Wind Power Plants Control Systems Based on SCADA System

Khairy Sayed, Ahmed G. Abo-Khalil, and Ali M. Eltamaly

Abstract The objective of this chapter is to introduce the state of the art technology in wind power plant control and automation. This chapter starts with a historical background about supervisory control and automation evolution in the last decades. Several remarks are made regarding the use of SCADA Systems in wind turbine power plants. The Supervisory Control and Data Acquisition (SCADA) systems are responsible for controlling and monitoring many of the processes that make life in the industrial world possible, such as power distribution, oil flow, communications, and many more. In this chapter, an overview of SCADA at the wind power plant is presented, and operational concerns are addressed and examined. Notes on future trends will be provided. Finally, recommendations are provided regarding SCADA systems and their application in the wind power plant environment. One of the most significant aspects of SCADA is its ability to evolve with the ever-changing face of Information Technology (IT) systems.

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Abbreviations

ANNs	Artificial neural networks
ANFIS	Adaptive neuro-fuzzy inference systems
CCTV	The closed-circuit television
CM	Condition monitoring
CMS	Condition monitoring system
DCS	Distributed control system
DC	Direct current
EPON	Ethernet Passive Optical Network
FIS	Fuzzy inference system
HVDC	High-voltage direct–current
HMI	Human Machine Interface
HV-IGBT	High voltage isolated gate bipolar transistor
IEDs	Intelligent electronic devices
IT	Information technology
KPIs	Key Performance Indicators
LVRT	Low Voltage Ride-Through
MPH	Mile per hour
MV	Medium voltage
NNs	Neural networks
OLT	Optical Line Terminal
OPC	Open connectivity
ONU	Optical network unit
PCC	PC Controller
PLC	Programmable Logic Controller
POS	Passive optical splitter
RTU	Remote Terminal unit
RPM	Revolution per minute
SCADA	Supervisory Control and Data Acquisition
SOE	Sequence of events
SVM	Support Vector Machine
TMA	VAWT vertical axes wind turbine
WTG	Wind turbine generator
WTC	Wind turbine controller
WPP	Wind power farms
WPP	Wind power plant
WTGs	Wind turbine generation system

1 Introduction

SCADA is an abbreviation that refers to "Supervisory Control and Data Acquisition." It is an essential tool to control and monitor various measurements of the wind turbine generation system (WTGs), and it's usual to include it together with the wind turbines. SCADA serves as the primary interface between the wind power plant operator and the wind farm equipment [1–4]. It allows integrating all the info about WTGs, meteorological mast, and substation in a single point of control, recapturing, and storing operation data from the WTGs and various alarm signals. Moreover, SCADA enables sending control signals from the wind power plant operator to the wind turbine controller. At present, with the trend toward electricity generation from renewable energy resources are widespread in many projects. Wind farms (WPPs) will be built in near future. This expected growing in wind power plants (WPP) will significantly affect control, operation, and control electricity network today. Many research work and investigations are conducted to study wind farm (wind) subsystems (Turbine, collector system, substations, etc.) that were discussed and addressed in many publications [5–10]. However, the infrastructure of SCADA systems and the related communication networks in wind power plants are relatively less processed and rarely discussed [10–12]. Typical wind power plant consists of wind turbines, meteorological system, and local wind turbine network, collecting point, and transformers substation. Power cables are used with various cross section areas to transfer power from wind turbines that are connected to the facility system through transformers and distribution lines [13].

The essential characteristics of SCADA required in a wind farm system can be summarized as follows:

- To integrate WTGs, substation, and meteorological tower data in a single system.
- To enable a frequent access to the wind power data from the local PC placed in the substation building and remotely from control centers.
- To enable modifying different control parameters of wind turbines.
- Communication protocols utilized by the system must be compatible with the others.
- Usually, to guarantee the safety of technicians working inside the wind power plant, a clear hierarchy must be predefined for all the users.
- Several parameters for each wind plant component must be displayed. Generally, the following conditions are required:

    1. WTGs data: digital data such as active alarms and status (ready, working, stopped, paused). Analog data such as power (kW), power factor, speed (wind turbine, generator, rotor), temperatures, currents, and voltages for the three-phases.
    2. Measurement tower: or Met (meteorological) Mast that measures wind speed and direction, pressure, temperature, battery status. A measurement tower or met mast can be a free-standing tower or a movable mast, which holds measuring instruments or meteorological instruments. Such instruments are

used to measure wind speed, wind direction, and thermometers. Met masts are important in the development of wind farms, as exact knowledge of the wind speed is basic to know how much energy will be generated, and whether the turbines will endure on the site.

3. Substation: Line voltages and currents, delivered active and reactive power, circuit breaker status, substation alarms, and protection system events. The user must be capable of changing various system parameters at any time. This includes also the opening and closing orders of the main switch.
4. WTGs: The start and stop commands of the WTG, use of the orientation system, transferring power generation data.

However, different reports can be produced with the data provided by the SCADA system, such as generated power, determination of the power curve, availability of the turbine, failures statistics, wind data (speed and turbulence), active, and reactive power and power factor (cos φ) at the substation. SCADA systems store, retrieve, and exports massive amount of data to a variety of stakeholders, everyone with diverse needs:

Remote control center: The control center should be able to manipulate the alarms and system conditions in a quick and effective manner, discriminating the root cause of faults without being concealed by cascading alarms. The SCADA system architecture for wind farms is shown in Fig. 1.

Remote monitoring and diagnosis: the remote operating center must be able to manipulate and interpret data rapidly to solve the operating and system problems.

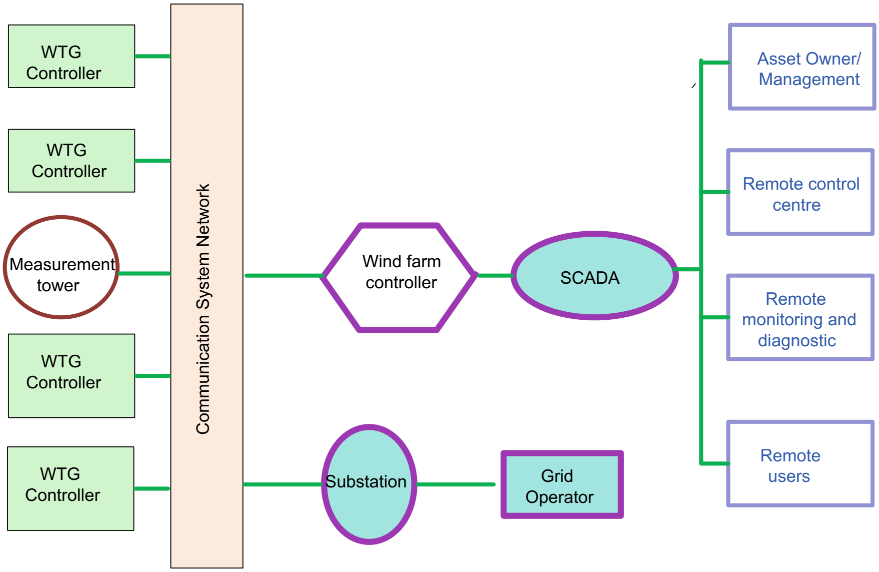

Fig. 1 SCADA system architecture in wind farm

Moreover, historical SCADA data can be used to authenticate computational models or improve new models.

Asset owners: This package uses SCADA output to calculate power revenue and calculation of energy losses, etc.

2 Wind Farm SCADA System

The wind turbine generator consists of the same wind turbines, circuit breakers, and step-up transformer. The generation voltage is stepped-up for each wind turbine using a voltage converter. Wind turbines are divided into groups, and each group is connected to a collector bus through the circuit breaker. Multiple grouped feeders are connected to a high-voltage (HV) transformer that raises the voltage to the transmission level [14–16]. Figure 2 shows a typical single line diagram of WPP. Wind power plants are divided into different regions: wind turbine area, collector feeding area, collector bus area, high-voltage transformer area, and transmission line area.

The main components of the wind farm are wind turbines, meteorological system, and electrical system [15]. However, SCADA systems are helpful in remote monitoring, data acquisition, data logging, and real-time control [16]. Remotely collect operation information from wind farm components and based on the information collected, the control center performs the appropriate procedures. Each WPP has a dedicated connection to the local control center for real-time monitoring and control. However, one control center can manage and control one or more wind power plants

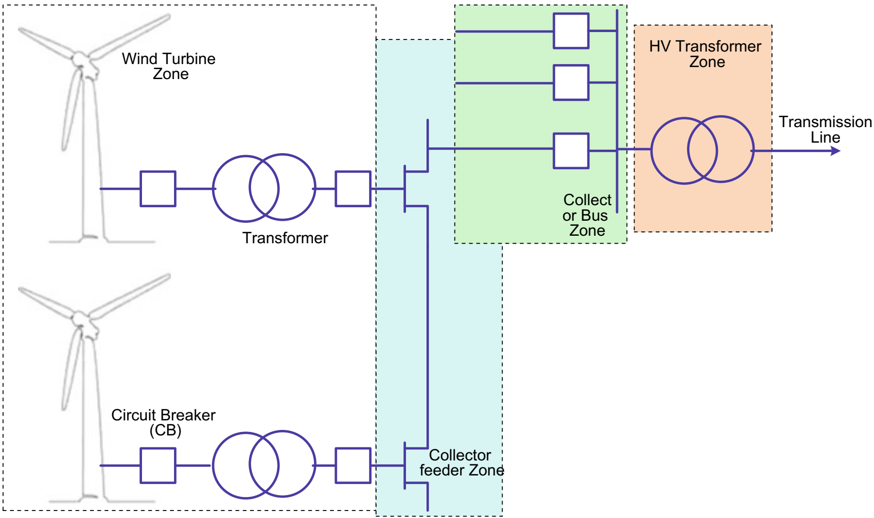

Fig. 2 Configuration of a typical wind power plant

remotely. There are many applications covered by SCADA systems in WPP. The three major applications are SCADA turbine system, SCADA wind power plant system, and SCADA security system [6–8].

Software system includes two types of software which are SCADA and applications software. The operator workstations are tied to networking architecture to enable monitoring operations in real-time. SCADA solutions include:

- SCADA solution to supervise, monitor, control, and report wind farm operations
- Sequence of events (SOE) recording for accurate alarm and event sequences that decrease troubleshooting time
- Network solutions include services that help with assessment, design, implementation, management, and audits of infrastructure
- Wind power application software
- Design and Operations Software that enables system expansion and upgrading
- Firewall and security software for Industrial Networks
- Wind Farm Management and Control.

A variety of solutions are required to effectively manage a wind farm. A high-performance wind turbine control system comprises SCADA software for monitoring, data acquisition, controlling, and reporting for wind turbine generators. Reliable automation systems and network technology support wind farms to fulfill with growing grid code regulations. SCADA systems and reliable wind turbine control systems enhance operation in wind turbine generator or totally in the entire wind farm. Generally, Wind turbine control systems are designed to maximize availability. Wind farms must respond quickly to the volatility of demand. A reliable control solution is required to optimize operations on individual wind farms and manage an entire fleet to increase efficiency, save costs, and improve overall asset management. The control system, together with the integrated wind turbine control unit and SCADA technology, can help manage both individual wind turbines and the wider wind farm resources to help reduce turbine generator downtime and increase availability.

The wind turbine control solutions embrace automation systems for wind turbines and wind farms. A broad range of wind turbine control systems can be used for off-shore and/or on-shore wind power generation and wind farm management. These solutions assist wind turbines and farms to operate smoothly and cost-effectively.

