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A Survey of Cyber-Physical Advances and Challenges of Wind Energy Conversion Systems: Prospects for Internet of Energy

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***Abstract*—Wind energy has the biggest market share of renewable energy around the world. High growth and development rates of wind energy lead to a massive increase in complexity and scale of wind energy conversion systems (WECS). Therefore, it is required to upgrade methods and strategies for design and implementation of WECS. Considering WECS as cyber-physical systems (CPS) will enable wind energy for the Internet of Energy (IoE). IoE is a cloud network where power sources with embedded and distributed intelligence are interfaced to smart grid and mass of consumption devices like smart buildings, appliances, and electric vehicles. Research trends of CPS for energy applications are mainly focusing on smart grids and energy systems for demand side management and smart buildings with less attention given to generation systems. This paper introduces potentials of cyber-physical (CP) integration of next-generation WECS. In addition, the paper surveys the advances and state-of-the-art technologies that enable WECS for IoE. Challenges and new requirements of future WECS as CPS like abstractions, networking, control, safety, security, sustainability and social components are discussed.**

***Index Terms*— Cyber-Physical Systems, Internet of Energy, Internet of Things, Wind Energy, Wind Energy Conversion Systems.**

I. Introduction

WIND energy has experienced a massive development rate in worldwide installed capacity. By 2014, the global production of wind energy has exceeded 369 GW with more than 51 GW as added capacity in 2014 only representing a grow rate of 16%. Countries with top installed capacity in 2014 are China with 23.4 GW, Germany with 5.3 GW, USA with 4.9 GW, Brazil with 2.5 GW, and India with 2.3 GW. Denmark has reached a new world record by 39% wind power share of the total electricity generation [1, 2]. Other countries also have high wind share of their electricity like Spain 21%, Portugal 20%, Ireland 16% and Germany 9% [3]. The world has ambitious futuristic deployment targets of wind energy. Global growth of wind energy imposes technological advancements such as large-scale, offshore, floating and airborne wind turbines. Deployment of these systems highlights the need for more rigid and comprehensive strategies for safe, secure, cost-effective frameworks for design, installation, operation and maintenance. Due to stochastic nature of the wind power process, fluctuations and undesirable dynamic variations in harvested power are big challenges that face wind energy. In addition, a wind turbine at high turbulence may experience damaging effects like fatigue and extreme loads. Therefore, wind turbine control systems primarily target the cost-effective capture of energy. That is to enable efficient generation of energy with certain power qualities while mitigating loads to increase the lifetime of the turbine and reduce maintenance cost. These objectives require complex and efficient control strategies.

The energy industry and decision makers are facing number of challenges due to the increase of energy demand and short supplies of fossil fuels. These challenges require the adaptation of innovative solutions for efficient and distributed energy production, management and consumption. For example, ubiquitous sensors with pervasive and real-time computing are deployed for intelligent coal mines and oil fields [4]. With respect to wind energy, the current technologies of WECS designs are migrating from centralized and classical structures to decentralized, distributed and more complex approaches to match different energy production requirements, consumption demands and variations in environmental conditions. Utility scale wind turbines are getting greater in size while wind farms are covering larger areas and gaining more interest of remote and offshore areas. Moreover, wind energy generates irregular production of electricity, which needs advanced power electronics and energy storage systems [5]. Therefore, increasing complexity in WECS and handling interactions and coordination between components require more comprehensive and systemic approaches.

On the meantime, recent progress in information and communication technologies are mainly based on two crucial

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driving forces: Embedded systems and global networks. Embedded systems are special purpose computing machines like those in high-tech devices, vehicles, aircrafts and smart buildings. Global networks include data and services available on World Wide Web and the Internet [6]. The integration of these two forces forms the Internet of Things (IoT). IoT is a complex CPS that integrates various devices with embedded sensing, identification, processing, communication and networking capabilities [7]. A CPS is where cyber and physical components form a collaborative integration. Cyber components may contain software or hardware computation entities, communication layers, and control functions. In the meantime, physical components are natural or manufactured entities that can be described by physical models. IoT and CPS are currently one of the hottest emerging trends in technology and engineering design with expectations to be applied heavily in industry. In [8], a vision for IoT impacts on human life is discussed. It is expected that CPS and IoT will revolutionize our interaction with the physical world in the same manner the Internet has affected people communications and interactions.

Nowadays, CPS play a vital role in energy management and distribution. Most research efforts in cyber-physical energy systems (CPES) focus on the distribution and consumption technologies, like smart grids and energy managements systems for buildings. More interest of CPES approaches needs to be directed towards the generation phase, especially the renewable sources like wind energy. Wind farms planning and construction represent a complicated decision that is affected by different technical, economic, environmental and social aspects [9]. With a thorough investigation of WECS, cyber and physical layers can be formulated within different technical and non-technical levels: Inside a wind turbine, collaborative wind farms, integration with smart grids, non-functional requirements, and interaction with social context. The coordination and interaction of cyber layers and physical components of wind turbines require handling number of challenges for essential feasibility and competiveness of future WECS.

This paper intends to provide an overview of a CP vision of WECS. First, the recent technological advances of cyber components in WECS are reviewed such as networking infrastructure, SCADA systems, condition-monitoring systems (CMS), and wireless sensor networks (WSN). Based on this survey, a layout can be inspired about next-generation WECS that are enabled for IoE by incorporating CP technologies. The CP integration is formulated over scales of wind turbines and wind farms. In addition, non-functional requirements that arise due to CP integration are also introduced and discussed. The rest of the paper is organized as follows. Section II illustrates the physical and cyber layers of WECS. Section III presents a vision and challenges for a CP implementation of wind turbines. Section IV discusses enablers for future wind farms for IoE. Section V introduces the CPS challenges of safety, security and sustainability of WECS. Section VI presents wind farms as cyber-physical social systems (CPSS). Finally, conclusions are summarized in Section VII.

II. Composition of WECS

A typical wind turbine is a complex system that integrates thousands of devices and components to harvest electrical energy from wind kinetic energy. In this section, a brief introduction to physical components of WECS is discussed. In addition, an overview of cyber layer components of WECS is introduced.

A. Physical Layer in WECS

Physical components of WECS contain blades, rotor hub, nacelle, and tower foundations. The nacelle includes shafts, gearbox, generator and other electrical and mechanical systems. A wind turbine components diagram is illustrated in Fig. 1. Those components are monitored and controlled through a mass of sensors and actuators. Sensors inside wind turbine measure different variables related to performance and health of each component. In the meantime, the control system manipulates and governs the wind turbine operation through a set of actuators. Examples of sensors and actuators inside a wind turbine are illustrated in Fig. 2.

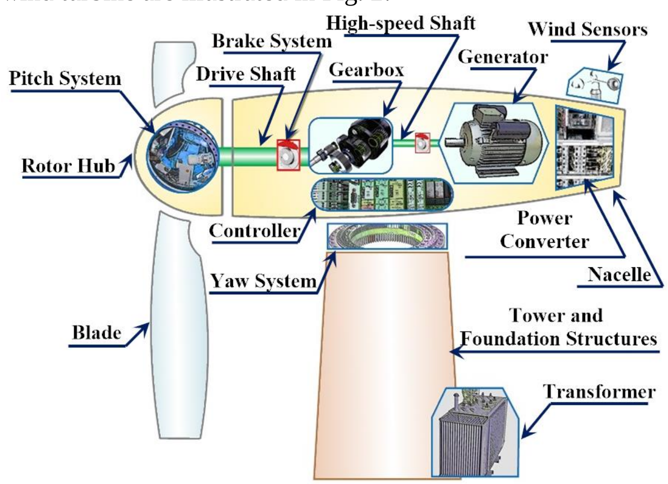

Fig. 1 Wind turbine components block diagram

B. Cyber Layer in WECS

The cyber layer in WECS integrates different hardware and software technologies that work together to achieve collaborative objectives. The cyber layer usually contains networking, SCADA, and (CMS) as in Fig. 3.

