A Recap of Modern Power Grid Control Systems

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***Abstract*—Wind power plants (WPPs) and photovoltaic power plants (PV systems) are the most popular types of renewable power plants (RPPs) in the formation of modern power grids. A lot of modern power grids have already been interconnected with WPPs. Control methods have been proposed and (or) developed in the existing research. However, it has been found that the existing literature does not clearly state the exact point where these control methods should be applied in the modern power grid. Also, till today, the existing literature does not look at and clearly define the difference between the control methods for the point of connection (POC) and the point of common coupling (PCC). In this article, the control methods applied in modern power grids are discussed, and the linkage between them has been described clearly.**

Keywords—Integration, modern power grid, point of common coupling (PCC), point of connection (POC), renewable power plants (RPPs), wind power plants (WPPs), wind turbine generator unit (WTGU), supervisory control and data acquisition system (SCADA).

I. INTRODUCTION

Voltage stability is part of dynamic and transient stability that branches from the concept of power system security and is defined as the ability of the power system to maintain its steady-state voltages at all busbars (or substations) after it has been subjected to disturbances like sudden increase or decrease in power [1]–[7]. Failure in this ability is known as voltage instability and may result in progressive and periodic decreases or increases of voltages in all substations leading to a complete power outage [8].

Control measures are taken in power systems, to deal with voltage instability, for example, destabilizing controls or other control actions like load shedding. These actions establish voltage stability globally and are only effective to certain limits [1], [5], [8].

The consumption of electrical energy has been increasing over the last decades. This consumption has been reported to grow by 56% from 2010 to 2040. Since voltage stability is associated with heavily loaded systems [8], this increase keeps leading to power grids operating close to voltage stability limits [9]–[11]. The solution to this is the conversion of traditional power grids to modern power grids by integrating renewable power plants (RPPs) such as wind power plants (WPPs) and (or) photovoltaic power plants (PV systems) [9], [10], [12]. This solution reduces operating costs and energy costs, contributing to keeping the electric power grid stable while withstanding the increased energy demand. RPPs like large-scale WPPs and large-scale PV systems are a technical and economical form of electrical energy worldwide [13]–[17]. However, large-scale WPP integration into the power grids has been leading over the last decades [18], [19]. This has also been shown by the publication about the global installed capacity of wind power in the past ten years, which indicates that the installation has increased from 180 GW in 2010 to 732 GW in 2020 [20], [21]. This means that a higher share of the total generation of electrical energy in the world will be from wind in the future. Therefore, out of these two RPPs, we explored our research on modern power grids integrated with WPPs.

Ensuring the safe and economical operation of modern power grids is a crucial requirement, necessitating a well-designed control system. Current research predominantly focuses on optimizing the output power of individual wind turbine generator units (WTGUs), with limited attention given to the point of common coupling (PCC) in modern power grids.

A complete control system in modern power grids covers the entire WPP up to the PCC, where the load demand on the power grid load side is also monitored so that WTGUs can be operated based on the load demand [17], [22]. That being said, a strong need has been identified, to further look at proposed and (or) developed control methods for modern power grids, to ensure that a proper foundation is laid for every step taken toward the improvement of modern power grids' design and operation.

This paper aims to address the gap between wind power plants (WPPs) wind turbine generator units' (WTGUs) control and the overall modern power grid. It reviews existing control systems, focusing initially on dynamic control for WTGUs and subsequently on the control system at the point of common coupling (PCC). The paper emphasizes the interconnection of these control systems in enhancing voltage stability in the modern power grid.

Following the introduction, Section II is an overview of modern power grids and voltage stability challenges. The overview of modern power grid control systems is discussed in Section III. Section IV is the review of the wind turbine generator unit (WTGU) supervisory control system and the wind turbine (WT) control system, while Section V is the review of modern power grid point of common coupling (PCC) control methods. Section VI discusses the integration of a WPP into the grid. The linkage between the control systems is described in Section VII, and finally, in Section VIII, conclusions and future work are stated.

