# Power Electronics for High-Power Wind Energy Conversion Systems

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## Abbreviations

**AC** Alternating current
**BTB** Back-to-back
**DC** Direct current
**DFIG** Doubly fed induction generator
**DPC** Direct power control
**DTC** Direct torque control
**FOC** Field-oriented control
**GSC** Grid-side converter
**HTS-SG** High-temperature superconducting synchronous generator
**HVAC** High-voltage alternating current
**HVDC** High-voltage direct current
**IGBT** Insulated gate bipolar transistor
**LV** Low voltage
**MMC** Modular multilevel converter
**MPPT** Maximum power point tracking
**MSC** Machine-side converter
**MV** Medium voltage
**MW** Megawatt
**NPC** Neutral-point clamped
**PCC** Point of common coupling
**PF** Power factor
**PMSG** Permanent magnet synchronous generator
**RSC** Rotor-side converter
**SCIG** Squirrel-cage induction generator
**VOC** Voltage-oriented control
**VSC** Voltage source converter
**VSI** Voltage source inverter
**VSR** Voltage source rectifier
**WECS** Wind energy conversion systems
**WF** Wind farm
**WRIG** Wound rotor induction generator
**WRSG** Wound rotor synchronous generator
**WT** Wind turbine

## Introduction

Wind energy industry has set new records in terms of installed capacity contributing to about 4% of the world's net electricity production. The cumulative wind energy capacity escalated from 6100 megawatt (MW) in 1996 to 432,883 MW by the end of 2015. The size of utility-scale wind turbine (WT) is also boosted to 10 MWs (Yaramasu et al., 2015). The WT manufacturers such as *Clipper*, *Sway Turbine*, *Sinovel*, *Mitsubishi*, *GoldWind*, *Mecal*, *MingYang*, *United Power*, *GE Energy*, and *Gamesa* have announced their future projects in the 10–15 MW class. High-power WTs are proven solutions in the present industry for more wind power extraction with lower installation and maintenance costs in comparison with a group of low-power WTs.

The class of wind generators in the present wind energy industry include squirrel-cage induction generator (SCIG), wound rotor induction generator (WRIG), doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG), wound rotor synchronous generator (WRSG), and high-temperature-superconducting synchronous generator (HTS-SG). By combining the wind generators with power electronic converters, various configurations for wind energy conversion systems (WECS) have been researched and commercialized over the past 35 years. The following five WECS types are offered by many WT manufacturers to achieve fixed-speed, semivariable speed, and full-variable speed operations:

- *Type 1*: Fixed-speed WECS with SCIG, soft starter, and reactive power compensator. The SCIG operates 1% above the synchronous speed.
- *Type 2*: Semivariable speed WECS with WRIG, converter-controlled variable rotor resistor, soft starter, and reactive power compensator. The operating speed range for WRIG is 10% above the synchronous speed.
- *Type 3*: Semivariable speed WECS with DFIG and partial power converter in rotor circuit. The DFIG speed can be varied within 30% above and below the synchronous speed.
- *Type 4*: Full-variable speed WECS with wind generator (SCIG, PMSG, WRSG, or HTS-SG) and full power converter in stator circuit. The wind generator speed can be varied from 0% to 100%.
- *Type 5*: Full-variable speed WECS with WRSG, torque converter, and field exciter in rotor circuit. The operating speed range of WECS is from 0% to 100%.

This article aims to provide an overview of power converters for fixed-speed, semivariable speed, and full-variable speed WECS. The single-, two-, and three-stage power converters for variable-speed WECS are discussed in low-voltage (LV) and medium-voltage (MV) categories. The grid integration of wind farms (WFs) by high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) transmission systems is discussed. The power converters for HVDC transmission are also discussed. Various technical

 http://dx.doi.org/10.1016/B978-0-12-409548-9.10094-6 

aspects, merits, and demerits of WECS are analyzed with respect to the industry standard solutions and promising approaches available in the literature.

This article is organized as follows:

- The configurations of Type 1–5 WECS are presented in sections "Type 1 WECS," "Type 2 WECS," "Type 3 WECS," "Type 4 WECS," and "Type 5 WECS," respectively. The comparison of WECS configurations is given in section "Comparison of WECS Configurations."
- Section "Grid Integration of Wind Farms" discusses the HVAC and HVDC transmission systems along with power converter for HVDC transmission.
- The future trends in high-power WECS and concluding remarks are given in sections "Future Trends in High-Power WECS" and "Conclusion," respectively.

## Type 1 WECS

The grid-connected Type 1 WECS with fixed-speed SCIG is shown in Fig. 1. The SCIG is connected to three-phase grid through a soft starter and a step-up transformer. This configuration is first developed by pioneers from Denmark; thus this configuration is also referred to as "Danish" concept. This configuration is developed by integrating electrical and mechanical components that are already existing in the market. The SCIG is simple, reliable, cost effective, and maintenance-free compared with other types of wind generators. The rugged construction and wide availability of SCIG in market has lowered the initial and maintenance costs. The overall system is reliable as less number of mechanical and electrical components are employed for power conversion.

The wind kinetic energy is converted into rotational mechanical energy by the WT blades. A three-stage gearbox is used between WT rotor and SCIG to increase speed from 6–25 to 1500–1800 rpm. The SCIG rotational speed is determined by the grid frequency and the number of poles of the stator winding. The SCIG contains four (or six) poles for 50 Hz (or 60 Hz) grid integration. The SCIG speed range is limited to 1% above the synchronous speed; therefore, this configuration is called fixed-speed WECS. For 50 Hz grid-tied operation, the speed range for the SCIG is from 1500 to 1512 rpm (0.8% higher than the synchronous speed of 1500 rpm). To facilitate two rotational speeds during varying wind speeds, pole-changeable SCIGs are also commercialized in the wind energy industry. The maximum conversion efficiency is achieved at rated wind speed, and the system efficiency degrades at other wind speeds. The aerodynamic power regulation can be achieved by passive stall, active stall, or pitch control. The modern Type 1 WTs employ active stall or pitch control.

The soft starter is realized by three-phase AC voltage regulator which consists of antiparallel thyristors and bypass switch in each phase. During the grid-tie procedure, the firing angles for the soft starter are gradually decreased from 150 to 0 degrees to smoothly apply grid voltage to the SCIG stator terminals. The dynamic performance of Type 1 WECS without and with soft starter is shown in Fig. 2A and B, respectively. In Fig. 2A, the SCIG is accelerated close to the rated speed and circuit breaker is closed to connect the SCIG directly to grid. The SCIG operates below synchronous speed during grid-tie procedure, therefore the operation can be regarded as motoring mode. The direct connection of SCIG to the grid causes excessive inrush currents with peak value of more than 10 per unit (pu), high electromagnetic torque (2 pu, peak), and high torque oscillations. The high inrush current damages the insulation of generator windings. Moreover, for the weak grids, the high inrush current will have adverse impact on the grid. The high torque oscillations cause excessive mechanical stress to the drive train. For this reason, the MW-level Type 1 turbines are connected to the grid through soft starter to reduce the inrush current and torque oscillations during grid-tie procedure.

In soft-start procedure, the SCIG is connected to the grid trough soft starter with initial firing angle in the range of 120–150 degrees. During the system start-up, low voltage is produced by the soft starter, and small stator currents flow through the generator. The firing angle is then decreased gradually from 150 to 0 degrees. The peak inrush current is reduced from more than 10 pu to approximately 3.3 pu. Since the inrush current is substantially reduced, the torque oscillations are almost eliminated. The absence of torque oscillations reduces mechanical stress in the drive train, increasing life span of the mechanical system and reducing

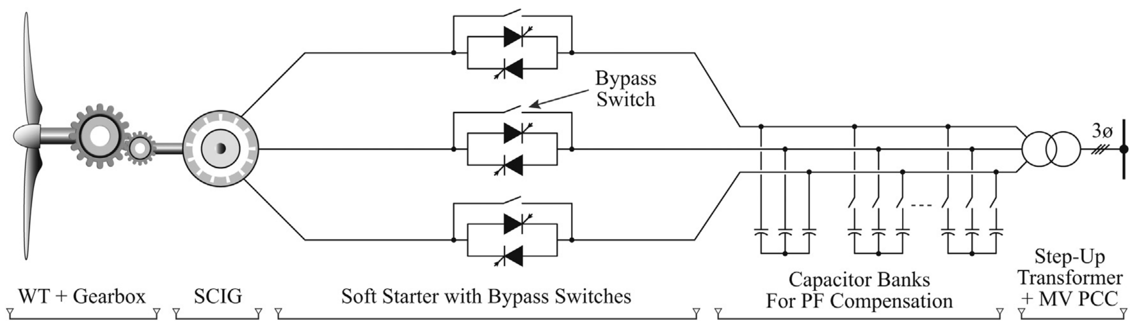


Fig. 1 Type 1 WECS with SCIG, soft starter, and reactive power compensator.

