The data content acquisition under rich measurement conditions has been largely expanded, bringing into the control center significant value in the applications and also major challenges. McDonald *et al.* (2007) proposed a data mart architecture, incorporating smart grid operational data and valuable non-operational information, which also clarifies the different data uses for diverse user groups of utilities using data requirement matrices.

Meanwhile, according to some earlier studies, smart grids should no longer be seen as an isolated infrastructure offering electrical energy, but a complex network interactively coupled with other associated systems. Besides the measured operation data, external information such as hazards of nature, vegetation growth, and EV charging periods is crucial for the future of SA, because the factors involved have strong impacts on smart grid operation. However, excellent performance in data applications requires highly compatible incorporation with ICT, and the modeling and computation layers (Fig. 6).

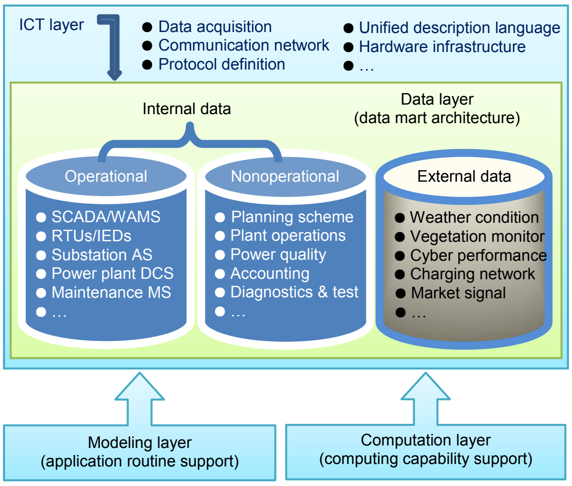


Fig. 6 Illustration of data layer components

3.2.4 Modeling layer

Many emerging participants have already accessed the smart grid. For example, plug-in EVs probably replace quite a number of oil fuel cars in the future. However, the time-varying charging and discharging loads significantly impact power system operation, especially at the distribution level. Technically, it is evidenced that modeling of EV charging behaviors will contribute to security estimation and the corresponding strategies of smart grids (Ortega-Vazquez *et al.*, 2013). Specifically, the modeling layer represents the complete collection of the mathematical models of components or sections integrated in the smart grid, which can be applied to perform prediction, simulation, optimization, and control for specific situational awareness targets.

Besides the modeling of new electrical components such as wind farms, photovoltaic generation, and Flexible Alternative Current Transmission Systems (FACTs), precise numerical models of market mechanisms and renewable energy trading schemes as well as multi-energy systems integration are necessary for identifying the comprehensively global security. A few novel methods of analogy including multi-agent technology have been employed in this area (Shafie-khah and Catalão, 2015).

On the other hand, to use a vast amount of historical measurement data to address the problems that cannot be straightforwardly solved by traditional modeling, data-driven methodologies containing data mining and knowledge discovery are studied and employed in fields such as security prediction and online dynamic equivalence. For example, a neural network was trained to replace a physical model of a wind turbine system (Kong *et al*., 2014). Novel data-driven analytics for establishing interactive visualization of power systems have also been investigated (Zhu *et al*., 2011). Additionally, efficient online dynamic modeling methods are being considered to improve dispatchers' awareness by employing the response trajectory of smart grids.

3.2.5 Computing layer

To determine operating vulnerability and recommend strategies as promptly as possible for dispatchers, the handling of the huge data that emerges and complicated models should be considered. This demand has already caused high computation intensity for control centers. Specifically, future implementations such as extremely large-scale contingency analysis, hybrid time-scale simulation, and a real-time even faster-than-real-time simulator (Matar and Iravani, 2013) necessitate advanced computing architectures to support SA execution. Novel calculation strategies, innovative computing infrastructure, and sufficient computation capabilities must therefore basically be evolved, which together constitute the computation layer. For example, a MapReduce-based computing framework assembling parallelized neural networks was investigated by Liu *et al*. (2016), to provide high performance for computation-intensive tasks, such as online identification of critical unstable generators.

So far, high performance parallels, distributed and grid computing with high scalability have been proposed for application in the smart grid (Shahriar Muttalib *et al*., 2013). However, the promising computation concept 'cloud computing' has drawn particular attention in recent years (Bera *et al*., 2015), owing to its innovative all-in-service architecture.

3.2.6 Display layer

The term 'display layer' refers to the technical packages facilitating user-friendly visualization interfaces for dispatchers. Mapping real-time snapshots and indices analyzed online into the dispatcher's mental picture in a concise and informative manner without absence of critical information is an important goal to be accomplished in SA. Although the visualization technologies applied nowadays have been studied for a long time from the viewpoint of functional design to graphic layout, it is not an easy task to establish a highly scalable and dynamically intuitive visual platform along with SA development (Dutta and Overbye, 2014).