Energy forecasts from wind farms are collected by system operators to improve the forward transmission schedule for wind farms and traditional generators to maintain system security with wind power fluctuations [14, 15]. The overall control framework of the wind power system is exemplified in Fig. 3. The wind farm control center takes power dispatch commands from the system operator. Consequently, distributes power reference levels to individual wind generator controllers, which in turn facilitates the wind farm to keep output power within the dispatch order from the system operator [16–19]. Furthermore, wind farms with power control competency are capable to contribute in the initial stage of wind power system restoration.

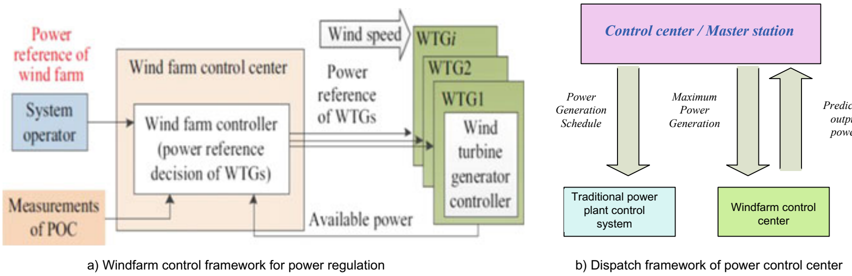

Fig. 3 Overall control framework for power system and wind farm

2.1 Wind Farm SCADA System Characteristics

Wind is an infinitely renewable energy source that can be harnessed as a premium energy source, given the right location and the latest turbine generation technology. On the farm, individual wind turbine generators are connected to the medium voltage (MV) gathering system and the communication network [20]. This medium voltage electricity then stepped up using a transformer to a high-voltage (HV) transmission system and electrical network. As the number of WTG generators increases within a wind farm, the need to manage these assets gradually becomes more significant.

The SCADA system offers real-time access to wind turbine generator diagnostics and generators and allows easy wind energy data management and continuous communication with remote wind power generation sites. Therefore, these systems should support multiple communication networks (microwave, cellular, fiber-optics network, radio, and more) and includes redundancy and failover schemes. Managing wind farm generating resources helps the reduction of turbine generation downtime and increases availability by making the wind SCADA system as a part of wind automation strategy.

2.2 Control of Wind Generation System Using SCADA

SCADA is used for supervision, monitoring, and control of wind turbines and wind parks remotely. The SCADA provides a full remote control and supervision of the entire wind park and individual wind turbines [21–23]. The SCADA system can run on the operator workstation in the control room of the wind power plant or it can be displayed on any internet-connected computer accessing the wind farm using TCP/IP communication protocol [24].

The overall control system of wind power plant is shown in Fig. 4. The main functions of the SCADA system can be summarized as follows:

- Wind park overview
- Wind park control

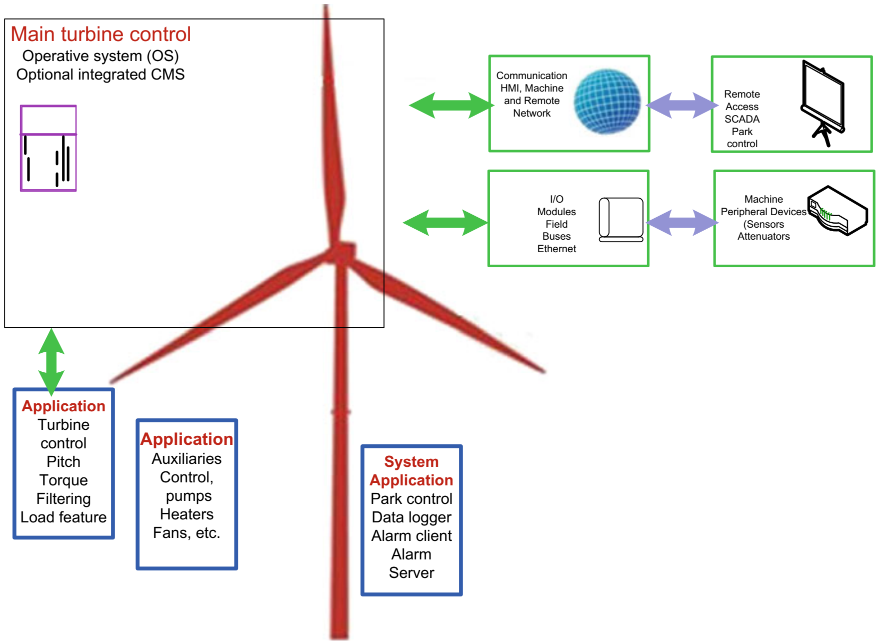

Fig. 4 Overall wind turbine control system

- Turbine overview
- Turbine control
- Log viewer
- Report Generation.

2.2.1 SCADA Systems in Wind Park

The SCADA system provides an overview of the wind park with a graphical user interface of the wind park representing the status of each individual turbine. Furthermore, currents, voltages, and wind power production data are shown.

2.2.2 Wind Park Control

The SCADA system in the wind park overview enables start/stop actions in the entire wind farm, groups of turbines, or separate wind turbines. Moreover, the park control is used for setting energy production limits for the entire wind farm. The aim of wind park control is to maximize energy production for the wind farm while reducing infrastructure and operating costs. For most projects, the economy is more sensitive to energy production change than infrastructure capital costs. Therefore, it is appropriate to use energy production as a dominant planning design parameter.

However, the complete design of the wind farm is assisted using wind farm design tools.

2.2.3 Wind Turbine Overview

The SCADA system has functions for turbine overview that gives a full overview of all important parameters of the wind turbine, for example, electrical parameters, rotation speed, pitch angle, temperature, and yaw system, etc. SCADA system is utilized to monitor the turbine parameter from the remote terminal area. Wind farm is controlled via a central interface that gathers the data from individual outstation components.

2.2.4 Log Viewer

SCADA event logger provides a complete high-level view on the power generation process that is continuous over time and captures information about user activities, system changes in the wind parks as well as system status updates. The SCADA system browses flexible structures of the log data of the wind turbine. All relevant log data are time-stamped, accessible, and can be arranged by various parameters.

2.2.5 Report Generation

SCADA system creates a report based on an alarm, status triggers create a report when something is on or off. Most owners require information that is regularly taken out from SCADA for operation analysis goals (loading studies, performance analysis, energy saving initiatives, etc.) [25, 26]. Reports can be generated automatically or manually. The reports can be generated by extracting information, and reformat usually a one-time time exceeds the cost to allocate and automate SCADA report. The report generator of the SCADA system makes it possible to make all relevant reports based on the data logging. The generated reports can be graphically represented to enable the best possible data review.

2.3 Main Tasks of Wind Turbine Control System

Figure 5 shows the wind generation control system. However, the main tasks of the wind turbine control system can be summarized as follows:

- Operational management and monitoring
- Wind park diagnostics, safety
- Communication, reporting, and data logging.

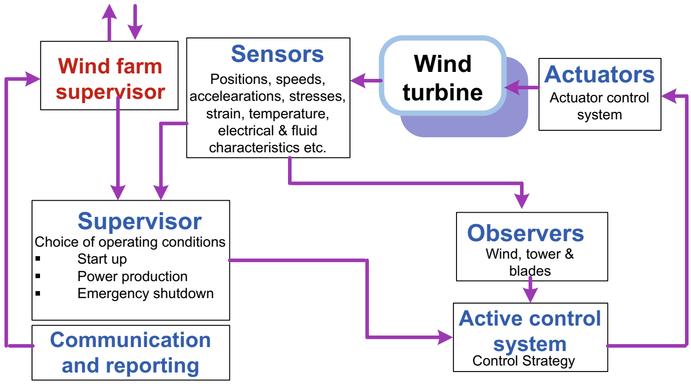

Fig. 5 Wind turbine control system architecture

Operational states of wind turbine comprise the following states: Idling, Start Up, Normal power production, Normal shutdown, and Emergency shutdown [15, 27–35].

The main input data to SCADA system include Wind speed, Rotor speed, Blade pitch, Electrical power, and Temperatures in critical area. However, some systems include strains, stresses (tower, blades), speed, position (yaw, blades, actuators, rotor tilt, teetering angle, fluid properties and levels, electrical system (currents, voltages, utility grid characteristics), icing conditions, lighting, humidity).

2.4 *Wind Farm SCADA System Functionality*

The SCADA system displays the WTG components in a graphical user interface and records the wind turbine conditions automatically. The system records the turbine availability, events, power generation, and fault data in real-time. One can use the pan, tilt, and zoom functionalities in the display panel. Therefore, wind farm operators can click on the figure representing wind turbine and monitor turbine performance by accessing a set of real-time data. Generally, the SCADA system in wind farm compromises seamless and open connectivity (OPC) and the operator can access dashboards anywhere, anytime, and on any connected device.

Wind farm SCADA system enables users to monitor and control remote operations and turbines in real-time. Operators can access precise, real-time information including updated weather and meteorological informs as well as fully configurable Key Performance Indicators (KPIs). Comparing energy production reports against historical information helps toward achieving accurate forecasts. However the master-station network is shown in Fig. 6.

Wind farm SCADA systems provide users with rich SCADA visualization and reports that are integrated real-time. Consequently, historical geographical terrain maps, and a quick overview of multiple operations and plants located anywhere in

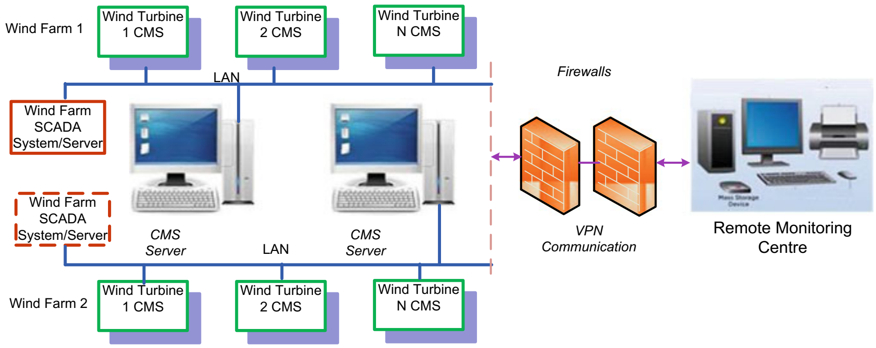

Fig. 6 Master-station network

the related electrical network. The SCADA wind farm system software is deployed over the web, is published, customized across the web, and delivered to any platform via different software technology [36, 37].

Based on open connectivity via OPC, Modbus, BACnet and IEC61400-25, the wind SCADA system software permits the integration of equipment, process and professional data into a single integrated plant operations' view, and provides control actions of the wind farm operation. Users are provided with a reliable, safe, and immediate response to energy, environment, and work requirements. SCADA in wind farm combines scalable mapping technology with classic supervisory control and data acquisition. For geographically dispersed assets, SCADA provides safe, scalable, and safe visualization and tracking of assets and wind turbines via GPS coordinates. SCADA technology enables easy navigation to quickly display alarm conditions and the condition of any site worldwide. Within seconds, the performance of assets, turbines, problems, or alarm conditions can be located and determined by integration with application software.

3 Structure of SCADA for Wind Power Plant

A SCADA system is responsible for gathering and managing all data collected from the remote terminal unit (RTU) at the outstation wind turbine and the SCADA server at the control center master-station for the sake of monitoring and supervisory control. The basic communication in the SCADA system utilized with WPPs is illustrated in Fig. 7. However, all the data from the wind farm are collected and sent over the communication link such as optical-fiber cables to the master-station (control center). The SCADA server in the WPP is an industrial computer which is considered as masters in the SCADA system while all RTUs act as slaves [1]. Sometimes, one RTU acts as a master to collect information from slave RTUs.

