Chapter 1

Introduction

1.1 Motivations behind the work

Electrification of remote areas is one of the prime focuses of world organizations. It is essential owing to the unplanned development focusing only potential buyer and user of electricity . Excess use of electrical power in remote areas has shown marked improvement in the performance of education, health, irrigation, productivity, communication, and micro-enterprises [1]. International organizations in collaboration with the state government, are running an endless list of programs to ensure excess of quality electrical power to every human being possible without sacrificing our mother nature. However, still, more than one billion people living in 300 million homes around the world are unelectrified [2]. Out of those, 260 million homes are from rural areas and reside in remote areas where grid extension, if not impossible, is not economically viable. These communities are said to be "off-grid."

Renewable energy-based power plants such as solar, wind, bio, fuel cell are best suited for electrification of off-grid communities owing to its local availability, capability of stand-alone operation in the absence of grid, decreasing levelized cost of energy (LCOE) owing to technological innovations, and their environment-friendly nature. However, renewable energy sources (RES) are not reliable due to their intermittent nature and depend on the availability of the resources locally.

Hybridization of different RES, the use of energy storage devices, and output power conditioning are essential solutions offered to compensate the intermittency in RES [3–5]. However, all the solutions offered, incur higher costs owing to an increase in number of active components and complexity of the system.

This thesis attempts a possible solution to the RES-based remote area electrification problem. The first objective of the present thesis is to propose a suitable solution to the problem of establishing an off-grid RES-based power plant for remote area locations. The second objective of this thesis is to improve the power quality of the off-grid RES-based power plant . The final work came into shape as a solar-wind hybrid power plant installed at the roof-tops of residential/small-enterprises buildings in off-grid locations.

The proposed technique has been tested in the lab environment on a proof-of-concept experimental testbed. The results have shown the capability of the system to take into account input as well as output intermittency.

1.2 Scientific contributions of the work

Following are the scientific contributions of the work done in this thesis:

1. Development of a roof-top wind energy conversion system.
2. Reduction in the complexity of the system, making it cost-effective and incurring less maintenance.
3. Designing a roof-top energy conversion system to maintain output power quality under highly intermittent RES.

4. Hybridization of solar and wind energy in an off-grid roof-top energy conversion system.

1.3 Recent trends in off-grid/ distribution generation

RES-based off-grid power generation has shown massive potential in electrifying remote areas in environment-friendly ways and, thus, has seen manifold growth in the last decade. The effect of off-grid renewable-based-generation can be judged by the fact that since 2011 number of people served has increased by six folds to 133 million people in 2016 [6]. Fig. 1.1 shows the distribution of people served by different renewable energy sources from 2007 till 2016. Among the total population served, solar lighting serves 100 million, solar home systems serves 24 million, and remaining connected to mini-grids.

The vast expansion in off-grid service is due to the decreasing cost of solar panels and the financial models of supply chains such as pay-as-you-go and micro-finances. Fig. 1.2 shows the distribution of different energy sources by capacity from 2008 to 2017. Solar technologies such as solar lighting and solar home systems, installed as a stand-alone system, serve the majority of the population, though occupy only 4 percent of the total installed capacity. Moreover, the end-usage of the technology only can serve basic lighting need that is unreliable or chargeable and comes under Tier-0 or Tier-1 level of multi-tier framework [9]. The advantage of using such systems is its simple operation and coverage of larger unelectrified areas in lesser time.

Micro/mini/small-grid-connected renewables such as a higher capacity solar home system, bio-energy, and wind serve tier 1 and above level. The usage of electricity is primarily institutional dedicated to the development of education, micro-industries, health services, irrigation, and communication. As per Fig. 1.2 it is observed that still wind energy proportion by capacity in the off-grid system does not match that of the grid-connected system. In conventional grid-connected systems, wind is second in terms of total installed

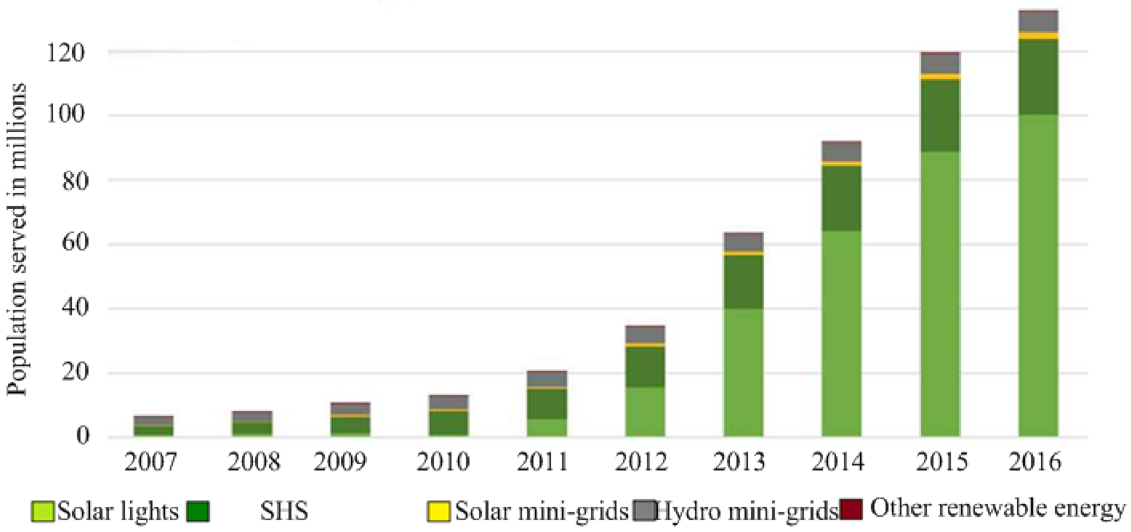


Fig. 1.1 Reach of renewable-based power from 2007 to 2016 [6].

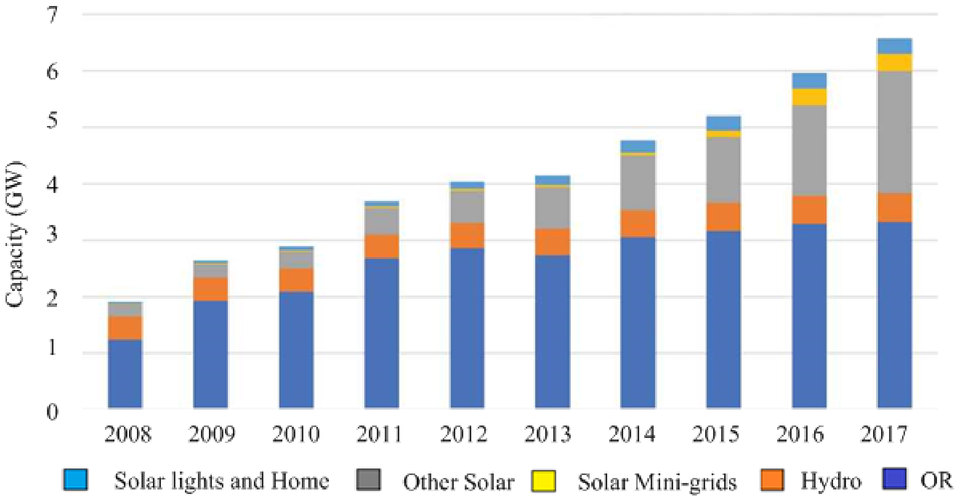


Fig. 1.2 Growth in the capacity of different renewable-based off-grid systems [6]

capacity. However, in the off-grid system, still, the market is dominated by SECS. Though, WECS has ample potential to play a more significant role in off-grid systems.

This thesis is an effort to maximize share of wind energy-based power generation in the total capacity of off-grid/micro-grid power generation by proposing simplified wind energy conversion system (WECS) that easily synchronizes to a micro-grid/grid and if needed could also be applied as a stand-alone generator in areas with decent wind throughout the year.

1.4 Recent trends in Wind Energy Conversion System (WECS)

Wind power industry has shown immense potential owing to decreasing per unit cost, strong commitment from established market such as North America, Europe, India, and China, opening of new market in Africa, Asia, and South America, sharp growth in offshore installations and lower financial cost due to increased reliability of running projects [10, 11]. In a recent study, wind power capacity on earth's surface estimates as to be 400 TW [12]. However, at the end of 2017, the total installed capacity of wind systems was 554 GW. The current total installed capacity of wind-based power generation is way behind its theoretical limit.

Wind industry installed a modest 52 GW in 2017, 55 GW in 2016, and 64 GW in 2015. Though annual added installation in terms of capacity has been continuously decreasing since 2015, still the overall annual growth is above 10 percent [13]. The reason behind decreasing annual installation is due to unstable government policies, strong competition from solar PV industry, and shift of focus from high wind to low-medium wind regions to avoid curtailment issues. Further, the new government policies of removing the subsidy from the wind power industry, lower Feed-in-Tariff (FiT), PPA-to-auction-based project allocations, ensuring customer satisfaction by introducing third-party certification have temporarily restricted wind energy growth, in the long run, would lead to stable wind energy market [10, 11, 14].