II. Modern Power Grids and Voltage Stability Challenges

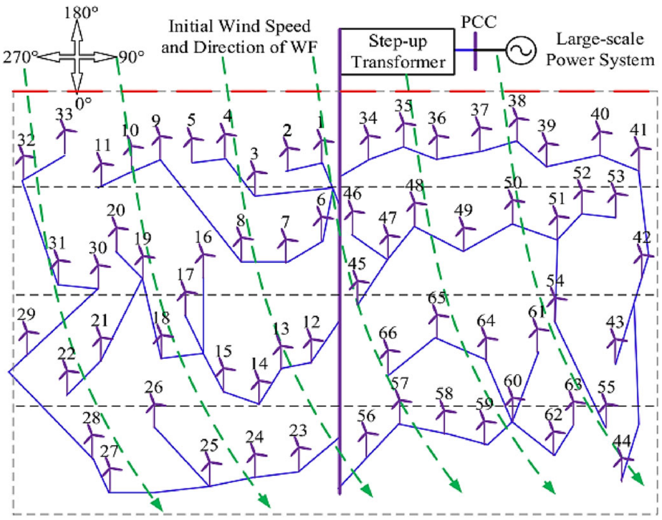
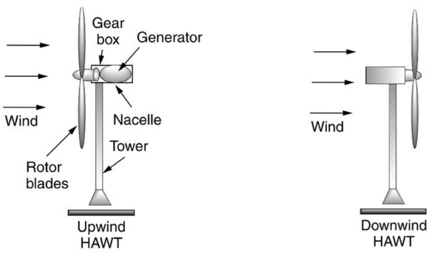


Fig. 1. A typical power grid integrated with a wind power plant [24]

Integrating renewable power plants (RPPs) into the traditional power grid modernizes the power grid [23]. Since this research mainly focuses on modern power grids inclusive of wind power plants (WPPs), we only present a modern power grid based on Fig. 1 [24]. The modern power grid in the figure has 66 wind turbine generator units (WTGUs) connected to the primary side (medium voltage terminal) of a step-up transformer linking them to the power grid (labeled Large-scale Power System in the figure).

There are two methods into which the WPPs are operated, either in grid-connected mode or standalone (islanded) mode of operation. However, because the study is based on the power grid voltage stability improvement, and thereof only the grid-connected mode is of interest. That being said, in grid-connected mode, WPPs contribute to adding more power to the power grid when the demand on the load side is too high [25].

Different types of WTGUs exist for building up a WPP and are classified in terms of the axis by which the wind turbine (WT) blades rotate. The most popular WTGUs are horizontal-axis wind turbines (HAWTs). HAWTs are either upwind machines or downwind machines. Some are vertical-axis wind turbines (VAWTs). Fig. 2 and Fig. 3 show the types of HAWTs and a VAWT [26], [27].



(**a**) (**b**)

Fig. 2. Horizontal axis wind turbines: (a) upwind HAWT. (b) downwind HAWT [26], [27]

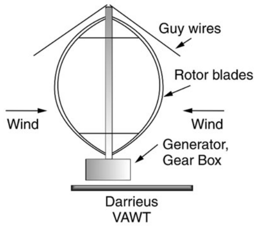


Fig. 3. Darriers vertical axis wind turbine [26], [27]

A WTGU converts the power extracted from a moving wind into electrical power. Today's WTGUs are called modern WTGUs, they consist of intelligent control systems designed for the optimization of power. Continuing from this definition, the design of modern WTGUs, the power output prediction, the WTGU electrical power production, and the researched challenges and their solutions associated with the power grid integrated with WPPs are discussed.

A. *Design of Modern Wind Turbine Generator Units*

This section is based on the HAWT since it is the most popular design of WTGUs. The HAWT consists of wind turbine (WT) blades and a hub. The combination of these two components is called the rotor. The rotor of the HAWT rotates parallel to the ground. An example of a horizontal axis wind turbine (HAWT) is shown in Fig. 4 with its major components [28].