1) Networking

Successful deployment of WECS requires reliable communication networks between subsystems inside a wind turbine. It also connects intelligent machines and deeply embedded devices over a wind farm. The main role of networking is to provide facilities for efficient transfer of data and control signals between controllers, actuators, sensors, supervisory centers and data storage stations. The design of communication networks of wind farms, especially offshore ones, has many factors to be taken into consideration related to transfer rates and resilience [10]. The influence of communication networks on the dynamic performance of a

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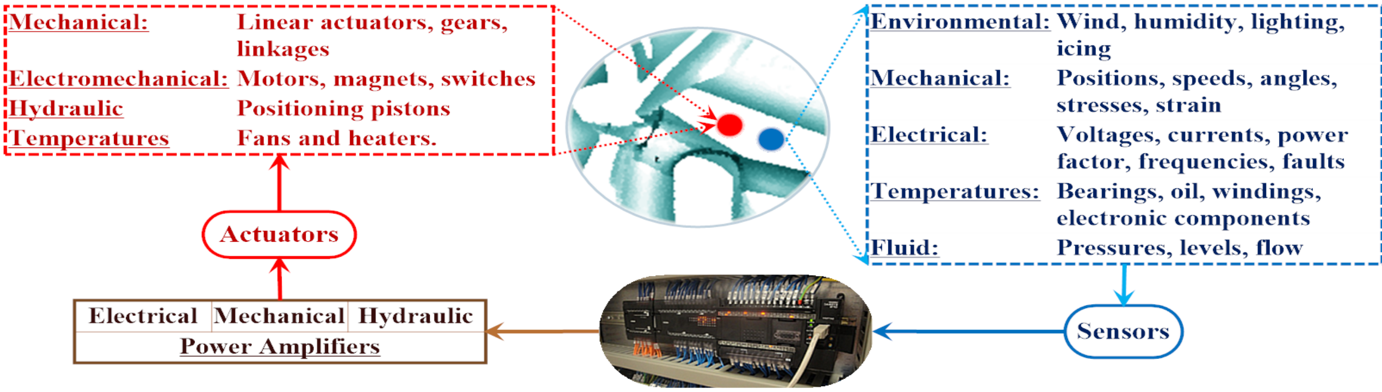

Fig. 2 Sensors and actuators inside a wind turbine

grid-connected wind farm is investigated in [11]. Several communication technologies for wind energy and photovoltaic systems are introduced in [12]. An analysis of different network architectures and protocols is conducted for data transmission between wind farms and central substations in [13].

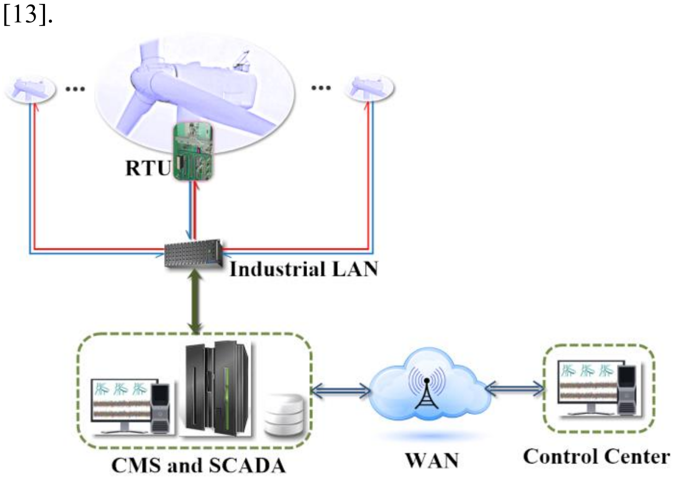

Fig. 3 Cyber layer in a wind farm

Due to the growth in wind power industry, IEC61400-25 standard is developed in order to provide unified information exchange for monitoring and control of wind farms in industry [14]. Based on this standard, a gateway is proposed in [15] to improve autonomy, standardization, extensibility and diagnostics. A communication network architecture applicable to IEC 61400-25 is developed for smart wind farms in [16]. Currently, Ethernet is the most popular protocol for implementation of local area networks (LAN). Ethernet networks are deployed in offshore wind farms in [17]. A hierarchical communication network architecture that consists of three domains: Turbine, farm and control area network is proposed for offshore wind farms in [18]. Another scheme is developed in [19] for distributed communication of wind parameters from multiple wind farms to central substation.

2) SCADA and CMS

SCADA systems are currently providing services and functions for WECS that exceed simple monitoring and control of wind turbines. Basic roles for operation and maintenance of wind power plants [20] are illustrated in Fig. 4. CMS are vital systems that are integrated with SCADA. CMS employ sets of techniques for earlier identification of faults in a wind turbine. Integration of CMS has showed significant improvements in operation and maintenance of wind turbines. A review is provided in [21] for condition-monitoring (CM) concepts, sets of techniques, algorithms and mathematical methods for CM. Unlike SCADA systems, CMS usually deploy heavy number of sensors with higher sampling rates. CMS add great challenges on data communication, computation and storage besides the increase in the overall cost [22]. Therefore, many solutions are suggested for using SCADA data for CM to reduce cost of WECS. Different model-based techniques are evaluated for CM and fault detection based on SCADA data in [23]. In [24], three SCADA-based monitoring techniques are compared for reliable failure detection: Signal trending, self-organizing maps and physical model. Faults identification with CM is proposed based on raw SCADA data in [25]. An ANFIS method is implemented for monitoring wind turbine performance based on normal behavior model via SCADA data in [26, 27].

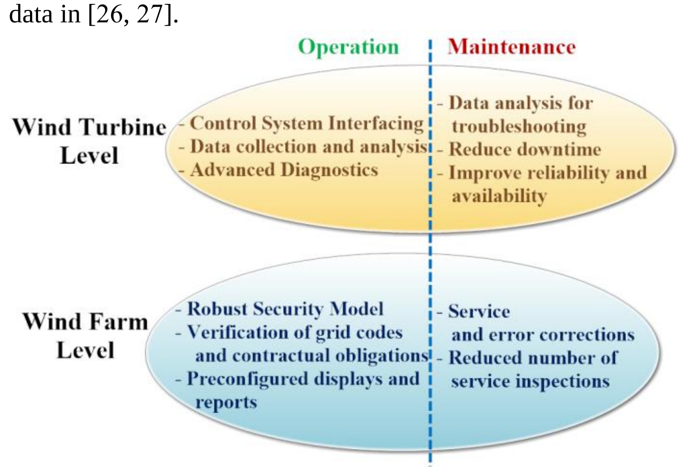

Fig. 4 Rules of SCADA systems in wind energy

However, a comparative study of dedicated CMS against SCADA-based CM indicates that CMS are quite high in cost but more capable of diagnosis due to higher information frequency over SCADA systems [28]. Therefore, number of studies addressed improvements for dedicated CMS. An industry application of CMS that is based on rough sensor equipment is introduced in [29]. A cost-effective CM technique that can extract fault features with low calculation

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times and for different wind turbine technologies is proposed in [30]. In [31], CM of small wind turbine gearbox is achieved by comparing three-phase currents and voltages of the generator with six accelerometer signals. TABLE I compares SCADA-based CM against dedicated CMS.

TABLE I COMPARISON OF SCADA-BASED CM AGAINST DEDICATED CMS

	SCADA-based CM	CMS
Sensors data	Currents, voltages, power, speeds, temperatures	Mainly vibrations, oil quality, strain, acoustic
Sampling	Low sampling rates	High sampling rates with wide range of frequencies depending on component type
Diagnosability	SCADA collected data are insufficient for some prognostics	Requires effective algorithms for vibrations and oil analysis
Validity	Sometimes overwhelming false alarms are raised	Requires accurate physical models, Not all abnormalities indicate faults
Cost	Cheap, primarily installed with WECS mainly for operation	Expensive, installing CMS adds additional costs
Fault anticipation	Faulty data indicate a late stage condition	Usually provides a prognostic lead time
Commercially available products	A detailed review in [28, 32]	A detailed review in [28, 33]

III. CYBER PHYSICAL INTEGRATION OF A WIND TURBINE

From a deep insight into layers of WECS, they can be considered as complex technologies with embedded systems. The collaboration of WECS layers, as illustrated in Fig. 5, shows a high level of heterogeneity and forms a typical CPS. Considering WECS as CPS adds new layers of adaptation of the technology and enhances the potentials of WECS to be integrated into smart grids and IoE.

A. Abstractions and modeling of CP wind turbines

Effective development of CPS raises the need for new models and design methodologies. These new models and methods must achieve balance between complexity and usefulness [34]. Modeling wind turbine systems with integrating all heterogeneous components of cyber and physical layers is a major challenge. Different aspects of properties are required to be considered for CPS compositional modeling [35]: *Functional*, *non-functional*, *physical*, *components interfaces* and *interface coordination*. Therefore, the complexity and heterogeneity of modern wind turbines components impose the same considerations to be applied for WECS. Comprehensive analysis and checking techniques need to be applied to assure the correct behavior of control systems of different electrical and mechanical components. Besides that, detailed models of wind resources and electrical loads that determine the operating conditions must be provided. In addition, a framework is required for maintaining sustainability, safety, security and resilience of WECS. This adds the need for verification tools of physical requirement like size, power, dynamics and memory for different computing and networking components of CPS in wind turbines. Moreover, tools are needed for checking interoperability of different interfaces of SCADA, CMS, sensors nodes and power electronics with control circuitry. Unified methodologies for extensibility of wind farms, integration with smart grids and human-machine interfaces are required for future WECS.

