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A REVIEW OF THE STATE OF THE ART OF GENERATORS AND POWER ELECTRONICS CONVERTER TOPOLOGIES FOR WIND ENERGY CONVERSION SYSTEM

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ABSTRACT

With rapid development of wind power technologies and significant growth of worldwide installed capacity of wind power, wind energy conversion system has become a focal point in the research of renewable energy sources. This paper provides comprehensive reviews of past and present power electronics converter topologies applicable to various wind turbine systems with different generators. An overview of different wind generator systems and their comparisons are presented, the contemporary wind turbines are classified with respect to both their control features and drive train types; their strength and weakness are described. The various generator –converter combinations are also compared on the basis of topologies. In addition, the possible method of using the power electronics technology for improving wind turbine performance such as power quality, efficiency and control complexity has been described.

Keywords: wind turbines, generator topologies, variable speed, direct-drive, power electronics, grid connection.

1. INTRODUCTION

Wind power has emerged as one of the most dominant renewable source of Energy with immense growth potential across the globe. In fact the global cumulative installed capacity of wind power reached 120 GW in the year 2008. According to Global Wind Energy Council 2012[39], global wind energy capacities have reached 238 GW at end of 2011 shown in fig-1& annual installed capacity of various region of the globe is shown in fig-2.Wind power is expected to provide a fifth of world's electricity by 2030. Wind energy is continuing to grow strongly in India, with over 3019 MW of new installed capacity in 2011, reaching a total of 17644 MW as on June 2012. The development of modern wind power conversion technology has been going on since1970s, and the rapid development has seen from 1990s. Various wind turbine concepts have been developed & different wind generators have been built. Three types of typical generator systems for large wind turbines exist [1,15, 17,18]. The first type is a fixed-speed wind turbine system using a multi-stage gearbox and a standard squirrel-cage induction generator (SCIG), directly connected to the grid. The second type is a variable speed wind turbine system with a multi-stage gearbox and a doubly fed induction generator (DFIG), where the power electronic converter feeding the rotor winding has a power rating of nearly 30% of the generator capacity; the stator winding of the DFIG is directly connected to the grid.

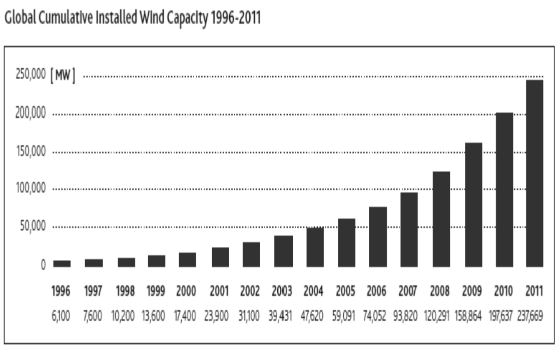

Fig.1World cumulative wind power installed capacity (1996–2011)

The third type is also a variable speed wind turbine, but it is a gearless wind turbine system with a direct-drive generator, normally a low-speed high-torque synchronous generator and a full-scale power electronic converter are used. Additionally, a variety of innovative concepts of wind turbines appear, for example, an interesting alternative may be a mixed solution with a gearbox and a smaller low speed permanent magnet synchronous generator (PMSG) [2,18,19], because direct-drive wind generators are becoming larger and even more expensive for increasing power levels and decreasing rotor speeds.

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In this paper, the possible combinations of converter and generators topologies for permanent magnet generators, caged rotor induction generators, synchronous generators and doubly fed induction generators are discussed and some of the possible control strategies are touched upon. This paper serves as a concise summary and comparison of the state of art regarding power electronic topologies and wind energy conversion systems.