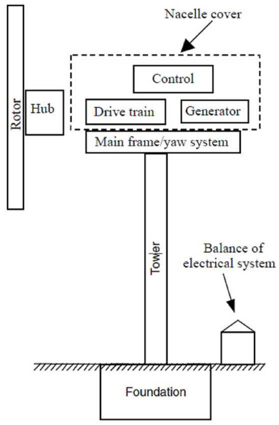


Fig. 4. The upwind horizontal axis wind turbine showing with its major components [28]

However, these components will not be described. For more information on their description, reference [28] can be consulted.

B. *Output Power Prediction of Modern Wind Turbine Generator Units*

The variation of the wind turbine (WT) output power is based on the wind speed. Each WT is designed with its power performance characteristic curve. This curve is used for the output power prediction without taking into consideration the technical details of its components. Moreover, the output electrical power given by the power performance characteristic curve is a function of the WT hub height and wind speed. Three scales of velocities make the WT power performance characteristic curve, and are listed and described below: There are three key points of the velocity scale to which the performance of a given wind turbine generator can be related, as described below [27], [29].

Cut-in speed: The minimum wind speed the WT uses to produce the useful power. 3 m/s to 4 m/s for most WTs. No power can be generated below this speed. **Rated wind speed:** The wind speed at which the WT-rated power is reached. The rated power is the output power of the electrical generator. Most WTs have a rated speed of 14 m/s. **Cut-out speed:** The maximum wind speed (usually 20 m/s to 25 m/s) at which the turbine is allowed to deliver power. It is usually limited by engineering design and safety constraints.

A typical example of a WT power performance characteristic curve is shown in Fig. 5 [27]. The power performance characteristic cures for WTs are usually obtained from WT manufacturers and are derived from field tests using standardized testing methods.

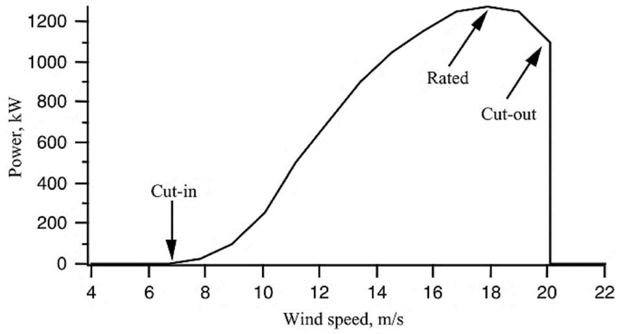


Fig. 5. General wind turbine power curve [27]

C. *Electrical Power Production of Modern Wind Turbine Generator Units*

An electrical generator is defined as an electronic device that converts mechanical power to electrical power. A squirrel cage induction generator (SCIG) is used in many wind turbine generator units (WTGUs) built for grid-connected applications. This type of generator operates at a range of speed slightly greater than its synchronous speed. As an example, a four-pole generator working on a 50 Hz grid has a synchronous speed of 1500 rpm. Moreover, the key benefits of a SCIG are that it is rugged, inexpensive, and simple to connect to an electrical network [28].

Wind turbine (WT) blades, supported by the hub, collectively form a low-speed shaft, rotating at the same speed as the blades (7-12 rpm). To generate electrical energy, the low-speed shaft's speed is increased through a gearbox, adjusting the turning speed before transferring it to the high-speed shaft of the generator (700-1200 rpm) [30], [31]. While some WTGUs lack gearboxes, modern WTGUs typically incorporate gear systems to optimize electrical output.

D. *Challenges and Solutions Associated with Power Grids Integrated with Wind Power Plants*

Voltage stability is classified into large (short-term) disturbances and small (long-term) disturbances. However, some large disturbances can also be long-term [4]. The authors in [31] looked at modern power grid voltage stability and divided voltage stability into four distinct phenomena as follows, namely short-term voltage instability (STVI), transient rotor angle instability (TRAI), fault-induced delayed voltage recovery (FIDVR), and converter-driven slow interaction instability (CSII).