Among all the hurdles to the wind energy market, the curtailment issue is prominent. One of the many reasons of curtailment is the transmission congestion [15]. Transmission congestion refers to the inability of the grid to take power from a renewable energy-based power plant due to the lack of power transmission infrastructure. The major example is in china that has to shift focus from northwest to mid and southwest China (regions with low-medium wind speed), decreasing annual installation by 16 percent to 9.7 GW in 2017 [10].

Another method of resolving transmission congestion is by Distribution Generation (DG). China is the highest bidder for DG plants, with the USA and UK having good demand [17]. Also, there are some regions such as Europe, United Kingdom, USA, and India were transmission congestion is seasonal, and therefore, wind energy market growth is impressive, however, incoming future, these regions will saturate, and transmission congestion would become a huge problem [15]. Therefore, DG is going to be an essential tool for sustainable growth in the wind energy industry. It is expected that the wind industry would be back on track and increase its capacity at a faster rate upon the end of the current transition phase from PPA to auction-based project allotment post-2018 [13]. The forecast is that the wind power industry would occupy 20 percent of the total electricity generated by 2030 and 30 percent by 2050 [14]. With support from Wind Power and other renewable energy partners, including nuclear power, it is not optimistic to say that the electrical power industry in the coming future would be free from petroleum-based fossil fuel and coal.

1.4.1 WECS in off-grid

In the UK since 2012, the number of wind turbine installations per year is 60 % off-grid and 40 % on-grid [17]. The application of an off-grid generation is rural residential electrification and telecommunication stations. Although remote area electrification is driving factor for off-grid installations, lack of basic infrastructure and supply chains, high soft costs, which are non-hardware balance-of-system costs such as transportation, project insurance costs, and continuous decline in solar PV costs have kept the market from growing at a faster rate [17].

From the inception of wind turbines to 2012, the trend was to use SWT (100 KW or less) and MWT (100-1000 KW) in distribution generation, mostly to fetch tax credits and government incentives. However, after economic slowdown since 2012, state governments of big markets such as China, the UK, and the USA started desubsidizing the wind energy market, lowered feed-in-tariff, and capped incentives for the manufacturer, installer, and customer. Therefore, considerable downfall in SWT installations has followed.

However, given the advantage presented by DG, uncertain government policies did not have any effect on number of installation in remote area electrification using sub 1 KW wind turbines. In the UK from 2005 to 2014, out of 60797 SWT and MWT sold 97.10 percent were sub 20 KW range. In 2014, SWT generated 166.19 GWh of energy, saving 71,551 tonnes of CO2 emission into the environment. Out of the same 81.70 GWh was generated from under 20 KW range SWT. Among small wind turbines, the sub 20 KW capacity units were installed off-grid. This trend has continued all over the world [18].

1.4.2 Application and usage

Applications of wind turbine are private households, small businesses, agriculture, and institutional. SWT are used in all the applications. While, MWT are mainly used for agriculture and small businesses. On the other hand LWT are specifically used for institutional purposes [18]. Fig. 1.3 shows usages of wind turbines among different applications.

The distributed wind market expansions would have the best chances in agriculture, commercial, and industrial end-use customers in low-density urban centers (industrial areas), suburban and rural areas. In general, SWT and MWT are best suited for remote area electrification given its low installation and transportation cost, and on the other hand, LWT is more useful for institutional and industrial applications.

Overall, WECS in distribution generation seems premature and still searching for policy support from government and technology improvements to compete against fossil fuel-based electricity generation and PV based renewable energy. However, given the vast potential of clean and plenty of wind energy available on the globe, this thesis work

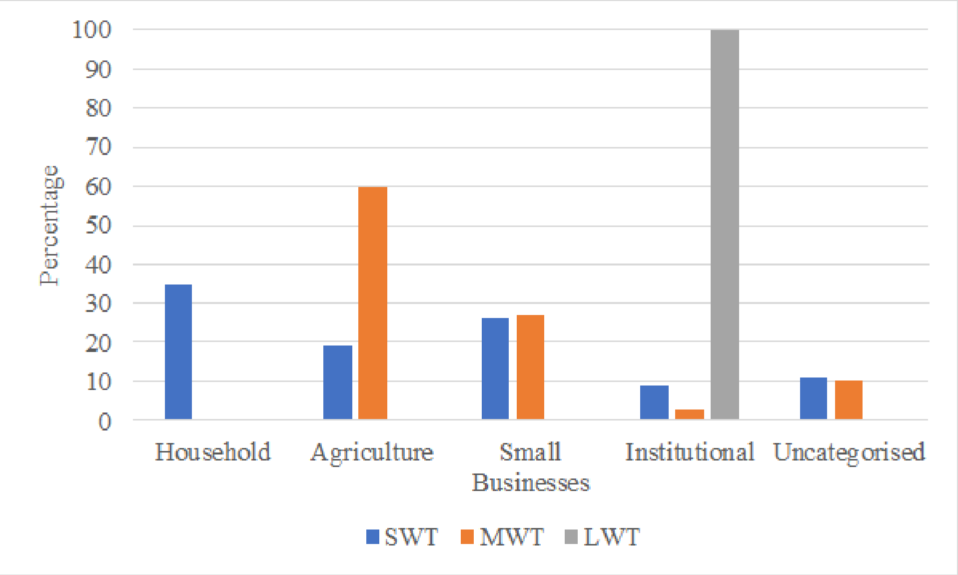


Fig. 1.3 Applications of different types of wind turbine.

proposes a dedicated off-grid rooftop wind energy conversion system for remote area electrification applications. The system compensates for the intermittent wind speed as well as the variable load. Further, the proposed system has been hybridized with a SECS to improve the performance of the system. In the next section, a rooftop wind energy conversion system has been designed by choosing each component of the system among the vast varieties of choices available.

1.5 Rooftop Wind Energy Conversion System (RWECS)

Rooftop Energy Conversion System (RECS) is a vital application in the field of energy generation for residential and small-scale industries. RECS is installed on the roof of residential/industrial buildings and, thus, use the area of the roof for capturing renewable energy. The immediate benefits are distributed energy generation, and reduced initial infrastructure requirements. One of the most popular technology in RECS is the Solar power system due to the ready availability of solar panels and its decreasing cost. One of the major challenges of the solar power system is its seasonal variation and requirement

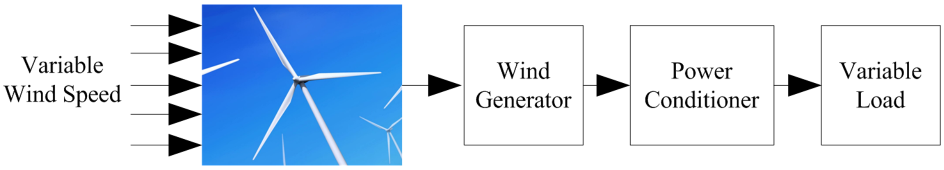


Fig. 1.4 Block diagram Representation of a rooftop wind energy conversion system.

of energy storage devices. The inclusion of energy storage devices increases their initial and maintenance costs [19]. Therefore, still, the rooftop solar power system is not suitable for the masses; thus, it needs the support of the government and the research fraternity for financial and technical support, respectively.

Hybridization of different RES is the most apparent solution offered by the research fraternity [5]. Among all the options available, hybridization of solar and wind energy sources is the best solution offered to generate maximum power from renewable energy owing to their complementary nature, while reducing the capacity of energy storage device needed [20]. However, the wind power system has not yet been standardized for RECS. The Rooftop Wind Energy Conversion System (RWECS) is still facing many challenges due to high intermittent and turbulent wind at rooftops. International Energy Association (IEA) prepared a dedicated team from around the world named Wind TASK 27 to provide guidelines in designing wind turbines for high turbulence wind conditions in rooftop applications [21].

WECS is an integration of a wind turbine, generator, and power conditioner to extract power from wind and convert into usable electrical power. The primary objective of the present work is to design a WECS under highly intermittent and turbulent wind conditions while reducing the complexity of the system. In this chapter, different technologies present in literature have been discussed, analyzed, and subsequently, suitable technology has been selected to build an RWECS. Block diagram representation of the proposed RWECS is provided in Fig. 1.4.

1.5.1 Choices of the Wind Turbine

Two types of wind turbines are available in the market, namely Horizontal-Axis Wind Turbine (HAWT) and Vertical-Axis Wind Turbine (VAWT). HAWT technology has dominated the market for the last 30 years occupying 74 % of turbine models available in the market. VAWT could occupy only 2-3 % market since its inception [16]. The advantages of HAWT are the provisions of blade pitch, yaw, furling, and stall control to limit wind power and protect the wind turbine at the time of gust of wind. However, in the rooftop energy generation application, the system power rating is low, and therefore the height of the turbine and radius of blades are not large. Blade pitch control has been used in high capacity turbines and, therefore, could be avoided in rooftop energy generation, simplifing the system and making it cost-effective.