Rather than showing measured operational information based on unchanging patterns, the ideal display layer should be able to automatically switch to the right user interfaces and highlight points according to the dispatcher's focus. In addition, intuitive visualization or virtual reality is needed to highlight the tracing of a situation's progress and rank strategy hints to dispatchers.

Compared with the conventional decision support suites applied in control centers today, the implementation of the aforementioned techniques for advanced online situational awareness has higher requirements, which are listed in Table 2.

3.3 Principles and demonstrations of architecture

3.3.1 Principles of situation awareness development

There are a few studies investigating the relationship between the thought patterns of human cognitive processing and situation awareness. Most of them are from the perspective of general systemic science rather than smart grid application. Some studies explained the problem of human-computer collaboration toward improving SA based on the theory of ontology (Kokar and Endsley, 2012). The logical cognitive models of the human brain have been studied using cognitive informatics and formal methodologies, which provide object-attribute-relation models to describe cognition procedures (Wang and Wang, 2006). Technically, the individual cognitive process of SA is limited to the amount of information and the level of complexity. The human-centered situation assessment was thus proposed, clarifying the cognition stages most concerned with damage assessment, object state estimation, and situation projection (Holsopple *et al*., 2010).

Table 2 The characteristics of the technical layers involved in the situation awareness framework

Layer	Characteristics & requirements
Architecture	High scalability, flexibility, and compatibility Plugging and playing modularization management Better adaptivity to dispatcher's thought process Restructuring online application routines
ICT	Standardization and scalability management Unified description and protocols Complete convergence for all participating components Enabling high interoperability and testability
Data	Operation & non-operation data acquisition Cross time-scale measureable information fusion Novel database design, such as Hadoop structures External data import and basic analytics
Modeling	Compatibility for data-driven methodologies Wide-area synchronized trajectory implementation Novel simulation mechanisms & algorithms Innovative application and routine development Support for non-operational application modeling
Computation	Enabling cloud computing infrastructure Sufficient computing capability and efficiency Enabling big data analytics Integrating abundant algorithm libraries Supporting user-defined computing workflow
Display	Facilitating intuitive online security perception Highly user-friendly graphical interfaces Compatibility for complicated data environments High flexibility of user-defined visual patterns Guidance roaming for emergency processing

With regard to implementation in smart grids, four levels of control center awareness, i.e., eye, reactive brain, analytical brain, and proactive brain, have been studied for better management of the future grid (Giri, 2015). In addition, a suite of novel visualization methodologies has been presented to enhance awareness competence for global system states (Schneiders *et al*., 2012). Aiming to aid dispatchers in being aware of a holistic situation under a highly uncertain environment, a multi-layer reasoning and analysis tool driven by measured data was proposed, particularly highlighting cognitive knowledge mining for the demand side (Lu *et al*., 2012).

The critical points of assisting security awareness for dispatchers, however, primarily focus on developing preferable assessment modules adapting to diverse time-scale modeling for more comprehensive operating scenarios, as well as facilitating excellent interaction between dispatchers and computers. Although each dispatcher has different operational habits, experience, and understanding, as discussed in the previous section, they basically expect informatively automated assistance in similar patterns. Particularly, oscillation identification and control assistance are regarded as the important tasks of synchrophasor solutions. Hence, an oscillation event shown in Fig. 7 is taken into account as an example to illustrate the event-tracing pattern of a dispatcher's thought process.

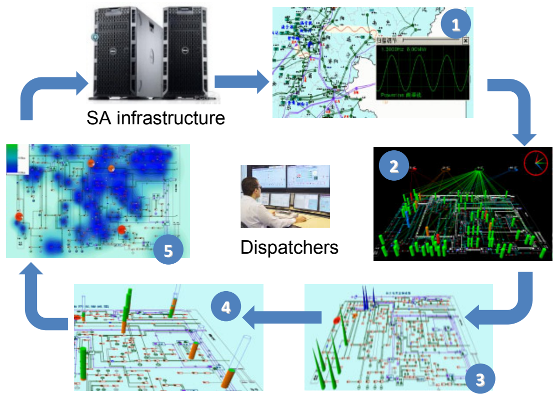


Fig. 7 An example of oscillation event tracing

As shown in Fig. 7, the cognition starts from identifying the power oscillation status and graphically alarming the situation to dispatchers (stage 1). The careful observation afterward, and especially a dynamic risk evolution, is necessary. Stage 2 shows the slow coherency based segment visual result, which enables dispatchers to globally evaluate the dynamic security of a power system as rapidly as possible, rather than just paying attention to a few oscillating transmission lines. In fact, not only coherency status, but also other important indicators assessing dynamic impacts on either a global or local level, should be rapidly computed and animatedly reflected to the control center. Fig. 8 presents the automated in-depth awareness for situation evolution, which belongs to stage 2 and is triggered by an oscillation event.

