Sensemaking and Robust Decision Engineering: *Synchrophasors and their Application for a Secure Smart Grid*

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***Abstract*— The growing complexity of electrical power grids is demanding increasingly innovative solutions to build more stable and secure grids, a trending that is particularly evident across the spectrum of industrialized countries. Such a need is also clear for emerging countries, wherein China has rapidly become a key development player whose technological solutions could have a pivotal impact on other infrastructure-hungry regions of the world (e.g. Sub-Saharan Africa). This paper provides an overview of the smart grid transmogrification, via the state-of-the-practice application of proactive and responsive nodes — synchrophasors — within the U.S. power grid and presents a comparison with the efforts of other actors, such as China and Sub-Saharan African. Specifically, the potential advantages of the application of synchrophasors, as well as the issues challenging their application, are taken into account. As happens in ecological systems, value is created "by making connections," and synchrophasors do indeed enable "collective intelligence," "promote collaboration," and well contribute towards scalability and sustainability — the realm of Digital Ecosystems.**

Keywords*— *Decision Engineering Science; Decision-making; Robust Decision Engineering; Sensemaking; Synchrophasor; Phasor Measurement Unit (PMU); Phasor Data Concentrator (PDC); Network Science; Relationship Science; Big Data; Big Insight; Cyber Security; Stability; Secure Smart Grid.

I. Introduction

The multi-dimensional expansion of electrical power grids is demanding increasingly innovative solutions to build more stable and secure grids [1]. This trending is particularly evident in the case for industrialized countries, such as the United States, whose electric power grid ranked first among the greatest engineering achievements of the 20th century by the U.S. National Academy of Engineering (NAE) [2]. Indeed, the technical and normative complexity of the U.S. electric grid appeared already evident in 2006 when Parashar et al. [3] remarked that "the electric power grid has evolved from a vertically integrated system to a mixture of regulated and deregulated competitive market system. Grid oversight is transitioning from local utilities to an assortment of transmission companies, regional Independent System Operators (ISOs), and Regional Transmission Organizations (RTOs). Regulatory and economic pressures have caused new transmission construction to lag [behind] the growth in demand. These forces have increased pressure on electricity markets and caused operators to maximize the utilization of the [current] system. The result is an operating environment wherein operators are faced with quick changing and previously unseen power flow patterns and unforeseeable operational conditions with limited information available for real-time operation and decision-making."

More recently, Venayagamoorthy defined the U.S. electric power grid as "the world's largest single machine ever built by man. [4]" During the State of the Union address in 2013, U.S. President Obama placed it among the most critical of infrastructures and called anew for legislation to protect it, adding that "our enemies are … seeking the ability to sabotage our power grid, our financial institutions, [and] our air traffic control system. [5]" Despite such evidence of the pivotal importance of the power grid, the sector is facing a major reduction in federal spending (with or without forced budget cuts through sequestration) with a 75 percent decline by 2014 compared to the surge of investment in 2009, and federal investments are set to diminish by more than half by 2014 [6]. As a result, the U.S. Department of Energy's (DOE) various offices would experience "substantial cuts" to "key R&D programs like the SunShot initiative and Smart Grid Demonstration Initiative. [7]" Within this framework, it is clear that the communications infrastructure will increasingly represent a critical element for a stable and secure smart grid. A recent Congressional Research Service (CRS) Report from the U.S. Congress stated that "whether the electricity industry adopts smart grid technology or not, it faces cybersecurity problems since legacy communication methods support[ing] grid operations also provide potential cyber attack paths. [8]"

Hence, within this multifaceted technological, normative and market nexus, sensemaking is being recognized as the pivotal mechanism of processes/techniques that will drive the implementation of the next generation of stable and secure smart grids, thanks to its potential for improving network monitoring and strengthening network stability, via the insights provided from the analytical domains [9]. Along with cloud computing, which is expected to address the needed "large scale real-time computing communication, transfer and storage of data generated by smart grid technologies, [10]" synchrophasors are emerging as the key instrument to implement smarter grids, because of their comparative advantages in both the predictive and forensic arenas.

This paper provides an overview of the application of synchrophasors within the U.S. power grid, and the comparison of the U.S., China, and Africa assists in articulating the state-of-the-practice and the priorities (e.g. interoperability) for defining roadmap towards a more energy efficient and greener world.