There are challenges associated with modern power grid voltage stability. The authors in [32] addressed challenges and the solutions associated with the power grid integrated with wind power plants (WPPs). According to these authors, WPPs produce a randomly varied power, at the same time their production is expected to be effective during peak hours. These authors reported that this variation impacts negatively the adequacy of the power grid. The same authors stated that the integration of large-scale WPPs into the grid causes difficulty in the participation of grid system services namely voltage and frequency control, self-start or black-start, islanding operations, etcetera. Furthermore, the WPPs are highly sensitive to grid voltage dips and frequency variations. Due to this, WPPs get disconnected during grid disturbances

"There are no technical limits to the integration of WPPs. However, to keep the reliability of the grid system, measures must be taken against the WPP variations, and this helps to keep the power grid operating within acceptable conditions". Said the authors in [32], while also mentioning that, Denmark has experienced grid stability challenges at the penetration rate of 20% to 30% of WPPs. Moreover, the authors mentioned that the limitation in the capacity of power grid lines and stations can cause serious problems if WPPs are located away from the point of common coupling (PCC). This contributes to the change in the power grid protection system due to the increased power of short circuits. According to these authors, new lines and stations need to be built for WPPs and managed by WPP operators."The direct connection of DFIGs into the grid causes unwanted high values of currents in the DFIG's rotor windings. These currents lead to the maloperation of the protection system preventing the rotor side converter (RSC) from operating and affecting the grid voltage stability". This was said by the authors in [33].

III. Modern Power Grid Control Systems

These authors in [34] and [28] divided (functionally) the wind power plant (WPP) control systems into three separate levels, namely, a controller that controls numerous WTGUs in a WPP, a supervisory controller for each WTGU, and separate dynamic controllers for various wind turbine (WT) systems in each WTGUS. These are three levels of control that operate hierarchically with interlocking control system loops.

Moreover, it is interesting to find the work in [17] and [22], where the importance of determining the load demand before designing a controller for WPPs that will be integrated into the grid was stated. Through this, it can be seen that a controller that controls numerous WTGUs in WPP should be aware of the grid load requirements and operate the WTGUs based on these requirements. Therefore, it is clear that this controller is a supervisory control and data acquisition (SCADA) system for a WPP and can be located at the point of common coupling (PCC) between the WPP and the power grid (collectively, the modern power grid).

In [28], it has been said that the function of a WPP SCADA is to initiate and shut down WTGU operations and provide coordination for the operation of a certain number of WTGUs. Here it can also be concluded that the WPP SCADA system communicates with both the WTGU supervisory control systems and the controllers of each WTGU. The purpose of the control system of each WTGU is to reduce operating costs, provide a consistent dynamic response, improve the quality of the output power, ensure safety, moreover to maximize the annual energy capture from the wind while minimizing individual wind turbine (WT) loads. This is according to [28].

IV. Review of Wind Turbine Generator Unit's Control Systems

Research by the authors in [17] and [29], [34]–[37] has clearly described the control systems of wind turbine (WT) systems as dynamic controllers. The work in [15] brought an overview of dynamic control techniques for controlling power in WTs. They classified these control techniques into five, namely, passive stall, active stall; pitch control (collective pitch control and individual pitch control), electric pitch control (robust controller, soft computing controller, conventional controller, and hybrid controller), and hydraulic pitch control. The operation of the control techniques mentioned above depends on the WTGU supervisory control systems.

Examining control systems for wind turbine generator units (WTGUs), the subsequent section delves into a comprehensive review of dynamic control techniques and supervisory control methods.

A. Dynamic Control Techniques

In [17], the author emphasizes the importance of a well-designed wind turbine (WT) control system that not only maximizes energy capture but also prolongs the lifespan of components like the gearbox. The study introduces an intelligent WT control system based on three integrated approaches: data mining, model predictive control, and evolutionary computation. The authors propose a multi-objective model with five weights to control WT performance, adjusting them based on fluctuating wind conditions and operational requirements. Testing the control method involves eight computational scenarios, considering factors such as wind speed, turbulence intensity, and electricity demand, with numerical results provided.