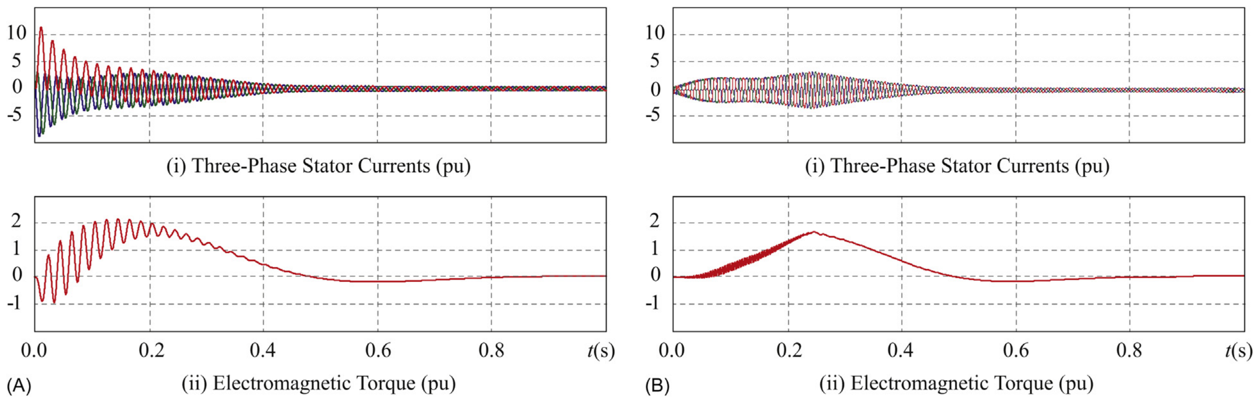


**Fig. 2** Dynamic response of Type 1 WECS: (A) without soft starter and (B) with soft starter.

maintenance needs. For both the cases, the sign of electromagnetic torque $T_e$ is positive due to motoring mode. When the SCIG reaches the synchronous speed, the $T_e$ becomes zero. When the grid-tie procedure is complete, the WT provides negative mechanical input torque to the SCIG by adjusting the pitch angle of blades. With this procedure, the SCIG operates in generating mode (super-synchronous mode) and produces active power output to the grid.

The thyristors are bypassed by a switch when the SCIG is tied to grid. The bypass procedure eliminates the power losses of thyristors. Therefore, it can be understood that the Type 1 WECS works without power converter after start-up procedure. The SCIG draws lagging (inductive) reactive power from the grid during the operation. Due to the absence of power converter, the reactive power output of SCIG cannot be regulated. Therefore, three-phase switched capacitor banks are employed to compensate the reactive power consumed by the SCIG. The switched capacitor banks can switch in and switch out of the system according to the active power extracted from wind. This arrangement leads to optimal reactive power (or power factor (PF)) compensation during varying wind speed condition (Wu et al., 2011).

Due to direct-grid connection of SCIG, the changes in wind speed cause grid frequency stabilization issues. On the other hand, grid faults cause severe stress on the gearbox and drive train of the WT. This configuration requires a sturdy mechanical design to absorb high mechanical stresses. The Type 1 WECS have been commercialized by many WT manufacturers such as *Bonus* (now *Siemens*), *Ecotècnia* (now *Alstom*), *Izar-Bonus*, *Made*, *NEG-Micon*, *Nordex*, *Nordtank*, *Repower*, *Vestas*, and *Zond* (now *Enron-GE*). The commercial Type 1 WTs in MW-range are *Vestas V82* (1.65 MW) and *Siemens SWT 2.3-101* (2.3 MW). The production of this configuration is obsolete in the present wind energy market; however, the previously installed WTs are still operational.

## Type 2 WECS

To increase the speed range of WTs and decrease stress on mechanical components, the wind energy industry developed semivariable-speed Type 2 WTs with WRIG during mid-1990s (Fig. 3). The system configuration is similar to a Type 1 WT in

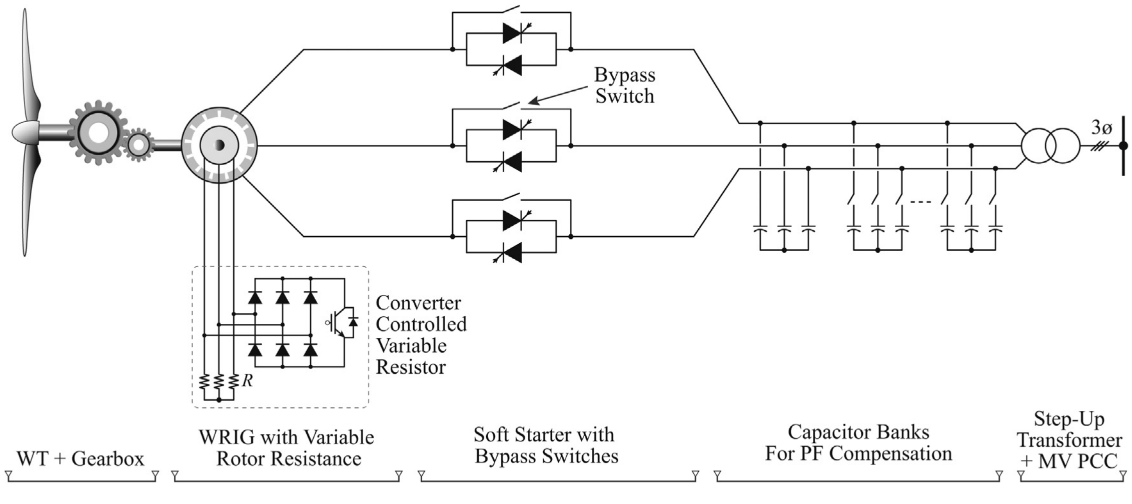


**Fig. 3** Type 2 WECS with WRIG, converter-controlled variable resistor, soft starter, and reactive power compensator.

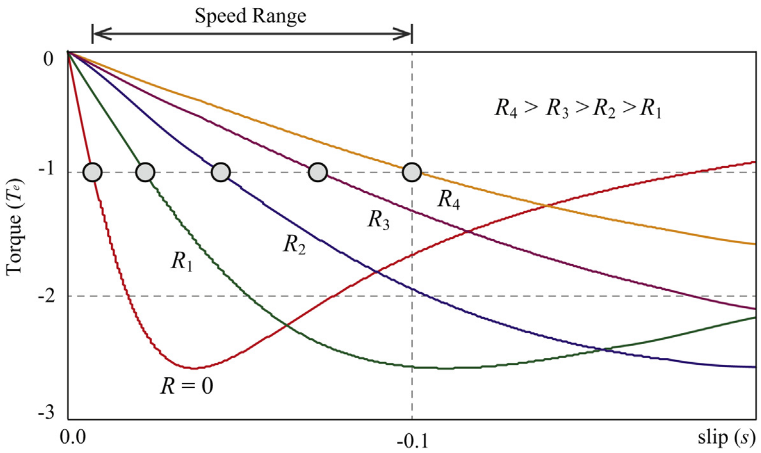


**Fig. 4** Torque–slip characteristics of WRIG with converter-controlled variable rotor resistance *R*.

Fig. 1 except that the SCIG is replaced by WRIG and rotor windings are connected to the converter-controlled variable resistor through slip rings and brushes. The power converter is realized by a three-phase diode-bridge rectifier and an insulated gate bipolar transistor (IGBT)-based chopper circuit. The Type 2 configuration is often called Optislip WT.