II. Sychrophasor: A Fundamental Unit of Future Smart Grids

Mathematician/electrical engineer Charles Steinmetz had introduced the notion of the phasor as early as 1893. Then, nearly a century later, Virginia Tech electrical engineers Arun Phadke and James Thorp invented, in 1988, the phasor measurement unit (PMU), and early prototypes of the PMU were built at Virginia Tech and Macrodyne in 1992. Next, in 2007, the U.S. DOE and the North American Electric Reliability Corporation (NERC), along with various electric utility companies and other organizations, formed the North American SynchroPhasor Initiative (NASPI).

Synchrophasors are sensors that sample the electricity grids at 30-60Hz and publish these measurements as streams that need to be delivered reliably and in real-time to a number of synchrophasor applications [11]. Whereas most existing smart grid devices report once every two to four seconds, synchrophasors will report back, on average, 30 times a second ("10 to 60 times a second" [12]). This higher frequency in sampling is expected to allow smart grid operators real-time identification of disturbances on the grid for the actuation of mitigating and/or compensating actions [13]. A phasor can be seen as a vector rotating about the origin in a complex plane as is shown in Figure 1.

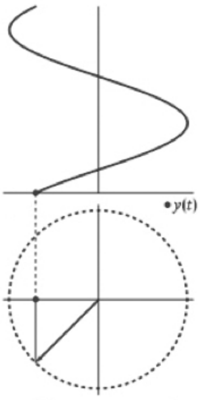

Fig. 1. Representation of a phasor as a vector.

A PMU reflects the measurement of the electrical waves on the electrical grid as is shown in Figure 2.

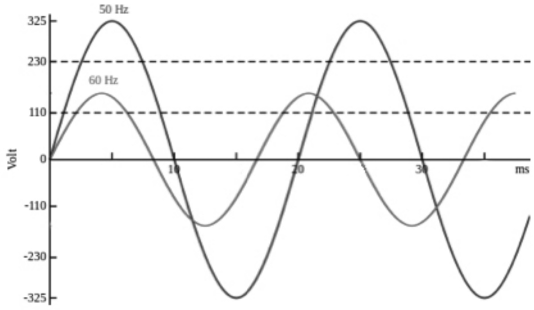

Fig. 2. Electrical waves as measured by a PMU.

Phasor angle difference can provide context as to the stability of the electrical grid as is shown in Figure 3.

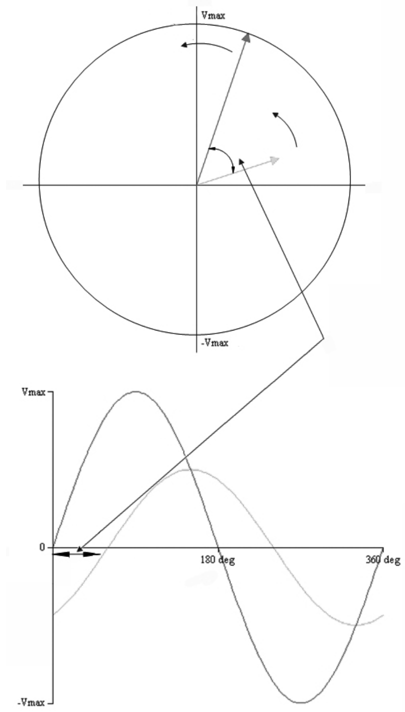

Fig. 3. Phasor angle difference reflected in electric current measurement.

As suggested by Overbye et al. (2010), bus phase angles are an important source of information about the overall system conditions of the electric grid, while most measurements currently used just provide a highly localized view of the status of the grid itself [14]. Indeed, they remark that "for example, if the upper Midwest is exporting power to the rest of the Eastern Interconnect this will probably be indicated by a higher phase angle difference between … two buses located on different sides of the Chicago Metro region (the Wempleton and Burnham 345 kV buses), [15]" and this sensitivity impacts the power injections throughout the Eastern Interconnect.