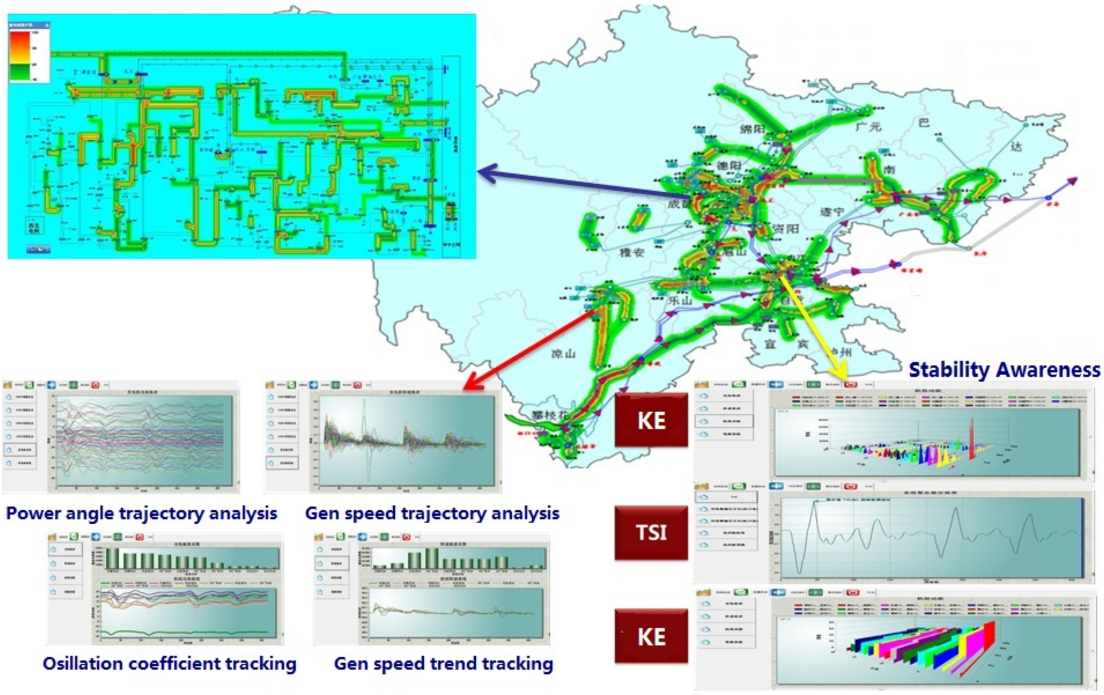


Fig. 8 Automated comprehensive analysis and visualization executed by an oscillation event

To mitigate oscillation efficiently, stage 3 provides the necessary parameters, such as primary oscillation mode, leading generators, and associated damping, reflecting the characteristics of on-going oscillation. However, it is probably not enough to make the most effective mitigation decision. Therefore, the next stage brings in the available controllable resources that dispatchers should be aware of, ramp-rate and reserve limitation, for instance. Incorporating the overall information, one or several sets of available solutions for enhancing dynamic stability will be involved in stage 4. In the final cognition stage the eventual strategy outcomes are evaluated as performance feedback.

The awareness of an oscillation event that seems to be of assistance has a quite similar workflow as presented in Fig. 4. The operation pattern managing the disturbances and abnormal events through a similar cognition procedure can be identified as dispatcher thought process based situation awareness. Generally speaking, the skeleton framework associated with the generalized functionalities of the proposed SA which enables the preferable security awareness for future control centers, is presented in Fig. 9.

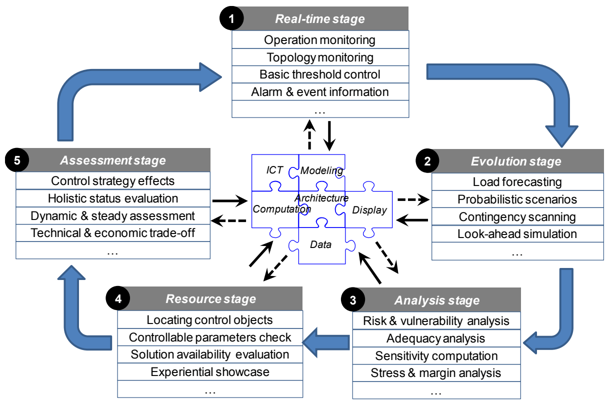


Fig. 9 Situation awareness framework enabling a pattern of assistance for dispatchers' perception

3.3.2 Practical implementation cases

To offer advanced assistance tools to dispatchers, a number of related techniques have been integrated according to the principles discussed, many of which have been practically deployed. For example, a real-time off-grid operation detection tool based on WAMS measurement was implemented in North America, providing a successful option to help dispatchers be aware of a dynamic situation from a frequency perspective (Guo *et al*., 2015). Similarly, the

Hydro-Quebec system has established a WAMS-based data-mining platform, aimed at alerting the control center of dynamic security limits (Kaci *et al.*, 2014).