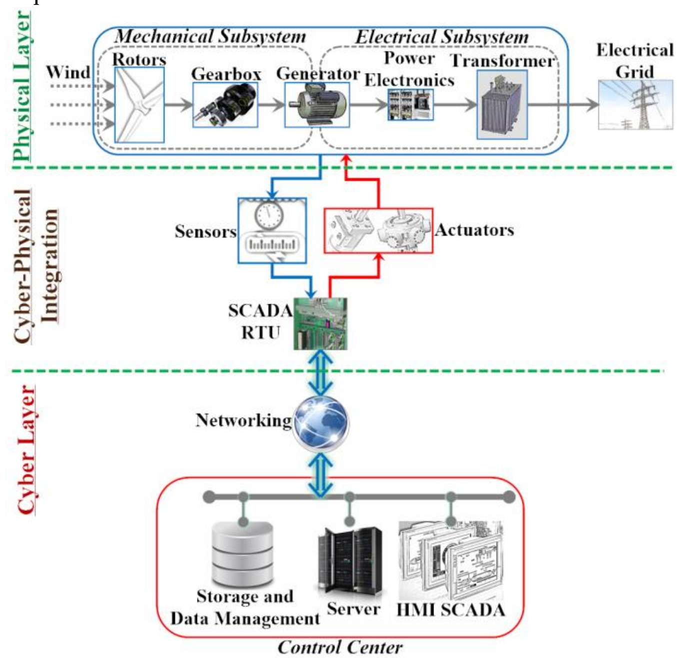

Fig. 5 CP integration of WECS

WECS models are supposed to contain continuous physical dynamics as well as capture discrete events. A unified notion of time is required between sensor nodes, network and computing platforms. Moreover, current wind turbine technology contains computing systems operating on different rates. SCADA systems in wind plants are operating at low timing frequency for logging performance data while CMS are operating on high timing frequency for effective monitoring of components. In addition, the physical dynamics of mechanical structures, aerodynamics, electrical components and power electronics need to be captured by descriptive programing abstractions. Therefore, it is becoming essential to merge abstract models of computation and information flow from *sensor networks* [36] with physical models of mechanical and electrical parts inside wind turbines. Fig. 6 suggests a CP modeling hierarchy for wind turbines.

WECS are modeled using either physical laws by aerolastic software codes like GH Bladed, FAST and HAWC2, or black box approaches based on system identification of real measured data from wind plants. Parametric models for power curve modeling are reviewed in detail [37]. TABLE II compares the advantages and disadvantages of different parametric modeling methods. Manufacturer provided power curve models may exhibit inaccuracies, as they are neither site-specific nor self-adaptive to wear and aging of turbine components. A good model for a wind turbine must provide the ability of: *assessment and prediction wind energy on site*, *aiding the developers to choose the optimum wind turbine*,

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monitoring and troubleshooting the components, and *predictive control and optimization* [37].

TABLE II Comparison of parametric power curve modeling methods

Method	Advantage	Disadvantage
Linearized segmented model	Simple	Assumes error-free wind measurements
Polynomial power curves	Gives accurate approximation of WTPC linear region	Requires higher orders for accuracy as lower orders are sensitive to manufacturer data
Maximum principle method	Empirical and simple	Overestimation and inaccuracy
Dynamical power curve	Produces an accurate machine-specific and site-independent model with short-term data	Requires high sampled data
Probabilistic model	Estimates the uncertainty of generated wind power in region 2	Assumes a normal profile of wind
Ideal power curve	Effective for assessment of wind energy available in test sites	Ignores site turbulence
Four and five parameter logistic functions	Gives the best results compared to other parametric models	Solving the logistic function parameters is a highly complicated process with large data sets

Current modeling techniques have insufficient semantics to address the heterogeneity, concurrency and sensitivity of time behavior in CPS [38]. New modeling approaches should be developed to implement cyber layer of information and communications network models with physical principles of electrical and mechanical components. Models, that rely on concepts of object-oriented component-based systems, need to be developed for wind turbine systems to compensate for current workflow languages that only support a subset of requirements [39]. For example, the approach that is introduced in [40] for modeling CPES can be applied also for wind turbines. This approach integrates modular components according to network constraints after obtaining representations for each cyber and physical component, sensors and actuators dynamics.

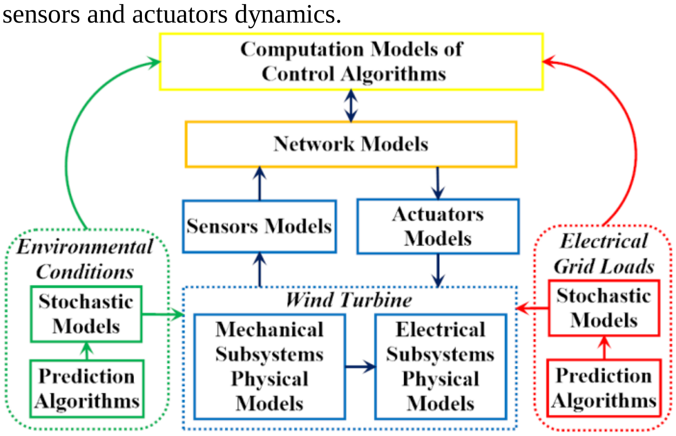

Fig. 6 Suggested modeling hierarchy for CP wind turbines

In [41], a group-based programming abstraction called Bundle is developed for CPS. This framework helps in programming applications with multiple CPS, different administrators and mobility support. Efficient real-time simulations are also a key-element of model-based design of CP wind turbines. In [42], a simulation environment is developed for modeling and validation of information and communication technology in CPES.

B. CP control for sustainable operation

Control systems of utility-scale wind turbines integrate different cascading and collaborative levels and objectives. These control tasks are overviewed in Fig. 7. Moreover, wind turbine control systems may need adaptation to different operating modes like grid-connected or microgrid operations. This concept represents an innovative design that is denoted as *universal WECS* as reported in [43]. Recent advances in control systems of wind turbines and wind farms are reviewed in [44]. One example for a complete framework of wind turbine control is project SusCon [45]. This project introduces a new concept of sustainable control to operate new generations of wind turbines with an integrated control platform. The functional layout of the sustainable control platform integrates four components with collaborative objectives: *Optimized feedback control, fault tolerant control, extreme event control* and *optimal shutdown control* [45].

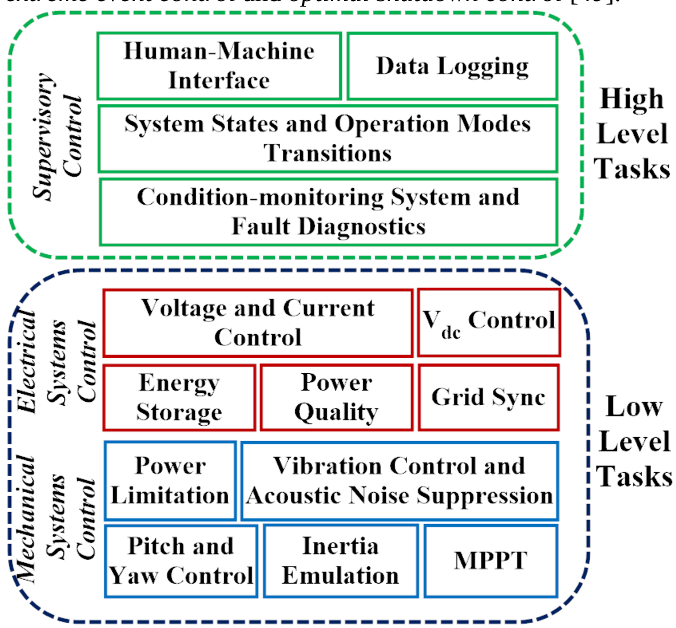

Fig. 7 Wind turbine systems control tasks

New design methodologies and techniques of CP control systems need to be tailored to meet the goals of WECS industry. The control systems inside WECS exchange data with sensors and actuators using several communication protocols like field bus controller area network (CAN) and industrial Ethernet protocol [44]. Designing a control system with networking and computation constraints is a great challenge. Therefore, such a complex control platform requires a CP approach for integrating the main controllers with the communication network. For example, a joint optimization algorithm for CPS is proposed in [46] that combines communication issues like packet losses and control issues like actuator constraints.

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C. WSN and CPS for next generation CMS

Reliable operation of wind turbines requires real-time and efficient systems for condition and health monitoring of the plant condition. WSN represent a promising solution that proved reliability and began to gain interest for condition and health monitoring. WSN deploy a heavy number of nodes where each one can autonomously control a set of transducers and apply complex signal and data processing with coordination with other nodes in the network [47]. Several industries are currently considering WSN such as ubiquitous sensing in healthcare systems [48], CM of aircraft components [49], and structural health monitoring (SHM) in civil infrastructures [50]. For wind power industry, several studies have addressed the deployment of WSN. In [51], WSN architecture is designed and integrated within a SCADA system for reliable and real-time monitoring of wind turbine operations. In [52], a method is suggested for increasing network lifetime of WSN deployed in offshore wind farms. In [53], a WSN is proposed for CM of offshore wind turbines. Current utility-scale wind turbines are considered as large flexible structures due to the massive increase in their size. This requires a real-time and cost-effective SHM of towers, nacelle and blades. A piezoceramic-based WSN for health monitoring of wind turbine blades is proposed in [54]. WSN for wind turbine towers SHM are investigated in [55]. However, a rich deployment of sensors from cross-domains that monitor heterogeneous components impose a CP approach that is beyond WSN. In [56], a review and arguments are discussed of how CPS can outperform WSN in exploiting physical data. CPS approaches will enable CMS and SHM for IoE by providing the following features:

1) Cross-field communications connected to Internet.
2) Cross-domain and intelligent knowledge discovery.
3) Mode-based and task-related sensing.