Yaw control in HAWT is used to direct the axis of wind turbines in the direction of the wind at low wind speed and away from wind direction at high wind speed limiting the power extracted by a wind turbine at high wind conditions.

Similarly, furling control is used to move the axis of wind turbines away from wind direction at high wind speed. Furling control is introduced in a HAWT by designing the blade to furl automatically at high wind speed. On the other hand, Stall control is used to limit the rotor speed at high wind speed, decreasing wind turbine operating tip-speed-ratio and thus its power coefficient. Furling and stall control are introduced in a HAWT by specially designed blades. Stall control can be executed by designing blades using unique airfoils or limiting generator output power [22, 23]. However, the use of the new blade design increases the cost of the system. Apart from the high cost and complexity of the HAWT, another problem of the same in rooftop applications is its installation. In HAWT, both turbine and generator with power conditioning units are installed with the support of a tower. Therefore, the installation and maintenance cost of the system increases.

On the other hand, VAWT technology is a dedicated low capacity wind turbines for households, and small business applications, with 75 % of the model rated less than 5 KW and average capacity of the unit sold to be 1.6 KW [16]. VAWT could never prosper against HAWT owing to its low energy conversion efficiency, absence of power control at high wind speed, and high operating noise. Still, 18 % of the manufacturing company makes VAWT, and 6 % company makes both HAWT and VAWT. The prime advantage of VAWT is that the generator and power conditioner install at the ground. Therefore, the installation and maintenance cost of the system is low. The second advantage is that VAWT blades are positioned such that it works with wind from any direction. However, the power control mechanism, such as yaw and furling control needed at high wind speed, is not present in the system. Thus, the only mechanism to regulate power extracted from the wind turbine is soft-stall control [24–28].

The VAWT has big advantage of reduced weight and cost, though it operates at low tip-speed ratio and is not self-starting for the most efficient 2-blade Darrieus Rotor (DR) and its variant H-rotor that can capture wind power through aerodynamic drag and lift [29]. Self-starting nature in DR is attained by pitching the blade [30] or altering the design of blade airfoils [31]. Self-starting characteristic in DR can also be attained by increasing number of blades to 3 or 5, though it increases the size of rotor and thus, the inertia of the system [32].

In the proposed RWECS, VAWT has been chosen as a wind turbine, owing to the simplification brought in and its low installation and maintenance cost of the system. VAWT proves to be a good choice in the rooftop applications.

1.5.2 Choices of the Wind Generator

In WECS, there are two types of generators used: Induction generator and synchronous generator. At the starting, the market was overwhelmed by a Squirrel-cage Induction Generator (SCIG) owing to its off-the-shelf components. However, the market has now grown to include more complex configurations of wind generators. Most popular of them are Doubly-Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG). Also, some unique generator technologies may strongly influence future energy markets such as Superconducting Generator, Direct-drive Generator, Brushless DFIG, and transverse-flux generator. Choosing any topology among all for a dedicated application such as RWECS is a complex problem.

The choice of a generator topology for WECS is based upon its efficiency, cost, size, energy yield, availability of local manufacturers, and its LVRT capability. Though generator with higher efficiency and low cost is better for the system, but not decisive since the Levelized Cost of Energy (LCOE) generated could be low for a system with a little higher initial cost [33].

Similarly, the technique of power dispatch may be standalone, microgrid, or conventional grid is decided based on the type of application. Therefore, any technology is not a clear winner. However, the following are generator technologies for WECS that are popularly used.

Squirrel-cage induction generator (SCIG)

SCIG is the first induction generator that became popular because of its off-the-shelf components, robustness, and operation simplicity. However, its principle of operation enabled a constant speed operation. At wind speed higher than rated speed, stall control or blade pitch control limited the extracted wind power to rated value. At wind speed less than rated value, SCIG disconnects from the grid. Moreover, the system faced high mechanical transients due to the gust of wind. These mechanical transients deteriorate gearbox connected between the wind turbine and generator. SCIG directly connects to the grid as presented in Fig. 1.5 and, therefore, incurs high starting inrush current[34–36].

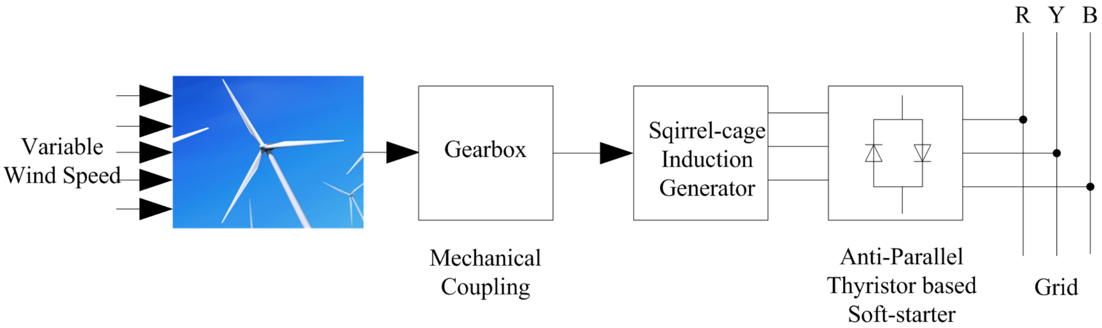


Fig. 1.5 Block diagram representation of squirrel cage induction generator connected to the grid through an anti-parallel thyristor-based soft-starter.

However, directly connecting to a grid made generator, running at a constant speed, vulnerable to grid disturbances and, therefore, unstable performance. Thus, SCIG based WECS faced transients from the input side as well as from the output side. However, in the late '90s, the system was popularly used for standalone applications, coupled with load shading, and with energy sources, those were more consistent such as micro-hydro [36, 37].

Moreover, some variants of SCIG could increase the rotor speed range of the generator; those are as follows.

Variable pole SCIG: This variant of SCIG consists of two stators with a different number of pole pairs that are used to control the speed of the generator. This provides the generator to work at two different speeds and thus extends its speed range [38].

Wounded rotor induction generator: This topology consists of winding on the rotor with the provision of slip-rings and brushes. In slip-rings and brushes, extra resistance could be added to the rotor circuit and, thus, varying the operating speed range of the generator. Fig. 1.6 presents a wound rotor induction generator. This technique dumps the excess wind power in the external resistance. Also, the presence of slip-rings and brushes increases the maintenance cost of the machine.

Self-excited induction generator: SEIG is very popular in the electrification of remote areas. SEIG has its reactive power feeder in the form of capacitors as shown in Fig. 1.7;

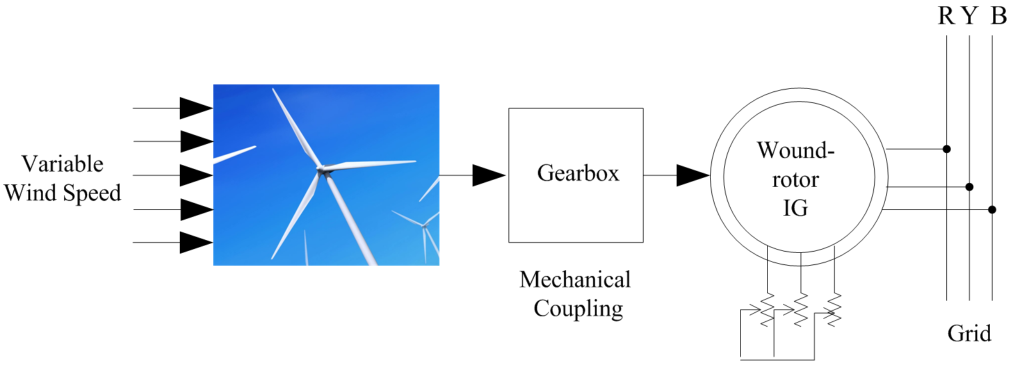


Fig. 1.6 Wound rotor induction generator with extra resistance in the rotor circuit to control the speed of the generator.

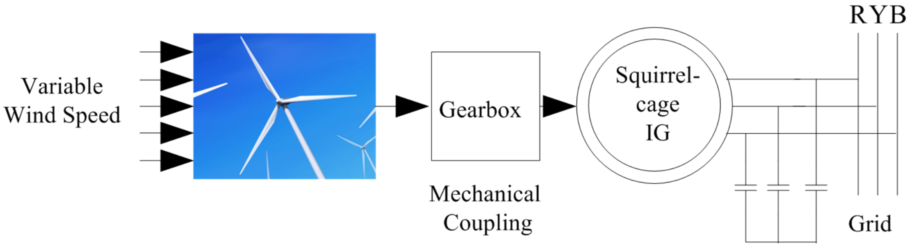


Fig. 1.7 Block diagram representation of a self-excited squirrel-cage induction generator.

