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Power Electronics for Grid Integration of Wind Power Generation System

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***Abstract*—The rising demands for a sustainable energy system have stimulated global interests in renewable energy sources. Wind is the fastest growing and promising source of renewable power generation globally. The inclusion of wind power into the electric grid can severely impact the monetary cost, stability and quality of the grid network due to the erratic nature of wind. Power electronics technology can enable optimum performance of the wind power generation system, transferring suitable and applicable energy to the electricity grid. Power electronics can be used for smooth transfer of wind energy to electricity grid but the technology for wind turbines is influenced by the type of generator employed, the energy demand and the grid requirements. This paper investigates the constraints and standards of wind energy conversion technology and the enabling power electronic technology for integration to electricity grid.**

***Keywords*—electric power grid; power electronics; power converters; renewable energy; wind power generation system; wind turbine.**

I. INTRODUCTION

African's electricity demand is blowing up due to its rapidly booming population, which is estimated to quadruple by the year 2100. Unfortunately, an estimate of 587 million people (≈42% of global population), which presently lacks access to electricity grid resides in Africa [1]. In particular, over 93 million people cannot access electricity in Nigeria – the most populous African country. In spite of this problem, the electricity supply is highly unreliable. Grid electricity can only be accessed for an average of 6 hours per day [2]. Nevertheless, if the electric power required to meet the electricity demand in Africa were to come from fossil fuel, it could hamper global efforts to reducing global warming.

Renewable power sources are becoming a key contributor to the electric power grid. The power generation of renewable sources is growing at an alarming rate and is projected to triple within the next few decades [3]. This is due to the growing need for energy sustainability. Wind power, one of the most viable and promising sources of renewable energy globally, is estimated to contribute 12% of the projected global electricity production by 2020 [4], [5], [6]. Nevertheless, due to the uneven nature of the wind, the system energy output exhibit variability, which creates a burden on the reliability, security, quality and stability of the grid network [2], [7], [8]. Therefore, the strategy for efficient control and transfer of wind energy into the grid is a critical aspect towards ensuring the techno-economic viability of grid integrated wind power system.

A major barrier to wind energy potentials in Africa is the dearth of robust electricity grids for integration of large amounts of wind power. Wind energy can be interfaced with the electricity grid using power electronics, an enabling technology, which achieves conversion of electric power from one form to another, using power semi-conductor devices. The framework of power electronics represents the focal point where electronics, power systems and control engineering converge and combine. Power electronic technology provides functionalities that affect wind sources for optimum energy harvest and power support to the electric power grid. The technology is required to adapt the dynamics of wind resources to human application because the natural forms are not displaceable and the energy generated needs to be stored or directly transferred into the grid.

The goal of this paper is to assess the prospects of the power electronic technology for large-scale integration of wind energy to electricity grid. Section II describes the requirements, control and standards of wind energy conversion technology. Section III discusses the power electronic technologies for the transfer of wind energy to electricity grid and the control techniques for a modern wind power system. The conclusion of this study is given in section IV.

II. WIND ENERGY CONVERSION TECHNOLOGY

Wind energy is harnessed by a Wind Energy Conversion System (WECS) [9], [10]. The core objective of a WECS is to convert the kinetic energy from wind into electric power and then inject the electric power into the grid [11]. The basic components of a WECS are shown in Fig. 1. Among the key enabling factors of the technological advancement of wind power are [12]: variable-speed operation of Wind Turbine Generators (WTGs) to harness optimum power, economy of scale due to availability of large-wind generation plants, accumulated field experience improving the capacity factor, advances in power electronics and reduced cost, and computer prototyping via precise system modelling and simulation.

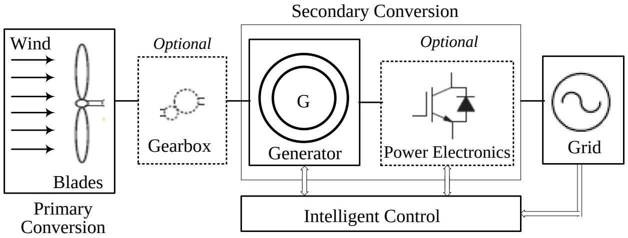

Fig. 1. Schematic of a WECS.