IV. Wind Farms for IoE

The energy market is moving progressively toward the collaboration of several producers and consumers for autonomous and intelligent generation, management and distribution. IoE represents the combination of IoT and smart grids. IoE will be the backbone of for connecting, supervising, and control the next generation energy sources and consumers. Therefore, renewable energy resources such wind power plants are required to advance to be compatible with IoE. In this section, different aspects of design and construction considerations are overviewed for compatibility with next generation IoE-enabled WECS.

A. Future SCADA systems and M2M for IoE-enabled wind farms

The nature of wind farms environments as harsh, wide and remote locations requires SCADA systems that are capable of providing efficient monitoring and control. Moreover, the complexity degree of a wind turbine imposes the view of wind farms as a system of systems [57]. Therefore, current SCADA systems used for monitoring and controlling grids and power plants including wind turbines should upgrade to next-generation multilayered interactive sensing, communication, and control to support the needs of future industry and energy demands [40]. For example, energy providers are presently demanding the integration of wind farms SCADA systems into their asset management software like enterprise resource planning (ERP) and customer resource management (CRM) [58]. The roles and objectives of future SCADA systems for wind energy are summarized in Fig. 8.

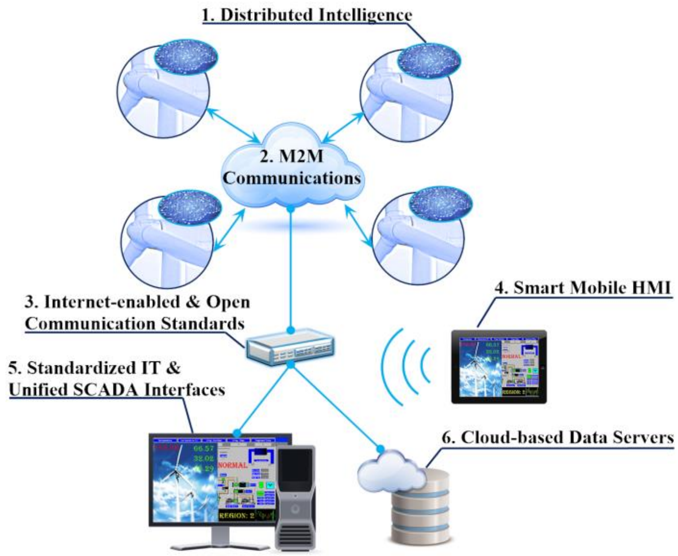

Fig. 8 Characteristics of future SCADA systems for WECS

The operation and management of future wind farms will impose CP SCADA systems with implementations based on IoT technology. The concept of IoT is demonstrated in [59] for deploying a WSN for an industrial process that can be monitored from anywhere over the internet. Based on a CP model of a power system, a flexible SCADA system is suggested in [60] to provide decentralized intelligence and decision ability. *Industrial Internet* is a quite new concept that is introduced by General Electric. It consists of three main components: Intelligent machines, analytics, and operators. This concept is applied for wind control platform to manage the coordination of wind turbines in a farm [61]. In a similar way, a service-based vision for next generation SCADA is introduced in [62]. This vision expects the SCADA system to benefit from recent advances in computing and networking to provide monitoring and control services over the internet, which is the core nature of IoT.

The need for efficient processing of massive raw data collections imposes self-organizing CPS networks [5]. Therefore, new network standards, protocols and infrastructures are required for CP wind farms. In [63], an on-demand communication strategy that is control-aware and handles real-time constraints for CPES is presented. Machine-to-machine (M2M) is a growing key-element of IoT. M2M communications allow intelligent machines to exchange information with each other as well as business applications and data servers [64]. New M2M concepts are expected to expand form one-to-one connections to a paradigm where

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producers and consumers are connected [65]. M2M networks are expected to invade many fields like industrial and agricultural automation, healthcare, transport systems and electricity grids [66]. They are currently utilized for many applications in wind energy. In [67], an M2M communications infrastructure is proposed for smart wind farms to provide intelligence and exchange the measured data between wind turbines. A cloud-based M2M telemetry system is proposed to process and visualize data for renewable energy suppliers in [68]. Moreover, CMS are becoming smarter with M2M. In [69], a prognostic system applies an M2M strategy to identify critical components affecting the turbine performance within a peer-cluster of turbines.

B. Integration of IoE-enabled wind farms into smart grids

The major problems of large-scale integration are the unsatisfactory predictability, non-dispatchability and variability of wind energy resources. Integrating wind energy into traditional grids leads to problems like fluctuations in voltage and frequency. This requires manual synchronization of wind farms with grids to avoid those problems. Modernization of the generation, distribution, consumption energy phases imposes more complexity in levels of autonomy for this cycle. Smart grid manages to solve this problem by automating the dispatch process between different power stations and enable the consumer to adjust loads and energy consumption. Smart grid is a CPES for intelligent, efficient and sustainable management and distribution of electricity. United States, China, United Kingdom, Europe and India are investing heavily in smart grids. In South Korea, a $65 million program is held the fully integrates a grid smart for 6000 homes with series of wind farms and distribution lines [70]. The concept of smart grid represents a corner stone in the IoE. In [71], a detailed review of IoT technologies with use of cheap, resource-constrained and ubiquitous computing devices that lead to an internet-based smart grids.

Smart grid simplifies the integration of wind farms in a plug and play manner to serve the new demands for electricity and offer the flexibility of controlling distributed generation and voltage regulation [72]. A review of several technology examples that enable reliable integration of wind energy with smart grids is discussed in [73]. Future wind systems require the redesign of new hardware and software systems inside wind turbines to incorporate reliable algorithms of wind forecasting. A multi-temporal model-based system design with more robust primary stabilization and frequency regulation hardware and considering predictability of wind resource is suggested in [74]. In [75], a case study of control strategies for collaboration between a smart grid, smart houses and distributed wind farms is discussed. Moreover, wind energy may need more complicated integration techniques to be applicable for future transportation trends like plug-in hybrid electric vehicle. A stochastic framework is developed in [76] to offer a vehicle-to-grid service that mitigates the effects of wind power fluctuations for the charging and discharging process of electric vehicles.

Reliability issues should be considered due to the challenging impacts of integrating wind energy on grid stability. These challenges include variability, low correlation with loads, forecast errors, congestion in transmission and distribution, and operational performance of frequency and voltage regulation [77]. The future demands of efficient and sustainable wind integration exceed the capabilities of currently deployed SCADA systems. A hardware/software infrastructure is expected to be standard in future smart grids to integrate economic signals with active management at demand side management. This approach results in better utilization of renewable resources with grid response flexibility to variations of generation and load [78]. For deploying such management systems, a network of wired and wireless sensor systems are expected to be integrated not only for power equipment systems but also for ambient sensing at generation and user-end [79]. Another vital issue in integrating wind energy with smart grids is communication systems. Communication between wind farm components and smart grid requires standard and flexible models for information exchange. In [80], an information model for integration offshore wind farms into smart grids is proposed by extending the IEC 61400-25 standard.

C. Wind farms for virtual power plants (VPP)

VPP is a collaborative integration and management of distributed generation resources as a unified power plant. The VPP scheme provides the coherence of central control and coordination of market integration for distributed power resources [81]. VPP has an internal energy management system that handles the objectives of minimizing costs and pollutions by maximizing utilization of renewable energy while exchanging power with the electrical grid [82]. A VPP contains an implemented CP strategy to coordinate the output of each distributed generator. At each node, the control strategy needs information from neighboring units while maintaining simple and robust communication networks between different distributed generators [83]. Fig. 9 shows the integration of VPP into smart grids.

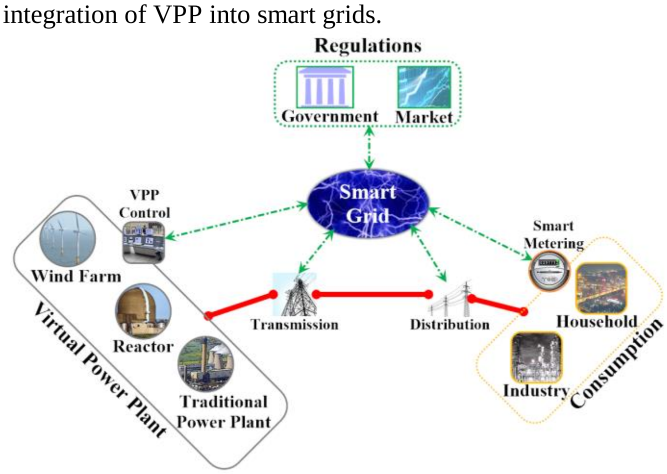

Fig. 9 The concept of VPP and smart grid

Challenges face sustainable VPP at run-time that integrate renewable resources. Because of their nature of

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unpredictability and inconsistence, probabilistic models of energy and optimal algorithms for matching produced and consumers are required [84]. In [85], a framework of VPP is suggested to compensate for wind unpredictability with flexible loads. The combination of wind farms with medium-scale reactors forms an effective VPP that leads to decreasing the variation in wind power by 80% to the grid [86]. In addition, VPP enhances the ability of wind energy to be easily and efficiently incorporated into the new paradigm of IoE. The IoE relies on the internet as the backbone of bandwidth, reliability and interconnection of smart grids [87]. Next generation wind farm technologies are expected to implement web-enabled communication standards for IoE. TABLE III illustrates how VPP can maximize benefits from wind energy.