As shown in Fig. 4, the change in the rotor resistance (*R*) affects the torque/slip characteristic of the WRIG. The equivalent value of *R* seen by the rotor varies with the duty cycle of the chopper. With different values of *R*, the WRIG can operate at different operating points. As the rotor resistance is increased, the slip of WRIG increases; therefore, the speed of WRIG increases up to 10% above the synchronous speed. The power rating of converter is proportional to the speed range achieved. For example, a 1000 kW Type 2 WT needs a power converter of 100 kW capacity (10% of total power). It should be noted that the power converter assists in changing the rotor resistance and it does not process the generator output power. With higher speed range, the WT captures slightly higher power from the wind with reduced stress on mechanical components. The wear-and-tear of gearbox and bearings is reduced and life cycle is increased due to semivariable speed operation. The semivariable speed range also leads to less effect on grid frequency. However, the initial cost of Type 2 WECS is higher than Type 1 WECS due to power converter in rotor circuit. The losses in rotor resistance lead to less system efficiency. This configuration needs more frequent maintenance due to slip rings and brushes in WRIG. Some WT manufacturers mount rotor resistance circuit on the rotor shaft to decrease maintenance requirements for slip rings and brushes (Wu et al., 2011). However, the generator requires extra cooling to compensate the heat produced by resistor. The WRIG cannot perform smooth grid connection and consumes reactive power similar to the SCIG. Therefore, this configuration also requires soft starter and reactive power compensation similar to Type 1 WECS. The reliability of overall system decreases due to more number of components.

The WRIG with variable rotor resistance is also commercialized up to couple of MWs. A few examples of commercial solutions are *Vestas V66* (2.0 MW) and *Suzlon Energy S88* (2.1 MW). This configuration is also becoming obsolete because of its limited speed range and low energy conversion efficiency.

## Type 3 WECS

In a continued effort to increase operating speed range and eliminate unnecessary components like soft starter and reactive power compensator, the wind energy industry has developed Type 3 WECS during late 1990s. The configuration of Type 3 WECS with DFIG, partial power converter, and three winding transformer is shown in Fig. 5. The partial power converter replaces the converter-controlled variable resistor in Type 2 WECS. The DFIG stator winding terminals are directly connected to the utility grid through a step-up transformer. The rotor windings are connected to utility grid through brushes, slip rings, partial power converter, and step-up transformer. The power from DFIG is injected to utility grid through both stator and rotor windings. By alleviating all the drawbacks of Type 1 and 2 WECS, this configuration became very successful with about 50% market share up until 2014.

A back-to-back (BTB) connected two-level voltage source converter (2L-VSC) is used to process the rotor circuit power which is 30% of the generator rated power (Pena et al., 1996). For example, a 2.5 MW Type 3 WT requires a 0.75 MW power converter. For power ratings higher than 2.5 MW, more number of BTB 2L-VSCs are connected in parallel. The BTB 2L-VSC is realized two-level voltage source rectifier (2L-VSR), DC link, and two-level voltage source inverter (2L-VSI). Therefore, this power configuration is also referred to as two-stage (AC/DC + DC/AC) power converter. The BTB 2L-VSC is commonly used by many WT manufacturers. The 2L-VSR and 2L-VSI are connected to rotor and grid terminals, respectively; therefore, they are also referred to as rotor-side converter (RSC) and grid-side converter (GSC) for convenience. Harmonic filters are used on the output sides of RSC and GSC to attenuate switching harmonics. Due to 30% capacity, the single-stage (AC/AC) power converter, also referred to as matrix converter, can be employed. The matrix converters provide more silicon-based power conversion by eliminating DC link components (Empringham et al., 2013).

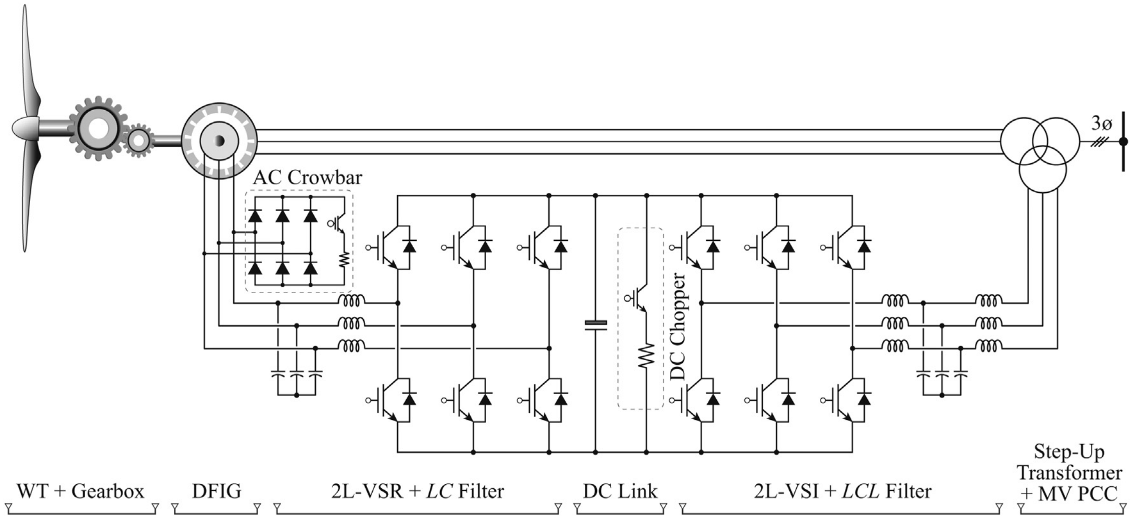


**Fig. 5** Configuration of Type 3 WECS with DFIG and BTB 2L-VSC.

The BTB 2L-VSC enables bidirectional power flow in the rotor circuit (power can flow from rotor to grid or vice versa) such that: (1) the variable-speed operation is extended to 30% above and below the synchronous speed, (2) the mechanical stress on the drive train during wind speed gusts is reduced, (3) the generator is smoothly connected to utility grid without employing a soft starter, (4) the PF at the point of common coupling (PCC) is adjusted without any external reactive power compensation, and (5) the generator exhibits robustness against power system disturbances compared with Type 1 and 2 WTs (Blaabjerg and Ma, 2013). At wind speeds exceeding the rated speed, the pitch mechanism changes the angle of rotor blades such that the output of wind generator is regulated to the rated value. The pitch control mechanism leads to optimum aerodynamic flow over blades and low overloading of blades. The DFIG is popularly used in modern wind energy industry because of its low converter cost, reduced power losses, and full controllability over active and reactive power. The initial cost and system complexity is high because of the power converter. The slip rings and brushes require regular maintenance. Another major drawback is the mandatory requirement of a gearbox, but the other advantages possessed by the Type 3 WTs make it a dominant technology in today's wind energy industry. In 2014, 7 out of the top 10 WT manufacturers used Type 3 technology. The commercial high-power Type 3 WTs are offered by *Senvion* (6.0 MW), *Bard* (5.0 MW), and *Acconica* (3.0 MW).

During grid faults, the WTs must provide full reactive power and zero active power to the grid. The active output power from DFIG cannot be made zero instantaneously. This condition leads to surplus energy. The AC crowbar and DC chopper are used to dissipate the surplus energy in rotor winding and DC link, respectively. During grid faults, the AC crowbar short circuits the rotor windings, making this configuration similar to Type 2 WECS. With this arrangement, the RSC is protected from rotor-side over voltages. The DC link-over voltages are mitigated by the DC chopper.

Given the success of Type 3 WECS, digital control techniques have been highly researched in the industry and academia. The decoupling between the RSC and GSC enables the use of two independent digital control systems. The RSC is popularly controlled by stator voltage or flux-oriented vector control techniques such as field-oriented control (FOC), direct torque control (DTC), and direct power control (DPC) (Cardenas et al., 2013). The GSC is controlled by grid voltage or flux-oriented vector control schemes such as voltage-oriented control (VOC) and DPC. In FOC of RSC, the maximum power point tracking (MPPT) operation and PCC PF are controlled through the regulation of $d$-axis and $q$-axis rotor currents, respectively. The reference stator reactive power can be set to zero for unity, positive for leading, and negative for the lagging PF of the PCC. The GSC reactive power reference is set to zero, thus indicating that GSC is not responsible for the overall WECS PF control. With VOC of GSC, the net DC link voltage control and zero grid reactive power are accomplished by controlling $d$-axis and $q$-axis grid currents, respectively.