A. Wind Turbine Technology

Wind turbines are classified based on mechanical structure as: vertical-axis and Horizontal-Axis Wind Turbine (HAWT). The HAWT designs, which modern wind turbines utilise, are modelled for either a fixed-speed or a variable-speed operation [13]. It is to be noted that variable-speed wind turbine has higher efficiency, lower cost-to-power ratio with reduced noise and mechanical stress compared to fixed-speed configuration. In addition, variable-speed turbines can trace the optimum power extraction point, hence, can generate more power than constant-speed type, but it requires advanced power electronics and intelligent control circuitry to provide constant frequency and power factor.

The generators employed for the WECS are either Permanent Magnet Synchronous Generators (PMSGs) or Doubly-Fed Induction Generators (DFIGs). DFIG is mostly used for wind energy conversion because of its benefits in cost, size and weight but the reliability of the gear box, brushes and slip rings is not suitable for certain applications. PMSG has higher efficiency and less maintenance because it does not require a gear box [14]. The PMSG drives attain a very high torque at low speeds with less noise and require no external excitation [15]. Multi-pole PMSGs with full-scale back-to-back power converters tend to be the future topology to be adapted by most wind turbine manufacturers, gradually replacing DFIG in wind energy conversion.

B. Standards for Grid Integration

Wind turbines are part of utilities with potential sources of low power quality. The standards based on International Electrochemical Commission (IEC) for the measurement and evaluation of the power quality requirements of grid-tied WTG consist of three components: harmonic, switching and flicker analyses. Importantly, the flicker analysis utilises current and voltage time series measured at the WTG terminals to simulate voltage variations on a fabricated grid without a source of voltage fluctuation. Moreover, current and voltage transients are measured during switching operations of the WTG while harmonic analysis is achieved by the Fast Fourier Transform Algorithm [16]. A detailed description of these techniques is presented in the literature.

Wind turbines should supply power (active and reactive) for voltage and frequency recovery, immediately after the occurrence of a fault [17]. The fault-ride standard stipulates that during fault occurrence, a WTG should remain steady and connected when the voltage at the point of connection drops to 15% of the nominal value for a period of 150ms [18]. In addition, when the voltage is within the shaded area, as shown in Fig. 2, the WTG should supply adequate reactive power to enable the electric power grid sustain grid-voltage restoration. The WTG can cut off from the grid, when the grid voltage falls below the curve, illustrated in Fig. 2 [17].

Meanwhile, despite the International Standards, special grid connection codes are available [19], [20], which define the effective limit of a WTG linked to the electricity grid in terms of voltage acceptance, frequency range, fault-ride through and power factor. These codes try to make the WECS judiciously manage the distributed power (active/reactive) based on the demand as well as to supply voltage/frequency assistance for the electricity grid. Moreover, the WTG must be capable of controlling the active power at the Point-of-Common-Coupling (PCC) [21]. Grid codes differ from one transmission operator to the other. In addition, it centres on the testing techniques utilised for validating the fault-ride through capability of WTGs and their performance during a grid fault. The stricter grid codes in the future could lead to an improved WECS with advanced power electronics technologies [3].

The requirements of wind turbines for fault-ride through capability and improved power quality have increased the monetary cost per kWh produced, but more appropriate wind energy are being captured and interfaced with the power grid.

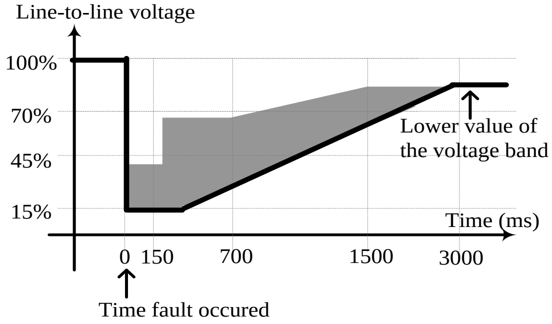

Fig. 2. Requirements for fault-ride through potential of WTG integrated to electricity grid [17].

C. Challenges for Grid Integration

Searching for greener and reliable energy has a knock-on effect on the quality and reliability of energy transferred to the grid [22]. The quality of power transferred to grid refers to the degree of variation from the standard sinusoidal (current and voltage) waveforms in the grid network. The level of acceptance depends on the sensitivity of the load demand [8]. Importantly, the main components that determine power system quality include harmonic distortions, flickers and voltage imbalance.