In [29], the authors investigated the behaviour of a wind turbine (WT) with variable speed and pitch-control capability in turbulent winds. Their study includes a fundamental comparison between a constant-speed WT and a variable-speed WT.

In [35], the authors effectively defined the dynamic controller and supervisory controller roles for wind turbines (WTs) in a modern power grid. They termed dynamic controllers as the middle-level control system and supervisory controllers as the uppermost-level controller. The supervisory controller oversees WT monitoring, while dynamic controllers manage generator torque, blade pitch, and yaw control. They highlighted the supervisory controller's role in determining WT start-up based on wind speed, shutting it off for safety in high wind conditions.

Meanwhile, authors in [38] introduced a dynamic control system for regulating wind turbine (WT) power output and torque under wind disturbances. Their approach relies on mechanical control using WT blade pitch angles (β) and generator torque actuators. Additionally, they compared the performance of linear quadratic regulator (LQR), linear quadratic regulator with integral action (LQRI), and model predictive control (MPC) in response to a wind disturbance step change. The study's MATLAB/Simulink simulations showed that LQRI outperformed both LQR and MPC controllers.

B. Supervisory Control Techniques

In the realm of wind turbine (WT) dynamic controllers, the initiation is carried out by supervisory controllers, a point underscored in [39]. The authors explained that the supervisory controller of a WT determines operational states by analyzing wind and generator speed data. It then transmits a control signal to the execution level for activating dynamic control. The study includes a block diagram illustrating two levels of the supervisory controller: the supervision level and the execution level.

Furthermore, in [40], the authors focused on designing a supervisory control system for speed control of wind turbines (WTs) using the torque-control method based on the buck converter. Their two-cascaded control loop approach demonstrated positive results when tested on a horizontal-axis wind turbine (HAWT), indicating an enhancement in WT power per wind speed compared to systems lacking speed control.

V. Review of Modern Power Grid Point of Common Coupling Control Techniques

The control methods to improve the point of common coupling (PCC) voltage of a modern power grid integrated with a wind power plant (WPP) are proposed by authors [18], [41]–[43]. A control method by the authors [41] shows a 5% voltage improvement as they compare it with the other conventional control methods. This control method increases the reactive power capability at the point of common coupling through the control of a WPP high-voltage transformer tap changer. The control method proposed by the authors [42] offers fast reactive power support for the PCC, and the method by the authors [43] improves voltage at the PCC under wind speed variations.

The authors in [44] proposed a wind power plant (WPP) control method based on the parallel control loops along with the look-up tables and gain scheduling. To test their control method, they used a WPP made of 32 wind turbine generator units (WTGUs), and their preliminary results show a significant cooperation effect by coordinating the operation of WTGUs in a WPP. Moreover, their control method shows some simplicity and effectiveness and suits industrial applications well.

In [45], authors highlighted challenges in coordinating interactive WTGUs in a WPP, attributing them to the significant wake effect. They addressed these challenges by proposing a control method that allocates power regulation tasks to individual WTGUs, utilizing kinetic energy and pitching capability for reliable and efficient fulfillment of external dispatch orders, showcasing superior control performance in varying and constant wind speed conditions.

In [46], a WPP control method was devised to optimize rotor kinetic energy, and validation using PSCADS/EMTDC demonstrated that the method could enhance the capability of primary frequency regulation.

In [47], the authors addressed the impact of integrating large-scale WPPs on frequency regulation, emphasizing the need for a novel approach involving the integration of wind turbines (WTs) into automatic generation control (AGC) to maintain satisfactory frequency regulation. Recognizing the limitations of conventional active power control (APC) methods such as pitch angle control (PAC) and rotor speed control (RSC), which exhibit slow response and a narrow regulating range, the authors proposed a coordinated APC method. This method involves simultaneous activation of PAC and RSC, leveraging rotor kinetic energy to enhance regulation performance in variable WTs. The study's simulations, focusing on both WTs and the power system, demonstrated the effectiveness of the proposed method, with notable improvements observed not only in individual wind turbine generator units (WTGUs) but also in the overall WPP regulation.