The dynamic performance of a 3.0 MW, 690 V, 60 Hz Type 3 WECS during a transition from the subsynchronous mode to the super-synchronous mode is shown in Fig. 6. A ramp change in wind speed is applied to increase the rotor speed from 0.7 pu (subsynchronous mode) to 1.0 pu (super-synchronous mode). The measured rotor speed $\omega_m$ is maintained at its reference value $\omega_m$* by the digital controller for RSC. During subsynchronous mode, $i_{ar}$ leads $i_{br}$, and $i_{br}$ leads $i_{cr}$ because of the positive slip value. In super-synchronous mode, the phase relation becomes the reverse because of the negative slip. The output active power $Po$ follows the $\omega_m$ spectrum and the output reactive power $Qo$ is maintained zero to achieve unity PF at PCC. The $Qo$ magnitude can be controlled through the regulation of $q$-axis rotor current.

## Type 4 WECS

To extend the operating speed to full range and fetch maximum possible energy from wind, the Type 4 WECS have been introduced during late 1990s. The Type 3 WECS process slip power, whereas the Type 4 WECS process entire generator output power.

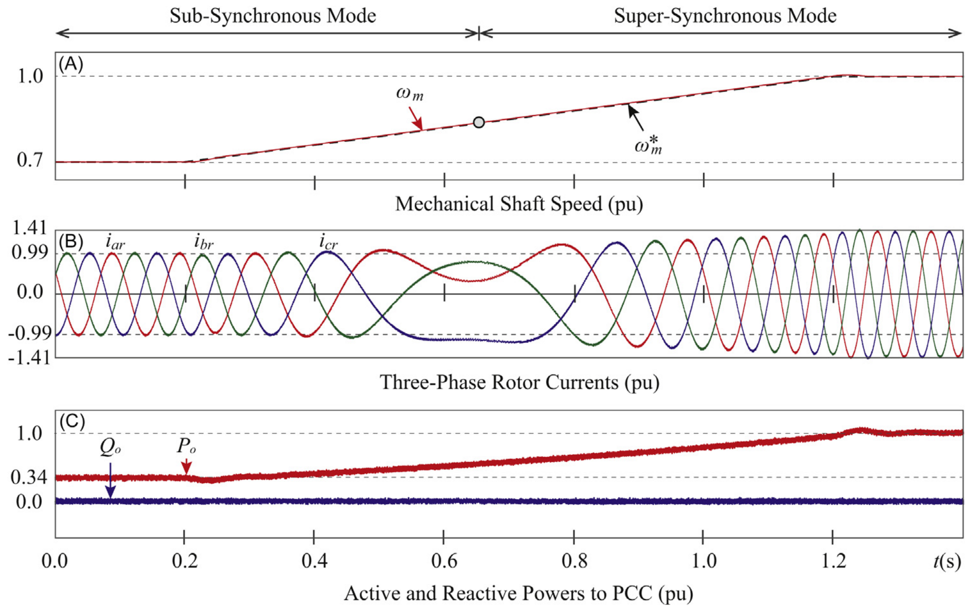


**Fig. 6** Dynamic response of Type 3 WECS during a transition from subsynchronous to super-synchronous mode.

To accomplish this operation, a power converter is employed between wind generator stator and grid. The power rating of converter increases to 100%; therefore, it is called full power converter. The Type 4 WECS have been commercialized for MW power level with SCIG, PMSG, WRSG, and HTS-SG. Among the classes of wind generators, PMSG is the most popular in Type 4 WECS due to high-power density and reliability, no need for excitation and gearbox, low rotor losses, and high efficiency. The power converters for Type 4 WECS are broadly classified as single-stage (AC/AC) converters, two-stage (AC/DC+DC/AC) converters, and three-stage (AC/DC+DC/DC+DC/AC) converters. The power converters further classified as LV converters for 500–1000 V operation and MV converters for 3000–4000 operation. The LV converters are employed with LV wind generators and MV converters are employed with MV wind generators. The full power converter performs smooth grid connection, reduces stress on drive train and gearbox, performs MPPT operation, and generates reactive power to meet grid codes. The full power converter increases the cost and power losses; however, the high-energy yield overshadows the aforementioned drawbacks. Among the top 10 WT manufacturers in 2015, 9 manufacturers have produced WTs based on Type 4 technology. The trend indicates that the wind energy market is shifting from Type 3 WECS to Type 4 WECS.

The configuration of Type 4 WECS with wind generator and full power converter is shown in Fig. 7. The full power converter is composed of machine (generator)-side converter (MSC), DC-link capacitor, and GSC. The converter configuration is similar to the partial power converter shown in Fig. 5. The MSC and GSC are realized by 2L-VSR and 2L-VSI. The switching devices are realized by LV-IGBTs arranged in the matrix form. A DC chopper is also used in DC link to dissipate the surplus energy during grid faults. The DC link provides decoupling between the generator and grid. Thus, the transients in the generator do not appear on the grid-side and vice versa.

The power rating of the BTB 2L-VSC is equal to the generator output power. For example, a 0.75 MW Type 4 WT requires a 0.75 MW power converter. To meet the recent grid codes such as reactive power generation (Tsili and Papathanassiou, 2009), the GSC is designed with higher MVA capacity than the MSC. An inductive–capacitive–inductive (LCL) harmonic filter is used on the grid side

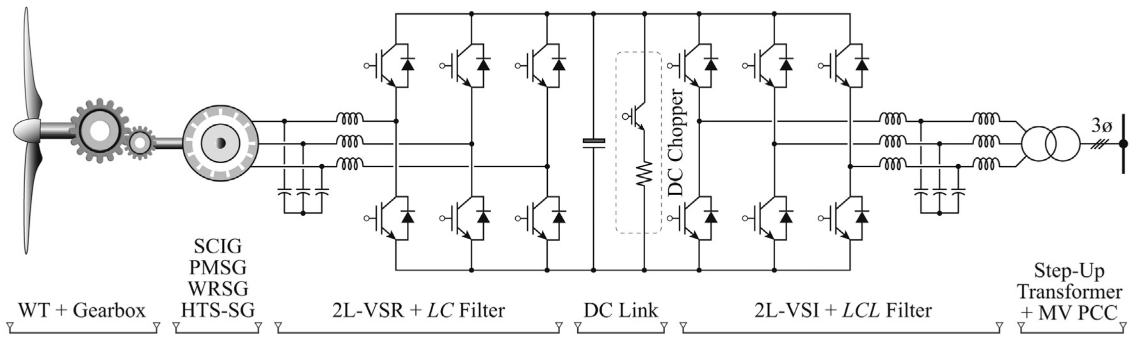


**Fig. 7** Type 4 WECS with wind generator (SCIG, PMSG, WRSG, or HTS-SG) and BTB 2L-VSC.

to reduce grid current total harmonic distortion. An inductive–capacitive (LC) harmonic filter is used on generator side to reduce harmonic distortion in the generator currents. The output of the grid-side *LCL* filter is connected through three-phase AC cables to the step-up transformer located at the bottom of the tower. The AC cables present significant cost and losses because they are rated for LV and high current operation. The cost of BTB 2L-VSCs is low because of the mass production. This configuration is mature in terms of technology status and market penetration and is used by about 90% of Type 4 WTs rated below 0.75 MW power level.

The digital control systems enable safe, reliable, and efficient operation of power converters to ensure maximum energy capture and compatibility to the grid integration requirements. The decoupling between the MSC and GSC enables the use of two independent digital control systems. To obtain high dynamic performance and decoupled torque and flux control, vector control strategies such as FOC and DTC are widely adopted for wind generators (Casadei et al., 2002). The FOC scheme for surface-mount PMSG is called zero *d*-axis current control. For interior PMSG, the FOC scheme is also referred to as maximum torque per ampere control. The GSC is controlled by VOC or DPC scheme similar to Type 3 WECS. The MPPT operation is achieved through the generator torque and speed control by MSC. The GSC controls the net DC link voltage and grid reactive power (Chinchilla et al., 2006).

The dynamic performance of Type 4 PMSG WECS during system start-up is shown in **Fig. 8**. From $t=0.2$–$1.2$ s, the wind speed is considered to increase from 3 m/s (0.25 pu) to 12 m/s (1.0 pu). The optimal tip-speed ratio MPPT algorithm produces the reference speed $\omega_m{}^*$ on the basis of the measured wind speed and rated WT parameters (Tan and Islam, 2004). Reference shaft speed $\omega_m{}^*$ increases linearly with respect to wind speed and reaches its rated value at $t=1.2$ s. The proportional–integral controller employed in the speed control loop regulates the PMSG speed at its reference value (**Fig. 8A**). The rated frequencies for PMSG and grid are 9.75 and 60 Hz, respectively. The magnitude and frequency of the PMSG stator currents increase with respect to the shaft speed $\omega_m$ (**Fig. 8B**). The grid current magnitude also increases proportionally to the PMSG active power output (**Fig. 8C**). The grid active power $P_o$ follows the $i_{ag}$ spectrum, and the grid reactive power $Q_o$ is maintained zero by the grid-side VOC scheme (**Fig. 8D**).