The power electronics converters used by variable-speed WTGs produce harmonics particularly in grids with low short-circuit capability. Modern forced-commutated inverters employed in variable-speed wind turbine applications generate both harmonics and inter-harmonics [23]. In contrast, the utilisation of fixed-speed WTGs causes flickers on the grid. Harmonics result in excessive heating of equipment and this reduces components lifetime while flickers can cause imbalance and core saturation of transformers and create an uncomfortable visual effect on the eyes, as well as thermal aging of induction motors [8]. Poor quality of electric power often results in energy losses, malfunctioning of equipment and perhaps, power system failure.

The output of a wind turbine generator varies strongly according to the wind regime as well as on the performance characteristics and the efficiency of the WECS [24]. Electric power system operators and planners are concerned about the variations of wind resource and the associated economic impacts on the power system stability when integrated into the grid [25]. Power imbalance affects the frequency of an electric power grid, which can result to loss of synchronism. The realisation of power balance between the generating plants and the load is more demanding for wind power production especially when the generating ratio is high [8]. Induction generators commonly used for most wind power applications are unable to inject reactive power into the grid and this impedes wind energy system interface with the grid.

The failure of the WECS will impose strong impacts on the stability of the grid, which results in increased cost to repair; thus the reliability performance of wind power systems is especially emphasized [3]. In addition, energy storage and balancing as well as cooling capability and power density are essential performance for WECS. Consequently, the requirements for efficient and reliable transfer of wind energy into the electric grid introduce additional demands such as dynamic grid support, effective protection, system monitoring and communication, and the control of power transferred into the electric grid.

III. POWER ELECTRONIC TECHNOLOGY FOR WIND ENERGY INTEGRATION

The current trend of renewable power generation requires new approach to the operation and efficient management of the electric grid as this could enhance the quality and reliability of power supply [17]. Power electronics technology performs a significant task in wind energy integration to the grid. Highly efficient and exceedingly reliable power electronics systems are required for interfacing wind energy to the grid, as well as to enable enhanced auxiliary functions such as Low-Voltage Ride-Through (LVRT) capability and grid support with reactive power injection [3].

A. Power Converter Topologies

Power electronics combined with advanced control systems are utilised as AC–DC–AC converters. The choice of a power electronic converter for WTGs is influenced by the type of generator employed, the energy demand and the grid requirements.

1) Variable-Speed Wind Turbines Technology: Among the widely utilised wind turbine system design configurations, the variable-speed WTGs (with partial-scale and full-scale power converters as depicted by Fig. 3) are presently domineering the markets [3].

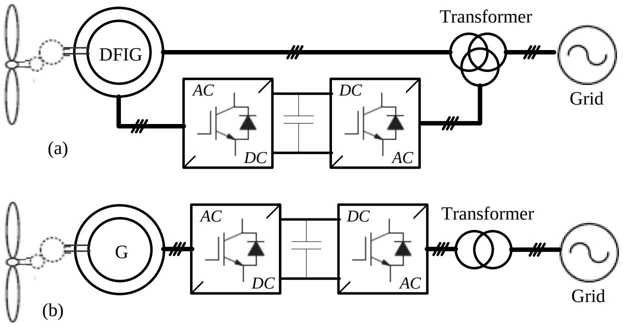

Fig. 3. Variable-speed wind turbine configurations with (a) Partial-scale power converter and (b) Full-scale power converter.

In variable-speed wind turbines, power electronics partly or fully decouple the rotor mechanical frequency from the grid electrical frequency to enable variable-speed operation [22]. The electrical rotor frequency of the DFIG can be varied when the power electronic converter supplies the rotor winding with the stator winding directly linked to the electric power grid, making variable-speed operation possible. The converter size is noticeably smaller than the rated capacity of the turbine generator utilised, which prevents full range operation, although the speed range is fairly adequate and losses are minimised [18]. In contrast, the generator is wholly decoupled from the electric grid in the full-scale converter configuration as shown in Fig. 3b. Wind turbines are mostly equipped for full-power converter operation, with multi-pole synchronous generators, due to increased reliability, reduction of monetary costs and losses, compared to the gearbox-based induction generator configurations.