TABLE III Comparison of decentralized and VPP-integrated wind farms

	Decentralized Wind Farms	Wind Farms integrated into VPP
Power Production	Intermittent generation due to nature of wind	Smoother production and better handling of fluctuations
Implementation	SCADA systems	Highly complex, secure and autonomous optimization and control systems
Economical	Pricing policies like feed-in tariff	Dynamic pricing and flexible trading
Compatibility	Requires upgrading technologies	Ready for smart grids and IoE

V. Safety, Security, and Sustainability of Wind Energy

Wind farms are expected to preserve reliable operation over large periods with little human intervention. The increase complexity of computing and communications of the cyber layer exposes WECS to vulnerabilities, software flaws and cyber-attacks. In addition, the tight couplings between physical parts and communication networks make them more vulnerable to cascading failures [88]. A wide acceptance of CPS imposes maintaining three requirements: Safety, security and sustainability [89]. Although CP interdependence enhances wind conversion systems, it adds more challenges in operation. In this section, a discussion of how those requirements can be achieved from a CP view of WECS.

A. Safety

Wind energy is one of the cleanest sources of energy with an exceptional safety record. However, the increasing complexity and growth rates of global demand add more safety requirements. The CP integration has to ensure safety of WECS at both development and run-time phases. In development phases, CPS researchers are interested in representing safety properties as computer science problems like formal verification [89]. Based on this approach a formal model of a wind turbine is developed in [90]. The developed model helps in verifying system correctness besides safety-critical properties of the wind turbine with respect to system timing behavior. In [91], an intelligent framework is developed for real-time assessment of the capabilities of a power grid with large wind penetration to survive contingencies and blackouts due to variable wind resource. Moreover, safe run-time operation needs efficient and reliable fault detection and isolation (FDI) and fault-tolerant control (FTC) methods to avoid system failures. In [92], the monitoring system integrates three layers of state abstraction, learning algorithms and state prediction for identification of wind turbine faults. Multi-sensor information fusion technique is used for fault diagnosis of wind turbines in [93]. Fuzzy scheduler FTC is proposed in [94] based on state estimation of the healthy observers. In [95], description FDI and FTC methods based on set-valued observers theory are provided.

B. Security

A wind farm deploys wide area systems to achieve real-time monitoring and control of plant parameters. These systems necessitates an efficient communications infrastructure in terms of speed and cost. A substantial issue is raised about cybersecurity challenges of the communication systems. Moreover, IEC61400-25 standard for wind energy allows more open access [58]. Also, the use of commercial-off-the-shelf information technology introduces the potential for new security vulnerabilities [96]. This raises a great concern about handling security issues. The cyber layer must guarantee system safety under untrusted codes or malicious commands. Moreover, control theory should be implemented in safety and security layers. For example, distribution of sensors and actuators must ensure the controllability and observability of the plant under single user compromise [97]. An overview for standardization of security solution for IoT systems is provided in [98]. In [99], a cybersecurity architecture for communication between grid and wind farms is proposed. The impact due to the proposed architecture on the real-time performance of measurement systems is also studied. A security standard for wind farm communications based on the web-service security standard is proposed in [100]. Different attack scenarios that targets the vulnerabilities of a SCADA system of a wind farm are investigated in [101]. Simulations of those scenarios showed that these cyber-attacks might lead to major problems from equipment damage and hardware failures to economy loss. In [102], an improved TLS protocol is used to develop a model of agent mechanism to provide security for wind farm communications. This design combines the security requirements in IEC61400-25-3 with the international safety standards IEC62351 and takes into account the embedded nature of wind turbine components.

C. Sustainability

Sustainable operation of power sources intends to provide reliable generation of energy. The wind turbine components exhibit gradual degradation of performance, faults and failures that require periodical maintenance. The maintenance of wind turbine components is a costly process that requires effective management. Therefore, a CP management approach is needed for automating maintenance processes and reducing downtimes. Future CMS should be able to automatically schedule and balance preventive and corrective maintenance processes. Preventive maintenance is a maintenance process that is applied either on schedule or due to CM to avoid failures while corrective maintenance is applied after failure occurs [103]. In [104], a unified framework is described that integrates all technical and administrative measures on the level of wind turbines and wind farms for operation and maintenance. A mathematical programming model for maintenance scheduling can be combined with the monitoring system for supporting the daily and long-term operation [105]. In [106], a probabilistic cost model is developed to quantify risks and uncertainties, and make an O&M decision model for wind turbines to provide practical cost-effective operations besides maintenance guidelines.

Forecasts and prediction are also vital issues for sustainable large-scale integration of wind power. Reliable wind speed prediction enables cost-effective and smooth power generation with coordination with other sources. The next generation of CP wind farms must integrate efficient and accurate forecasting methods for short and long-term periods. These methods will assist in smoothing the wind farm output and reducing the operational cost of other power stations in load management. In [107], a wind forecast system that integrates database, data processing, application servers and specialized forecast software is described. The enhanced system can be used by all nationwide wind energy shareholders. In [108], a supervisory control unit is developed based on neural networks that combines a wind speed predictor. The developed control unit tends to reduce the size of energy storage systems for minimizing power fluctuations. Multiple wind power forecasting technologies and components are integrated together to form a system that can predict wind speed and power at each turbine in [109]. In [110], an analytic model is developed for reliability calculations of large-scale wind farms. A set of approaches is introduced in [111] for reliability assessment of wind farms that take into account grid failures and wind variability. An algorithm is designed in [112] for electricity market that addresses simultaneously the wind uncertainty and variability, and correlation between wind input and load. For residential levels, typical wind profiles data from local weather stations may not be accurate. Therefore, a framework is proposed in [113] based on neural networks with global forecast systems to obtain more accurate predictions of daily wind speed.

VI. Towards a Cyber Physical Social Vision of WECS

Although CPS integrate multidiscipline technical components, these components are usually placed within human framework. CPS are not just self-contained and isolated integration of technical systems, but also interact with social environment. A CP view of power generation systems will make them more reliable and environmentally friendly [114]. CPSS is an expansion of the CPS concept where people are involved with complex and intelligent infrastructures. The integration of social context includes factors like usability and functionality of interfaces, intuitive operating of machines, and coordination between human and machines [115]. The interaction between a social community and a SCADA system is discussed for a microgrid in rural or isolated areas in [116]. This interaction suggests social SCADA systems that integrate local community through the phases of decision-making, development and operation. With small-scale, simplified interfaces and basic training programs, a social SCADA system reinforces community resilience. Legislation of wind energy deployment and operation differs extremely between countries. Due to the stochastic nature of wind, governments have approved certain laws for grid and renewable facilities to achieve the balance between consumers and producers [117]. Therefore, WECS manufacturers are obliged to adapt their systems and implement algorithms in correspondence to local legislation in each country.

VII. Conclusions

Wind energy has an ambitious future as a renewable source for power generation. The massive deployment plans for wind farms impose new strategies of implementation that benefit from recent and expected technology advancements in computation, control, communications and physical components of WECS. In this paper, an overview for state-of-the-art layers, components and methods for WECS is presented. In addition, formulations and challenges of CP integration of WECS are introduced. The outcome of future CP WECS will be an enabler for the next generation power networks of smart grids and IoE. The following points are concluded from this presented vision:

1. The increasing complexity of controllers, SCADA, networks and physical components inside wind farms requires a CP approach for WECS.
2. New abstractions and models of WECS are involved in CP WECS. These models need new languages, that exceed the current modeling methods and languages of WECS, to model different aspects and domains.
3. Complex controllers with multi-objectives require new calculus for implementation to integrate both continues and event-based dynamics in a unified approach.
4. Future CMS will implement mass of sensors for health monitoring that are deployed as WSN with a CPS approach.
5. Next generation SCADA systems of wind farms will have more intelligent capabilities like M2M communications that conform to smart grids. Moreover, control centers of wind farms will be integrated with other energy sources to form a VPP for more sustainable power generation.
6. As a CPS, WECS must conform to safety and security requirements. Current backbone structures of cyber technologies like PLCs and RTUs should be improved for safety and security.
7. A sustainable power generation imposes an automated CP maintenance approach to reduce downtimes.
8. Finally, the social component of local acceptance and

effects of WECS needs to be considered for effective deployment as social IoT.

References

[1] Global Wind Energy Council, "Global Wind Statistics 2015," 10 February 2014 2015.

[2] World Wind Energy Association, "NEW RECORD IN WORLDWIDE WIND INSTALLATIONS," ed, 2015.

[3] World Wind Energy Association, "Key Statistics of World Wind Energy Report 2013 ", Shanghai7 April 2014 2014.