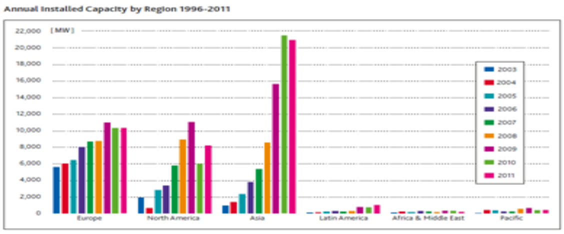

Fig 2. Annual installed Capacity by region 1996-2011

2. WIND ENERGY CONVERSION

Wind turbines capture power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is three in a modern wind turbine. As the blade tip-speed should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For multi-MW wind turbines the rotational speed is typically 10-15 rpm. The most weight efficient way to convert the low-speed, high-torque power to electrical power is to use a gear-box and a standard generator including a power electronic interface as illustrated in Figure-3

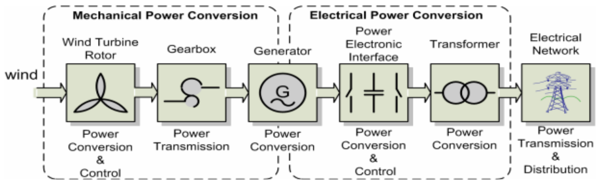

Fig.3. Power conversion stages in a modern WT

The gear-box is optional as multi-pole generator systems are also possible solutions. Between the grid and the generator a power converter can be inserted The possible technical solutions are many and a technological roadmap starting with wind energy/power and converting the mechanical power into electrical power is shown in Figure 5. The electrical output can either be AC or DC. In the last case a power converter will be used as interface to the grid. The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist and it is now proven technology. It is important to be able to control and limit the converted mechanical power at higher wind speed, as the power in the wind is a cube of the wind speed.

The power limitation may be done either by stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed) [14], [21], [5] and [40]. The basic output characteristics of these three methods of controlling the power are summarized in Figure 6. The modern wind turbines use only active stall and pitch control

2.1. Wind Turbine Concepts & Generator Types

Referring to the rotation speed, wind turbine concepts can be classified into fixed speed, limited variable speed and variable speed. For variable speed wind turbines, based on the rating of power converter related to the generator capacity, they can be further classified into wind generator systems with a partial scale and a full-scale power electronic converter. In addition, considering the drive train components, the wind turbine concepts can be classified into geared drive and direct-drive wind turbines. In geared-drive wind turbines, one conventional configuration is a multiple-stage gear with a high-speed generator; the other one is the multibrid concept which has a single stage gear and a low-speed generator [4]. In this section, according to contemporary wind turbine concepts, the basic configurations and characteristics of different wind generator systems are described.

2.2. Fixed speed Wind Turbine

This configuration corresponds to the so called Danish Concept that was very popular in 80's. This wind turbine is fixed speed controlled machine, with asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer as shown in Figure 4. This concept needs a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the production variation (5-25 steps) Smoother grid connection occurs by incorporating a soft-starter. Regardless the power control principle in a fixed speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. These can yield to voltage fluctuations at the point of connection in the case of a weak grid. Because of these voltage fluctuations, the. fixed speed wind turbine draws varying amounts of reactive power from the utility grid (in the case of no capacitor bank), which increases both the voltage fluctuations and the line losses This concept does not support any speed control, requires a stiff grid and its mechanical construction must be able to support high mechanical stress caused by wind gusts.

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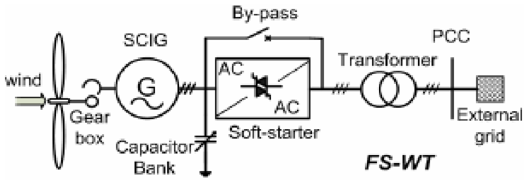

Fig.4. Fixed speed WT with directly grid connected SCIG

2.3 .Limited variable speed Wind Turbine

This configuration with a multiple-stage gearbox is also known as the Optislip concept. This wind turbine concept uses a wound rotor induction generator (WRIG) with variable rotor resistance by means of a power electronic converter and the pitch control method, as shown in fig-5 The stator of WRIG is directly connected to the grid, whereas the rotor winding is connected in series with a controlled resistor. Variable-speed operation can be achieved by controlling the energy extracted from the WRIG rotor; however, this power must be dissipated in the external resistor. With the increase in variable speed range, a higher slip means a high power extracted by the rotor, and the lower generator efficiency, so that the rating of the resistor must also be higher. Therefore the dynamic speed control range depends on the size of the variable rotor resistance, and the energy extracted from the external resistor is also dumped as heat loss in the controllable rotor resistance.