For power ratings greater than 0.75 MW in Type 4 WTs, the current carrying (power-handling) capability can be increased by connecting the BTB 2L-VSCs in parallel along with harmonic filters. **Fig. 9** shows Type 4 WECS with two parallel BTB 2L-VSCs and common DC link. In the *Enercon E-126* model, more than 10 full power converters are connected in parallel to reach a power rating of 7.5 MW. This configuration offers energy efficiency and redundancy. For example, one or more converters can be turned-off to achieve high system efficiency when the wind speed is low. When a converter fails, other converters can still deliver the power but with reduced capacity. Circulating currents exist in both the MSCs and GSCs because of mismatch in the converter and grid-side filter parameters. Harmonic filters are connected between each converter to reduce the circulating currents. The multiphase generator and open-winding transformer are alternative approach to increase the power-handling capacity while decreasing the circulating currents in both MSC and GSC. The *Gamesa G10x* 5.0 MW PMSG WT employs this concept with four sets of three-phase windings and four BTB 2L-VSC modules in parallel. The large number of LV converter modules in high-power WTs leads to higher cost, converter derating, and complex configuration and control.

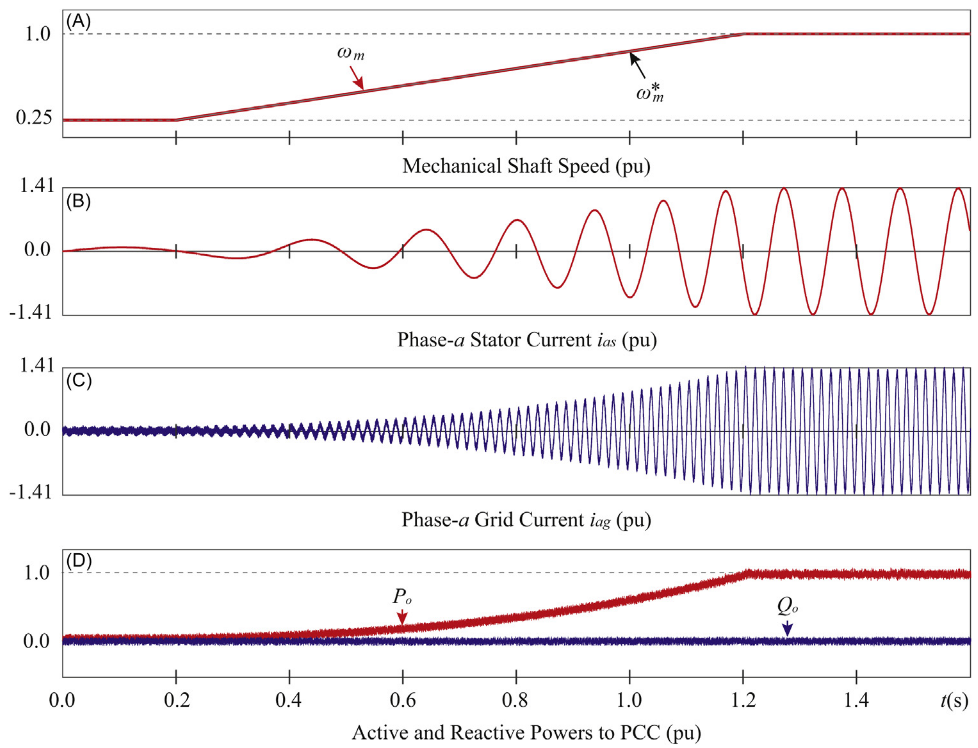


**Fig. 8** Dynamic response of Type 4 direct driven PMSG WECS during system start-up.

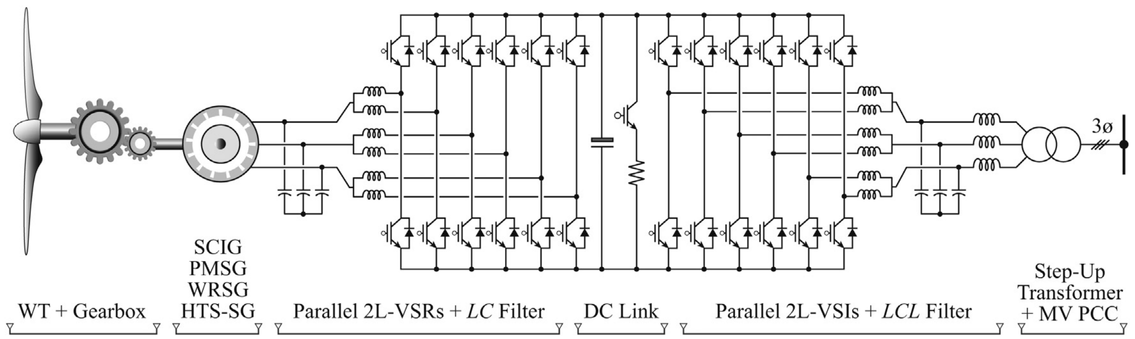


**Fig. 9** Type 4 WECS with wind generator (SCIG, PMSG, WRSG, or HTS-SG) and parallel BTB 2L-VSCs.

As the power rating of WT increases, the number of parallel LV converters increases. For power levels greater than 3.0 MW, the MV power converters are more efficient, cost effective, reliable, and economical (Yaramasu and Wu, 2014). The cost of energy is reduced by about 2%–4% with MV power converters in comparison with LV power converters. The configuration of Type 4 WECS with wind generator and BTB connected neutral-point clamped (NPC) converter is shown in **Fig. 10**. The switching devices and clamping diodes are rated for half the total DC-link voltage. The semiconductor devices are available in the current market for MV level and high current; therefore, it is not required to connect the semiconductor devices in series are parallel. The power converter manufacturers such as *ABB*, *Converteam*, and *Ingeteam* are offering NPC converters for wind power application. Though it is technically feasible to employ SCIG, PMSG, WRSG, or HTS-SG for MV operation, only PMSG is used in current MV WTs. The configuration in **Fig. 10** with PMSG is commercialized by WT manufacturers such as *Areva*, *Shandong*, *XEMC-Darwind*, and *Zephyros* for power levels up to 6.0 MW. The NPC converter offers many advantages in comparison with the 2L-VSC: higher output voltage levels, lower *dv*/*dt*, increased equivalent switching frequency, lower output current ripple, smaller harmonic filter size, and reduced electromagnetic interference (Rodriguez et al., 2010). The major challenges for NPC converter are neutral-point voltage control and thermal design to facilitate uneven switching losses.

To capture the advantages of MV operation for WTs, many MV power converters are proposed in the literature such as active NPC converter, current source converter, modular multilevel converter (MMC), and cascaded matrix converter. The active NPC converter employs MV-IGBT in place of clamping diode to solve the uneven switching losses issue of NPC converter. The current source converter provides reliable short-circuit protection in addition to simple topology, low switch count, and low switching *dv*/*dt*. The MMC employs modular connection of H-bridge converters leading to transformerless operation, and high efficiency and power density (Perez et al., 2015). The cascaded matrix converter also offers modular structure with sinusoidal input and output currents. The DC components are eliminated in cascaded matrix converter leading to compact size and high reliability.

The power flow in SG-based Type 4 WECS is unidirectional; therefore, passive diode-bridge rectifiers can be used for AC/DC conversion. The diode rectifiers are more reliable and economical than the VSR (Yaramasu and Wu, 2014). The configuration of Type 4 WECS with six-phase SG, six-phase diode rectifier, parallel boost converters, and parallel 2L-VSIs is shown in **Fig. 11**. This configuration is commercialized by *Vensys* and *GoldWind* for 1.5 MW power level. The capacitor in the first DC link filters the ripple in diode rectifier output. The boost converters perform MPPT and voltage step-up. Due to interleaving operation of boost converters and 2L-VSIs, the inductor and grid current ripple becomes lower. The 30-degree phase shift between the three-phase windings of SG helps to cancel the fifth and seventh harmonics in stator currents. This feature helps to lower the electromagnetic torque ripple caused by diode rectifier to acceptable level.