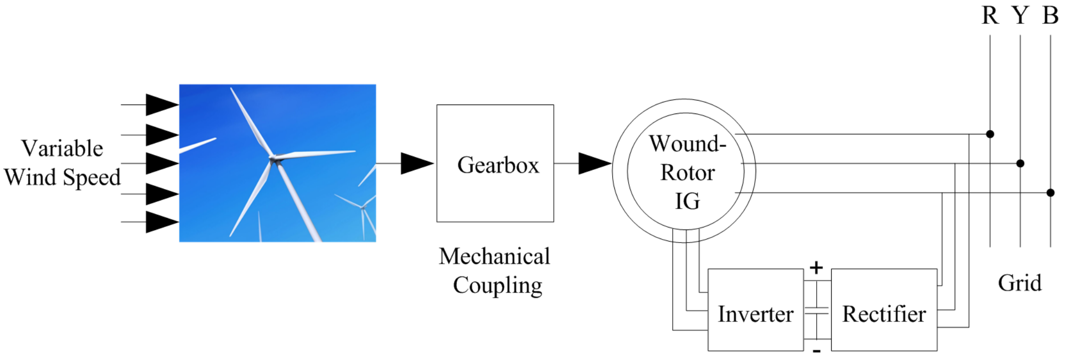


Fig. 1.8 Block diagram representation of a doubly-fed induction generator connected to the grid.

those could be varied in taps to operate at different rotor speeds [39]. However, adequate and popular, the need for external reactive power source remained a big problem for the system to be economically feasible.

Doubly-fed induction generator

One of the most popular wind generator technology that occupies more than 50 % of market share is DFIG. The prime advantage of DFIG is its wide operating rotor speed range from roughly 60 % to 110 % of rated speed. Injection of variable power into rotor winding through slip-ring and brushes achieves wide operating rotor speed range. Fig. 1.8 presents the block diagram representation of a DFIG connected to the grid.

The power injected into the rotor windings is controlled such that the generating frequency is constant though rotor speed varies as per input wind speed. The power to be injected into the rotor winding comes from the grid through a power converter. The power converter needed, are rated to one-third of the rating of the generator, thus, saving cost and increasing efficiency of the power converter and the overall system [40]. DFIG extends a wide speed range and cost-effective solution to the wind energy conversion system. However, its dominance is limited by its high maintenance cost owing to the presence of brushes and slip-ring in rotor winding and its inability to sustain grid disturbances. Though,

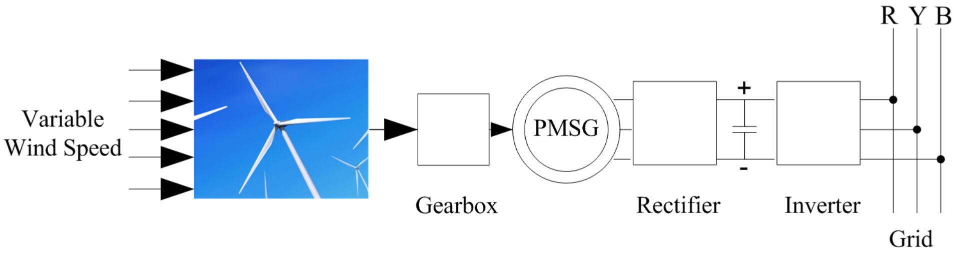


Fig. 1.9 Permanent magnet synchronous generator-based wind energy conversion system with gearboxes.

much research in DFIG on improving its capability of remaining connected to the grid in case of fault has led to its acceptance by major players in the wind energy market [41–44].

Permanent magnet synchronous generator (PMSG)

One of the biggest competitors of DFIG in the wind energy market is PMSG. The most important advantage of using PMSG is its decoupling with grid and, therefore, its good low-voltage-ride-through (LVRT) capability under grid-faults [36]. The generator interface through the power converter decouples the grid. However, full generated power needs to flow through the power converter and, thus, increases rating, cost, and losses of the power converter and the overall system. Also, PMSG suffers from an exorbitant and inconsistent cost of magnets used in the generator. With stable magnet cost PMSG would play a more significant role in the coming future. PMSG has got many variants; those are as follows.
Geared-drive PMSG: Wind turbine rotates with rotor speed around 15-30 RPM to limit noise and mechanical losses. Therefore, the wind turbine is mechanically coupled to a high-speed generator through multilevel gears. Fig. 1.9 shows block diagram representation of a PMSG based WECS using gearbox to increase the rotor speed of the generator.

Usually, a three-level gearbox is connected between the turbine and generator, achieving 6-10 times rotor speed amplification per stage. Geared drive with less number of gearbox stages run with medium speed and high torque capacity generators. High torque capacity generators have smaller gauge wire and therefore require larger slot areas in the stator that increase the overall size of the generator. Polinder et al. [33] shows that a

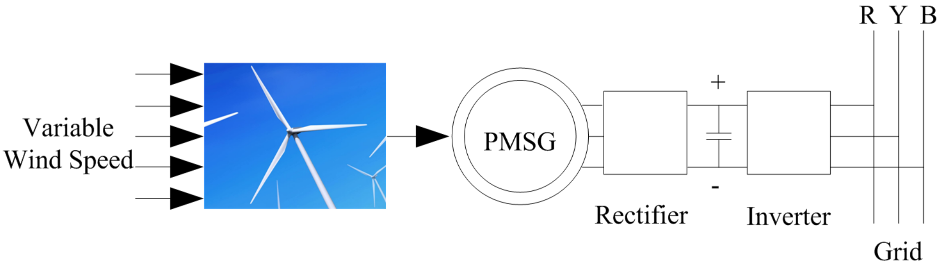


Fig. 1.10 Permanent magnet synchronous generator-based wind energy conversion system without gearboxes.

single-stage gearbox system combined with an increased size of generator achieves low Levelized cost of energy due to omission of extra levels from the gearbox.

Direct-drive PMSG: In direct-drive systems, gearboxes are entirely omitted and therefore save all the disadvantages of using a gearbox. Fig. 1.10 provides the block diagram representation of a direct-drive system. However, this system requires low speed and high torque capacity generators. High torque generators face challenges in terms of size and cost of a larger volume of magnet, copper, and laminations required by the generator. Research is ongoing on the topologies with high rated torque capability. The following are the topology with high rated torque capability generators.

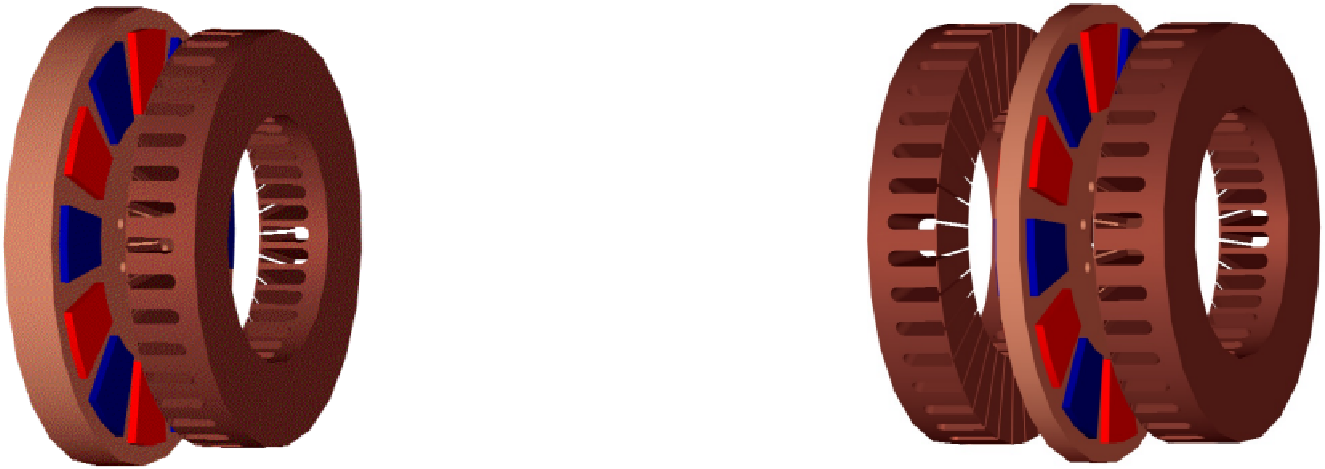
Transverse-flux Permanent Magnet Generators: Transverse-flux generators is a high torque machine [45]. However, its torque capacity could not increase beyond what is achievable in the radial-flux machine owing to larger air-gap in the machine. High flux-leakage and thus, low power factor of the topology is also one of the reasons that limited its growth [46].