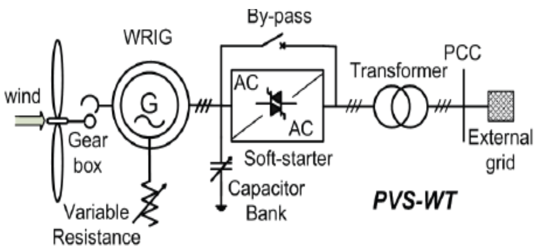

Fig. 5. Partial variable speed WT with variable rotor resistance

2.4. Variable Speed concept with a partial-scale power Converter

This configuration is known as the DFIG concept, which corresponds to a variable speed wind turbine with a WRIG and a partial-scale power converter on the rotor circuit, as shown in fig-6 the stator is directly connected to the grid, while the rotor circuit is connected through a partial-rating power converter. Different technologies can be used for this power converter such as: back-to-back voltage source converter (VSC), multilevel converter (three-level) or matrix converter [22]-[23]. However, the existing wind turbines on the market are based on the back-to-back VSC topology.

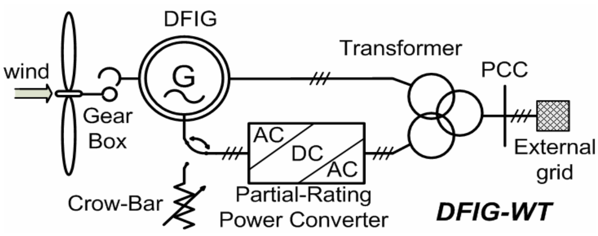

Fig 6.Variable speed WT with partial scale power converter

The power rating of this converter defines the speed range (typically ±30% around synchronous speed). Stator active and reactive power is controlled through this power converter in the rotor circuit. Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wide compared to that of PVSWTs. Moreover, it captures the energy, which in the PVS-WTs concept is burned off in the controllable rotor resistance. The smaller rating power of this converter makes this concept attractive from an economical point of view. Moreover, the power electronics is enabling the wind turbine to act as a more dynamic power source to the grid [16], [6-7], [8], [9,24]. However, its main drawbacks are the use of slip-rings and the protection schemes in the case of grid faults. It requires a crow-bar in the rotor circuit during faults .

2.5. *Variable speed direct-drive concept with a full-scale power converter*

This configuration corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a full-rating power converter as shown in Fig.7. The power converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The stator windings are connected to the grid through a full-scale power converter. Recently, due to the advancement in the power electronics the squirrel-cage induction generator has also started to be used for this concept. Some variable speed wind turbines systems are gearless.

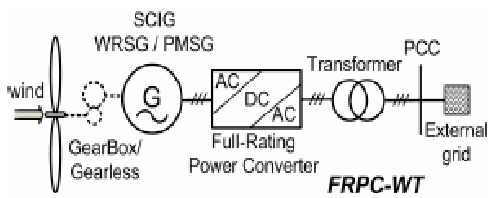

Fig 7 Variable speed WT with full-rating power converter

In these cases, a direct driven multi-pole generator is used. The variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide operation, it is possible to continuously adapt (accelerate or decelerate) the rotational speed range of wind speed. By introducing the variable speed of the wind turbine to the wind speed, in such a way that tip speed ratio is kept constant to a predefined value corresponding to the maximum power coefficient. Contrary to a fixed speed system, a variable speed system keeps the generator torque nearly constant. Thus, the variations in wind are absorbed by the generator speed changes Seen from the wind turbine point of view, the most important advantages of the variable speed operation compared to the conventional fixed speed operation are: reduced mechanical stress on the mechanical components such as shaft and gearbox, increased power capture and reduced acoustical noise.