The MV operation for Type 4 WECS can also be realized with diode rectifier and boost converter. The SG WECS with a MV diode-bridge rectifier, a 3L boost converter, and an NPC inverter is shown in **Fig. 12**. The diodes are connected in series to withstand MV

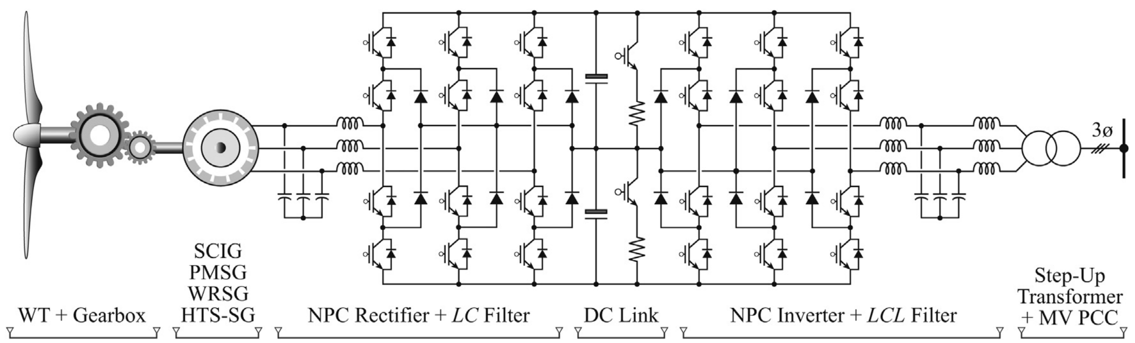


**Fig. 10** Type 4 WECS with wind generator (SCIG, PMSG, WRSG, or HTS-SG) and BTB NPC converter.

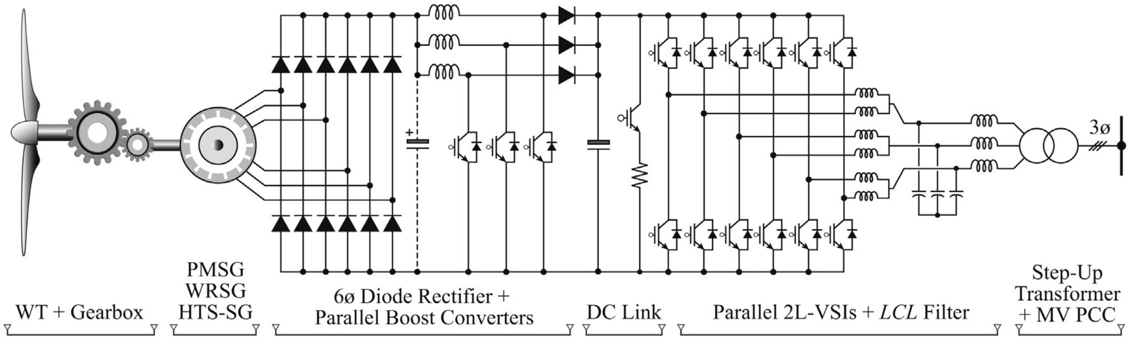


**Fig. 11** Type 4 WECS with SG, parallel boost converters, and parallel 2L-VSIs.

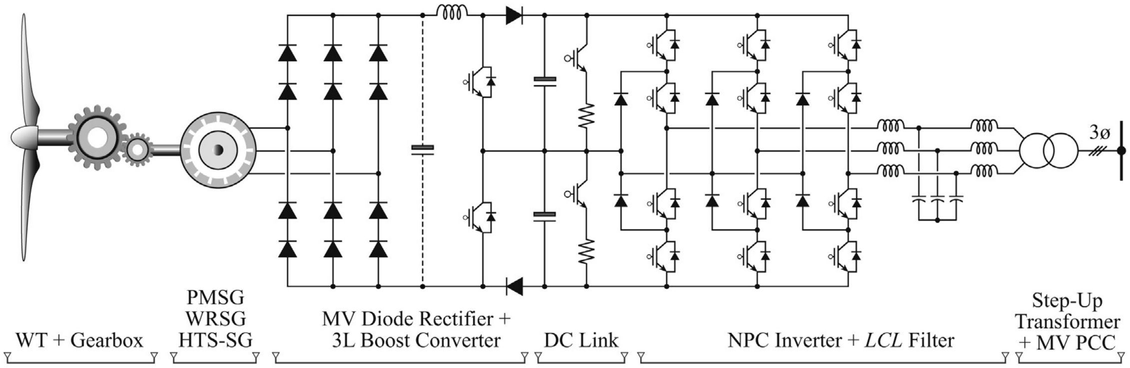


**Fig. 12** Type 4 WECS with SG, three-level boost converter, and NPC inverter.

output of SG. The three-level boost converter performs MPPT operation and control of neutral-point voltage. The switching losses and reverse recovery losses of three-level boost converter are lower than the two-level boost converter in Fig. 11. The NPC inverter controls the total DC-link voltage and grid reactive power. Similar to the NPC inverter, the semiconductor devices in three-level boost converter are rated for half the total DC-link voltage. The advantages of generator-side passive converters and grid-side multi-level converters are combined in this topology (Yaramasu and Wu, 2014). This configuration is promising for future developments.

## Type 5 WECS

The configuration of Type 5 WECS with a WRSG is shown in Fig. 13. This configuration with a gearbox and torque converter is widely used in electric drives industry since 1970s. The SGs are also popularly used in power generation industry and they have been tested over a period of decades. This technology is first introduced in 2006 by *Wikov–Orbital* through the 650 kW WT model.

The WT rotor is connected to generator through a two-stage planetary gearbox and torque converter. The torque converter is placed closed to the WRSG to reduce torsional vibrations and misalignment. The WT rotor speed is stepped-up by the gearbox. The *DeWind D9.2* WT model uses the 1:25 gear ratio, whereas the *Wikov–Orbital W2000SPG* WT model uses the 1:136 gear ratio. The torque converter also known as variable ratio transmission covers a wide speed range and provides fixed-speed input to the WRSG. The torque converter facilitates full-variable speed range (0%–100%); therefore, wind energy conversion efficiency is high similar to Type 4 WECS (Yaramasu et al., 2015). The absence of full-scale power converter leads to improved reliability and availability, and compact nacelle design than the Type 4 WECS. The WRSG can be designed with MV stator voltages for direct connection to PCC. This configuration is favorable for direct-grid connection of WTs to distribution lines. This configuration is proven as an alternative solution in comparison with the full or partial power converters based utility-class WTs.

The WRSG running at a fixed-speed is directly connected to the three-phase grid through a synchronizing circuit. The synchronization circuit with an embedded control unit facilitates the synchronization process. The WRSG output line–line voltages are in the range of 4.16–13.8 kV. The output of WRSG is connected through MV three-phase cables to the switchgear located at the bottom of tower.

The WRSG rotor carries a three-phase field winding to produce rotor flux. With the help of rotor field excitation, the WRSG can be smoothly connected to the grid. The frequency output of WRSG is regulated through a gearbox and a torque converter. The reactive output power of WRSG is adjusted by changing the excitation current for WRSG. The rotor field excitation circuit consists of an AC/DC