Superconducting Generators: Research is ongoing in high torque capacity superconducting generator that uses superconductors for field winding and, therefore, could achieve high air-gap flux in the machine. However, the superconductivity is achievable only at very low temperatures and therefore needs special arrangements to do the same. Moreover, research is also ongoing on materials that can have superconductivity at room temperature. In the future, the superconducting generator would be used on a larger scale, given that materials are discovered that could achieve superconductivity at room temperature [47].

Axial-flux Permanent Magnet Generators (AFPM): Recently, AFPM has been one of the most researched options as a direct-drive generator owing to its compact geometry, high torque density, and modular nature. AFPM exhibits high efficiency and high magnet usability index and therefore requires a lesser volume of PM [45, 48]. Also, its construction permits proper ventilation and cooling of stator even at low rotor speed and, therefore, achieves high electric loading [49].

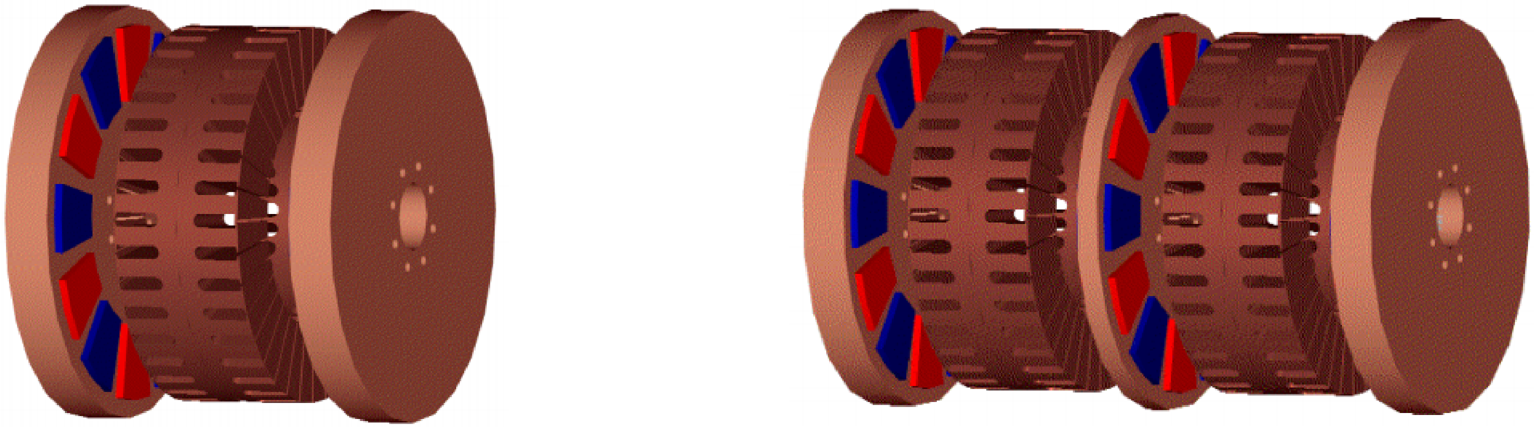
AFPM generators have the advantage of modular constructional feature and therefore, has seen many topological changes in recent literature. Fig. 1.11 (a)-1.11 (d) show four popular topologies, namely: Single-stator and single-rotor (SSSR), single-stator and dual-rotor (SSDR), Dual-stator and single-rotor (DSSR), and multi-stator and multi-rotor (MSMR) configuration of an AFPM generator. The SSSR topology has been rarely used since it exhibits high axial forces [50]. It is challenging to design a support system to hold stator and special bearings that bear the strong axial forces in the machine. Therefore, DSSR and SSDR are more popular than SSSR. In DSSR and SSDR, a magnetic symmetry is observed that cancels the high axial-forces in the machine. However, due to mechanical tolerance, there is bound to have a small dissymmetry in the topology, and therefore, a small unbalanced axial-force is unavoidable. On the other hand, MSMR is used in special applications that require multiple stator arrangement.

However, increasing number of stators beyond two increases the cost and constructional complexity of the machine. Another problem of using AFPM is the stator laminations. AFPM requires stator laminations with different radius. Generally, AFPM stators are manufactured by rolling lamination ribbon into a pancake shape arrangement.To create slots in the stator, the ribbon passes through a pre-programmed die that creates slots in the ribbon, which, upon rolling, set into radial slots. Slots are also created by using a laser cutting process. To reduce the manufacturing cost, slots on the stator are even made through the



(a) Single-stator and single-rotor topology of Axial-flux permanent magnet generator.

(b) Dual-stator and single-rotor topology of Axial-flux permanent magnet generator.



(c) Single-stator and Dual-rotor topology of Axial-flux permanent magnet generator.

(d) Multi-stator and Multi-rotor topology of Axial-flux permanent magnet generator.

Fig. 1.11 Axial-flux permanent magnet generator topologies [50].

milling process, though, increases the eddy current losses in the stator [51, 52]. Fig. 1.12 and Fig. 3.16 show a pancake-shaped stator of an AFPM. Here, the slots are created by drilling the stator core in the radial direction.

To solve the manufacturing difficulties of fabricating AFM stator, researchers have proposed to use yokeless and segmented armature. The individual segment of stators are made of high electrical resistance soft magnetic composite (SMC) [53]. Fig. 1.13 shows an AFPM with segmented stators assembled to form a full stator.

Researchers have even supported a coreless AFPM to get rid of axial forces between PM and stator core and to lower the cost of manufacturing stators. A direct-drive coreless AFPM is a cost-effective option for low-power WECS for remote area electrification applications [54].

Magnetic Geared-drive generator: Mechanical gearboxes increase the rotor speed of the generator and, thus, reduces the size and cost of the generator. However, mechanical gearbox inures higher maintenance, losses, noise, and decreased reliability. Recently magnetic gear has attracted researchers owing to its apparent advantages over mechanical gearbox. The magnetic gear shows similar torque transfer capability as of mechanical gears.

The easiest way of integrating magnetic gear and high-speed generator is to mechanically couple both devices. Researchers have also proposed a system in which mechanical gear and generator have been mechanically as well as magnetically integrated. In one of the work [55] as shown in Fig. 1.14, a high-speed rotor with permanent magnets interacts with stationary poles on the stator through the low-speed rotor with ferromagnetic poles. Through the process the torque is transferred from high-speed rotor to low-speed rotor.

The stator winding interacts with the high-speed rotor through ferromagnetic poles to generate the electromagnetic torque in the machine. The topology is useful and reduces the cogging torque in the machine. Other topologies have also tried integrating magnetic gear

Fig. 1.12 Stator laminations of an Axial-flux permanent magnet generator.

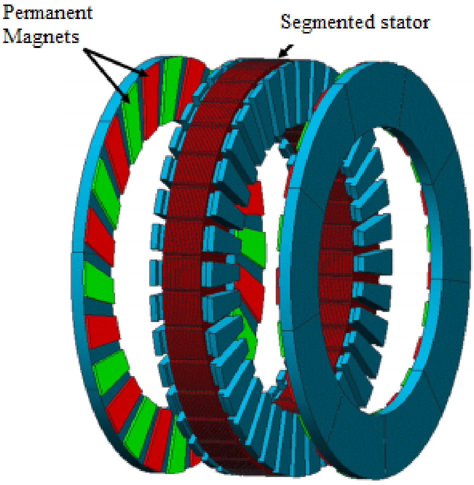


Fig. 1.13 Axial-flux permanent magnet generator with segmented stator [53].

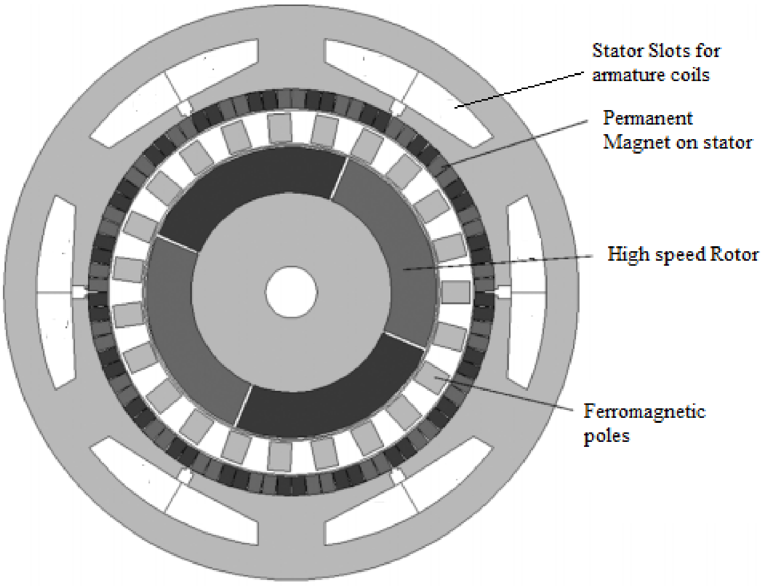


Fig. 1.14 Magnetic gear, as proposed by Atallah et al. [55].

with high-speed generator. Jian Et al. proposed a topology in which a coaxial magnetic gear circumscribes a high-speed generator [56]. The magnetic gear and generator shared their high-speed rotors. The topology is compared with a direct-drive generator and found to be more cost-effective in terms of material used. However, any magnetic gear topology uses high volume of magnets, and the cost of the machine depends upon the cost of the magnet and its supply.