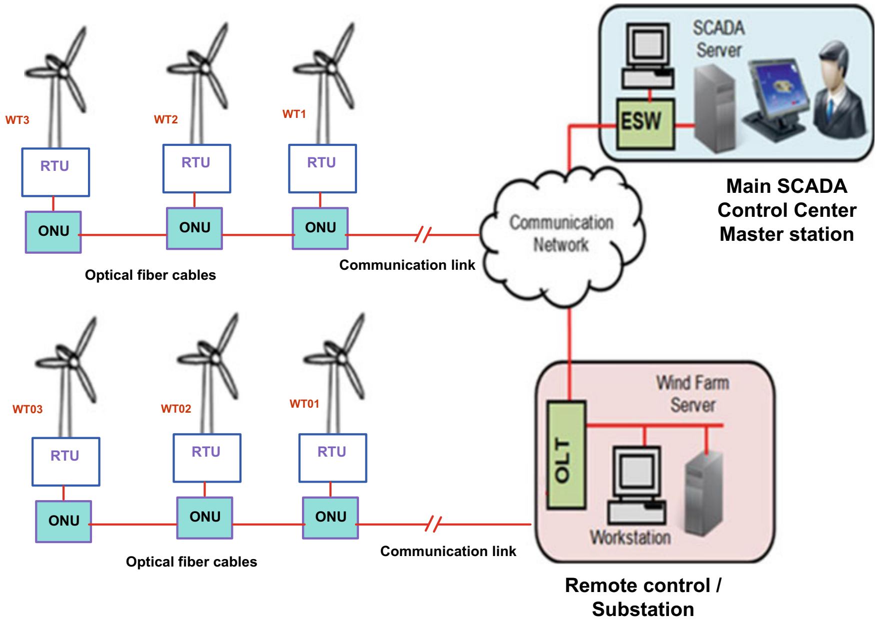

Fig. 7 Communication system architecture in wind farm SCADA

Due to increasing numbers of wind farms and its related components, it should be integrated into smart microgrid. These components are secondary power substations, distributed energy resources, public charging stations, virtual power stations, microgrids. However, new energy automation applications, such as automatic meter reading, meter data management or demand response, lead to extra communication requirements.

The communication networks for wind farms systems should be designed carefully. In this respect, the development of cost-effective and reliable communication architecture is vital. In this regard, Ethernet Passive Optical Network (EPON) is considered as a promising and attractive option. Fiber-optic based communication networks are utilized for advancing automation solutions. The network consists of an optical network unit (ONU) that is deployed on the wind turbine site. All ONUs servers wind turbines are linked to a main Optical Line Terminal (OLT). The EPON architecture of the OLT unit and the ONU unit placed at wind turbine outstation are comparable to the master/slave operation between the SCADA server and the RTUs in the WPP. The SCADA server polls data from RTUs at well-defined time-periods, and it can conduct control actions as needed. Therefore, in EPON system the OLT polls data from ONUs every few milliseconds. To explain this theory, a simple data-polling scheme is illustrated in Fig. 7. For instance, consider a polling cycle time to be 2 ms, this means that the wind turbine will be scanned for data 500 times during 1 s. In this arrangement, the OLT control center sends a GATE message to WT_i, and then waits for data until the control center sends it to WT_{i+1}. In this arrangement, an effective improvement in the performance of the OLT network could be achieved in terms of communication channel utilization and average delay of packet.

4 Data Network Configuration for SCADA System

The SCADA system is a vital component of this process. All wind turbines have a control box on top that contains PLC or RTU, power adapter, control panels, and I/O. Data of wind speed, wind direction, shaft rotation sensors are collected and transferred to the PLC. After sensing the wind direction, the SCADA control system can utilize the yaw gear motor to convert the turbine completely in the right direction to track the maximum generated power. All RTUs (or PLC) related to wind turbines are connected to a local area network (LAN), where the control box in each antenna uses an Ethernet network to be connected to redundant fibrous LAN link that is fixed at the bottom of the tower. The local network LAN is connected to a remote control master-station that operates the control system that gathers and manages data, regulates turbine settings, troubleshooting, offers intelligent alarms and reporting functionalities in the master-station.

These individual turbines, substations, meteorological stations, and other wildlife monitoring systems are connected to the central control room in Wind Control Center. It provides visibility to the operator to oversee the behavior of all wind turbines on all wind farms. By maintaining a log of activity on an interval basis, SCADA enables the operator to define corrective and corrections actions, if any, to be engaged. The system records the output power, availability, events, and alarm signals. It provides the ability to implement various control requirements in the voltage drop, power factor, and interactive energy generation. Therefore, the wind power plant contributions to both the voltage and frequency of network are facilitated. Operator workstation enables operators to manage the output power according to network requirements in real-time. SCADA communicates with the turbines over a communication link that uses optical fibers for almost all of its bonds. Wind turbines of various types can be controlled by one SCADA system. Some turbine suppliers provide their control/HMI display system.

The main advantages of SCADA system are that it can be used for different types of wind turbine. The PLC can provide data reports and analysis formats regardless of the type of turbine. It is important for wind farm operators to use many types of turbines and countless PLC types. SCADA should be easy to use and easy to configure. The ability of demonstrating animated mimics, using of pop-ups, and reduced risk of overlapping important information demonstrate simplify of the SCADA software. Also, creating content and behavior templates ensure the consistency of all the animations in the display boards. SCADA uses the rights to access and multi-level menus that are associated with each operator or user. Therefore, navigation within the application is tailored to the permissions and needs of each individual user. This ensures a layer of security, tracking, and control of user actions.

Wind turbines are installed to operate in coordination with other sources such as nuclear, solar, and hydro power in a network arrangement to improve performance. At present, congestion has become a major problem as wind energy suppliers balance energy production with the inputs available for transmission. A more scalable/modular system is required to accommodate the recent trends of renewable energy market.

To manage their growing industry, fiber-optic networks were installed on wind farms. Generally, there is a central facility whereby the SCADA system is capable to access wind farms throughout the country remotely and to access station alarms, events, and conditions. Centralized SCADA configuration offers the capabilities for traceability and management of the various wind application. It also updates the stations events automatically. Generally, each wind turbine gives about 300–350 data points.

SCADA alarms are highly configurable to address the diverse requirements of maintaining wind farm application. Alarm messages can be displayed, printed, and organized in alarm lists and archived.

Moreover, WPP operators can configure alarms using groups, sorting, acknowledgment, filters, and hiding. It also creates alarm meters and links specific actions to any alarm. Operators can recognize alarms directly from the mimics and these actions can be automatically broadcasted to all workstation on the Master-station computer network.

SCADA in wind farms uses OPC as the communications protocol, besides other protocols to collect data from different types of PLCs/RTUs. Wind power plant application often uses OPC and a driver to communicate smoothly with miscellaneous systems. OPC data access client exchanges data with communication servers in real-time. Moreover, the OPC data acquisition server assists data interchange with third party applications. The collected data are routed back to the master-station of control center. SCADA software in main control center should be proven to be high functional operation and user-friendly. Moreover, it should prove scalable, reliable, and easy to configure.

Wind SCADA provides a single user view that provides easy visual viewing and comprehensive management of turbine-equipped control systems. A simple and easy system is required to read graphical user interface so that can interact automatically to monitor the weather, managing, and controlling the turbines. The SCADA software communicates with the wind turbines through the graphical user interface (GUI) that acts as a light client for the application program and managing data elements. This configuration provides the user/operator with all the essential information about the turbine signals.

SCADA uses the distributed client–server architecture with the iteration mechanism to ensure that the design bears errors. By using the included redundancy features, SCADA is able to ensure continuous data collection in the event of a system component failure. Moreover, it also supports dual networks redundancy for communication with field equipment and between wind turbine stations, see Fig. 8. Every component in any substation in the configuration has a validity status to allow operators to display the system status in real-time. These OPC client stations communicate with

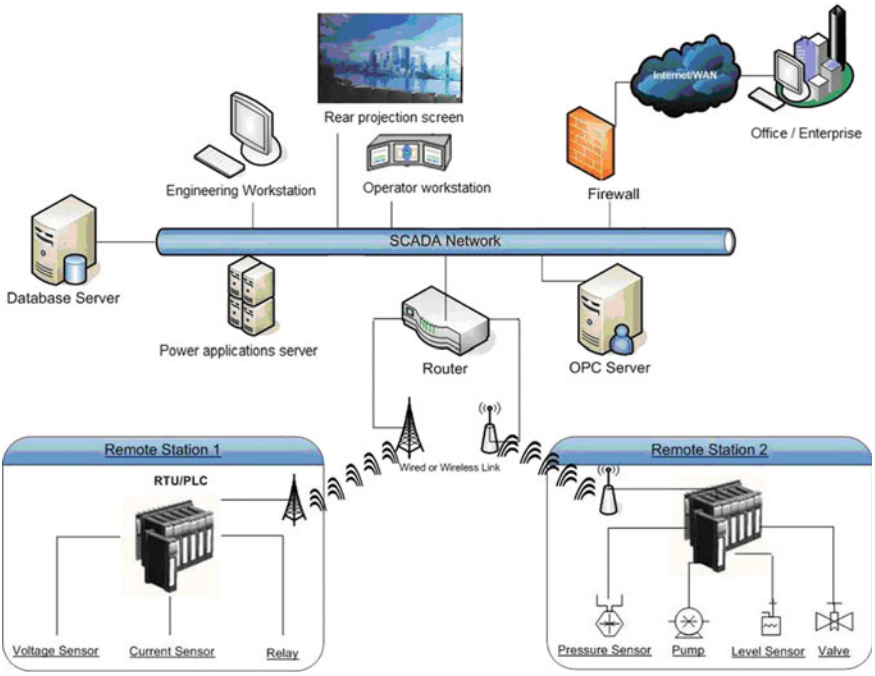

Fig. 8 SCADA system network configuration

increased front ends connected to a 1000 Mbps TCP/IP Ethernet network. Each front end is capable of receiving up to 60,000 input/output. The SCADA server communicates with the turbines via a communications network. The communication method depends on the distance from the master-station. Usually, WPP SCADA uses optical fibers to communicate with the nearby wind turbines.

Using the SCADA architecture, WPP operators can see in-depth details of data gathered from remote-site wind turbines in a real-time. WPP supervision is organized on two levels to manage the large amount of data and to enable the operation and troubleshooting of the facilities.

The first supervisory level offers an overview of the most important warnings, values, and counters, which are sufficient to oversee normal turbines and detect faults that need to be corrected. A more detailed supervision level is turned on demand to display the specific data from the turbine so that operators can instantly diagnose any malfunctions that occurred and accurately determine the treatment operations. Received data can be processed as defined points, historical reports, alarm management, and data trends, etc.

The control system collects all major operational information from outstations, generators, and associated substations. The control system is connected to the master-station control center through a remote communication channel, which facilitates maintenance. The center receives and processes this information in a streamlined and simplified structure that allows for easy identification and diagnosis of failure. This triggers the appropriate procedures to resolve it: remotely reset or activate local maintenance teams. As a result, the average downtime reduces and availability of the system increases.

5 SCADA System Instruments

The SCADA system in WPP connects the individual turbines, the wind power substation, and meteorological stations to a central master-station. The associated communications system allows the WPP operator to monitors the performance of all the wind turbines and also supervises the wind farm as a whole. The system keeps a record of all events and activities that allow the operator to determine necessary corrective actions. SCADA instruments record the produced energy, output availability, and error signals. The SCADA system deals with instruments to measure reactive power, voltage, and frequency. WPP SCADA dispatches generated power according to instructions from the network operator (regional control center).