3. POWER CONVERTER TOPOLOGIES FOR WIND TURBINES

Basically two power converter topologies with full controllability of the generated power are currently used in the commercial wind turbine systems. These power converters are related to the partial-rating power converter wind turbine and the full-rating one. The power converter topologies for different generators are presented in this section:

3.1. *Converter Topologies for SCIG System*

The use of induction generators (IG) is advantageous since they are relatively inexpensive, robust and they require low maintenance. The nature of IG is unlike that of PMSG, they need bi-directional power flow in the generator-side converter since the induction generator requires external reactive power support from the grid. The use of back-to-back PWM converters, Fig.8, along with the implementation of one or more fuzzy logic controllers is a consistent converter-control combination [10,25–26]. The advantages of fuzzy logic control are parameter insensitivity, fast convergence and acceptance of noisy and inaccurate signals. A PI type fuzzy logic controller takes in the DC voltage error and change in DC voltage error [25]. The controller outputs the d-axis reference current used in real power flow control. In a similar manner, the q-axis current is kept zero to maintain unity power factor.A control scheme using three fuzzy logic controllers has also been investigated in [10].The first controller tracks the generator speed with the wind velocity to extract maximum power. The second controller programs the machine flux for light load efficiency improvement. More specifically, the machine rotor flux can be reduced from the rated value to reduce the core loss and thereby improve the efficiency. The rotor flux may be reduced by continually decreasing the magnetizing current until the maximum power increase is obtained.

The third controller gives robust speed control against wind gust and turbine oscillatory torque. Unlike the second controller, the third fuzzy logic controller is always active. An atypical WECS converter setup has been explored [26]. Instead of the usual back-to back PWM converter scheme, the authors use a fixed-capacitor thyristor-controlled reactor static VAR compensator at the generator terminals to regulate its voltage. The mechanical input power is controlled using the blade pitch angle. The design techniques used for the control systems are based on the state space linearized model of the system. Two controllers, a state feedback controller and output feedback controller were designed. The output feedback control is preferred since all the output signals are available for measurement and an observer are not needed as in the state feedback control [11].

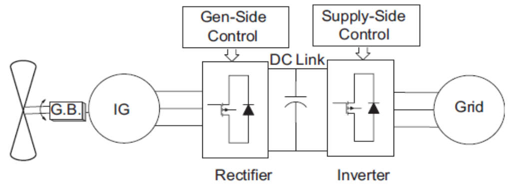

Fig.8.Induction generator with back to back converters

3.2. *Converter Topologies for DFIG System*

The advantage of using doubly-fed induction generator (DFIG) is to generate the output more than its rated power without becoming overheated and it is able to transfer maximum power over a wide speed range in both sub- and super-synchronous modes. The DFIG with variable speed operation is an excellent choice for high power applications in the MW range. As earlier said, Enercon fabricated a wind turbine of 4.5 MW with rotor diameter of 112.8 meters using DFIG. This section presents the various converter topologies used for wind turbine driven DFIG available in the literature [27]-[31].

A. Static Kramer Drive System

The static Kramer drive consists of a diode rectifier on the rotor side and a line commutated inverter connected to the grid side as illustrated in Fig 9 [27]. With this converter, various control methods have been applied like fuzzy logic, sliding mode control technique to provide a suitable compromise between conversion efficiency and torque oscillation smoothing. These controllers regulate the thyristor inverter firing angle to attain the ideal compromise [27]. This converter is able to provide the active power from both stator and rotor sides respectively, under super-synchronous operation only. For generating the power during both sub and super synchronous modes, other methods replace the diode rectifier with another thyristor rectifier (SCR) [27].