[4] C. Shanzhi, X. Hui, L. Dake, H. Bo, and W. Hucheng, "A Vision of IoT: Applications, Challenges, and Opportunities With China Perspective," *Internet of Things Journal, IEEE,* vol. 1, pp. 349-359, 2014.

[5] R. Rajkumar, L. Insup, S. Lui, and J. Stankovic, "Cyber-physical systems: The next computing revolution," in *Design Automation Conference (DAC), 2010 47th ACM/IEEE*, 2010, pp. 731-736.

[6] "Cyber-Physical Systems — Changing Economy and Society," in *Cyber-Physical Systems*, ed: Springer Berlin Heidelberg, 2011, pp. 11-13.

[7] X. Li Da, H. Wu, and L. Shancang, "Internet of Things in Industries: A Survey," *Industrial Informatics, IEEE Transactions on,* vol. 10, pp. 2233-2243, 2014.

[8] J. A. Stankovic, "Research Directions for the Internet of Things," *Internet of Things Journal, IEEE,* vol. 1, pp. 3-9, 2014.

[9] K. Fanxin, D. Chuansheng, L. Xue, and Z. Haibo, "Quantity Versus Quality: Optimal Harvesting Wind Power for the Smart Grid," *Proceedings of the IEEE,* vol. 102, pp. 1762-1776, 2014.

[10] A. L. Pettener, "SCADA and communication networks for large scale offshore wind power systems," in *Renewable Power Generation (RPG 2011), IET Conference on*, 2011, pp. 1-6.

[11] K. Gajrani, A. Bhargava, K. G. Sharma, and R. Bansal, "Dynamic performance improvement of wind power integrated grid using TCP/IP communication network," in *Clean Energy and Technology (CEAT), 2013 IEEE Conference on*, 2013, pp. 405-410.

[12] F. R. Yu, Z. Peng, X. Weidong, and P. Choudhury, "Communication systems for grid integration of renewable energy resources," *Network, IEEE,* vol. 25, pp. 22-29, 2011.

[13] R. Tiwari and A. K. Mishra, "Study of data transfer from wind farm substation to SLDC & case study," in *Electrical Energy Systems (ICEES), 2014 IEEE 2nd International Conference on*, 2014, pp. 106-109.

[14] International Electrotechnical Commission, "IEC61400-25-1: Communications for monitoring and control of wind power plants – Overall description of principles and models," ed. Geneva: International Electrotechnical Commission, 2006.

[15] H. Lingxiang, B. Duan, L. Yuanyuan, and T. Shujuan, "Design of IEC 61400-25 gateway for RIU replacement," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on*, 2009, pp. 1-5.

[16] M. Ahmed and Y.-C. Kim, "Communication Network Architectures for Smart-Wind Power Farms," *Energies,* vol. 7, pp. 3900-3921, 2014.

[17] W. Mu and C. Zhe, "Study of LANs access technologies in wind power system," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-6.

[18] M. Ahmed and Y.-C. Kim, "Hierarchical Communication Network Architectures for Offshore Wind Power Farms," *Energies,* vol. 7, pp. 3420-3437, 2014.

[19] V. Stankovic, L. Stankovic, W. Shuang, and S. Cheng, "Distributed Compression for Condition Monitoring of Wind Farms," *Sustainable Energy, IEEE Transactions on*, vol. 4, pp. 174-181, 2013.

[20] B. Badrzadeh, M. Bradt, N. Castillo, R. Janakiraman, R. Kennedy, S. Klein, *et al.*, "Wind power plant SCADA and controls," in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1-7.

[21] A. Kusiak, Z. Zhang, and A. Verma, "Prediction, operations, and condition monitoring in wind energy," *Energy,* vol. 60, pp. 1-12, 10/1/ 2013.

[22] Y. Wenxian and J. Jiesheng, "Wind turbine condition monitoring and reliability analysis by SCADA information," in *Mechanic Automation and Control Engineering (MACE), 2011 Second International Conference on*, 2011, pp. 1872-1875.

[23] M. Schlechtingen and I. Ferreira Santos, "Comparative analysis of neural network and regression based condition monitoring approaches for wind turbine fault detection," *Mechanical Systems and Signal Processing,* vol. 25, pp. 1849-1875, 7// 2011.

[24] M. Wilkinson, B. Darnell, T. van Delft, and K. Harman, "Comparison of methods for wind turbine condition monitoring with SCADA data," *Renewable Power Generation, IET,* vol. 8, pp. 390-397, 2014.

[25] W. Yang, R. Court, and J. Jiang, "Wind turbine condition monitoring by the approach of SCADA data analysis," *Renewable Energy,* vol. 53, pp. 365-376, 5// 2013.

[26] M. Schlechtingen, I. F. Santos, and S. Achiche, "Wind turbine condition monitoring based on SCADA data using normal behavior models. Part 1: System description," *Applied Soft Computing,* vol. 13, pp. 259-270, 1// 2013.

[27] M. Schlechtingen and I. F. Santos, "Wind turbine condition monitoring based on SCADA data using normal behavior models. Part 2: Application examples," *Applied Soft Computing,* vol. 14, Part C, pp. 447-460, 1// 2014.

[28] W. Yang, P. J. Tavner, C. J. Crabtree, Y. Feng, and Y. Qiu, "Wind turbine condition monitoring: technical and commercial challenges," *Wind Energy,* vol. 17, pp. 673-693, 2014.

[29] Y. Amirat, M. E. H. Benbouzid, E. Al-Ahmar, B. Bensaker, and S. Turri, "A brief status on condition monitoring and fault diagnosis in wind energy conversion systems," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2629-2636, 12// 2009.

[30] Y. Wenxian, P. J. Tavner, C. J. Crabtree, and M. Wilkinson, "Cost-Effective Condition Monitoring for Wind Turbines," *Industrial Electronics, IEEE Transactions on,* vol. 57, pp. 263-271, 2010.

[31] J. P. Barton and S. J. Watson, "Analysis of electrical power data for condition monitoring of a small wind turbine," *Renewable Power Generation, IET,* vol. 7, pp. 341-349, 2013.

[32] B. Chen, D. Zappalá, C. J. Crabtree, and P. J. Tavner, "Survey of commercially available SCADA data analysis tools for wind turbine health monitoring," DU, Technical Report2014.

[33] C. J. Crabtree, D. Zappalá, and P. J. Tavner, "Survey of commercially available condition monitoring systems for wind turbines," DU, Technical Report2014.

[34] C. A. Macana, N. Quijano, and E. Mojica-Nava, "A survey on Cyber Physical Energy Systems and their applications on smart grids," in *Innovative Smart Grid Technologies (ISGT Latin America), 2011 IEEE PES Conference on*, 2011, pp. 1-7.

[35] W. Kaiyu, D. Hughes, M. Ka Lok, and T. Krilavicius, "Composition challenges and approaches for cyber physical systems," in *Networked Embedded Systems for Enterprise Applications (NESEA), 2010 IEEE International Conference on*, 2010, pp. 1-7.

[36] C. Zhu, L. Shu, T. Hara, L. Wang, S. Nishio, and L. T. Yang, "A survey on communication and data management issues in mobile sensor networks," *Wireless Communications and Mobile Computing,* vol. 14, pp. 19-36, 2014.

[37] M. Lydia, S. S. Kumar, A. I. Selvakumar, and G. E. Prem Kumar, "A comprehensive review on wind turbine power curve modeling techniques," *Renewable and Sustainable Energy Reviews,* vol. 30, pp. 452-460, 2// 2014.

[38] P. Derler, E. A. Lee, and A. S. Vincentelli, "Modeling Cyber-Physical Systems," *Proceedings of the IEEE,* vol. 100, pp. 13-28, 2012.

[39] R. Seiger, C. Keller, F. Niebling, and T. Schlegel, "Modelling complex and flexible processes for smart cyber-physical environments," *Journal of Computational Science*.

[40] Ilic, x, M. D., X. Le, U. A. Khan, and J. M. F. Moura, "Modeling of Future Cyber-Physical Energy Systems for Distributed Sensing and Control," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* vol. 40, pp. 825-838, 2010.

[41] P. A. Vicaire, E. Hoque, X. Zhiheng, and J. A. Stankovic, "Bundle: A Group-Based Programming Abstraction for Cyber-Physical Systems," *Industrial Informatics, IEEE Transactions on,* vol. 8, pp. 379-392, 2012.

[42] H. Georg, S. C. Muller, C. Rehtanz, and C. Wietfeld, "Analyzing Cyber-Physical Energy Systems:The INSPIRE Cosimulation of Power and ICT Systems Using HLA," *Industrial Informatics, IEEE Transactions on,* vol. 10, pp. 2364-2373, 2014.

[43] N. A. Orlando, M. Liserre, R. A. Mastromauro, and A. Dell'Aquila, "A Survey of Control Issues in PMSG-Based Small Wind-Turbine Systems," *Industrial Informatics, IEEE Transactions on,* vol. 9, pp. 1211-1221, 2013.