In addition to the basic equipment needed for a working wind farm, it is also desirable, if the size of the project can guarantee investment, to erect some permanent meteorological devices on opposite masts. This equipment allows carefully monitoring and understanding the performance of the wind farm. In the absence of good wind data on the site, this decision will not be possible. Usually, large wind power plants contain one or more permanent meteorological masts, which are installed during the installation of wind power plant.

6 Wind Energy Power Plant Management System

At present, there is a strong focus on designing planning and operating tools for operating the electrical system under random demand and production conditions (which are still well anticipated). The system has complete control only over wind park management, and the overall power system may not operate in an improved manner. Therefore, systems that combine energy management systems at the transport and distribution level should be considered.

Smart grid technologies, along with forecasting tools, warehousing facilities, and demand-side management, may lead to new opportunities for increased integration capabilities. In this context, wind farm output forecasting tools within a maximum of 48 h should be more accurate than the current ones. In addition, both large-scale and regional projections of advanced network and energy management systems will be required. Besides the need to improve the physical integration of wind energy, management tools, and systems will be needed to integrate random wind energy into existing energy markets. Once again, advanced forecasting systems combined with improved storage capabilities and management measures are key to achieving this goal. Then the technical and economic aspects of the systems will be considered, in order to enable the incorporation of wind energy production on the grid and into the electricity market. The power management system is designed for distributed wind power system; the power management system switches the power supply mode and controls the system according to the wind power condition and load requirements.

A distribution generating system, along with a battery bank, can provide the user with reliable electrical power as shown in Fig. 9. The power management system is implemented from the microprocessor and data acquisition system. This power management system is applied in experimental equipment. A hybrid generating system controlled by the power management system, when random wind speed and solar radiation difference appears, provides constant electric power. A wind turbine management system that regulates the output power of the turbine, where the wind turbine includes a rotor with at least one rotating blade set at an adjustable angle to the rotor and the rotor management system regulates the speed within the predetermined wind speed range by changing the angle of the rotor blade in order to adjust Nominal output and reduces, by increasing a specific threshold that depends on the wind speed, the output power of the operating turbine to a smaller amount of nominal output but greater than the output where the wind turbine is turned off, and where the threshold value dependent on the specific wind speed is the angle of determining the specific rotor blade.

The management system maintains the angle of the rotor blade at a constant value until the nominal output is reached and the management system adjusts the angle of

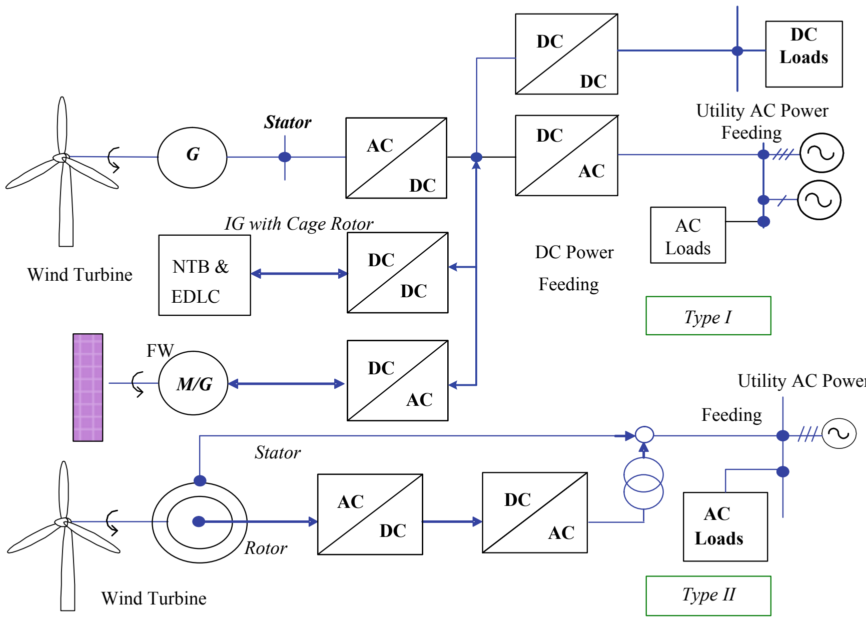

Fig. 9 Distributed wind power system

the rotor blade with respect to wind speed in order to maintain the nominal output at a fixed value.

A method for regulating the output power of a wind turbine with at least one rotating blade set at an adjustable rotor angle that includes steps: regulating the rotor speed within the predetermined wind speed range by changing the angle of the rotor blade in order to adjust the nominal output; The operational turbine output, which exceeds a specific threshold value dependent on wind speed, is reduced to a smaller amount of nominal output but greater than the output where the wind turbine is turned off, where the specified wind—the velocity-dependent threshold value is a specific angle for the rotor blade.

The offshore installation is one of the leading trends in wind turbine technology. There are significant wind resources at sea to install wind turbines in several areas where the sea is relatively shallow. Marine wind turbines may have a slightly better energy balance than land turbines, depending on wind speed conditions. In places where wild wind turbines are usually placed on flat terrain, offshore wind turbines can commonly produce about 50% more energy than the turbines placed on a near land site. This is because there are no obstacles and less friction on the sea. In addition, building and laying the foundation needs 50% more energy than land turbines. However, it must be remembered that marine wind turbines have a longer average life than land turbines. The reason is that the low turbulence at sea gives less stress to wind turbines.

Therefore, offshore wind turbines require increased corrosion protection, while reducing maintenance and service requirements and improving the supervision and control system. Inner corrosion protection comes from improved coating systems and a dry environment inside the machine. Prerequisite for a dry indoor environment is a sealed machine. The gear and generator are cooled by heat exchangers that recycle the air used in the air cooling system, instead of the traditional air-cooled components in previous turbines. To maintain low indoor air humidity, dehumidifiers are placed in the tower and nacelle chamber. The dehumidification system maintains the internal relative humidity lower than any steel corrosion risk limit (60%). For additional protection, the main electrical components (generators, control systems, etc.) have backup heating systems, which prevent condensation, even during sudden temperature differences.

7 Standards of Grid-Connected Wind Farms

7.1 Voltage Fault Ride-Through Capabilities of Wind Turbines

To enable widespread application of wind energy without compromising the stability of the power system, the turbines must remain connected and contribute to the electrical network in the event of a disturbance such as a voltage drop. Wind farms must behave as conventional power plants, to supply the active, and reactive powers to restore frequency and voltage, immediately after the error occurs.

Wind turbines can now remain online, for the first time, supplying the reactive power to the electrical network through major system disturbances. The Low Voltage Ride Through (LVRT) feature enables wind turbines to meet transmission reliability standards similar to those required from thermal generators. LVRT adds significant new flexibility to wind farm operations while more facilities require it.

7.2 Power-Quality Issues in Grid-Connected WPPs

The reason for this interest is that wind turbines are potential sources of poor energy quality. Measurements show that the power-quality of wind turbines has improved in recent years. Especially, variable speed wind turbines have some flicker-related advantages. However, a new problem arose with the variable-speed wind turbines. Modern inverters with forced commutated function used in variable-speed wind turbines not only produce harmonics, but also harmonics.

The power transmission system with optional reactive power (VAR) control provides support and control for the local network voltage, which improves transmission efficiency, and provides an interactive utility power grid (VARs), which increases network stability. VAR function maintains specified network voltage levels and power quality in fractions of a second. This feature is especially useful with weak grids or larger turbine installations.

7.3 Variable Speed Control

Variable speed control is utilized to maximize wind power capture and reduce turbine-load group loads. The wind turbine control system, through its advanced electronic devices, constantly adjusts the angle of inclination of the wind turbine blade to enable it to achieve optimum rotational speed and maximum towing lift at every wind speed. The “variable speed” operation increases the capacity of the turbine to remain at the highest level of efficiency. In contrast, constant speed wind turbines achieve the highest efficiency at a single wind speed. The result: increased annual energy production compared to plants running at a constant speed.

In addition, while the fixed speed rotors must be designed to direct strong wind loads, variable speed operation enables the loads from the storm to be absorbed and converted into electrical energy. The torque of the generator is controlled by the frequency converter. This control strategy allows the turbine rotation to override in strong winds and gales, thereby reducing torque loads in the powertrain. Variable-speed wind turbines convert the extra energy in the wind gusts into electrical energy. The turbine speed range is noticeably broader than the “slip” range used by other technologies, which produces heat rather than electrical energy when regulating energy in strong winds.

7.4 Active Damping

The variable speed operation provides active damping of the entire wind farm system, which results in significantly lower oscillation of the towers compared to the fixed speed wind turbines. The active damping of the machine also reduces the maximum torque, which provides greater reliability for the powertrain, reduces maintenance cost, and increases the life of the turbines.

Active-damping of tower oscillations is accomplished using the pitch angle as the control input. The flexible multi-object system is used to derive a directed model for controlling the first bending mode of the tower, which works to design a stable control law. The oscillation damping is integrated with a scheduled feedback control for multivariate gain that allows tracing the paths required for angular velocities of both turbine and generator.

8 WPP Control System

This section explores variable speed operating schemes for wind turbine generation applications. The main goals are to maximize energy production, provide tight startup, and reduce torque load on system components. This is done while maintaining the control strategy that operates in the variable power generation mode between the cut-in speed up to the speed of the main generator 900 rpm and working in the continuous power operation mode from the base speed to the maximum speed of the 1350 RPM generator.

The main functions of the proposed control and management system are:

(1) Supervising and controlling the interconnection of the wind turbine power station with the utility network.
(2) Control the frequency converter output performance,
(3) Improve the energy conversion efficiency of wind turbines,
(4) Provide system performance measurements to evaluate the operator,
(5) Achieve a safe closure under normal and emergency circumstances.

The control strategy shown here uses the rotor speed, torque, and generator strength as the feedback signals. In the normal operating area, the rotor speed is used to calculate a target energy that corresponds to the optimal operation. With power as a control target, the power transformer and generator are controlled to track the target power at any rotational speed.

8.1 Wind Turbine Control

One of the main aims in the development of offshore wind energy is cost reduction and increasing the availability. Due to the larger turbine sizes load control is becoming more and more important. Wind turbine control is essential to guarantee low maintenance costs and efficient performance. The control system also ensures safe operation, optimizes output power, and ensures long structural life. The schematic diagram of control unit of wind turbine is shown in Fig. 10. Maintaining the system stability is becoming more difficult as the frequencies of the turbine are getting closer to each other as well as closer to the frequencies of wind and waves. The turbine control system therefore is of crucial importance. In research domain, models for the design of advanced wind turbine control algorithms were developed. The control system of wind turbine is illustrated in Fig. 11. Those models and tools are including aerodynamic and structural dynamic modules. With the control tools, multi-parameter control algorithms can be developed, taking into account the complex and strong dynamic influences to which the turbines are exposed. This approach offers solutions for the following specific operational problems:

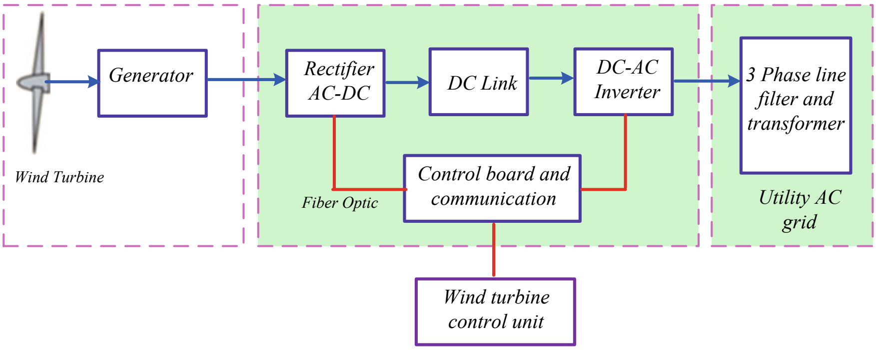

Fig. 10 A simple wind turbine control unit

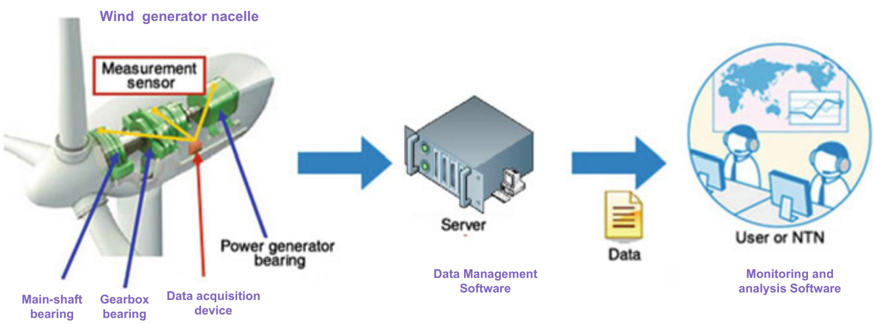

Fig. 11 Wind turbine Management system

- unnecessary stand-still due to an isolated approach of control and safety systems;
- high costs and limited possibilities for up-scaling due to high turbine loads and stability problems;
- uncertainty of energy output and high loads at extreme weather conditions;
- Accumulation of damage in case of a turbine shutdown caused by a severe failure.