In essence, phase angle differences across PMUs are indicators of static stress across the grid. It then follows that "greater phase angle differences imply larger static stress across that interface; larger stress could move the grid closer to instability. [16]" However, Parashar et al. (2006) suggested that the “PMUs across which the angle difference should be monitored, as well as their relevant alarming thresholds for these pairs, are assumed at this stage and need further validation. For the near-term, one suggested approach has been to study the observed phase angle profiles over an extended period of time, so as to ascertain their behavior under normal system conditions, and to use these long-term trends to define either hard limits (i.e. fixed limits) or soft limits (i.e. statistical bounds) for these metrics. [17]”

Other than these technical advantages of synchrophasors, there are also evident forensic advantages. Indeed, synchrophasors can ascertain which failures materialized first as well as which were merely secondary effects of the first order failures in the case of power outages (e.g. power cut, blackout, or power failure). For example, establishing the sequence of events that led up to the cascading failure Northeast Blackout of 2003[1] was difficult for investigators, because while the individual parts that shut down had individual data loggers, the clocks on them were not coordinated, thereby making it difficult to establish where the disturbance began [18]. Not surprisingly, “recommendations from the investigation of this blackout carried out by the U.S.-Canada Joint Task Force included the need for wide-area visibility and situational awareness to address problems before they propagate, the use of time-synchronized data recorders, and better real-time tools for operators and reliability coordinators. [19]”

III. Main implementation issues of the synchrophasor in the U.S.

Interoperability surely represents one of the most prominent challenges for implementing a comprehensive robust smart power grid in the U.S., thanks to the adoption of synchrophasors.

Indeed, at present, utility companies in the U.S. utilize Energy Management Systems (EMS) and Supervisory Control and Data Acquisition (SCADA) systems to collect local real-time data and to monitor and control their portion of the power system measured by PMUs and Phasor Data Concentrators (PDC) [20]. “While control areas share their SCADA data with reliability coordinators, via Inter-control Center Communications Protocol (ICCP), ICCP data is transmitted at varying rates (up to minutes in periodicity) and is not time synchronized. Conversely, synchrophasor data is time synchronized and nicely complements existing SCADA systems [so as] to address [the] emerging need for wide area grid monitoring and management, while continuing to use existing SCADA infrastructure for local monitoring and control. After all, traditional SCADA/EMS systems are based on steady state power flow analysis, and therefore cannot observe the dynamic characteristics of the power system, while synchrophasor technology augments these existing systems by overcoming this limitation. These measurements provide time synchronized sub-second data, which are ideal for real-time monitoring of power system dynamics on a wide area basis as well as improving post disturbance assessment capability. Additionally, this provides a layer of backup visibility should the operator’s primary tool fail. [21]”

It is within this framework that, in 2006, a conflict of interest arose for determining the standards for the smart grid when the North American Electric Reliability Corporation (NERC) was designated by the Federal Energy Regulatory Commission (FERC) as the organization responsible to establish and enforce reliability standards in the electric domain. In fact, NERC is essentially made up of private sector bulk power generators [22] and regulations “are essentially being established by the entities who are being regulated, … and acceptable standards may conceivably result from the option with the lowest costs. [23]”

The interoperability issue among different PMUs vendors is, therefore, a challenge for the U.S. power grid, particularly with regards to the possible synchronization issues among measurements with same time stamps [24]. Inaccurate readings can be yielded by PMUs produced by different vendors; for example, “in one test, readings differed by 47 microseconds — an unacceptable variance. [25]” Utilities need the guarantee of reliability and accuracy of PMUs and also the seamless interchange among the PMUs from different vendors before they will invest heavily in them [26].

“The recent IEEE C37.118 standard on the synchrophasors outlines certain stringent requirements in terms of how to precisely measure the phase angle with respect to the global time reference — the coordinated universal time (UTC), and how to report the phasor information. The standard also specifies the Total Vector Error (TVE) allowed in evaluating the phasor for different compliance level[s] to allow interoperability between different vendor PMUs. [27]”

IV. A comparison between the implementation of the synchrophasor in the U.S., China, and Africa

With regards to interoperability issues, for China, the “solution was to build all its own PMUs adhering to its own specifications and standards so there would be no multi-vendor source of conflicts, standards, protocols, or performance characteristics. [28]” As in the U.S., a number of different manufacturers were active on the market, but the State Grid Company — in conjunction with domestic manufacturers — drafted a Chinese standard for the PMU and Wide Area Measurement System (WAMS) in 2003 that was later issued in 2005. The resulting synchrophasor standard “supplements transmission protocol of historical data on the basis of IEEE Std 1344-1995 (R2001) … [and] … provides a