At the computing layer, a novel trusted cloud-computing framework has been deployed in the UK grid, which can provide highly scalable computational capabilities for data-intensive smart grid applications (Sule *et al.*, 2015). A number of advanced hardware architectures were gradually deployed to ensure a high-performance-computing scheme for situational awareness (Deese and Nwankpa, 2014).

3.3.3 Illustrative demonstration

According to the general concept of situation awareness, using visualization to enable mental picture mapping for dispatchers is an important option to achieve highly efficient SA. In this section, a few demonstrations of the techniques discussed are simply illustrated based on our development experience with realistic power systems.

Fig. 10 shows a screenshot of the smart grid cyber security monitoring and alarm system (SINMAS) that we developed, which is partly modeled using a cyber vulnerability model (Vellaithurai *et al.*, 2015) and can provide alert information reminders of cyber malfunctions that occurred in the EMS, dispatch communication network, and PMIS to the dispatchers. Applying this technique can help dispatchers understand the health level of a cyber environment as quickly as possible and avoid potential problems in operation due to errors of the cyber systems.

Fig. 11 illustrates four essential visualization perspectives of smart grid operation integrated in an online application suite, which enables dispatchers to easily facilitate tracing the evolution of a situation and investigating emergencies efficiently, aided by the backstage modeling and computation layers.

Along with the rapid progress in graphic programming and visual analytics, the increasing amount of modeling methodologies and more adequate data acquisition can be applied to support future display platforms. Basically, the display layer should enable the SA framework to visualize the contents categorized as follows:

1. Systematic operation level: to graphically illustrate real-time steady and dynamic information via SCADA and PMU, respectively.

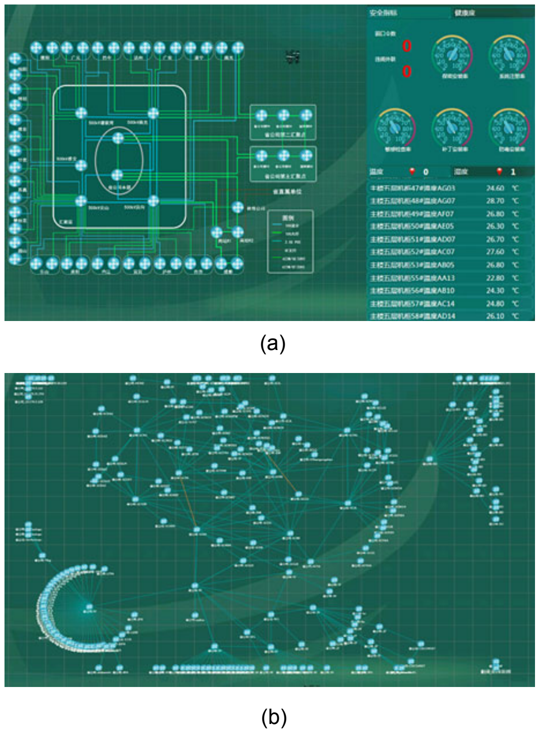


Fig. 10 Performance monitoring of cyber systems for one provincial power grid company and its own distribution companies (a) and routing network monitoring and malfunction diagnosis of information system topology of the smart grid (b)

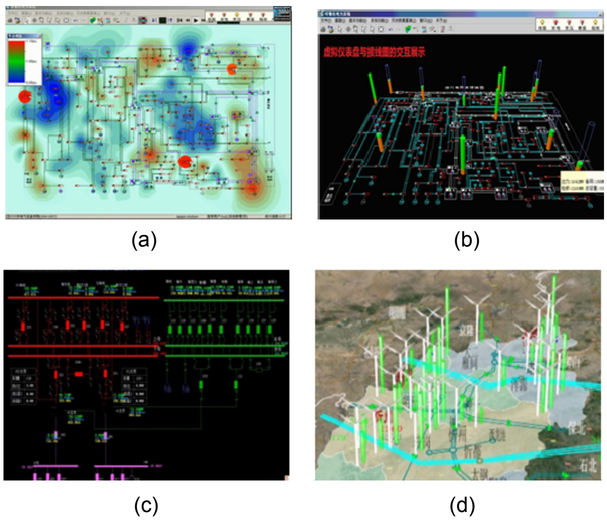


Fig. 11 Steady operational situation (a), capacity real-time monitoring (b), substation diagram alarm (c), and critical component monitoring (d)

2. Substation and device level: to display operating data and measured status information of transmission devices, including transformers, GIS, lines,