Brushless Doubly-fed induction generator (BDFIG)

BDFIG is a variable-speed generator that incorporates the advantages of a DFIG and a brushless generator. A BDFIG consists of two different pole pair stator windings running a unique squirrel cage rotor. One of the stator windings namely ‘Power winding’ is connected to the grid and the other stator winding namely ‘Control winding’ is used to control rotor speed by controlling the amount of power fed electronically through power converters into the generator as done in conventional DFIG [57–60]. The generator shows terminal voltage control by controlling the flux through the control winding. However, the generator size increases due to the incorporation of both windings in the stator. Moreover, this generator is only useful in a grid-connected system owing to the necessity of external power to be fed into the generator to control its rotor speed.

Selection of generator topologies in RWECS

In a particular application, selecting the right electrical machine is a matter of prime concern for a system designer. For RWECS, the choice of generator among different topologies, as presented above, is a subtle task. A wind generator for RWECS should have characteristics of variable operating speed, high torque capability, low cost and maintenance, high efficiency, local availability, and excellent LVRT capability. Moreover, in proposed RWECS, a dedicated low power Vertical-Axis Wind Turbine has been selected. Therefore, a dedicated wind generator is needed, which is cost-effective and efficient at low power ratings.

There are two choices available from different generator topologies: Induction and Synchronous. Here, the synchronous generator has been selected over the induction generator owing to its wide operating speed range, stand-alone operation, and excellent LVRT capability. However, there are many topological variations available with the synchronous machines. Among all, axial-flux permanent magnet machines (AFPM) exhibit high torque to inertia ratio, high efficiency, high magnet usability index at power rating less than 50 KW [61]. Therefore, AF PM Synchronous Generators (AF PMSG) has been selected as a wind generator in the proposed application.

In proposed RWECS, the DSSR topology of AF PMSG (DSAF PMSG) has been chosen as wind generator owing to the presence of magnetic symmetry, maximum torque to inertia ratio, the ability of utilization of magnet most efficiently, minimum copper losses and minimum weight/size in comparison to other AF PMSG topologies [48]. Moreover, it has a minimum moment of inertia compared to others, which enables it to respond frequently to the varying wind speed in rooftop applications [48]. Further, an extra stator in the topology enhances the fault-tolerant capability of the system [50].

1.5.3 Choices of the Power Conditioning Unit

Wind energy at rooftops is one of the most intermittent renewable energy sources, and thus, power conditioning of the same is essential for its efficient usages. Power electronics do the work of power conditioning of electrical power in WECS. It controls the elemental parts of electrical power, i.e., voltage, current, and frequency. Voltage, current, and frequency control is essential before interconnecting WECS to conventional/off-grid. Power electronics have developed as per their application requirements.

Initially, at the time of the use of fixed speed induction generators in WECS, power electronics were used in the form of thyristor-based-soft-starter. Soft-starter use limits the charging current at the time of the interconnection of the generator to the grid. Subsequently, soft-starter is by-passed at steady-state condition. Therefore, power electronics requires to operate for a short time. However, with the development of variable-speed wind generators such as wound-rotor induction generator, power electronics converters require to operate in continuous mode. The use of power electronics is to control external rotor-resistance in the wound-rotor induction generator.

With further advancement of variable-speed wind generators such as DFIG, power electronics in the form of power converters are used to inject power from the grid to the rotor circuit of DFIG at variable frequency. This requires increased rating and continuous operation of power electronic switches. Moreover, the required power rating of the power converter in DFIG-based WECS is only rated to nearly one-third of the generator rating.

In recent times, with the advancement of PMSG, power converters are being used to decouple the grid from the generator. Therefore, power converters ratings have equaled the rating of generators. Consequently, the reliability of power electronics switches has raised questions. Therefore, modularity in power converter topologies are highly researched. Different topologies of power converters in the literature are as follows.

Unidirectional power converter

With the advent of PMSG in the wind market, power flow in the wind system has become unidirectional. Therefore, PMSG-based wind systems use unidirectional power converters. Unidirectional power converters such as diode rectifier use has reduced the total cost of the system and simplified the control circuitry of the converter. However, diode rectifier even multiphase comes with higher lower-order current harmonics in generator winding. Thus, torque pulsation increases the chances of shaft-resonance in the machine. Researchers have suggested many active and passive damping techniques, such as trap filter for minimizing lower-order harmonics [62]. Moreover, the problem amplifies as the power rating of the system increases.

For maximum power point (MPP) operation, throughout the wind speed variation range, it is needed to operate a wind turbine at critical tip-speed to wind-speed ratio. There are many MPPT techniques present in different publications [63, 64]. MPPT techniques require generator current control, and thus, a DC/DC chopper in conjunction with the diode rectifier is used at the generator end. The DC/DC chopper regulates the power flow from wind generator to grid. It is inferred that any MPPT control technique needs a DC/DC chopper in conjunction with a unidirectional power converter. However, some stand-alone/weak-grid systems in place of using any MPPT technique follow the principle of the generation-load balance technique [65]. Such systems do not need a DC/DC chopper and, thus, reduce overall cost and simplification of the system. However, the wind turbine operates at a non-optimal operating point.

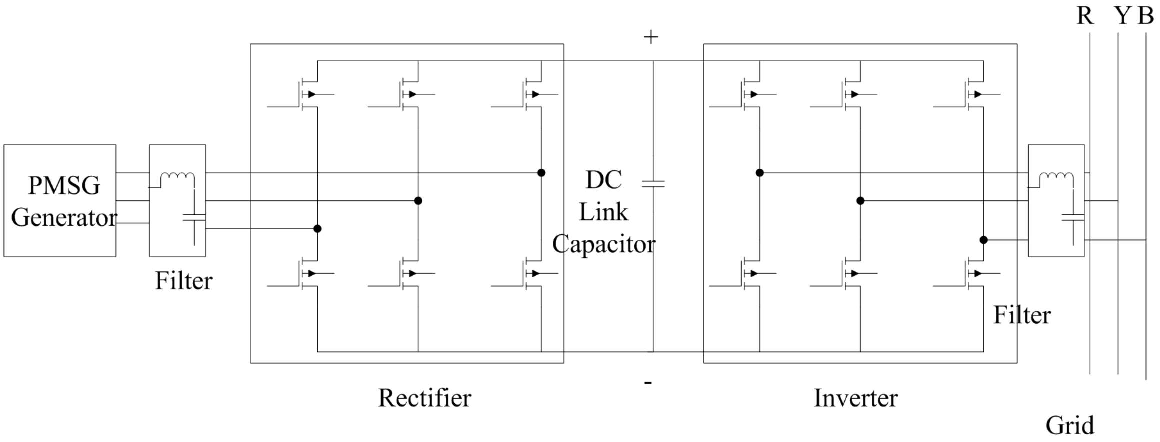


Fig. 1.15 Permanent magnet synchronous generator integrated to Grid through a two-level back-to-back power converter.

Conventional two-level back-to-back H-bridge power converter (2L BTB HB)

2L BTB HB power converter is a well-established technology in the field of AC-AC power conversion.This basic configuration includes a generator-side power converter (AC to DC power conversion), a grid-side power converter (DC to AC power conversion), and a DC-Link capacitor (AC filter) integrating both converters as shown in Fig. 1.15. The advantages of a two-level power converter are lesser no. of components and simple structure. Moreover, the performance of the converter has been found reliable and well documented [66]. However, the simplicity of the system and, therefore, the reliability loses as the power and voltage rating of the system increases. The two-level power converter suffers from an increase in dv/dt stresses on cable and motor load/transformers. Moreover, switching losses also increase as per the increase in power and voltage rating of the system. Further, lower-order harmonic content in the output is higher in magnitude in comparison to other power converter, as described in the next section. Two-level power converters categorize among two types based on the modulation index, namely linear modulation region and overmodulation region.

Linear modulation region: Modulation index, m_a, is defined as the ratio of peak value of the control voltage to the peak value of the triangular signal (kept constant). In the linear modulation region, m_a is less than 1. In this region, variation in m_a regulates the output voltage. The systems whose DC-link voltage is dynamic and changes with other parameters of the system use this technique. One example is maximum power point tracking in the wind energy conversion system [63, 64].

Non-linear modulation region: In this technique, the ma is greater than 1. It is similar to the square-wave switching scheme. Here, the output voltage is uncontrollable. The systems with regulated DC-link voltage use this technique. One example of the technique is in systems operating on the principle of the generation-load balance technique [65]. The advantage of the system is its simplicity and low switching frequency leading to low switching losses. However, the frequency spectrum contains more harmonics, and therefore use of this technique is limited to low-voltage low-power applications.