[1] The Northeast Blackout of 2003 occurred throughout parts of the Northeastern and Midwestern United States and the Canadian province of Ontario on Thursday, August 14, 2003, just before 5:10 p.m. EST. While some power was restored by 11 p.m., many did not get power back until two days later. The blackout affected an estimated 10 million people in Ontario and 45 million people in eight U.S. states. The blackout's primary cause was a software bug in the alarm system at a control room of the FirstEnergy Corporation in Ohio. Operators were unaware of the need to re-distribute power after overloaded transmission lines hit unpruned foliage. What would have been a manageable local blackout cascaded into widespread distress on the electric grid.

technical specification for manufacturers and allows interchange of data between a wide variety of users of both real time and off-line phasor measurements, which is of great importance for Chinese WAMS implementation. [29]" As a result, the key commercial product of PMU to be commissioned for the Chinese power grid in 2003 — vis-à-vis the PMU — was available to Chinese manufacturers at the end of 2002 [30].

Such an implementation solution has ramifications beyond the Chinese power grid. Indeed, China has a prominent role in infrastructural development for Sub-Saharan Africa [31], with "at least 35 African countries engaging with China on infrastructure finance deals. [32]" In Sub-Saharan Africa, electrification is expected to expand dramatically to reach half of its population by 2030, according to Business As Usual (BAU) scenarios [33], while today 7 out of 10 Africans do not have access to modern electricity [34]. The significance of synchrophasors, among other advanced transmission technologies, is that it facilitates the promotion of smart grids within Sub-Saharan Africa and represents an enhancement to the more advanced existing grids [35]. The number of PMUs in Africa is still limited, but notable application of synchrophasors to prevent voltage collapse and minimize load shedding in South Africa are reported [36, 37]. Within the same domain, applications of advanced transmission technologies such as voltage-source converters for high-voltage, direct current power transmission (VSC-HVDC), are reported in Namibia [38].

Chinese investments in critical infrastructures of many African countries [39] are substantially growing, with specific regard to Information and Communications Technology (ICT), power, and transportation infrastructures [40]. As a result, African countries partnering with China for the deployment of their electric power grids are very likely to implement their power grid by employing PMUs and WAMS that are compliant with the Chinese standard. For the better or the worse, incorporating the Chinese standard may be a cost-effective solution for the development of an integrated smart grid within Africa. A parallelism can be drawn here with the past implementation of railway infrastructures by colonial powers, which left a high variety of gauges within the continent [41] — and even within individual countries [42] — thereby complicating regional and continental interactions (e.g. the transfer of people and goods). Hence, what is likely to happen in the near future is a counter-phenomenon, with the possible emergence of a single standard to allow for the monitoring and management of future energy infrastructures. Some scholars have already highlighted the potential Chinese contribution to regional integrations in Africa [43], and Chinese investments to interconnect countries in Southern Africa, via high-voltage power transmission lines, are also reported [44].

Comparing the orders of magnitude for investment on synchrophasors in the U.S. and China, the efforts of both countries in leveraging such technology for the implementation of a smarter power grid is evident. The U.S. DOE is currently using American Recovery and Reinvestment Act (ARRA) funding to promote the adoption of synchrophasors so as to increase the reliability of the electric power grid and reduce financial costs for consumers [45]. To support this installation of synchrophasors across the U.S., the DOE is reported having spent $70 million as seed money to cover the area from the Rockies to the Pacific as well as the Midwest since 2010 [46]. Total expenditures on synchrophasors can be roughly estimated in the 7 digit to low 8 digit realm, given the high costs of instantiating PDC and SCADA systems to record and handle the data, despite the relatively low unit cost of synchrophasors (i.e. $2,000 to $3,000) [47]. The Smart Grid Interoperability Panel Priority 13 (SGIP PAP13) standards "support the necessary interoperability of the over 1000 PMUs, funded under ARRA Smart Grid Investment Grants (SGIGs) [48]" and in, 2010 it was reported that the U.S. had "about 250 units in place. [49]" More recently in 2013, it was reported that the deployment of PMUs had reached 2000 worldwide, with China and North America accounting for one third of this figure — with 1000 and 500 units respectively [50]. Of note, in China, the market cumulative number of synchrophasors units installed is expected to grow to 3,846 million units by 2020, thus projecting China as the leading nation for smart meter and synchrophasor deployment within the Asian Pacific region [51, 52].