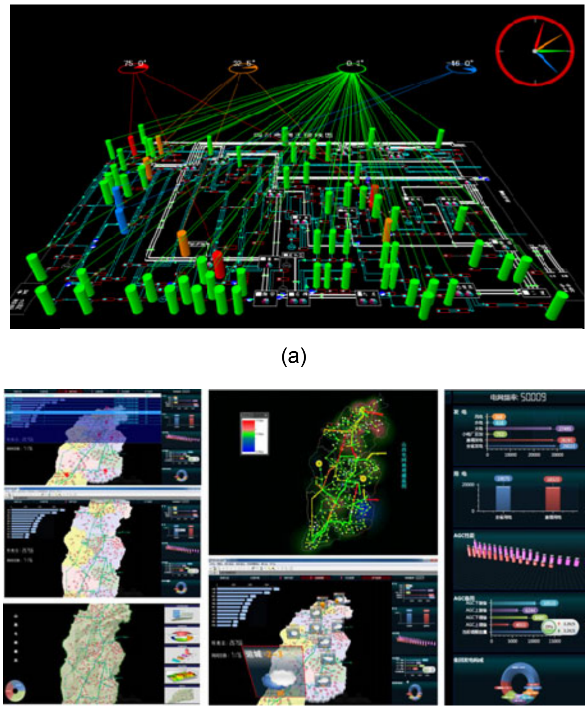
and cables.

3. Non-operational level: to visualize the necessary repositories of non-centralized measured data for dispatchers to improve global understanding.

4. Trend level: to show the predictive operation scenarios especially for post-fault conditions interacting with the configurations of the dispatchers and analyzers.

5. Analytics level: to intuitively reflect data- and model-driven calculated security indices including a variety of margins, vulnerabilities, and risks to provide quantified early warning.

Fig. 12a shows the coherency monitoring and analysis based on WAMS, which is able to integrate the analysis methods presented in previous papers, for example, energy function-based assessment and online mode identification. Fig. 12b illustrates our SA application environment developed for smart grid control centers. The platform coordinates the technical layers discussed in Section 3 and organizes each function considering the dispatcher's thought process.



(a)

(b)

Fig. 12 Coherency monitoring and analysis based on the Wide Area Measurement System (a) and an overview of the application environment (b)

4 Conclusions

Acquiring adequate situational awareness for a control center can assist dispatchers in operating the power system in a more secure and economic manner. To investigate related SA solutions and fundamental techniques, a variety of technical fields including architecture, ICT, data, modeling, computation, and display were discussed. Based on the tiered technical components, a principle for SA designed in accordance with the dispatcher's thought process was proposed. A number of demonstrations were illustrated. This work may contribute to the establishment of an innovative SA framework in the future. Although the functionalities highlighted in this paper basically lie in software implementation, it should be emphasized that the hardware innovations, including measurement sensors, computing cluster servers, and communication infrastructure, practically play a fundamental role in supporting the proposed framework.

However, it is worth noting that the existing EMS and related decision-making systems have been successfully implemented in power systems for a few decades. The aim of the SA architecture presented here is not to replace those well-established platforms; instead, it aims to incorporate SA concepts to enhance dispatchers' capabilities in the realm of security awareness and situational inferences within their routine operations.

References

Albano, M., Ferreira, L.L., Pinho, L.M., 2015. Convergence of smart grid ICT architectures for the last mile. *IEEE Trans. Ind. Inform.*, **11**(1):187-197. http://dx.doi.org/10.1109/TII.2014.2379436

Bera, S., Misra, S., Rodrigues, J.J.P.C., 2015. Cloud computing applications for smart grid: a survey. *IEEE Trans. Parall. Distr. Syst.*, **26**(5):1477-1494. http://dx.doi.org/10.1109/TPDS.2014.2321378

Britton, J., Brown, P., Moseley, J., *et al.*, 2016. Optimizing operations with CIM: today's grid relies on network analysis (and a lot of data). *IEEE Power Energy Mag.*, **14**(1):48-57. http://dx.doi.org/10.1109/MPE.2015.2481783

Chen, Q.Q., Yin, X.G., You, D.H., *et al.*, 2009. Review on blackout process in China southern area main power grid in 2008 snow disaster. IEEE Power & Energy Society General Meeting, p.1-8. http://dx.doi.org/10.1109/PES.2009.5275700

Chompoobutrgool, Y., Vanfretti, L., 2013. Identification of power system dominant inter-area oscillation paths. *IEEE*

Trans. Power Syst., **28**(3):2798-2807. http://dx.doi.org/10.1109/TPWRS.2012.2227840

Dahal, N., Abuomar, O., King, R., *et al.*, 2015. Event stream processing for improved situational awareness in the smart grid. *Expert Syst. Appl.*, **42**(20):6853-6863. http://dx.doi.org/10.1016/j.eswa.2015.05.003