Multilevel power converter

2L BTB HB power converters are suitable for low-voltage and low-power applications, as inferred in the previous section. The performance of the same deteriorates as the voltage and power rating of the system increases. Extra switches are connected in parallel or/and series to improve the performance of the converter with the same rating switches, which increases the voltage/current rating of the converter. Consequently, the advantage of using the converter, i.e., its simplicity and reliability, is sacrificed, and with it, its attractiveness also fades. Therefore, researchers have proposed a power converter with an increased voltage level. An extra level of voltage in the output voltage profile reduces the dv/dt stress on the system components such as cable and transformer/motor load, and improving output voltage harmonic spectrum [68, 69]. The following are some of the multilevel techniques prevalent in the wind energy market.

Three-level neutral-point diode clamped (NPC) back-to-back power converter: This configuration uses two extra switches per leg, as given in Fig. 1.16. The voltage handling

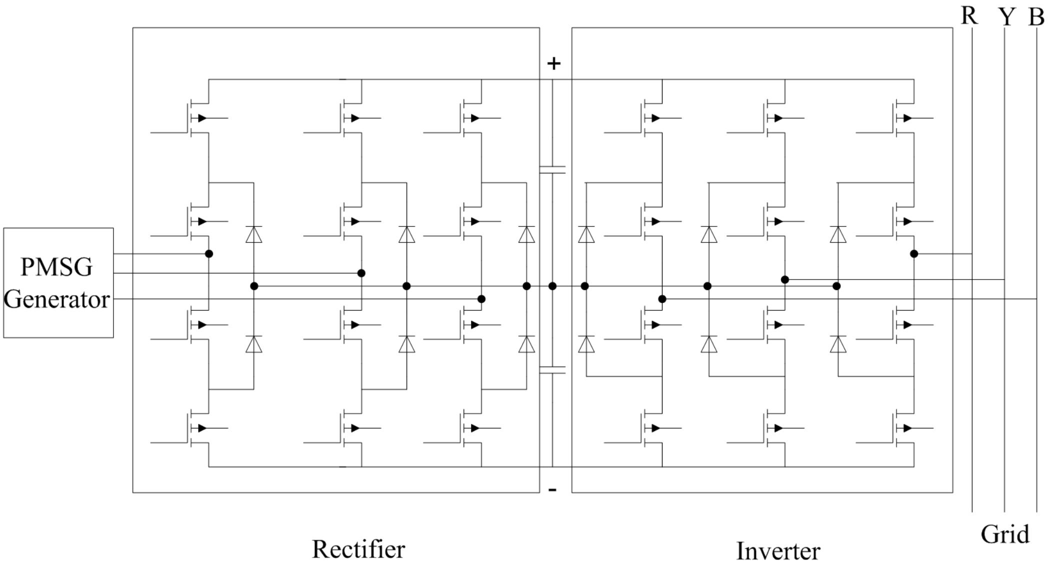


Fig. 1.16 Three-level neutral-point diode clamped (NPC) back-to-back power converter.

capacity of the converter is double in comparison to the 2L HB converter. Therefore, the industry widely uses this converter. However, in this configuration, two capacitors are used at the DC-bus bar, and voltage at the common node connecting two capacitor fluctuates, which is a significant drawback in the configuration. Moreover, losses in inner switches and outer switches are different, and therefore, the converter is not used to its full capacity [68, 70, 71]. Active research is going on in this configuration to find a solution to the above problems.

Three-level H-bridge (HB) back-to-back power converter: In this configuration back to back H-bridge converters are used for all three phases isolated with each other, as presented in Fig. 1.17.

The performance of the converter is similar to that of NPC configuration. It is to be noted that, each phase carries the same no. of switches as used in NPC but eliminates the unequal distribution of losses among switches. Moreover, there is no splitting of DC-bus, and therefore, no voltage fluctuation is present in the same [70, 72, 73]. Also, an open winding transformer/generator improves the fault sustainability capacity of the system and simplifies maintenance. However, isolation of each phase requires an open wounded

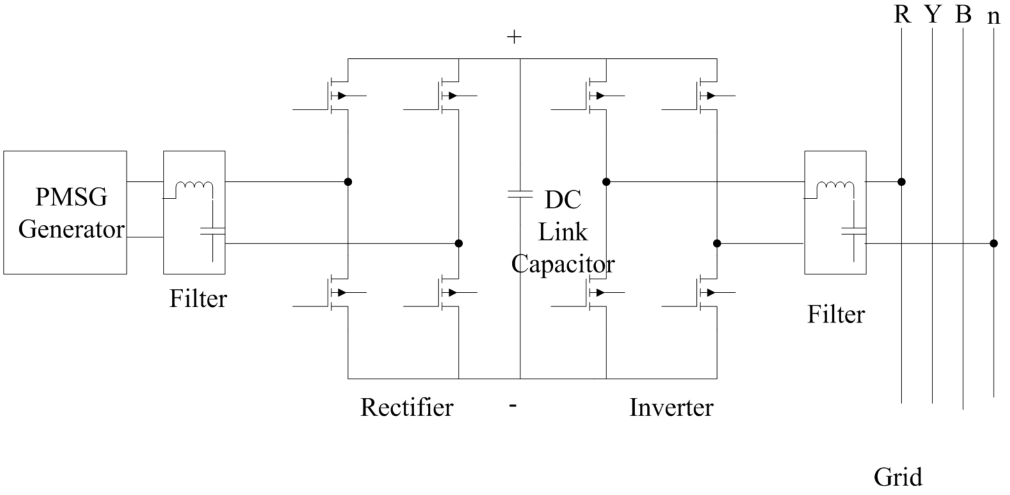


Fig. 1.17 Single-phase equivalent circuit diagram of three-level H-bridge (HB) back-to-back power converter.

transformer/generator and extra length of the cable for connection. This factor increases the cost and weight of the system. Moreover, in HB configuration, zero sequence current is present in the system that increases losses in the generator/transformer and reduces the current capacity of the system [74].

Five-level H-bridge back-to-back power converter: This configuration is an extension to 3L HB configuration. Each leg of the configuration connects in NPC configuration as given in Fig. 1.18.

In the configuration, the advantage and disadvantages of NPC configuration carry-forwards to this configuration with an added advantage of extra levels in output voltage. The advantage of increasing voltage level reduces dv/dt stress on the system components [69, 75]. However, the configuration consists of two capacitors at DC bus, and thus, voltage balancing across two capacitors is an issue. Moreover, it also needs an open winding transformer/generator, increasing the cost of the system. Further, the zero-sequence current is also present in the system, as seen in the HB configuration.

Three-level NPC for generator side and Five-level HB at grid side: This configuration is used to include the advantages and remove disadvantage as far as possible from 3L NPC

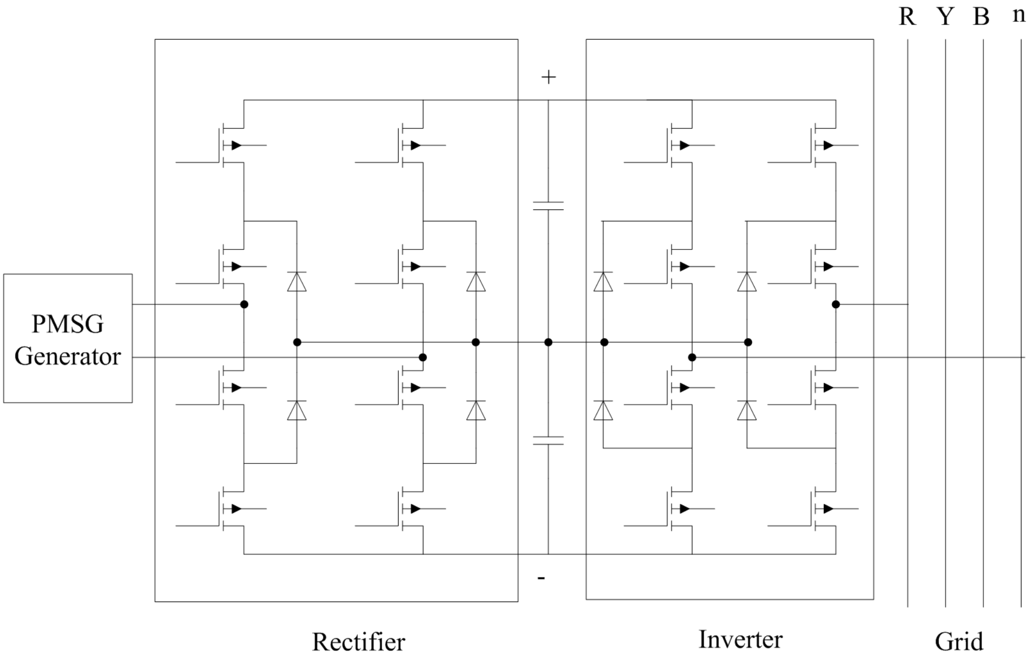


Fig. 1.18 Single-phase equivalent circuit diagram of Five-level H-bridge back-to-back power converter.

and 5L HB configurations. This configuration follows the fact that grid integration rules are stricter in comparison to generators [76]. Therefore, 5L open winding configuration is used at the grid-side, and 3L NPC configuration is used at the generator-side. It uses a standard generator and an open winding transformer. Therefore, cable length and zero sequence current are saved at the generator end, and harmonics and dv/dt stresses are avoided at grid-end [74].