V. IMPROVING SECURITY AND STABILITY OF SMART GRIDS VIA SYNCHROPHASORS AND SENSEMAKING

Among the various peculiarities of future smart grids, stability will definitely be a quintessential feature of the future electric power networks, and synchrophasors will represent a pivotal tool to deploy the next generation of such infrastructures. Particularly, sensemaking applications could leverage the potential of synchrophasors by serving as a force multipler by, for example, interconnecting PMU data (at the publisher level) to real-time smart grid applications (at the subscriber level) in Quality of Service (QoS) sensitive cyber-physical systems [53].

It can be also expected that synchrophasors will promote the integration of renewable energy sources into the high voltage electric power grid by increasing its overall reliability [54]. To do so, the need to strengthen the ability to coherently measure real-time data into electric power grids for improving the stability of the overall power system will increasingly become an operational priority. Hence, an important issue is that of dimensionality, with specific reference to the data transferred from PMUs to network applications — typically during a system underload status. Issues do arise during system overload, and a series of strategies have been proposed to mitigate network overload impact on the transmission of PMU data across the network, including random discard of data and video streaming related techniques [55]. Within this framework, Arya et al. [56] promulgated the employment of voltage monitoring systems based on ad hoc metrics (i.e. Voltage Stability Index, VSI, calculated as the minimum of the stability indices of all network buses) as an effective strategy to improve network stability by localizing vulnerable hot-spots in real-time. In such case, data from synchrophasors can be aggregated at intermediate nodes across network during system overload without jeopardizing the functioning of smart grid application.

Another important aspect to highlight is that sensemaking and Decision Engineering are coupled when it comes to prioritization of limited computational resources amidst compressed decision cycles. It is thus interesting to note that not all data from all PMUs are equally important for computing stability-related indexes. By way of example, employing heuristic techniques to reduce network load, via assignment of priority values to substations according to their historical performance (i.e. lower frequency of voltage problems), have been successfully proposed [57].

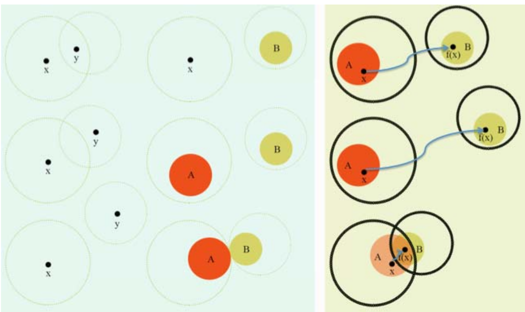

Fig. 4. Coupling sensemaking and decision engineering for data prioritization.

VI. CONCLUSIVE REMARKS

The future pathway for smarter electric power grids is very likely to be marked by synchrophasors and related advanced sensemaking applications, which will facilitate integrated monitoring/analysis of power grids. Technical and forensic advantages from the application of PMUs are evident, and the comparative advantage of their applications has rapidly become clear for both public and private sector power electric grid stakeholders as well as for practitioners of Complex Environment Engineering striving for smarter cities and, eventually, the world. Nevertheless, a series of implementation issues needs to be addressed to allow the cost effective deployment of such grids. Interoperability surely represents a possible bottleneck for the development of effective monitoring systems beyond the sub-national level, especially in the U.S. Moreover, the increasingly interlinked nature of information and power infrastructures exposes power grids to stability issues, requiring the deployment of communication networks capable of allowing the cost-effective monitoring of distributed electric power supplies. In addition, cyber security threats to such information-energy grids pose serious threats to the network stakeholders, as they could prevent international integration.

Finally, the implications for sustainability and global development are also evident. To start, synchrophasors may foster investments into renewable energies by facilitating their integration into existing grids. Moreover, synchrophasors could have a key geo-political function to integrate markets as well as increase energy efficiency at the regional level. For the energy-hungry areas of the world (e.g. China, Sub-Saharan Africa), these aspects constitute a significant impact on sustainability, and in conflict-sensitive regions, such aspects may even represent a factor of political stability. Energy is indeed a key element of sustainability for the different societies composing our world. With such societies being more interlinked and interdependent, synchrophasors can help facilitate socio-economic stability by fostering the energy and information nexus, thereby epitomizing the spirit of the Digital Ecosystem.

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