2) Onshore versus Offshore Technology: The energy balance of offshore wind turbines can be more advantageous than onshore turbines; these advantages depend on the local meteorological conditions. The offshore topology has a longer life span, about 25–30 years due to lower fatigue loads on the wind turbine resulting from low turbulence from sea [17]. Nevertheless, the maximum possible length and transmission capacity of Heating–Ventilation–Air Conditioning (HVAC) cables is restricted for offshore application. High-Voltage Direct-Current (HVDC) transmission systems are mainly competitive at transmission distances over 100km or power levels in the range of ≈ 200 to 900MW [26]. The HVDC transmission proffers several benefits over HVAC, namely: independent sending and receiving frequencies, mainland disturbances are isolated from offshore installation and vice versa. In addition, the power flow is controllable and entirely defined, power losses of cable are low and power-transmission capacity per cable is higher [27]. In the classical LCC (Line Commutated Converter)-based HVDC transmission system design, the thyristors require an AC voltage source to facilitate commutation and can only transfer power amid two active AC networks [26]. In addition, the LCC-based HVDC transmission schemes generate considerable amounts of harmonics; hence, the use of bulky filters is unavoidable and lacks the possibility to offer an autonomous power monitoring and control. As a result, they are rarely used in wind farms.

VSC (Voltage Source Converter)-based HVDC transmission technology is attracting significant attention for grid integration of large-scale onshore and offshore wind power systems. This technology is made possible by the Insulated Gate Bipolar Transistor (IGBT) device, which can switch-off currents. This property eliminates the requirement for an active commutation voltage. As a result, VSC-based HVDC system does not need a robust onshore or offshore AC network. Moreover, the system can start up against a dead network [17]. The active and reactive powers when controlled separately can lessen the demand for reactive power compensation, which helps to stabilise the AC network at the PCC as depicted in Fig. 4.

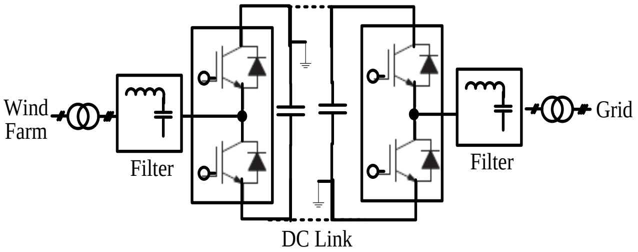

Fig. 4. VSC-based HVDC transmission scheme.

3) High-Power Medium-Voltage Technology: The multi-level power converter topologies are mainly categorised into five multi-level configurations comprising [28]: bidirectional switch interconnection, diode clamped, capacitor clamped, multiple three-phase inverters and cascaded single-phase H-bridge inverters. In theory, these configurations can be constructed with n levels (randomly chosen) but in reality some designs are easier to implement than others. In addition, the multi-level converters have the least demand for input filters. For a similar harmonic content as a two-level converter, the switching frequency of a multi-level converter can be decreased by 75%, which leads to lower switching losses [17].

Although the multi-level converter has higher conducting losses, overall efficiency varies with the ratio of switching to conducting losses. The rise in voltage rating permits direct link between the converter and the wind power system network, thus, eliminating the use of large transformers. The main shortcoming of the multi-level topology is the need to attain different independent sources DC voltage required for the multi-level modulation. The utilisation of low-speed permanent-magnet generators with a large number of poles helps in attaining DC sources from the multiple wounds of the electric machine as shown in Fig. 5 [17]. The multi-level cascaded topologies are commonly used for industrial applications due to the continuous decrease of the monetary cost per kW of the Power Electronic Building Blocks (PEBBs).

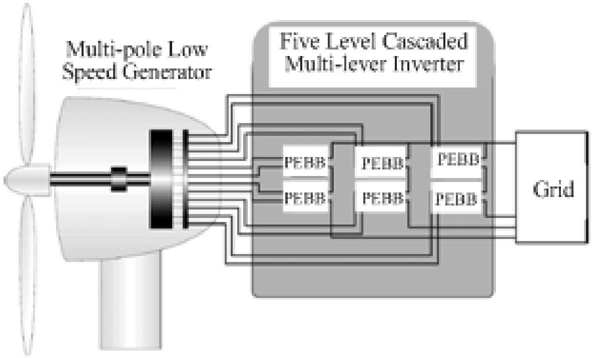

Fig. 5. Five-level cascaded multi-level converter linked to a multi-pole low-speed wind turbine [17].