Multiple cell power converter

Another configuration which is popular in industries is by cascading multiple module/cell of 2L BTB HB power converters in series or parallel as given in Fig. 1.19.

One major drawback of the configuration is the need of a DC-link capacitor with every 2L BTB HB converter module/cell. This configuration requires a complex multiphase transformer with increased weight and volume [69, 77]. The system has been improved by the European UNIFLEX-PM Project [78] by isolating DC-DC converter through a medium

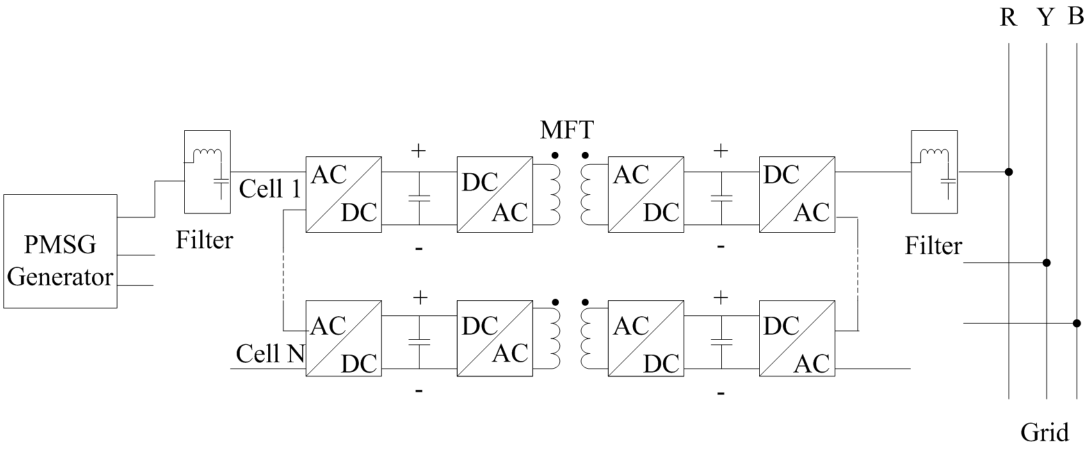


Fig. 1.19 Two-level back-to-back H-bridge multicell converter connected in parallel and series.

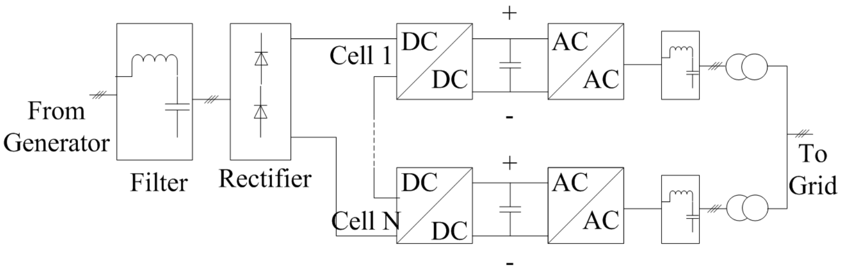


Fig. 1.20 Two-level back-to-back H-bridge multicell converter connected in series at generator end and parallel at grid end.

frequency transformer. The advantages of the changes introduced are the reduced size of the transformer, high-quality voltage output, and filterless configuration.

Another configuration uses a medium-voltage DC (MVDC) link interface at the generator-end. Conventional 2 L converters are series cascaded to MVDC and parallel cascaded at the grid end, as presented in Fig. 1.20.

The advantage of such configurations is the use of low-level converters [79]. Also, there are some configuration that cascades multiple cells of the power converter in parallel at generator-end as well as grid-end [80, 81].

In [82], a multi-winding generator is used to build a transformerless wind energy system. Here, each winding of the generator connects to the AC-AC converter; those are series cascaded at the grid-end as presented in Fig. 1.21. This configuration is also

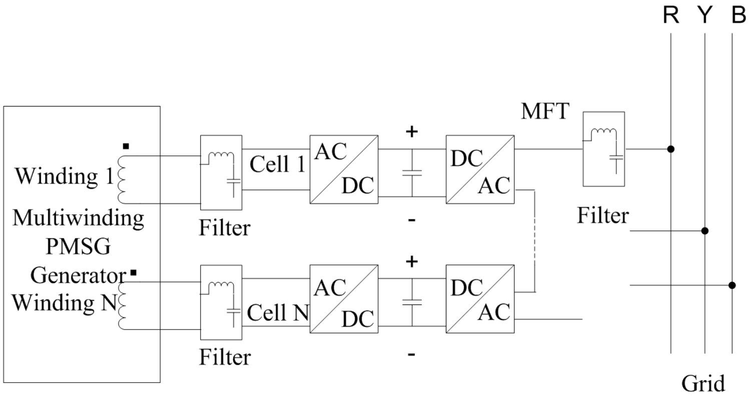


Fig. 1.21 A transformer less topology using two-level back-to-back H-bridge converter and multi-winding generator topology with open windings.

referred to as magnetic parallel configuration. Similarly, multi-winding transformers are used to build a magnetic parallel configuration at grid-end, and matrix converters are series cascaded at the generator-end [83].

Selection of power converter topology in proposed RWECS

As per the application, an RWECS is a low-voltage low-power system that primarily connects to a weak-grid system or works as a stand-alone system. As discussed before, it is justified to use a PMSG in RWECS owing to the decreasing cost of permanent magnets and the high efficiency of the generator. A PMSG based energy conversion system has the advantage of using a unidirectional power converter at the generator-side. Therefore, the proposed RWECS uses a three-phase diode rectifier. Moreover, the use of a 2L HB converter at the grid-side is recommended owing to low-voltage and low-power rating of the system. However, the use of a unidirectional power converter at the generator-side characterizes the system as a variable DC-link system. Therefore, it is required for the system to regulate its output voltage before integrating it to the grid.

There are two options available for output voltage control, as discussed above; namely, the use of a DC/DC converter in conjunction with the unidirectional converter at the generator-side and another is by varying the modulation index of 2L HB converter at grid-side in linear region. Both of the options have their limitations, as discussed before. Therefore, in the next chapter, alternate methods of voltage regulation have been discussed, analyzed, and suitable technology has been selected to be incorporated in the proposed RWECS.

1.6 Plan for work

1. Development of a roof-top wind energy conversion system.
2. Selection of wind turbine topology, wind generator topology, and power conditioning technique to reduce the complexity of the system, making the proposed roof-top wind energy conversion system cost-effective and incurring less maintenance.
3. Selection of voltage regulation technique to maintain output power quality under highly intermittent RES, to reduce the complexity of the system, making the proposed roof-top wind energy conversion system cost-effective and incurring less maintenance
4. Wind turbine emulation using a seperately- excited DC-motor and dSPACE microprocessor board.
5. Fabrication of a proof-of-concept dual-stator axial-flux permanent magnet synchronous generator as a wind generator.
6. Enabling the wind generator with a provision of swinging frame for mechanical field-weakening of the generator.
7. Fabrication of experimental proof-of-concept setup to validate the principal of operation of the present thesis.

8. Performing experimentations for accessing the performance of proposed system under variable wind speed supplying variable load in an off-grid mode and testing the low-voltage ride-through capability of the system.

9. Proposing a control technique to hybridize the proposed wind energy conversion system with a solar energy conversion system working in an off-grid mode with an objective of reducing the complexity and maintenance cost of the system.

10. Experimental validation of proposed hybrid wind-solar energy conversion system.

1.7 Conclusion

This chapter puts forward the current scenario of wind energy-based power generation in the world energy market. WECS has seen tremendous growth owing to the increased per unit size of wind turbines leading to low LCOE. However, the growth of WECS in remote area electrification has been limited due to the absence of a dedicated, cost-effective solution. Moreover, uncertain government policies and strong competition from solar PV industries are some other prominent issues.

Therefore, a rooftop wind energy conversion system (RWECS) has been proposed in this chapter. The proposed WECS has primary components as a wind turbine, generator, and power conditioner. Further, this chapter provides recent technologies available for each component. Consequently, the most suitable technologies for an RWECS have been selected based upon the simplification of the overall system ensuring satisfactory operation for a stand-alone/weak-grid system.

However, in the proposed system, output voltage changes as per input wind speed. In the next chapter, the voltage regulation capability of the system has been discussed.