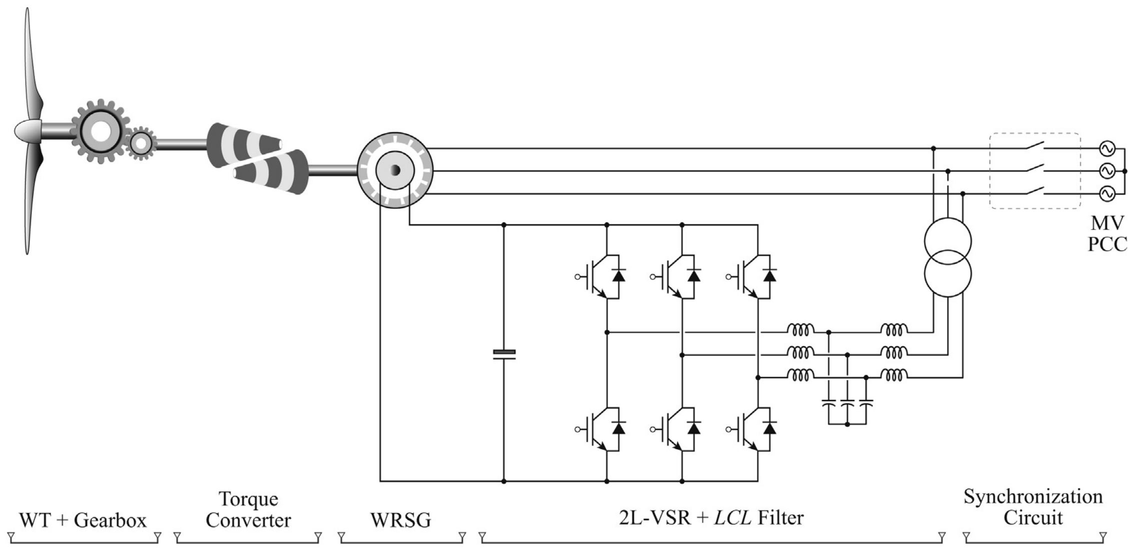


**Fig. 13** Type 5 WECS with WRSG, torque converter, and rotor field excitation.

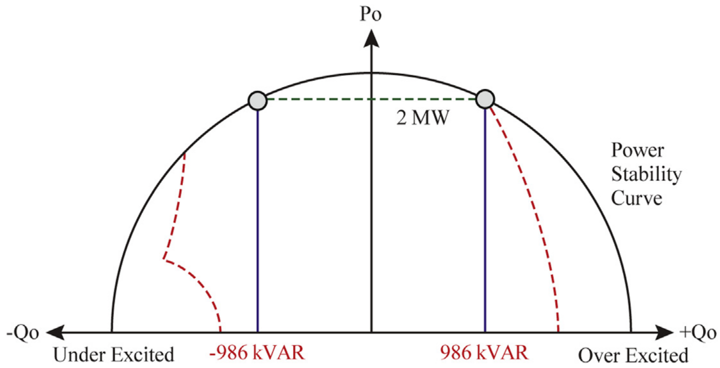


**Fig. 14** Active and reactive power generation capabilities of Type 5 WECS (*DeWind D9.2* data).

converter and step-down transformer that is connected to a three-phase grid. The DC excitation current is supplied to the rotor field winding through brushes and slip rings. The rotor field winding losses lead to lower generator efficiency in comparison with the PMSG where rotor flux is generated by permanent magnets. The brushes are also subjected to extensive wear and tear; therefore, regular maintenance is needed. To alleviate this issue, some WT manufacturers (e.g., *DeWind*) offer brushless excitation for WRSG. In brushless excitation, the rotor shaft driven PMSG along with a diode-bridge rectifier provides excitation current for the WRSG.

Unlike in Type 1 and 2 WECS, there is no need for reaction power compensation. The reactive power generation capability of WRSG is shown in Fig. 14 by considering for *DeWind D9.2* WT as an example. The WRSG is rated at 2.2 MVA to operate from 0.9 lead to 0.9 lag PF at peak output power. The higher WRSG capacity allows for excellent transient response during grid disturbances.

In electric drives industry, the mean time between failures for this technology is proven as more than 40 years. The same observations can be attributed to the utility-scale Type 5 WTs. Despite many advantages possessed by this configuration, only a few WT manufacturers are offering this technology due to complexity in the design of torque converter.

## Comparison of WECS Configurations

The main features of all five types of WECS configurations are summarized in Table 1 with respect to type of wind generator, number of stages in gearbox, aerodynamic power regulation method employed, operating speed range, MPPT operation, contribution of power electronics, converter capacity, requirement for soft starter, reactive power compensation approach, and market penetration. The Type 1 WECS uses SCIG, three-stage gearbox, soft starter for smooth grid connection, capacitor banks for reactive power compensation, and active stall or pitch control for aerodynamic power regulation. The power electronics is used to realize soft starter. The operating speed range is 1% above the synchronous speed. The Type 2 WECS employs WRIG, three-stage gearbox,

**Table 1** Summary of the five types of WECS configurations

| | *Fixed speed* | *Semivariable speed* | | *Full-variable speed* | |
|---|---|---|---|---|---|
| Type of WECS | Type 1 WECS | Type 2 WECS | Type 3 WECS | Type 4 WECS | Type 5 WECS |
| Wind generator | SCIG | WRIG | DFIG | SCIG, SG | WRSG |
| Gearbox | Three-stage | Three-stage | Three-stage | Multistage | Two-stage |
| Aerodynamic power control | Active stall or pitch | Active stall or pitch | Pitch | Pitch | Pitch |
| Speed range (%) | 1 | 10 | $\pm 30$ | 0–100 | 0–100 |
| MPPT operation | Nor feasible | Nor feasible | Feasible by RSC | Feasible by MSC | Unknown |
| Power electronics | Soft starter | Variable resistor | Partial converter | Full converter | Field exciter |
| Converter capacity | No converter for output power processing | 10% | 30% | 100% | No converter for output power processing |
| Soft starter | Required | Required | Not required | Not required | Not required |
| Reactive power compensation | By capacitors | By capacitors | By converter | By converter | By excitation |
| Market penetration | Outdated | Outdated | Second highest share | Highest share | Limited |

soft starter, capacitor banks, and active stall or pitch control similar to Type 1 WECS. The power electronics is used to realize variable resistor in rotor circuit. The operating speed range is 10% above the synchronous speed. Both Type 1 and 2 WECS are outdated in the present wind energy market.

The Type 3 WECS employs DFIG, three-stage gearbox, pitch control, and partial power converter. The smooth grid connection, grid reactive power compensation, and MPPT operation are achieved by controlling the power converters. The operating speed range in Type 3 WECS is 30% above and below the synchronous speed. The Type 3 WECS hold second highest share in the present wind energy market. The Type 4 WECS uses SCIG/PMSG/WRSG/HTS-SG, multistage gearbox, pitch control, and full power converter. The full power converter facilitates smooth grid connection, grid reactive power compensation, and MPPT operation. The operating speed range in Type 4 WECS is 0%–100%. The present wind energy market is dominated by Type 4 WT installations. The Type 5 WECS uses WRSG, two-stage gearbox, torque converter, pitch control, and rotor field exciter. The operating speed range in Type 5 WECS is 0%–100%.

## Grid Integration of Wind Farms

Traditionally, onshore WFs have been developed for the ease of construction, low initial and maintenance costs, improved proximity to transmission lines, and low-power transmission losses. Nowadays, offshore WFs are gaining more attention because power production can be increased and stabilized with the help of strong and steady winds. The WF performance, reliability, and efficiency greatly depend upon the optimal interconnection of WTs. The parallel connection WT output AC terminals is a commonly practiced technique in the present wind energy industry. The AC coupling enables use of all the five types of WECS depicted earlier because the WT step-up transformer is a common element to all these configurations. The choice between HVAC and HVDC for grid integration of WFs is decided according to the power to be delivered and distance of WF to the nearby utility grid.

The WF with parallel connection of WT output AC terminals and HVAC transmission is shown in Fig. 15. This configuration is used by the first-generation WFs (e.g., Horns Rev in Denmark with a capacity of 160 MW) which are located close to the utility grid. The offshore substation houses the PCC, switch gear, offshore transformer, etc. The WT power converter output voltages (690 V for LV and 3000 V for MV) are boosted to 33 or 34.5 kV by the WT step-up transformer. The PCC connects all WTs in a WF. To simplify the diagram, only one PCC is shown; however, in the practice more number of PCCs are used to increase the power-handling capacity and reliability. The PCC voltage is then stepped-up to HVAC in the range of 60–245 kV by the offshore transformer.