4) Direct-Drive Wind Turbine Technology: Direct-drive technology is growing due to the exclusion of the gearbox. The direct-drive generator reduces the total size, lowers the installation and maintenance cost, offers a variable control technique and rapid response to wind variations and load fluctuations. Different concepts for direct-drive generators are available in the literature for grid integrated WECS. A description of a low-speed direct-drive permanent-magnet generator for WECS application is given in [29]. A common trend for propulsion systems applications is the utilisation of an axial flux machine, which is employed in small-scale direct-drive WTGs since larger torque density can be attained conveniently [30].

B. *Advances in Semi-Conductor Technology*

The essential performance characteristics of power electronics for wind energy applications are directly connected to the viability of power semi-conductor devices with improved electrical properties at reduced cost. The rapid advancement of power electronics in recent times is due to the development of semi-conductor devices with fast switching speed and high power handling capability as well as the establishment of real-time computer controllers capable of implementing intelligent control algorithms. The monetary cost of power semi-conductor devices is declining, 1-5% per annum for similar output performance; hence, the cost of power electronics technology is also decreasing [22]. The potential silicon-based semi-conductor technologies include the Integrated Gate Commutated Thyristor (IGCT) and the IGBT.

The IGBT is a special class of transistor with similar function as a BJT but its base is driven by a field-effect transistor while the IGCT is a member of a larger family of combination devices, in which multiple semi-conductor chips are packaged together to perform a single power function [31]. The IGBT technology can adapt to a very high-power range (from 1 to 200kW) and can favourably compete with gate turn-off thyristors for high power applications. The IGBT exhibits superior qualities for frequency converters in WECS applications. The switching frequency is higher compared to IGCTs, which results in a reduced amount of distortion in the electric power grid. In addition, the modular packaged IGBT silicon chip is separated from the cooling plate and can be linked to ground for low electromagnetic emission even with higher switching frequency [23]. This configuration results in negligible thermal stress and increased lifespan of the device by approximately ten folds.

In contrast, heating and cooling of the IGCT can mechanically stress the silicon chip making the device to exhibits high electromagnetic emission. Consequently, the lifespan of the IGCT is significantly reduced, particularly for wind turbine applications. Nevertheless, the main advantage of the IGCT is the lesser ON-state voltage drop of the device, ≈ 3.0V for a 4.5kV device. The power dissipation for a 1500-kW converter, due to a voltage drop, is 2.4kW per phase [17] compared to power dissipation 5 kW per phase for an IGBT device.

Although the power capability of the SiC (Silicon Carbide)-based devices are currently inadequate for wind energy integration, the technology is promising for potential wind energy converter configurations made up of paralleled/cascaded converter cells, where the requirements for current and voltage ratings are much lower. The key challenges for SiC devices are their bonding technology, shortcoming of the stray inductance, slimmer chips as well as higher dv/dt stress and higher operating temperature – these limitations must carefully be accounted for in the design and packaging of SiC converter systems [32].

C. *Control of a Modern Wind Power Generation System*

The control of electric power produced from wind is difficult; if adopted in large quantities, can cause local voltage and frequency fluctuations with severe impact on the quality of power supply. Direct transfer of wind energy to electricity grid can introduce power quality issues owing to the erratic nature and the dynamics of the wind power generation system. The use of advanced power electronics allow wind generators to function in variable-speed mode enabling additional wind energy to be captured and controlled [33]. Power electronic converters must be properly controlled so as to deliver the range of current, voltage, or frequency required for the load as well as to guarantee the needed dynamics. The converter if properly designed can serve as smooth interface between most loads and the grid. In addition, the WECS should provide ancillary services so as to ensure a sustainable wind power conversion.

Fig. 6 depicts the control function blocks of a modern WECS. The Distribution/Transmission system operators give preference to determining a solution that can ensure stable operation of the WECS and allow additional wind resources. The wind power from the turbine is rectified to the DC link. The DC energy is then inverted to appropriate AC energy to be transferred into the electric grid. The DC link stores energy captured from the wind in the capacitors, which can instantaneously be transferred to the electric grid. This process reduces the total harmonic distortion coefficient, thereby enhancing the quality of electric power delivered into the grid. The DC bus stabilisation, current regulation and grid synchronisation can be rapidly executed by the power electronic converter using the proportional-integral/resonant controllers.