8.2 Sustainable Control

The sustainable control is a developing and integrated design approach for the control system of offshore wind turbines. In this approach four parts can be distinguished:

- Optimized Feedback Control
- Fault-Tolerant Control
- Extreme Event Control
- Optimum Shutdown Control.

8.3 Design Tool for Wind Turbine Control Algorithms

Due to the increased importance, the increasing complexity and the increasing interaction with the structural and aerodynamic design, knowledge, and tools which enables wind turbine manufacturers to develop and validate their own advanced control algorithms. An open-source design environment is important for developing and Real-Time testing of control systems. Figure 12 shows wind farm energy systems that are based on reliability and maturity of technology. Control models and strategies for wind farms have been developed, with the aim of improving the operation of wind farms taking into account participation in controlling the energy system (frequency)

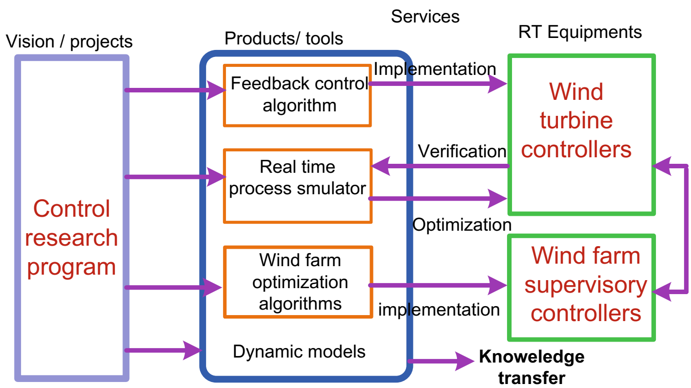

Fig. 12 An overview of the wind farm control

and reactive energy (voltage), maximizing energy production, improving the impact on quality energy and reducing mechanical loads and life-time consumption. Wind farm control will rely on signals from wind turbine controllers. These signals will be used to predict wind speed in individual wind turbines in the short term (i.e., from seconds to minutes) in order to enable individual wind turbine controllers to respond in an ideal manner to wind speed fluctuations.

The concepts for wind farms include electric components such as squirrel cage induction generator, doubly fed induction generator, and modern high-voltage direct current (HVDC) techniques. HVDC systems are based on converters with full control capabilities that are based on force commutated semiconductor devices. The included wind turbines will be pitch controlled as well as (active) stall controlled. Consequently, the characteristic curve of the torque speed is formed to output the generator to increase the energy conversion to the maximum power capture area. However, the target power is constantly updated at any rotation speed (rpm) in the operation range. During extreme operating condition, for example during startup, shutdown, generator overload, or overspeed, various strategies driven by other system considerations should be used as variables to control input as well. Wind energy is proportional to the cube of wind speed. Therefore, in order to regulate output power as the wind increases, there should be a mechanism to decrease the output power of the wind turbine while the capturing area remains constant. Wind turbines with constant speed automatically achieve this, because in high winds their blades stop. The resulting lower lift and increased drag significantly reduce the blade’s ability to fine wind capacity. The vector control strategy can be used for frequency converters. By using the vector control, the specified torque and limitation can be effectively maintained. With the closed-loop control, maximum dynamic performance could be accomplished. This is because the current components of the torque and flow can be controlled independently of each other. However, closed-loop frequency control can be realized with a speed sensor or sensorless control. During normal operation of wind power stations, constant variations occur in both wind speed and direction. As the wind velocity increases, the turbine rotational speed will increase slowly. By adjusting the frequency of the frequency converter, the velocity of the stator field of rotation can be adjusted to yield the desired slip and thus the desired torque can be obtained. Therefore, the rotating speed of the wind turbine must adapt to the prevailing wind speed. If the wind speed of the wind turbine increases above the generator base speed, the frequency converter increases its frequency while decreasing the torque reference in order to achieve rated or constant output power up to the maximum rotational speed of the generator. If the wind speed drops below the starting speed or the traveled speed, the wind turbine will stop and the frequency converter will go into standby mode. Thus, by controlling the frequency, one can control the output power and torque of the wind generator. This results in optimum wind turbine performance over wind speeds and wind conditions. There are two different control strategies. The first is to control the generator speed in relation to wind speed and wind turbine rotational speed by providing a speed reference signal to the frequency converter. The second method is to control the generator torque with respect to wind speed

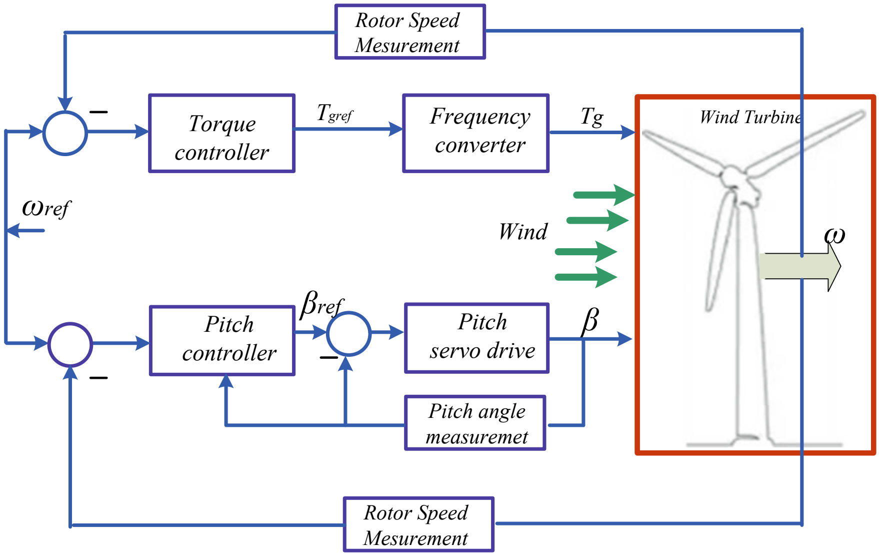

Fig. 13 Detailed control system for wind turbine

and wind turbine torque by providing a reference torque to the frequency converter. Figure 13 shows a simplified control strategy for wind turbine.

The favored control strategy is the generator that is controlled to provide the required torque and wind velocity relationship. The wind turbine can operate near the maximum power factor at low and moderate wind speeds, which represent furthermost of the energy capture at specific wind locations. In case of high wind speed, the torque is controlled to keep a steady energy production while increasing of WT generator speed. Moreover, the transition from moderate to high wind speeds should be occurring smoothly to avoid overloading the WTG components. The reason behind choosing the subsequent strategy as a preferred strategy is that there will be fewer fluctuations in energy on the grid in case of locations that have high wind speeds. As the wind turbine rotation decrease, the maximum force that can be generated reduces. At low and medium wind speeds, the generator torque is controlled to work near the optimum output curve producing the maximum energy. The rotor speed is expected to be regulated and limited within the higher limit of the generator RPM region although existing of higher wind speeds at the WPP site. The gearbox design and gear ratio selection are also critical in getting optimal operation.

9 Wind Power Plant Control and Management

Computer Console (PCC) is an automation engine that is designed to meet automation system and wind plant management requirements for substation applications. PCC is a platform for information control and automation applications including the human sub-machine interface (HMI), sub-station data, fault data extraction and indexing, sub-station level sequence collection (SOE), power quality analysis, predictive/preventive maintenance, Smart reports, and condition management. The PCC also delivers data management tools for treating historical and diagnostic data according to SOE.

The wind turbine controller consists of an external loop controller, which can be an RTU or PLC. The PLC is connected to the wind farm management system. The communication interface is implemented by a communication server or processor on the PCC end and connected to the PLC through a PROFIBUS-DP communication link. PROFIBUS-DP is the distributed I/O protocol. It allows for ultra-high-speed periodic connectivity that includes small amounts of data with data transfer rates of up to 12 Mbps. PROFIBUS is the carrier system for communication in small cell networks and with the field device. PROFIBUS is European standard EN 50 170 and is applied worldwide in the environmental field. PROFIBUS provides the advantages of being a reliable and high-speed network that can easily interact with all smart subsystems used in the wind power plant. PROFIBUS can be either shielded by two wires of fiber or optical fibers. Optical fibers provide the advantage of use in the external environment while avoiding problems due to lightning. The plant control and management should ensure reliability and automated operation of WPPs. For achieving this, the related components and WT variables should be supervised and monitored. The supervision is done by continuously maintaining the value ranges and setting permissible values of system variables. The control and management decide predefined operating states and identify errors and emergency situations immediately. For this, the combined wind turbine frequency transformer, external loop control system (PLC), and factory management system (PCC) together should influence the wind power operating behavior based on pre-set control signals and required values, and interaction of changes in system variables or errors. In addition to reliable operation, another very important goal is to achieve the perfect match between the output power quality, the low mechanical pressure, and the electrical load of the plant on all its components. Power stations are equipped with frequency converters to convert wind turbine energy into electrical energy and provide consistent low-quality distortion energy to the utility grid. The malfunctions feedback will be determined based on operational conditions and control logic flow charts along with reaction agenda documents and attached with wind turbines.

10 Operation of the Outer-Loop Controller

The external-loop control system is implemented using the PLC controller. The structure of the program and all internal frequency converter functions and variables are monitored continuously along with many external device functions and variations. Depending on the results of the logical decisions, the method of operation and the points of determination of the specified value, the appropriate decision and reaction will be taken. Single wind turbines are normally powered in automatic mode. However, manual and semi-automatic operating methods with manual input of required values are necessary during commissioning, troubleshooting, and maintenance.

Temporary operating conditions may last only for a limited period. Thus its duration is monitored. After exceeding the preset maximum intervals, the error is turned off, as an error should be assumed. The duration of static operating cases (S) is not monitored by the control and management system. The manufacturer remains in these cases as long as all normal operating conditions are met. In all operating conditions, all normal operating conditions must be checked continuously. Only one condition is required to switch between "Stop operation," "Normal Shutdown," "Fault/Overspeed Shutdown," or "Emergency Stop" states. By contrast, to start the "start" or "Run-up" operating states, all conditions must be met.