[44] B. R. Karthikeya and R. J. Schutt, "Overview of Wind Park Control Strategies," *Sustainable Energy, IEEE Transactions on,* vol. 5, pp. 416-422, 2014.

[45] S. Kanev, T. v. Engelen, W. Engels, X. Wei, J. Dong, and M. Verhaegen, "Sustainable Control: A new approach to operate wind turbines," ECN-E–12-028, June 2012 2012.

[46] C. Xianghui, C. Peng, C. Jiming, and S. Youxian, "An Online Optimization Approach for Control and Communication Codesign in Networked Cyber-Physical Systems," *Industrial Informatics, IEEE Transactions on,* vol. 9, pp. 439-450, 2013.

[47] S. Giannoulis, C. Koulamas, C. Emmanouilidis, P. Pistofidis, and D. Karampatzakis, "Wireless Sensor Network Technologies for Condition Monitoring of Industrial Assets," in *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*. vol. 398, C. Emmanouilidis, M. Taisch, and D. Kiritsis, Eds., ed: Springer Berlin Heidelberg, 2013, pp. 33-40.

[48] Z. Yuan, S. Limin, S. Houbing, and C. Xiaojun, "Ubiquitous WSN for Healthcare: Recent Advances and Future Prospects," *Internet of Things Journal, IEEE,* vol. 1, pp. 311-318, 2014.

[49] K. Sampigethaya and R. Poovendran, "Aviation Cyber-Physical Systems: Foundations for Future Aircraft and Air Transport," *Proceedings of the IEEE,* vol. 101, pp. 1834-1855, 2013.

[50] G. Hackmann, G. Weijun, Y. Guirong, S. Zhuoxiong, L. Chenyang, and S. Dyke, "Cyber-Physical Codesign of Distributed Structural Health Monitoring with Wireless Sensor Networks," *Parallel and Distributed Systems, IEEE Transactions on,* vol. 25, pp. 63-72, 2014.

[51] B. Xingzhen, M. Xiangzhong, D. Zhaowen, G. Maofa, and H. Zhiguo, "Design of Wireless Sensor Network in SCADA system for wind power plant," in *Automation and Logistics, 2008. ICAL 2008. IEEE International Conference on*, 2008, pp. 3023-3027.

[52] D. Agarwal and N. Kishor, "A Fuzzy Inference-Based Fault Detection Scheme Using Adaptive Thresholds for Health Monitoring of Offshore Wind-Farms," *Sensors Journal, IEEE,* vol. 14, pp. 3851-3861, 2014.

[53] Z. Fu and Y. Yuan, "Condition health monitoring of offshore wind turbine based on wireless sensor network," in *IPEC, 2012 Conference on Power & Energy*, 2012, pp. 649-654.

[54] G. Song, H. Li, B. Gajic, W. Zhou, P. Chen, and H. Gu, "Wind turbine blade health monitoring with piezoceramic-based wireless sensor network," *International Journal of Smart and Nano Materials,* vol. 4, pp. 150-166, 2013/09/01 2013.

[55] G. Kilic and M. S. Unluturk, "Testing of wind turbine towers using wireless sensor network and accelerometer," *Renewable Energy,* vol. 75, pp. 318-325, 3// 2015.

[56] F.-J. Wu, Y.-F. Kao, and Y.-C. Tseng, "From wireless sensor networks towards cyber physical systems," *Pervasive and Mobile Computing,* vol. 7, pp. 397-413, 8// 2011.

[57] K. Rannat, L. Motus, M. Meriste, and J. Preden, "On dynamic models for wind farms as systems of systems," in *System of Systems Engineering (SoSE), 2012 7th International Conference on*, 2012, pp. 113-118.

[58] "SCADA 2014 systems for wind," Bachmann, http://www.wpmexpertreports.com/ExpertReport/SCADA-2014-SYSTEMS-FOR-WIND3/2014 2014.

[59] F. Corso, Y. Camargo, and L. Ramirez, "Wireless Sensor System According to the Concept of IoT -Internet of Things," in *Computational Science and Computational Intelligence (CSCI), 2014 International Conference on*, 2014, pp. 52-58.

[60] Z. Vale, H. Morais, P. Faria, H. Khodr, J. Ferreira, and P. Kadar, "Distributed energy resources management with cyber-physical SCADA in the context of future smart grids," in *MELECON 2010 - 2010 15th IEEE Mediterranean Electrotechnical Conference*, 2010, pp. 431-436.

[61] R. Burra, A. Ambekar, H. Narang, E. Liu, C. Mehendale, L. Thirer*, et al.*, "GE Brilliant wind farms," in *Power Electronics and Machines for Wind and Water Applications (PEMWA), 2014 IEEE Symposium*, 2014, pp. 1-10.

[62] S. Karnouskos and A. W. Colombo, "Architecting the next generation of service-based SCADA/DCS system of systems," in *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, 2011, pp. 359-364.

[63] E. Moradi-Pari, N. Nasiriani, Y. P. Fallah, P. Famouri, S. Bossart, and K. Dodrill, "Design, Modeling, and Simulation of On-Demand Communication Mechanisms for Cyber-Physical Energy Systems," *Industrial Informatics, IEEE Transactions on,* vol. 10, pp. 2330-2339, 2014.

[64] A. Aijaz and A. H. Aghvami, "Cognitive Machine-to-Machine Communications for Internet-of-Things: A Protocol Stack Perspective," *Internet of Things Journal, IEEE,* vol. 2, pp. 103-112, 2015.

[65] I. Stojmenovic, "Machine-to-Machine Communications With In-Network Data Aggregation, Processing, and Actuation for Large-Scale Cyber-Physical Systems," *Internet of Things Journal, IEEE,* vol. 1, pp. 122-128, 2014.

[66] Z. Yan, Y. Rong, M. Nekovee, L. Yi, X. Shengli, and S. Gjessing, "Cognitive machine-to-machine communications: visions and potentials for the smart grid," *Network, IEEE,* vol. 26, pp. 6-13, 2012.

[67] M. A. Ahmed and K. Young-Chon, "Machine-to-machine communication infrastructure for smart wind power farms," in *Intelligent Energy Systems (IWIES), 2013 IEEE International Workshop on*, 2013, pp. 137-142.

[68] G. Suciu, S. Halunga, O. Fratu, A. Vasilescu, and V. Suciu, "Study for renewable energy telemetry using a decentralized cloud M2M system," in *Wireless Personal Multimedia Communications (WPMC), 2013 16th International Symposium on*, 2013, pp. 1-5.

[69] E. R. Lapira, H. Al-Atat, and J. Lee, "Turbine-To-Turbine Prognostics Technique For Wind Farms," ed: Google Patents, 2013.

[70] S. Massoud Amin, "Smart Grid: Overview, Issues and Opportunities. Advances and Challenges in Sensing, Modeling, Simulation, Optimization and Control," *European Journal of Control,* vol. 17, pp. 547-567, // 2011.

[71] N. Bui, A. P. Castellani, P. Casari, and M. Zorzi, "The internet of energy: a web-enabled smart grid system," *Network, IEEE,* vol. 26, pp. 39-45, 2012.

[72] K. S. Reddy, M. Kumar, T. K. Mallick, H. Sharon, and S. Lokeswaran, "A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid," *Renewable and Sustainable Energy Reviews,* vol. 38, pp. 180-192, 10// 2014.

[73] M. Glinkowski, J. Hou, and G. Rackliffe, "Advances in Wind Energy Technologies in the Context of Smart Grid," *Proceedings of the IEEE,* vol. 99, pp. 1083-1097, 2011.

[74] X. Le, P. M. S. Carvalho, L. A. F. M. Ferreira, L. Juhua, B. H. Krogh, N. Popli, *et al.*, "Wind Integration in Power Systems: Operational Challenges and Possible Solutions," *Proceedings of the IEEE,* vol. 99, pp. 214-232, 2011.

[75] A. M. Howlader, N. Urasaki, and A. Y. Saber, "Control Strategies for Wind-Farm-Based Smart Grid System," *Industry Applications, IEEE Transactions on,* vol. 50, pp. 3591-3601, 2014.

[76] M. Ghofrani, A. Arabali, M. Etezadi-Amoli, and M. S. Fadali, "Smart Scheduling and Cost-Benefit Analysis of Grid-Enabled Electric Vehicles for Wind Power Integration," *Smart Grid, IEEE Transactions on,* vol. 5, pp. 2306-2313, 2014.

[77] K. Moslehi and R. Kumar, "A Reliability Perspective of the Smart Grid," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 57-64, 2010.

[78] C. Cecati, C. Citro, and P. Siano, "Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid," *Sustainable Energy, IEEE Transactions on,* vol. 2, pp. 468-476, 2011.

[79] T. Chen-Khong and L. Tie, "Sensing-Driven Energy Purchasing in Smart Grid Cyber-Physical System," *Systems, Man, and Cybernetics: Systems, IEEE Transactions on,* vol. 43, pp. 773-784, 2013.

[80] N. Trinh Hoang, A. Prinz, T. Friiso, and R. Nossum, "Smart grid for offshore wind farms: Towards an information model based on the IEC 61400-25 standard," in *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*, 2012, pp. 1-6.