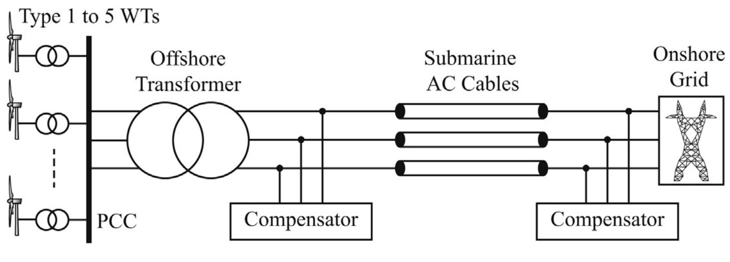


**Fig. 15** Grid integration of WF by HVAC transmission.

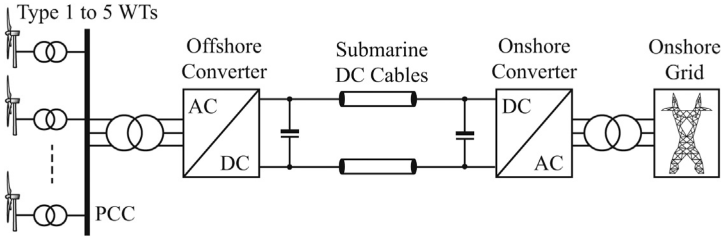


**Fig. 16** Grid integration of WF by HVDC transmission.

The WF is connected to the onshore utility grid through submarine AC cables. The reactive power compensators such as static compensator (STATCOM) or static VAr compensator are connected at both sides of AC cables to improve the transmission efficiency. The faults on the AC cables adversely affect the WF and vice versa (Blaabjerg and Ma, 2013).

Fig. 16 shows the grid integration of WFs by HVDC transmission. This configuration is commonly used by the high-power WFs located far away from the onshore grid. The offshore substation houses the offshore converter in addition to the PCC, switch gear, and offshore transformer. The HVAC output of offshore transformer is converted to DC by an AC/DC converter. The submarine DC cables interconnect the offshore substation with onshore grid via an onshore substation. The receiving-end onshore substation contains DC/AC converter and a step-down transformer. The huge initial and maintenance costs are the main drawbacks of HVDC transmission.

The earlier HVDC systems have been implemented with line-commutated converters along with reactive power compensators. In the present industry, VSC-based HVDC transmission systems are popularly used due to compact size, flexible layout of substation, independent control of active and reactive power, black-start capability, and fast dynamic response (Flourentzou et al., 2009). The traditional VSC–HVDC systems have been built using 2L-VSCs and NPC converters with hundreds of switching devices and clamping diodes in series to withstand the high DC voltage. These converters are derated due to the series connection of switching devices. The MMC has become an important milestone in VSC–HVDC systems. This converter features low size, modular structure, transformerless operation, enhanced reliability, less derating of semiconductor switches, fault-tolerant operation, near sinusoidal output waveforms, and high efficiency (Perez et al., 2015). The 2L half-bridge-based MMC submodule is commonly employed in the present industry. The MMC–VSC–HVDC systems are being offered by *Siemens* (HVDC Plus™), *ABB* (HVDC Light™), *Alstom* (HVDC MaxSine™), and *EPRI* (HVDC Flexible™) for the interconnection of offshore WFs.

## Future Trends in High-Power WECS

The present wind energy industry has witnessed development of 10 MW WT (*AMSC SeaTitan*). The global WT manufacturers have already released their future plans for 10–15 MW class WTs. At this high-power level, new technologies are anticipated for gearbox, wind generators, power converters, grid integration of WFs, and digital control. The new technologies help to achieve lower cost and weight, increase reliability and redundancy, enhance fault-tolerant operation and efficiency, and to comply with strict grid codes.

The Type 4 WTs with PMSG are expected to lead the wind energy market. The multiphase PMSGs are expected to become more successful in future WT projects as they offer effective fault-tolerant operation. It is anticipated that HTS-SGs will become popular for 10–15 MW class WTs (Snitchler et al., 2011). The direct-drive technology eliminates the maintenance requirements for gearbox in offshore WTs. However, the direct-drive WTs are heavier than the standard three-stage gearbox-based turbines. It is anticipated that the medium-speed PMSGs with single-stage gearbox will provide a best compromise between maintenance requirements and overall weight of turbines.

Due to limited space in nacelle, high-power density converters are need by the WT manufacturers. The MV power converters will be dominant for the next-generation multi-MW WTs as they offer cost effective and compact design. The new and hybrid power converters such as nested NPC converter, active NPC converter, MMC, and current source converter are promising candidates for the MV operation of Type 4 WTs. Apart from the power converters, the power semiconductor devices based on wide band-gap materials such as gallium nitride and silicon carbide offer substantial performance improvements over the silicon-based counterparts.

The future offshore WFs are expected in gigawatt range and in deep sea. The HVDC systems will become dominant in coming years as they are preferred for bulk power transfer over long distances. The MVDC grids have a bright future as they offer economical and technical benefits in comparison with the MVAC grids (Meyer et al., 2007). The DC/DC converters with galvanic isolation for MVDC grids are expected to go through intensive research. It is anticipated that the ride-through requirements continue to evolve and would have significant effect on the design and operation of modern high-power WTs.

The digital control of WT and WF power converters leads to higher energy conversion. The progress in power converter topologies, control requirements, and grid code requirements are placing a strong emphasis on digital control schemes for WT and WF power converters. With the evolution of digital control expertise, the realization of advanced and high-performance control algorithms is now possible. It is anticipated that research and development activities on advanced control schemes such as finite control-set model predictive control would become rigorous.

## Conclusion

In this article, a comprehensive analysis on state-of-the-art and emerging power electronics for high-power Type 1 to 5 WECS is presented. The main features, drawbacks, and commercial applications of each converter are discussed in detail. Grid integration issues for WFs are presented with respect to optimal interconnection of WTs, and HVAC and HVDC transmission systems. The future trends in high-power WECS are discussed. It is anticipated that Type 4 PMSGs will be dominantly used in the future wind energy industry to achieve technical and economic benefits.

## References

Blaabjerg, F., Ma, K., 2013. Future on power electronics for wind turbine systems. IEEE Journal of Emerging and Selected Topics in Power Electronics 1 (3), 139–152.
Cardenas, R., Pena, R., Alepuz, S., Asher, G., 2013. Overview of control systems for the operation of DFIGs in wind energy applications. IEEE Transactions on Industrial Electronics 60 (7), 2776–2798.
Casadei, D., Profumo, F., Serra, G., Tani, A., 2002. FOC and DTC: two viable schemes for induction motors torque control. IEEE Transactions on Power Electronics 17 (5), 779–787.
Chinchilla, M., Arnaltes, S., Burgos, J., 2006. Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid. IEEE Transactions on Energy Conversion 21 (1), 130–135.
Empringham, L., Kolar, J., Rodriguez, J., Wheeler, P., Clare, J., 2013. Technological issues and industrial application of matrix converters: a review. IEEE Transactions on Industrial Electronics 60 (10), 4260–4271.
Flourentzou, N., Agelidis, V., Demetriades, G., 2009. VSC-based HVDC power transmission systems: an overview. IEEE Transactions on Power Electronics 24 (3), 592–602.
Meyer, C., Hoing, M., Peterson, A., De Doncker, R., 2007. Control and design of DC grids for offshore wind farms. IEEE Transactions on Industry Applications 43 (6), 1475–1482.
Pena, R., Clare, J., Asher, G., 1996. Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation. IEE Proceedings of Electric Power Applications 143 (3), 231–241.
Perez, M., Bernet, S., Rodriguez, J., Kouro, S., Lizana, R., 2015. Circuit topologies, modeling, control schemes, and applications of modular multilevel converters. IEEE Transactions on Power Electronics 30 (1), 4–17.
Rodriguez, J., Bernet, S., Steimer, P., Lizama, I., 2010. A survey on neutral point-clamped inverters. IEEE Transactions on Industrial Electronics 57 (7), 2219–2230.
Snitchler, G., Gamble, B., King, C., Winn, P., 2011. 10 MW class superconductor wind turbine generators. IEEE Transactions on Applied Superconductivity 21 (3), 1089–1092.
Tan, K., Islam, S., 2004. Optimum control strategies in energy conversion of PMSG wind turbine system without mechanical sensors. IEEE Transactions on Energy Conversion 19 (2), 392–399.
Tsili, M., Papathanassiou, S., 2009. A review of grid code technical requirements for wind farms. IET Renewable Power Generation 3 (3), 308–332.
Wu, B., Lang, Y., Zargari, N., Kouro, S., 2011. Power conversion and control of wind energy systems. Wiley-IEEE Press, Hoboken, NJ.
Yaramasu, V., Wu, B., 2014. Predictive control of a three-level boost converter and an NPC inverter for high-power PMSG-based medium voltage wind energy conversion systems. IEEE Transactions on Power Electronics 29 (10), 5308–5322.
Yaramasu, V., Wu, B., Sen, P.C., Kouro, S., Narimani, M., 2015. High-power wind energy conversion systems: state-of-the-art and emerging technologies. Proceedings of the IEEE 103 (5), 740–788.