Deese, A.S., Nwankpa, C.O., 2014. Development of custom FPAA hardware for faster-than real-time analysis of power system dynamics. IEEE PES General Meeting | Confe. & Exposition, p.1-5. http://dx.doi.org/10.1109/PESGM.2014.6939094

de la Ree, J., Liu, Y.L., Mili, L., *et al.*, 2005. Catastrophic failures in power systems: causes, analyses, and countermeasures. *Proc. IEEE*, **93**(5):956-964. http://dx.doi.org/10.1109/JPROC.2005.847246

Dutta, S., Overbye, T.J., 2014. Feature extraction and visualization of power system transient stability results. *IEEE Trans. Power Syst.*, **29**(2):966-973. http://dx.doi.org/10.1109/TPWRS.2013.2283276

Endsley, M.R., 1995. Towards a theory of situation awareness in dynamic systems. *Human Factors*, **37**(1):32-64. http://dx.doi.org/10.1518/001872095779049543

Evangelopoulos, V.A., Georgilakis, P.S., 2014. Optimal distributed generation placement under uncertainties based on point estimate method embedded genetic algorithm. *IET. Gener. Transm. Distr.*, **8**(3):389-400. http://dx.doi.org/10.1049/iet-gtd.2013.0442

Giri, J., 2015. Proactive management of the future grid. *IEEE Power Energy Technol. Syst. J.*, **2**(2):43-52. http://dx.doi.org/10.1109/JPETS.2015.2408212

Giri, J., Parashar, M., Trehern, J., *et al.*, 2012. The situation room: control center analytics for enhanced situational awareness. *IEEE Power Energy Mag.*, **10**(5):24-39. http://dx.doi.org/10.1109/MPE.2012.2205316

Gungor, V.C., Sahin, D., Kocak, T., *et al.*, 2013. A survey on smart grid potential applications and communication requirements. *IEEE Trans. Ind. Inform.*, **9**(1):28-42. http://dx.doi.org/10.1109/TII.2012.2218253

Guo, J.H., Zhang, Y., Young, M.A., *et al.*, 2015. Design and implementation of a real-time off-grid operation detection tool from a wide-area measurements perspective. *IEEE Trans. Power Syst.*, **6**(4):2080-2087. http://dx.doi.org/10.1109/TSG.2014.2350913

Gutierrez-Martinez, V.J., Canizares, C.A., Fuerte-Esquivel, C.R., *et al.*, 2011. Neural-network security-boundary constrained optimal power flow. *IEEE Trans Power Syst.*, **26**(1):63-72. http://dx.doi.org/10.1109/TPWRS.2010.2050344

Hauss, Y., Eyferth, K., 2003. Securing future ATM-concepts' safety by measuring situation awareness in ATC. *Aerosp. Sci. Technol.*, **7**(6):417-427. http://dx.doi.org/10.1016/S1270-9638(02)00011-1

Holsopple, J., Sudit, M., Nusinov, M., *et al.*, 2010. Enhancing situation awareness via automated situation assessment. *IEEE Commun. Mag.*, **48**(3):146-152. http://dx.doi.org/10.1109/MCOM.2010.5434386

Huang, Y.H., Zhou, X.X., 2015. Knowledge model for electric power big data based ontology and semantic web. *CSEE J. Power Energy Syst.*, **1**(1):19-27. http://dx.doi.org/10.17775/CSEEJPES.2015.00003

Kaci, A., Kamwa, I., Dessaint, L.A., *et al.*, 2014. Synchrophasor data baselining and mining for online monitoring of dynamic security limits. *IEEE Trans. Power Syst.*, **29**(6):2681-2695. http://dx.doi.org/10.1109/TPWRS.2014.2312418

Kalyani, S., Swarup, K.S., 2013. Pattern analysis and classification for security evaluation in power networks. *Int. J. Electr. Power Energy Syst.*, **44**(1):547-560. http://dx.doi.org/10.1016/j.ijepes.2012.07.065

Kezunovic, M., 2011. Translational knowledge: from collecting data to making decisions in a smart grid. *Proc. IEEE*, **99**(6):977-997. http://dx.doi.org/10.1109/JPROC.2011.2112631

Kezunovic, M., Bose, A., 2013. The future EMS design requirements. 46th Hawaii Int. Conf. on System Sciences, p.2354-2363. http://dx.doi.org/10.1109/HICSS.2013.520

Kokar, M.M., Endsley, M.R., 2012. Situation awareness and cognitive modeling. *IEEE Intell. Syst.*, **27**(3):91-96. http://dx.doi.org/10.1109/MIS.2012.61

Kong, X.B., Liu, X.J., Lee, K.Y., 2014. Data-driven modelling of a doubly fed induction generator wind turbine system based on neural networks. *IET Renew. Power Gener.*, **8**(8):849-857. http://dx.doi.org/10.1049/iet-rpg.2013.0391