Authors in [48] proposed a comprehensive supervisory control and data acquisition (SCADA) system for the modern power grid, extending from the wind turbine generator unit (WTGU) level to the grid. Referred to as central model predictive control (MPC), their strategy stands out as the most effective among the reviewed methods for complementing the modern power grid control system.

In [49], the authors specify that their active power coordinated control method, based on model predictive control (MPC) for a wind power plant (WPP), is designed specifically for the sending end (PCC). Their approach involves reducing the active power of wind turbine generator units (WTGUs) by increasing the wind turbine speed.

Based on the above details, the control scope of the WPP supervisory control and data acquisition (SCADA) system extends seamlessly from the grid to the wind turbine generator units (WTGUs). Nonetheless, a critical requirement persists to explain the interface among the WPP SCADA system, supervisory control for individual wind turbines (WTs), and distinct dynamic controllers specific to diverse wind turbine systems within each WTGU. Prior to delving into this discussion, an overview of WPP integration in the subsequent section is covered.

VI. Wind Power Plant Integration

Wind power plant (WPP) integration involves thermally rated electrical conductors, transformers, and switchgear for connection and disconnection. Adequate conductor sizing is crucial to minimize voltage drops from wind turbine generator units (WTGUs) to the point of common coupling (PCC) with the electrical power grid, as highlighted in the references [16], [27], and [28].

There is a significant distinction between the two terms POC and PCC. POC is the term used to describe the link between a group of WTGUs, whereas PCC describes the point at which all the WTGU groups are commonly connected to the power grid [16]. Large-scale WPPs are usually connected to the grid at the transmission level. Depending on the agreement between the grid operator and the WPP operator, the transmission line interconnecting the WPP to the grid can either be operated by the WPP operator or the grid operator. Also, the modern power grid SCADA system will be managed by the power system operator if the decision is made that the transmission system that interconnects the WPP and the grid will be managed by the power system operator. However, this SCADA system will also have access to the control systems of each WTGU of the WPP operated by the WPP operator.

VII. Interaction of Dynamic Control Systems and Overal Modern Power Grid Control

A work of cyber-physical wind power plant system (CPWPPS) consisting of four layers such as a WPP layer, SCADA layer, communication network layer, and application layer is proposed in [50] and [51]. These authors performed in-depth modeling for a WPP system with its WTGUs, meteorological mast (met-mast), and substation based on IEC 61400-25 and IEC 61850 standards. The parameters they used for a WPP are adopted from a real-offshore WPP project of the Korean Southwest. The proposed architecture by these authors enables communication from the PCC up to the WTGUs in the WPP area. The work of [28] and [52] stated that the WPP SCADA system continuously checks the operating conditions of a WPP based on the pre-set limits of its control and protection devices and takes appropriate action such as shutting down any WTGU should the measurements exceed a safe value.

Hardware relay logic or intelligent electronic devices (IEDs) and electrical circuits are used for the switching tasks. However, most often, nowadays industrial computers are used. The main tasks performed by the SCADA system in a WPP are monitoring for safe operation, information gathering and reporting, monitoring for operation, managing wind turbine (WT) operation, and actuating safety and emergency systems [28].

VIII. Conclusions

In our previous work, we looked at the design of wind power plants (WPPs) and modeled a large-scale WPP. Following the aforementioned work, we saw the need to explore the existing work on the control methods for modern power grids integrated with WPPs. The literature has been discussed in this paper, with the existing integration challenges regarding voltage stability, and control methods for improving the voltage stability of modern power grids. From the reviewed work, it has been found that the supervisory control and data acquisition (SCADA) system is the type of control system applied at the point of common coupling (PCC), where in there it looks at the entire system from up to the WTGUs at the WPP area. This has been confirmed through the work explored in the references [44], [45], [49], and [51].

The future work will focus on the method for conducting a voltage stability study of the traditional power grid into which the WPP modeled in our previous work will be integrated.

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