10.1 Wind Farm Plant Testing

The monitoring components and the influencing and changing variables must be tested and recorded after successful commissioning of control and management systems. Outputs of all subsystems must be queried for shutdown values and all mechanical actuators for testing purposes. Sensors can check the correct reactions for configurations. If errors occur, they must be recorded. Errors cause the additional process to stop until the error is corrected and the factory release manually. All plant components and their marginal values should be checked in all operating conditions. This system works properly for all systems, operating temperatures, and ground error condition. After successful test, the factory goes to a later operating state; Otherwise, the factory operating state test is repeated until all release conditions are fulfilled, such as operator orders, unlock after emergency stop, network availability and appropriate function, component function, ground failure detection, temperatures and marginal values.

10.2 Stop Operation

Fixed rotor characterizes shutdown state. Moreover, in this operating condition, the rotor mechanical brakes are activated and can also be tested to obtain the appropriate functions. The generator is turned off and disconnected from the supply network. The conditions that prevent the manufacturer from moving to the initial operating state are tested. Then a system scan is performed. If all conditions are positive, start conditions are checked. If this is also achieved, the change to "start" will occur. As with factory testing, the appropriate operating condition number distinguishes "mechanical brake assembly" and "contact switch" for the generator open. The available wind speed is continuously monitored in each individual wind power generator independently by a wind meter, such as an anemometer. Turning on individual wind turbines occurs when minimum wind speeds are available.

10.3 Starting of Wind Generation System

The rotor is stable and still attached to mechanical brakes. In a repeated sequence, the conditions for turning off errors are tested and initiation of appropriate routines if necessary. The starting signal from the management system is also examined during this sequence. PLC gives a wired output signal to the digital control unit to start the frequency converter. The frequency converter then passes its power on the sequence routine. Bipolar Isolated Gate Transistors (IGBTs) are checked and feedback signals tested, cooling fans are turned on, the DC connection is pre-charged, then the frequency converter turns off the generator connector switch. Once the generator contactor switch closed status is achieved by the PLC, the wind turbine moves to the “Standby” operating condition, provided that the trigger order for the “Automatic” command is given by the WPP management system.

10.4 Standby State

In the event of readiness, all components of the wind turbine generator are constantly checked to determine whether they are indeed ready for operation (standby state). In a repeated sequence, the conditions for turning off errors are tested and initiation of appropriate routines if necessary. The average available wind speed is also constantly checked to determine the minimum available wind speed. The generator system is already connected to the network supply system during the previous operating state. Breakdown closure conditions, operator orders conditions, and operating settings are checked one by one. If the suitable conditions are met, the relevant operating cases are entered. If standby is kept for a long time, for example, five minutes or more, the management system is notified with a message that the wait time has been exceeded and the control goes to shutdown and then returns to the steady shutdown state.

10.5 Run-Up State

Speed can be increased if the combined average wind velocity is greater than 5 m/s and the instantaneous wind speed is not very high (Run-up is possible). The frequency converter is first checked to ensure that it is ready for power generation as well as the network connection system that is still connected. In repeated sequences, normal shutdown and shutdown conditions are tested and suitable procedures are initiated if necessary. The speed and torque references are checked for an initial value of zero and if this is correct, then the inverter gate will be enabled. Once the inverter gate is enabled, the frequency converter will begin capturing and synchronizing the rotary generator. The rotation direction and acceleration limit values are checked. The torque or velocity reference value is then released from the PLC and adjusted itself to match the feedback values of the charged generator rotor. If synchronization is achieved within the allowed time period, the rotor speed of the wind power plant can be operated to a value at which sufficient active energy can be generated for the grid. With little or no interactive force pulled from the network via the frequency converter, the rotor speed lies within a range determined by the outer ring control system, and is affected only by the available wind speed immediately. The wind turbine generator is now ready to go into a stable variable-power operating state.

10.6 WPP Variable Power Operation

When the desired target speed is achieved, the generator system and frequency converter are able to generate enough active energy for the supply network, then the electrical energy of the grid system is provided. In the variable energy process, the generator system provides variable electrical energy (kWh) in the supply network. The sliding frequency phase angle is adjusted or adjusted to the optimum value, so that maximum output power or minimum component loads are possible. The outer-loop controller provides a reference value for the output power related to wind speed and energy demand. In the variable power process, the speed or output power is regulated by the frequency transformer of the generator system. Torque or speed is maintained within a permissible range by adjusting torque or speed according to the previously required values. When the control reserve value is reached, the target torque or speed value is changed according to the characteristic line of optimum power speed. Throughout variable power operation, normal shutdown condition, malfunction shutdown conditions, and standby shutdown conditions are constantly tested. In the variable power process as well, all conditions of normal operation are checked, and if necessary, appropriate actions are initiated. It is important to check temperature limits, acceleration limits, vibration level, low-speed limits, and power stability limits periodically. Essential messages are listed in the Variable Power On mode. Due to the sufficiently high average available wind velocity, the wind turbine generator automatically switches to the “continuous power” steady state.

10.7 WPP Constant Power Operation

If the average wind velocity is available high enough, the wind turbines inside the power plant will move from “variable energy” to the “continuous energy” process. In this operating condition, the external loop control system determines the desired values of rated output power, nominal system output, and fluctuating range. Rotary values for speed/torque, slip frequency regulations and torque bounds are constantly supervised to adjust the constant output power. Thus the output fluctuations in the turbine lead to small changes in speed. Speed is maintained within the regulation range by lowering the torque and adjusting the slip frequency. A small set of overload is permitted in the event of instant wind gusts, so that the wind turbine speed does not need to be adjusted quickly or often. However, the overload range should be of limited duration, depending on the thermal behavior of the entire system. During continuous power operation, normal shutdown conditions, malfunctions/excessive shutdown conditions, and "standby shutdown" conditions are constantly tested. In continuous power operation as well, all normal operating conditions are checked, and if necessary, appropriate procedures are initiated. The vibration level, acceleration limits, temperature limits, over-speed limits, and power stability limits are constantly checked. Figure 14 illustrates the plant operation overview. The shutdown conditions

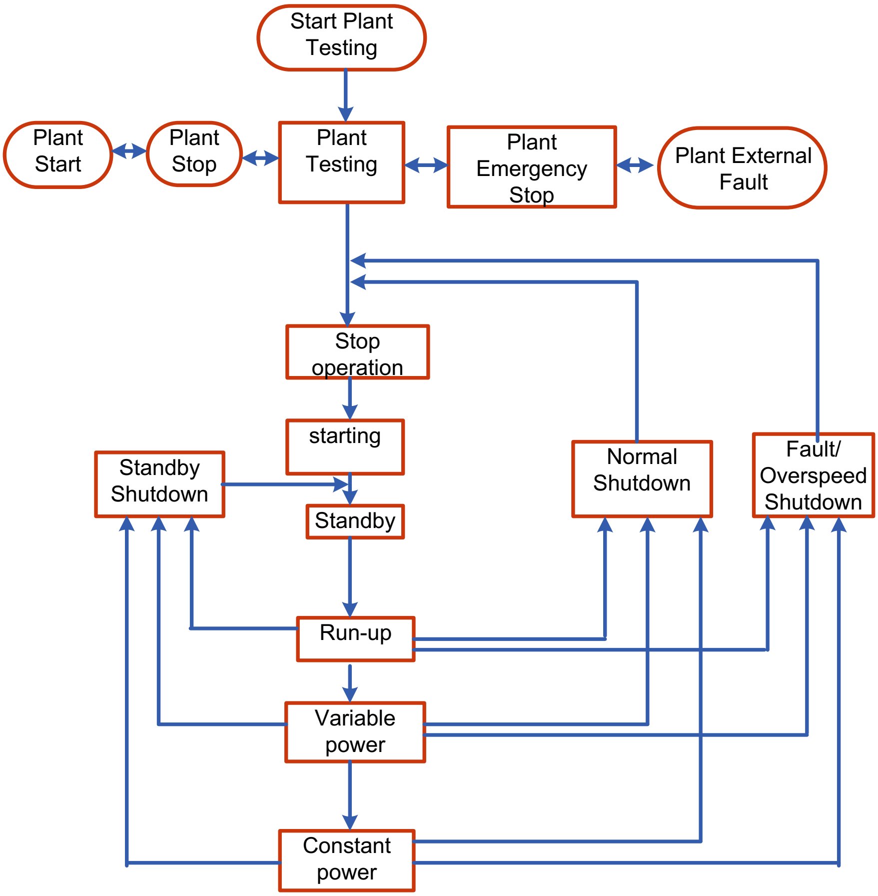

Fig. 14 Plant operation overview

of this operating state are constantly checked, and the necessary messages appear in the continuous power operation. If the rotor speed is less than the minimum pre-set value by the outer ring control system to maintain continuous power operation, the single wind turbine generator returns to the variable power operating state.

10.8 Standby Shutdown

The variable power and the continuous power operation should be possible at all times to start the standby mode of the individual wind turbines and bring it to the operating state in the standby mode and report the appropriate messages. If the average available wind speed is less than the minimum value previously determined by the outer ring control system, the wind turbine will start. Standby mode and individual wind turbines are turned off if “standby” is on. Failure stop/excessive speed, torque, or speed conditions are continuously checked in a repeated sequence. After turning off the standby mode successfully, the individual wind turbines return to “standby” state.

10.9 WPP Normal Shutdown

The plant shall be capable of discontinuation of any operating condition. The normal shutdown process is similar to the shutdown process except for the generator contact switch being opened later during the normal shutdown process. If the speed has fallen below the minimum value previously determined by the external loop control system (<2.5%), then the wind turbine brake will be mechanical brake and the wind turbine is off. Even during a shutdown state, “overspeed failure/stop” and braking conditions should be checked and status messages displayed.

10.10 Over-Speed/Fault Shutdown

Fault conditions influence the design and lifetime of wind power plant due to their transient effects. WPP is shutdown in order to prevent the components from being damaged or destroyed. Safe shutdown of the wind turbine takes place in the event of any electrical problems. Fault Shutdown procedure is similar manner to Normal Shutdown.

The over-speed shutdown can be started in case of higher operating speeds that violate the upper speed limit. Therefore, the mechanical braking system must be wisely taken into consideration in its power rating and duty-cycle rating factors.

10.11 Overspeed/Over-Temperature

When the wind power plant is in “Constant-Power” operation, i.e. at wind speeds above the nominal range, the speed is kept within the permissible range by extended range of speed control. If the operating speed still exceeds above the maximum upper limit speed (e.g. higher than 150% over nominal value), a “Fault/Overspeed Shutdown” is started.

In case of over temperature, WPP components are designed such that in normal operation, no critical high temperatures occur. If the temperature violates limits, then it is realized that there is a fault or overload in the system. Therefore, the “Normal Shutdown” operation must be initiated and the proper message is displayed.

11 Condition Monitoring for Wind Farms

Wind turbines are often subject to intense mechanical stress. CMS system ensures stability, long service life, and optimal design of wind turbine components (rotor blades, drive assemblies, inverters …). Thus, it prevents complete failure, is costly, and allows significant savings. Failure of the gearbox accounts for a large portion of the wind turbine’s downtime. Therefore, gaining reliability and efficiency is the important key. Thus, measurements can be used as a tool to increase both. With monitoring, it is possible to track component status and detect potential malfunctions in a timely manner, thus preventing damage and possibly increasing the service life of the components.

11.1 Fault Diagnosis and Prognosis

A defect is a physical defect, or defect that occurs within the system. This may cause a failure: Some due or expected actions are not performed. Error detection is the determination of errors in the system and the time of detection. Error isolation is the determination of the type, location, and time of the error. Error detection follows, and includes error isolation and identification [38]. The forecast is an approach that combines information about the current state of each device with historical data from machines of the same class, physical models of failure components, and expected short-term use to predict the probability of failure of this individual device in the future. That is, the forecast gives probability expectations for each machine, which allows a strategy to balance the risks of operating the machine and indicators of damage against revenue lost while waiting for maintenance [39]. The data analysis of wind turbine using SCADA is illustrated in Fig. 15.