[81] P. Moutis and N. Hatziargyriou, "Decision Trees Aided Active Power Reduction of a Virtual Power Plant for Power System Over-Frequency Mitigation," *Industrial Informatics, IEEE Transactions on,* vol. PP, pp. 1-1, 2014.

[82] P. Nezamabadi and G. B. Gharehpetian, "Electrical energy management of virtual power plants in distribution networks with renewable energy resources and energy storage systems," in *Electrical*

Power Distribution Networks (EPDC), 2011 16th Conference on, 2011, pp. 1-5.

[83] X. Huanhai, G. Deqiang, L. Naihu, L. Huijie, and D. Chensong, "Virtual power plant-based distributed control strategy for multiple distributed generators," *Control Theory & Applications, IET,* vol. 7, pp. 90-98, 2013.

[84] S. Biswas, D. Bagchi, and Y. Narahari, "Mechanism design for sustainable virtual power plant formation," in *Automation Science and Engineering (CASE), 2014 IEEE International Conference on*, 2014, pp. 67-72.

[85] J. Mohammadi, A. Rahimi-Kian, and M. S. Ghazizadeh, "Joint operation of wind power and flexible load as virtual power plant," in *Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on*, 2011, pp. 1-4.

[86] D. Shropshire, A. Purvins, I. Papaioannou, and I. Maschio, "Benefits and cost implications from integrating small flexible nuclear reactors with off-shore wind farms in a virtual power plant," *Energy Policy,* vol. 46, pp. 558-573, 7// 2012.

[87] Y. Ye, Q. Yi, H. Sharif, and D. Tipper, "A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges," *Communications Surveys & Tutorials, IEEE,* vol. 15, pp. 5-20, 2013.

[88] S. Dong-Hoon, H. Shibo, and Z. Junshan, "Robust, Secure, and Cost-Effective Design for Cyber-Physical Systems," *Intelligent Systems, IEEE,* vol. 29, pp. 66-69, 2014.

[89] A. Banerjee, K. K. Venkatasubramanian, T. Mukherjee, and S. K. S. Gupta, "Ensuring Safety, Security, and Sustainability of Mission-Critical Cyber-Physical Systems," *Proceedings of the IEEE,* vol. 100, pp. 283-299, 2012.

[90] J. Suryadevara, G. Sapienza, C. C. Seceleanu, T. Seceleanu, S. E. Ellevseth, and P. Pettersson, "Wind Turbine System: An Industrial Case Study in Formal Modeling and Verification," 2013.

[91] X. Yan, D. Zhao Yang, X. Zhao, M. Ke, and W. Kit Po, "An Intelligent Dynamic Security Assessment Framework for Power Systems With Wind Power," *Industrial Informatics, IEEE Transactions on,* vol. 8, pp. 995-1003, 2012.

[92] A. Kusiak and A. Verma, "A Data-Mining Approach to Monitoring Wind Turbines," *Sustainable Energy, IEEE Transactions on,* vol. 3, pp. 150-157, 2012.

[93] H. Jun, Z. JianZhong, and C. Ming, "Fault diagnosis of wind turbine based on multisensors information fusion technology," *Renewable Power Generation, IET,* vol. 8, pp. 289-298, 2014.

[94] E. Kamal, A. Aitouche, R. Ghorbani, and M. Bayart, "Fuzzy Scheduler Fault-Tolerant Control for Wind Energy Conversion Systems," *Control Systems Technology, IEEE Transactions on,* vol. 22, pp. 119-131, 2014.

[95] P. Casau, P. Rosa, S. M. Tabatabaeipour, C. Silvestre, and J. Stoustrup, "A Set-Valued Approach to FDI and FTC of Wind Turbines," *Control Systems Technology, IEEE Transactions on,* vol. 23, pp. 245-263, 2015.

[96] W. F. Young, J. E. Stamp, and J. D. Dillinger, "Communication Vulnerabilities and Mitigations in Wind Power Systems," presented at the American Wind Energy Association WINDPOWER 2003 Conference, Austin Texas, 2003.

[97] S. McLaughlin, "Securing Control Systems from the Inside: A Case for Mediating Physical Behaviors," *Security & Privacy, IEEE,* vol. 11, pp. 82-84, 2013.

[98] K. Sye Loong, S. S. Kumar, and H. Tschofenig, "Securing the Internet of Things: A Standardization Perspective," *Internet of Things Journal, IEEE,* vol. 1, pp. 265-275, 2014.

[99] K. Gajrani, A. Bhargava, K. G. Sharma, and R. Bansal, "Cyber security solution for wide area measurement systems in wind connected electric grid," in *Innovative Smart Grid Technologies - Asia (ISGT Asia), 2013 IEEE*, 2013, pp. 1-5.

[100] L. Nian, Z. Jianhua, and L. Wenxia, "A Security Mechanism of Web Services-Based Communication for Wind Power Plants," *Power Delivery, IEEE Transactions on,* vol. 23, pp. 1930-1938, 2008.

[101] Y. Jie, L. Chen-Ching, and M. Govindarasu, "Cyber intrusion of wind farm SCADA system and its impact analysis," in *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES*, 2011, pp. 1-6.

[102] L. Yuanyuan, D. Bin, S. Yongxin, and Y. Xiong, "Research on the security of supervisory control communication in wind farm," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on*, 2009, pp. 1-5.

[103] J. Nilsson and L. Bertling, "Maintenance Management of Wind Power Systems Using Condition Monitoring Systems—Life Cycle Cost Analysis for Two Case Studies," *Energy Conversion, IEEE Transactions on,* vol. 22, pp. 223-229, 2007.

[104] P. Joschko, A. H. Widok, S. Appel, S. Greiner, H. Albers, and B. Page, "Modeling and simulation of offshore wind farm O&M processes," *Environmental Impact Assessment Review*.

[105] F. Besnard, K. Fischer, and L. B. Tjernberg, "A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 443-450, 2013.

[106] B. Eunshin, L. Ntaimo, and D. Yu, "Optimal Maintenance Strategies for Wind Turbine Systems Under Stochastic Weather Conditions," *Reliability, IEEE Transactions on,* vol. 59, pp. 393-404, 2010.

[107] E. Terciyanli, T. Demirci, D. Kucuk, M. Sarac, I. Cadirci, and M. Ermis, "Enhanced Nationwide Wind-Electric Power Monitoring and Forecast System," *Industrial Informatics, IEEE Transactions on,* vol. 10, pp. 1171-1184, 2014.

[108] F. Islam, A. Al-Durra, and S. M. Muyeen, "Smoothing of Wind Farm Output by Prediction and Supervisory-Control-Unit-Based FESS," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 925-933, 2013.

[109] W. P. Mahoney, K. Parks, G. Wiener, L. Yubao, W. L. Myers, S. Juanzhen, *et al.*, "A Wind Power Forecasting System to Optimize Grid Integration," *Sustainable Energy, IEEE Transactions on,* vol. 3, pp. 670-682, 2012.

[110] A. S. Dobakhshari and M. Fotuhi-Firuzabad, "A Reliability Model of Large Wind Farms for Power System Adequacy Studies," *Energy Conversion, IEEE Transactions on,* vol. 24, pp. 792-801, 2009.

[111] N. B. Negra, O. Holmstrom, B. Bak-Jensen, and P. Sorensen, "Aspects of Relevance in Offshore Wind Farm Reliability Assessment," *Energy Conversion, IEEE Transactions on,* vol. 22, pp. 159-166, 2007.

[112] F. Bouffard and F. D. Galiana, "Stochastic Security for Operations Planning With Significant Wind Power Generation," *Power Systems, IEEE Transactions on,* vol. 23, pp. 306-316, 2008.

[113] C. S. Ioakimidis, L. J. Oliveira, and K. N. Genikomsakis, "Wind Power Forecasting in a Residential Location as Part of the Energy Box Management Decision Tool," *Industrial Informatics, IEEE Transactions on,* vol. 10, pp. 2103-2111, 2014.

[114] R. Rajkumar, "A Cyber-Physical Future," *Proceedings of the IEEE,* vol. 100, pp. 1309-1312, 2012.

[115] B. Krämer, "Evolution of Cyber-Physical Systems: A Brief Review," in *Applied Cyber-Physical Systems*, S. C. Suh, U. J. Tanik, J. N. Carbone, and A. Eroglu, Eds., ed: Springer New York, 2014, pp. 1-3.

[116] G. A. Jimenez-Estevez, R. Palma-Behnke, D. Ortiz-Villalba, Nu, x00F, O. ez Mata, *et al.*, "It Takes a Village: Social SCADA and Approaches to Community Engagement in Isolated Microgrids," *Power and Energy Magazine, IEEE,* vol. 12, pp. 60-69, 2014.

[117] J.-M. Gallardo-Calles, A. Colmenar-Santos, J. Ontañon-Ruiz, and M. Castro-Gil, "Wind control centres: State of the art," *Renewable Energy,* vol. 51, pp. 93-100, 3// 2013.