Kundur, P., Paserba, J., Ajjarapu, V., *et al.*, 2004. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. *IEEE Trans. Power Syst.*, **19**(3):1387-1401. http://dx.doi.org/10.1109/TPWRS.2004.825981

Liu, Y., Liu, Y., Liu, J., *et al.*, 2016. High-performance predictor for critical unstable generators based on scalable parallelized neural networks. *J. Modern Power Syst. Clean Energy*, **4**(3):414-426. http://dx.doi.org/10.1007/s40565-016-0209-4

Lu, N., Du, P.W., Greitzer, F.L., *et al.*, 2012. A multi-layer, data-driven advanced reasoning tool for intelligent data mining and analysis for smart grids. IEEE Power and Energy Society General Meeting, p.1-7. http://dx.doi.org/10.1109/PESGM.2012.6345180

Makarov, Y.V., Reshetov, V.I., Stroev, V.A., *et al.*, 2005. Blackouts in North America and Europe: analysis and generalization. IEEE Power Tech, p.1-7. http://dx.doi.org/10.1109/PTC.2005.4524782

Makarov, Y.V., Du, P.W., Lu, S., *et al.*, 2012. PMU-based wide-area security assessment: concept, method, and implementation. *IEEE Trans. Smart Grid*, **3**(3):1325-1332.

http://dx.doi.org/10.1109/TSG.2012.2193145

Matar, M., Iravani, R., 2013. The reconfigurable-hardware real-time and faster-than-real-time simulator for the analysis of electromagnetic transients in power systems. *IEEE Trans. Power Del.*, **28**(2):619-627. http://dx.doi.org/10.1109/TPWRD.2012.2229723

McDonald, J.D., Rajagopalan, S., Waizenegger, J.R., *et al.*, 2007. Realizing the power of data marts. *IEEE Power Energy Mag.*, **5**(3):57-66. http://dx.doi.org/10.1109/MPAE.2007.365821

Moray, N., Vincenzi, D.A., Mouloua, M., *et al.*, 2004. Human Performance, Situation Awareness and Automation: Current Research and Trends. LEA, Mahwah.

Morison, K., Wang, L., Kundur, P., 2004. Power system security assessment. *IEEE Power Energy Mag.*, **2**(5):30-39. http://dx.doi.org/10.1109/MPAE.2004.1338120

Moulin, L.S., da Silva, A.P.A., El-Sharkawi, M.A., *et al.*, 2004. Support vector machines for transient stability analysis of large-scale power systems. *IEEE Trans. Power Syst.*, **19**(2):818-825. http://dx.doi.org/10.1109/TPWRS.2004.826018

Olek, B., Wierzbowski, M., 2015. Local energy balancing and ancillary services in low-voltage networks with distributed generation, energy storage, and active loads. *IEEE Trans. Ind. Electron.*, **62**(4):2499-2508. http://dx.doi.org/10.1109/TIE.2014.2377134

Ortega-Vazquez, M.A., Bouffard, F., Silva, V., 2013. Electric vehicle aggregator/system operator coordination for charging scheduling and services procurement. *IEEE Trans. Power Syst.*, **28**(2):1806-1815. http://dx.doi.org/10.1109/TPWRS.2012.2221750

Panteli, M., Kirschen, D.S., 2015. Situation awareness in power systems: theory, challenges and applications. *Electr. Power Syst. Res.*, **122**:140-151. http://dx.doi.org/10.1016/j.epsr.2015.01.008

Panteli, M., Crossley, P.A., Kirschen, D.S., *et al.*, 2013. Assessing the impact of insufficient situation awareness on power system operation. *IEEE Trans. Power Syst.*, **28**(3):2967-2977. http://dx.doi.org/10.1109/TPWRS.2013.2240705

Sarmadi, S.A.N., Dobakhshari, A.S., Azizi, S., *et al.*, 2011. A sectionalizing method in power system restoration based on WAMS. *IEEE Trans. Smart Grid*, **2**(1):190-197. http://dx.doi.org/10.1109/TSG.2011.2105510

Schneiders, C., Vanzetta, J., Verstege, J.F., 2012. Enhancement of situation awareness in wide area transmission systems for electricity and visualization of the global system state. Proc. 3rd IEEE PES Int. Conf. and Exhibition on Innovative Smart Grid Technologies, p.1-9. http://dx.doi.org/10.1109/ISGTEurope.2012.6465665

Shafie-khah, M., Catalão, J.P.S., 2015. A stochastic multi-layer agent-based model to study electricity market participants behavior. *IEEE Trans. Power Syst.*, **30**(2):867-881. http://dx.doi.org/10.1109/TPWRS.2014.2335992