Data mining is a process for extracting useful information and patterns from big data. It is also termed as knowledge discovery process, knowledge mining from

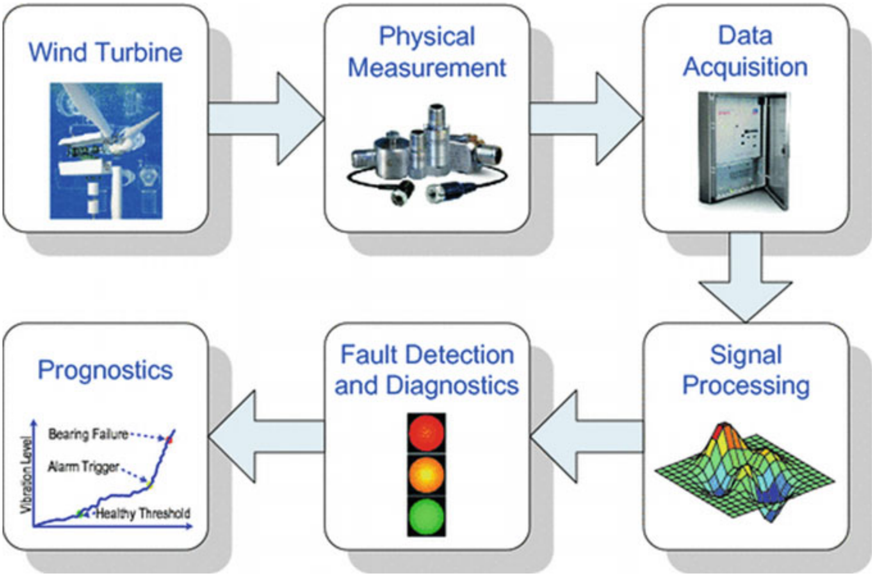

Fig. 15 Wind turbine data analysis using SCADA data

data, knowledge extraction, or data/pattern analysis [40]. The crucial goal in fault diagnosis and diagnosis is to determine the suitable maintenance approach.

11.2 Fault Diagnosis and Prognosis Systems on WT

Condition monitoring (CM) can detect errors early and prevent major malfunctions. This is associated with a significant decrease in maintenance costs. Moreover, it allows improving maintenance schedules, thus reducing downtime and enhancing equipment availability, safety, and reliability [41]. An attention on the technique of sensing (data acquisition and analysis to diagnose errors was focused [42]. Important vital information in the field of CM was provided [43]. Major malfunctions of the WT are generated due to the main gearbox; generator, main bearings and rotor blades and the possibility of malfunctions in terms of proportions are 32%, 23%, and 11% and less than 10% respectively as defined by the insurance company German Lloyd. CMS is a tool that provides component status information and can also predict expected failure/error. Table 1 summarizes the diagnostic malfunctions used and the techniques used in CMS on different parts of the WT. Digital filtering, modeling, signal, and spectrum analysis are key parts of data processing in CMS [39–42, 44]. The next step is to predict the component life and to adopt a suitable maintenance strategy.

Table 1 Summary of CMS on WT [38]

Part of WT	Fault	Technique	Sensor/monitoring quantity
Gear box	Gear tooth damages, bearing faults	Vibration monitoring and spectrum analysis, AE sensing detects pitting, cracking	Transducers, velocity sensors, accelerometers, spectral emitted energy sensors
		Oil analysis	Temperature, moisture, contamination
Generator	Stator, bearing, rotor inside	Current signature analysis	Current measurement
Rotor blades	Creep and corrosion, imbalance, fatigue, roughness	Radiography, Shearography, AE sensing	AE sensors, strain gauges, Fiber bragg grating
Tower and blades	Ultrasonic testing techniques	Time–frequency techniques and wavelet transforms	Ultrasonic sensors, Fiber brag grating
Pitch mechanism, Yaw system, power electronics/electrical system	Current and voltage analysis, electrical resistance	Spectrum analysis, eddy current, thermography	Current and voltage measuring equipment

11.3 SCADA Based Condition Monitoring of WT

Condition monitoring systems essentially offer the necessary sensor and capability of data capture required for monitoring. These systems enable diagnostic and fault detection algorithms to be installed at the sensor or RTU mounted on the turbine. Thus the gathered SCADA data have to be analyzed in order to realize the overall health of the wind turbine as well as its related components. An operational wind farm typically generates vast quantities of data. The SCADA data contain information about every aspect of a WPP including output power and wind speed and any other error registered within the system. SCADA data effectively provide early warnings of possible failures Fig. 16 shows the fault diagnosis framework. Typical parameters recorded by SCADA on a WT could be broadly categorized into wind parameters, performance parameters, vibration parameters, and temperature parameters. These parameters could be used in fault diagnosis and prognosis activity. The wind parameters are wind speed and wind deviations. The performance parameters include output power, rotor speed, and blade pitch angle. The vibration parameters comprise tower acceleration and drive train acceleration. The temperature parameters include bearing temperature and gearbox temperature. Measurement SCADA data, vibration monitoring could be used for CM [43]. One can use the combination of abnormal detection and data-trending techniques summarized in a multi-agent framework for the improvement of a fault detection scheme for WTs.

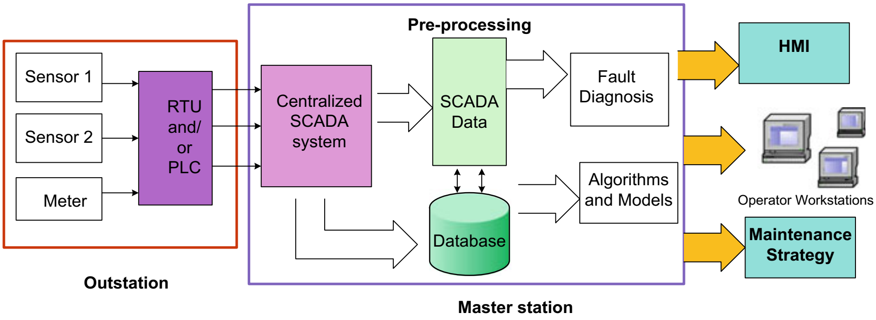

Fig. 16 Intelligent frame work for fault diagnosis and prognosis of WTs

11.4 AI Methods for Analysis of SCADA Data from WTs

Pre-processing of SCADA is a must for extraction of useful information and patterns from huge data. The various AI methods being used for analysis of SCADA data from WTs are artificial neural networks (ANNs), fuzzy systems, and arrangement techniques like adaptive neuro fuzzy inference systems (ANFIS). Figure 17 summarizes different methods.

ANNs can be used for a wide range of applications. They are inspired by the mechanism of the brain and can be classified by diverse categories that depend on the learning mechanism. Some of the key characteristics for neural networks (NNs) are their high processing speeds which are due to their massive parallelism, their demonstrated ability to be trained and produce instantaneous and correct responses from noisy or partially incomplete data, and their ability to generalize information

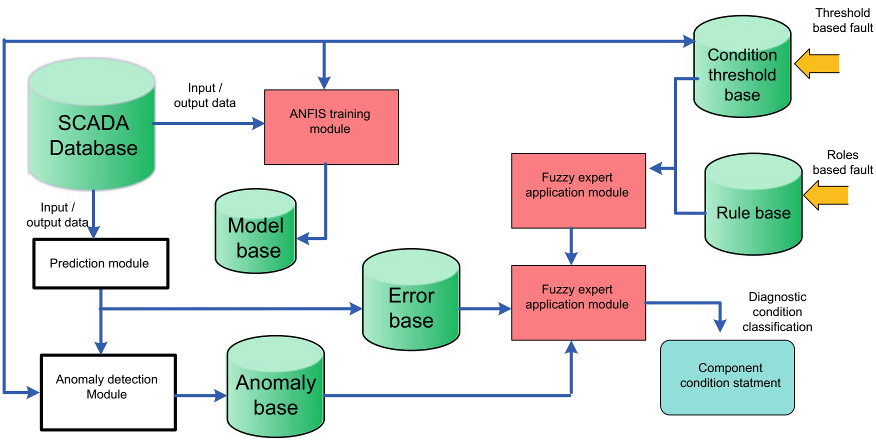

Fig. 17 Block diagram of AI methods in WT SCADA

over a wide range. These features make them a good choice for applying to WTs' data analysis.

Fuzzy systems are very useful in two general contexts like in situations involving highly complex systems whose behaviors are not well understood and in situations where an approximate, but fast solution is desired. A further advantage of fuzzy systems is that the existing expert knowledge can be implemented to improve the approximation by tuning, removing, or adding of membership functions and rules.

Fuzzy neural networks have shown to be very advantageous in dealing with real-world problems. These neuro-fuzzy systems combine the benefits of these two powerful paradigms into a single capsule. This gives the capability to accommodate both data and present expert knowledge about the issue under investigation. Recently, ANFIS has suggested for WT condition monitoring. For this purpose, ANFIS normal behavior models for common SCADA data were developed in order to detect abnormal behavior of the gathered signals and specify component faults or malfunction using the error prediction.

12 SCADA Based Abnormal Detection of Wind Turbine

The SCADA system changes the operating mode of wind farm systems with a healthy work environment and reduces operating and maintenance costs. However, a wide range of high dimensions and many types of data are not fully used or developed; only staying on data in real-time and statistics reporting historical data are usually monitored or collected. Therefore, it is important to make full use of the data collected by the electrical and electronic control systems were identified as most likely to fail, but gearbox and generator malfunctions caused the longest downtime. Figure 18 shows the components of condition monitoring system of wind turbine.

Several researchers have conducted research on observing large wind turbines and diagnosing malfunctions [5], based on a statistical learning method for detecting abnormal situations through a weighted least-square wind turbine response model to

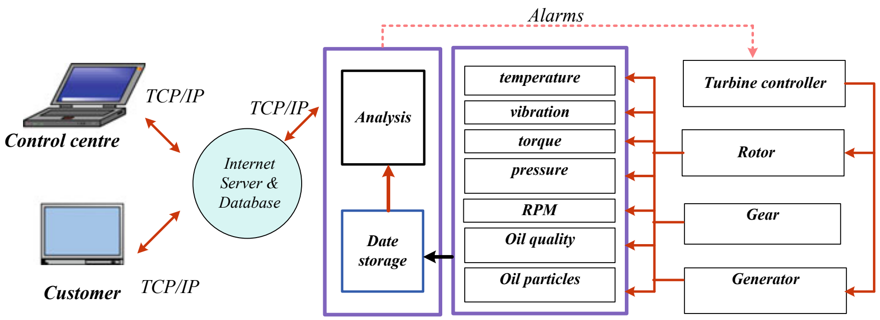

Fig. 18 Condition monitoring system for wind plant

support a vector-based wind power generator and external slope conditions [6]. The results showed that the model is better than traditional prediction methods.

Based on statistical analysis, it generally requires large data sets to provide meaningful indicators: Therefore, the most common view is that SCADA can detect initial errors at a late stage [39] using artificial neural networks, for their ability to reconstruct nonlinear dependency between Input and output, and simple formulas for diagnosing faults that occur at the gearbox level. Datasets used have a 10-min sampling time for common SCADA control systems; Gearbox vibrations and gearbox temperatures are defined as the model's target output. The time accuracy of SCADA will turn out to be very rough for reliable vibration analysis, which should be observed somewhat on its appropriate time scale (several Hz). At present, data mining methods such as agglomeration and statistical model are widely used in domestic and foreign companies, but the cleaning process is complicated and the cleaning conditions are harsh [45–49]. Therefore, in order to perform a reliable analysis of the power generation performance of wind turbines, an effective and varied cleaning method is urgently needed. In light of this, this chapter first extracts the features from the big data and high dimensions that SCADA collects and removes the unrelated and unnecessary parameters.