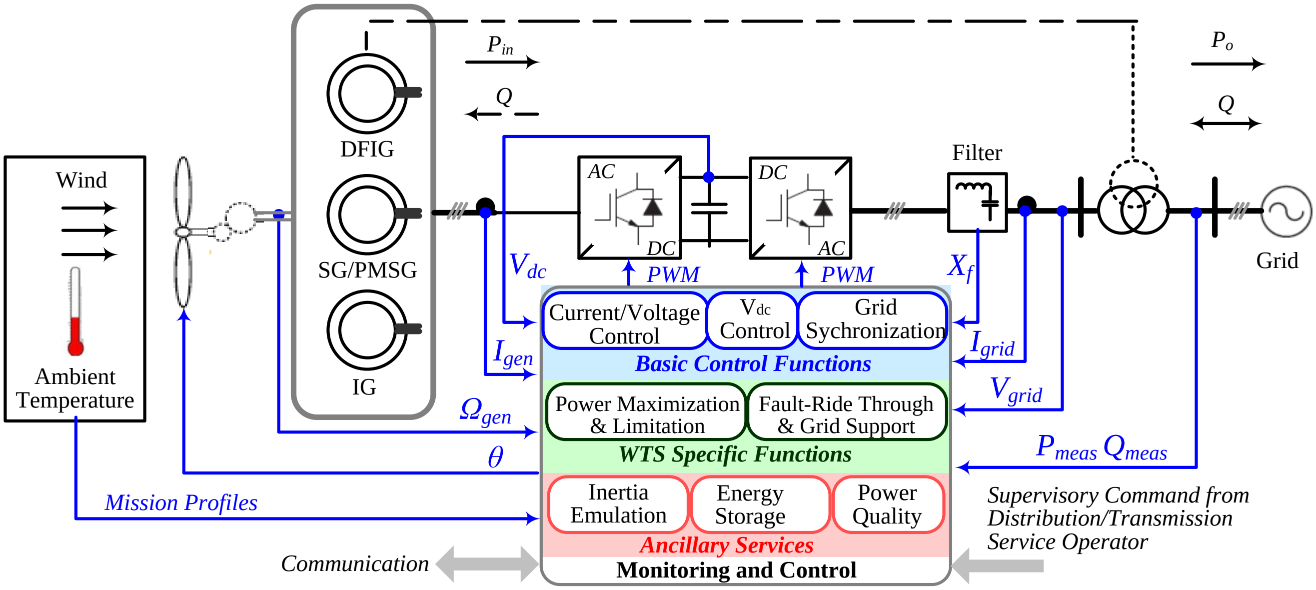

Fig. 6. Common control function blocks for modern WECS [3].

Some key strategies for reactive power transfer during LVRT operation in WECS are: positive and negative sequence control, unity power factor control and constant active/reactive power control [34]. The control signal maintains a constant reference to the voltage of the DC link, controlling the amount of energy transferred to the grid. The grid-side converter allows wind power transfer to the electric grid. The understanding of grid conditions significantly influences the control techniques. For instance, the discovery of grid faults and the removal of positive and negative sequence currents are essential for controlling the wind power in LVRT operation modes [3]. Grid synchronisation concern plays a vital role as the current transferred into the grid must synchronise with the grid voltage. The second-order generalised integrator-based phase-locked loop gives an improved performance compared to other techniques, particularly for single-phase systems – a good candidate for the synchronisation utilised in industrial applications [35].

IV. CONCLUSION

Wind power generation is growing at an alarming rate due to expeditious growth in global energy demand, rising call for energy sustainability and advances in power electronic technology. Wind energy can be integrated into the grid using power electronics, an enabling technology that achieves conversion of electric power from one form to the other, using power semi-conductor devices. Power electronics technology enables optimum performance of the WECS, transferring suitable and applicable wind energy into grid. In order to smoothen the progress of larger-scale integration of wind energy into the grid in the future, more research in the field of power semi-conductors are on going to cater for emerging demand for power flow control, grid connection standards, communication and protection. Improvements on efficiency of power electronics technology can be achieved by developing more advanced power semi-conductor devices with improved reliability, power ratings and lifetime, as well as enhanced control capabilities.

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