Shahriar Muttalib, A.Z.M., Taylor, G., Bradley, M., 2013. Investigating scalable computational tools and infrastructure to enable interoperable and secure control of large-scale power systems. 48th Int. Universities' Power Engineering Conf., p.1-6. http://dx.doi.org/10.1109/UPEC.2013.6715043

Shetty, R., Fan, J.Y., McDonald J.D., 2012. Improving utility operational excellence through non-operational data management. IEEE PES Innovative Smart Grid Technologies, p.1-6. http://dx.doi.org/10.1109/ISGT.2012.6175623

Shi, X.Y., Li, Y., Cao, Y.J., *et al.*, 2015. Cyber-physical electrical energy systems: challenges and issues. *CSEE J. Power Energy Syst.*, **1**(2):36-42. http://dx.doi.org/10.17775/CSEEJPES.2015.00017

Sodhi, R., Sharieff, M.I., 2015. Phasor measurement unit placement framework for enhanced wide-area situational awareness. *IET Gener. Transm. Distr.*, **9**(2):172-182. http://dx.doi.org/10.1049/iet-gtd.2014.0215

Sule, M.J., Li, M.Z., Taylor, G.A., *et al.*, 2015. Deploying trusted cloud computing for data intensive power system applications. 50th Int. Universities Power Engineering Conf., p.1-5. http://dx.doi.org/10.1109/UPEC.2015.7339864

Tesseron, J.M., 2008. Mission: reliability. *IEEE Power Energy Mag.*, **6**(1):42-48. http://dx.doi.org/10.1109/MPAE.2008.4412939

Tian, F., Zhang, X., Yu, Z.H., *et al.*, 2016. Online decision-making and control of power system stability based on super-real-time simulation. *CSEE J. Power Energy Syst.*, **2**(1):95-103. http://dx.doi.org/10.17775/CSEEJPES.2016.00014

Ummels, B.C., Gibescu, M., Pelgrum, E., *et al.*, 2007. Impacts of wind power on thermal generation unit commitment and dispatch. *IEEE Trans. Energy Conv.*, **22**(1):44-51. http://dx.doi.org/10.1109/TEC.2006.889616

Vellaithurai, C., Srivastava, A., Zonouz, S., *et al.*, 2015. CPIndex: cyber-physical vulnerability assessment for power-grid infrastructures. *IEEE Trans. Smart Grid*, **6**(2):566-575. http://dx.doi.org/10.1109/TSG.2014.2372315

Verma, K., Niazi, K.R., 2012. Supervised learning approach to online contingency screening and ranking in power systems. *Int. J. Electr. Power Energy Syst.*, **38**(1):97-104. http://dx.doi.org/10.1016/j.ijepes.2011.12.025

Vidulich, M., Dominguez, C., Vogel, E., *et al.*, 1994. Situation Awareness: Papers and Annotated Bibliography. Report No. AL/CF-TR-1994-0085. Armstrong Laboratory, Human System Center, CA.

Wan, C., Zhao, J., Song, Y.H., *et al.*, 2015. Photovoltaic and solar power forecasting for smart grid energy management. *CSEE J. Power Energy Syst.*, **1**(4):38-46. http://dx.doi.org/10.17775/CSEEJPES.2015.00046

Wang, W.Y., Barnes, M., Marjanovic, O., *et al.*, 2016. Impact of DC breaker systems on multiterminal VSC-HVDC stability. *IEEE Trans Power Del.*, **31**(2):769-779. http://dx.doi.org/10.1109/TPWRD.2015.2409132

Wang, Y.X., Wang, Y., 2006. Cognitive informatics models of the brain. *IEEE Trans. Syst. Man Cybern. Part C*, **36**(2):203-207. http://dx.doi.org/10.1109/TSMCC.2006.871151

Yin, J., Lampert, A., Cameron, M., *et al.*, 2012. Using social media to enhance emergency situation awareness. *IEEE Intell. Syst.*, **27**(6):52-59. http://dx.doi.org/10.1109/MIS.2012.6

Zhao, X.Y., Zhou, H.F., Shi, D., *et al.*, 2015. On-line PMU-based transmission line parameter identification. *CSEE J. Power Energy Syst.*, **1**(2):68-74. http://dx.doi.org/10.17775/CSEEJPES.2015.00021

Zheng, X.S., McConkie, G.W., Tayi, Y., 2004. Dynamic monitoring of traffic flow: the driver's situation awareness. Proc. 5th Human Performance, Situation Awareness and Automation Conf.

Zhu, J., Zhuang, E., Ivanov, C., *et al.*, 2011. A Data-driven approach to interactive visualization of power systems. *IEEE Trans. Power Syst.*, **26**(4):2539-2546. http://dx.doi.org/10.1109/TPWRS.2011.2119499

ZigBee Alliance, 2013. Smart Energy Profile 2.0 (ZigBee SEP 2.0). Application Protocol Standard.

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