13 Data Mining of Characteristic Parameters for Wind Turbines

The data collected and recorded by SCADA wind turbine system has high dimensional properties. Figure 19 illustrates obtaining typical data for wind turbines. Therefore, in this chapter, a data mining algorithm based on the degree of gray correlation [46] has been proposed to overcome the above-mentioned shortcomings and to improve the accuracy and effectiveness of wind turbine operating condition assessments.

Variables in wind turbine information are recorded by the SCADA system. Figure 18 shows the observing variables collected by the SCADA wind turbine system and its response code. The aim of the study in this chapter is that wind turbines are in an unlimited state of energy and healthy running. They have some monitoring quantities such as the control and alarm mode for some parameters recorded in SCADA system, speed mode, column 1 status, column 2, axis 3, etc. Variables can be ignored in a fixed state. Table 1 is part of the parameter alarm information from the GE wind turbine manufacturer. To address these self-vectors beforehand, we must remove these self-vectors to avoid the dimensional disaster caused by many features.

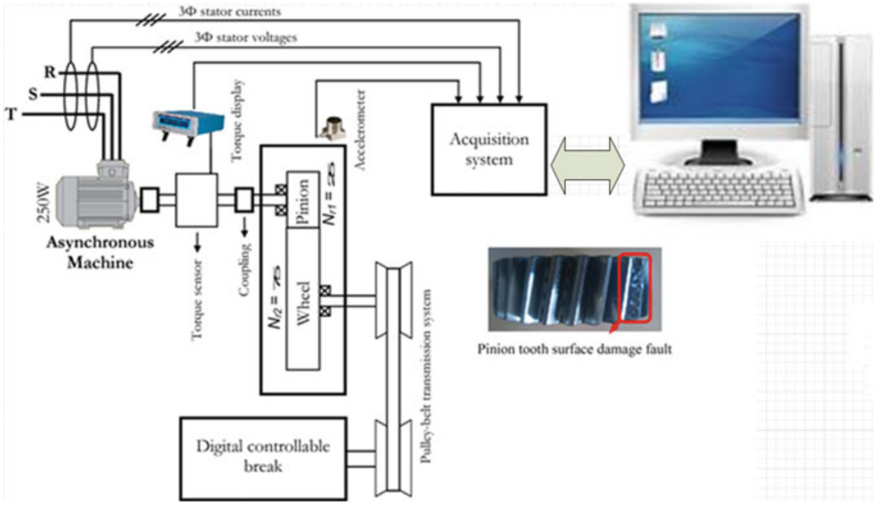

Fig. 19 Data acquisition in wind turbine

13.1 Communication Network for Wind Power Farms (WPPs)

The SCADA system enables operators to monitor, control, and record wind power plant data from a remote location called a central control station [1, 2]. It consists of three main components as shown in Fig. 20. Inside the turbine tower, including wind turbine controller (WTC), remote terminal units (RTU), smart electronic devices (IEDs), and sensors. The World Trade Center collects all data using short communication links, making them available for processing and transfers to the control center. A closed circuit television system (CCTV) and internet connection can share or use a separate network between the wind turbine and the control center.

A communications network is based on Ethernet equipment (Gigabit Ethernet), to transfer data between teams and the control center. Most WPP s use the same SCADA power cable paths as they used for power distribution. The Control Center connects individual work teams and meteorological stations with the Control Center. Operators manage the behavior of all teams as a whole. It requires a long distance to transfer data.

13.2 Ethernet Passive Optical Network (EPON)-Based Communication Network for WPPs

EPON consists of a control center OLT, multiple ONUs, and POS. Downstream, EPON is a point-to-multipoint network; OLT broadcast controls messages and data packets on all operating units via the passive partition unit. On the upside, EPON is a

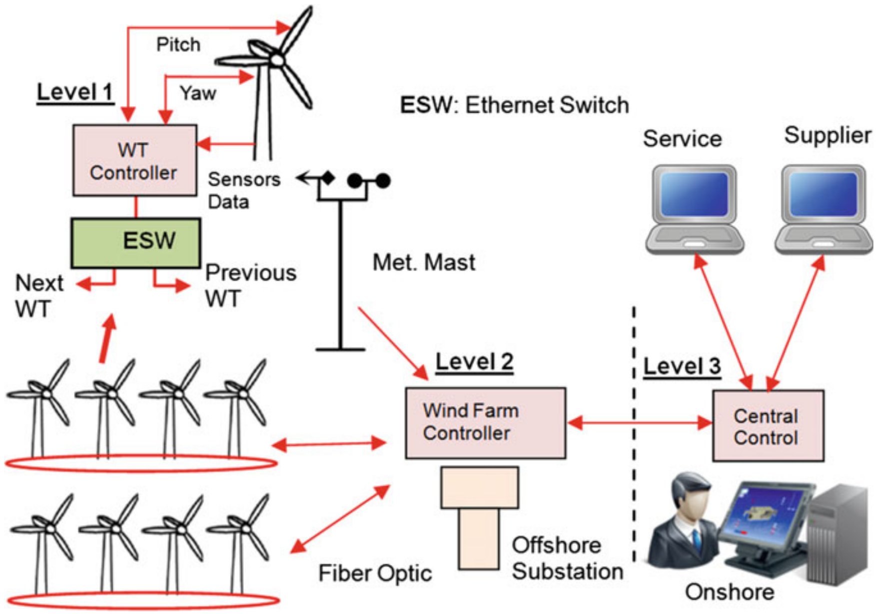

Fig. 20 Schematic view of conventional wind power farms (WPP) network

multi-point network. Multiple ONUs send data to OLT by passive combination [18]. Figure 21 shows a schematic view of the EPP-based communication network for WPP [24]. The proposed network consists of an optical network device (ONU) that is deployed on the WT side to collect various data, including wind turbine operation, meteorological data, and fault and safety parameters from different internal networks. All ONUs from different WTs connected to OLT unit, located on the side of the control center. The path between WTs and the Control Center does not contain any active elements, which saves costs and reduces the complexity of maintenance and deployment, compared to the current switched Gigabit Ethernet.

In Fig. 21, the shown architectures (star, cascade, etc.) represent the design of a new WPPs scheme. Mixed configuration (Ethernet switch and ONU) represents the modification of existing WPPs to support EPON technology, which is outside the scope of this work. In the astral configuration, four wind turbines with fibers distributed are connected to the control center using a single point of sale (1×4). In succession configuration, four points of sale (1×2) are connected in succession. One port is connected to the next weight, while the other port is connected to the WT-ONU.

For example, EPON uses a 1Gbps single fiber, with a transmission range of 20 km. Different wavelengths are used to support current flow from current to direction, 1,490 nm and 1310 nm, respectively. Each WT sends data in its own time slots, to avoid data collisions. EPON must use a media access control (MAC) mechanism, to control access to the shared media, to prevent collision of different ONU data in

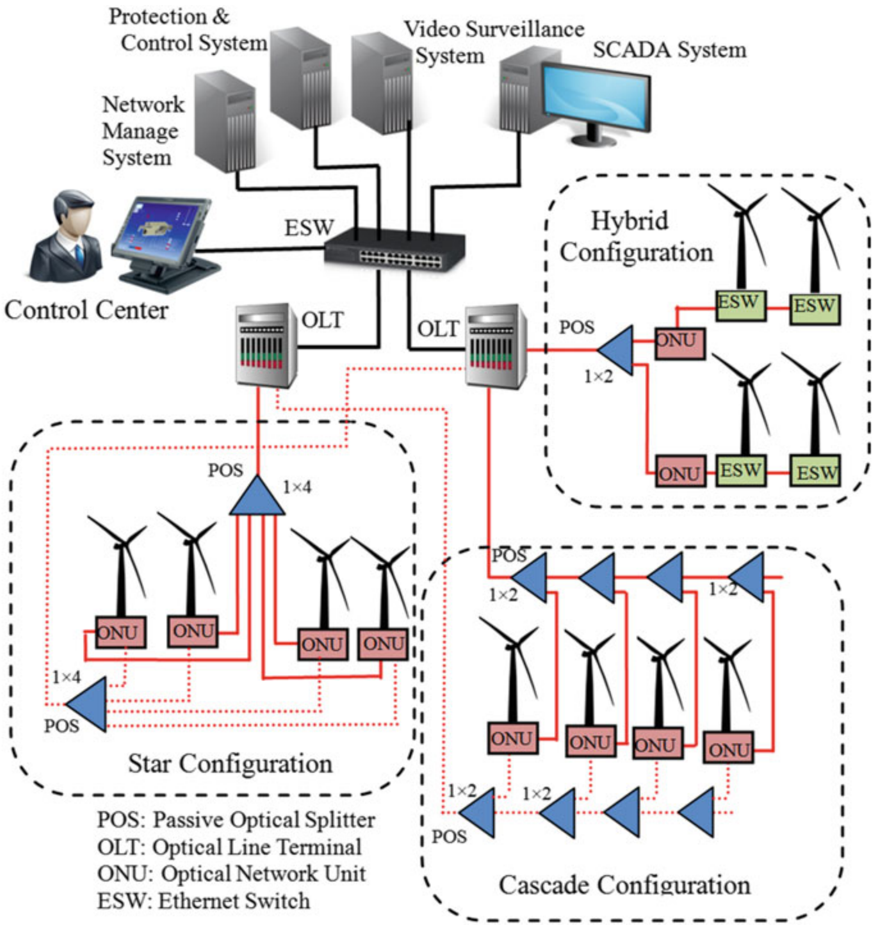

Fig. 21 Schematic view of Ethernet passive optical network (EPON) communication network for WPP

the opposite direction. OLT efficiently shares transmission bandwidth between all turbines ONUs. Failure to reach this shared channel in a timely manner can negatively affect communication and should be considered an aspect of reliable communication. There have been many studies and frameworks for managing medium access control at [1, 5, 18, 24].

14 Future Challenges

From the literature reviewed, researchers have successfully demonstrated that by tracking wind speed and energy output parameters, the overall health of the turbine can be supervised. Moreover, SCADA data can be used for CM from WTs and fixing errors. There was success in using SCADA data for power forecasting, optimum control settings, performance appraisal, turbine malfunction prediction (steering acceleration/tower acceleration/gearbox failure) as well as vibrations on WT. Many AI technologies have been applied including NN, Fuzzy, ANFIS, GA's, etc. It is also proposed to use data consolidation techniques to monitor the health of WTs' [47]. Some challenges that must be overcome before SCADA data analysis becomes completely successful: SCADA data can vary from turbine to turbine and SCADA data change with operational conditions. Therefore, it becomes difficult to distinguish between real error and false error as a big challenge.

Moreover, WT SCADA data is usually an average of 10 min data, so some information is lost. Thus with reference to the WT status monitoring research, it is suggested that a framework that takes SCADA data as well as high-frequency data from sensors (some of them) be proposed to diagnose and forecast traditional data and SCADA data. After comparing the two results, the appropriate method for making maintenance decisions can be chosen. The performance of AI-based data mining algorithms and CM algorithms are showing very promising results. Hence using mathematical intelligence models more efficient models can be obtained thereby enhancing the model's accuracy and durability. Data mining (AI-based) and evolutionary accounts are combined to build prediction and monitoring models.

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