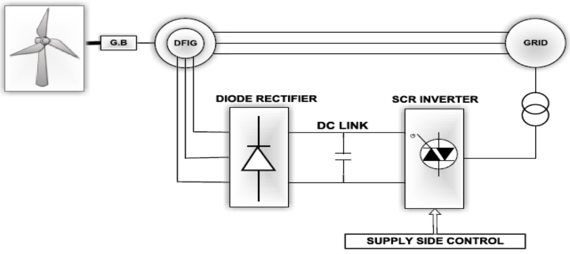

Fig.9 Schematic of static Kramer drive

The replacement of diode rectifier by SCR converter in the rotor side allows the generator to receive reactive power from via rotor-side converter system, and the active power flow is bi-directional. When DFIG is connected to the wind turbine, the optimum performance is obtained by adjusting the gear ratio, of the gear box, to its optimum value. In comparison to the Kramer drive, this system produces more power output because of lack of reactive power available with a diode rectifier in Kramer drive and this system is referred as modified Kramer drive. A major drawback of this method includes firing and commutation problems with the rotor-side converter and harmonic distortion to the grid, created by the grid-side thyristor converter system [40].

B. Back-to-Back PWM Converters for DFIG System

In the earlier stage of 1980s, due to advent of BJT and IGBT power semiconductor devices, a more technologically advanced method using back-to-back converters has been developed, The back-to-back rectifier-inverter pair is a bidirectional power converter consisting of two conventional pulse-width modulated (PWM) voltage-source converters (VSC), as shown in Fig. 10 [28]. One of the converters operates in the rectifying mode, while the other converter operates in the inverting mode. These two converters are connected together via a dc-link consisting of a capacitor.

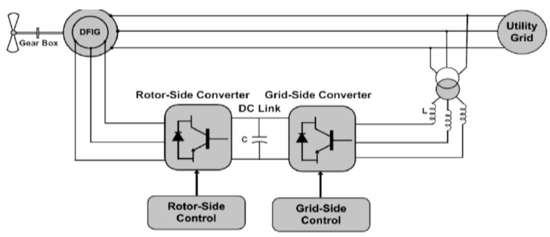

Fig.10. DFIG with back-to-back PWM converter

The dc-link voltage will be maintained at a level higher than the amplitude of the grid line-to-line voltage, to achieve full control of the current injected into the grid. Consider a wind turbine system including the back-to-back PWM VSC, where the rectifier and inverter are connected to the generator and the electrical grid, respectively.

The control details of the back-to-back PWM VSC arrangement in the wind turbine applications has been designated in several papers [29]-[31], although the converter used in these works are almost similar, great differences lie within the applied control strategy and complexity. Eguchi and Imura were first proposed vector current control of the grid connected PWM voltage source converter in 1986 [29]. Most viable option is to apply vector control to the grid-side converter, with a reference frame orientated with the d-axis along the stator voltage vector. The grid-side converter is controlled to keep the dc-link voltage constant by adjusting the d-axis current component. It is also responsible for reactive power control through regulation of the q-axis current component. As for as rotor side converter is concerned, the decoupled control of the electromagnetic torque and the rotor excitation current is possible by applying vector control in the rotor side converter [30]. DFIG is controlled in a synchronously rotating reference frame with the d-axis orientated along the stator-flux vector, Providing maximum energy transfer. On the contrary, in [30], the rotor current was decomposed into d–q components, where the d-axis current is used to control the electromagnetic torque and the q-axis current controls the power factor. Both types of rotor-side converter control employ the use of PI controllers. PWM switching techniques can be used, or alternatively space vector modulation (SVM) is used in order to achieve a better modulation index.

C. Resonant DC-link Converter for DFIG

Deepak M.Divan [31] proposed this topology very first in 1986. Fig.11 illustrates the resonant DC link uses one resonant circuit to provide soft switching for the entire converter. The DC link is forced to oscillate, so the resonance circuit is located on the DC link side and not on the load side, since only one resonant circuit is required instead of one for each phase. The idea behind the use of resonant converter is that ideally the converter should only change state at zero link voltage. The resonant circuit is formed by *Lres* and *Cres*, where the resonant capacitor is usually having the value less than the DC link capacitor *Cdc*. The resonant link voltage swings between zero and twice the DC link voltage, which means that the voltage rating of the switches has to be higher. The modulation strategy for this topology requires that the resonance frequency is much higher than the switching frequency [31].

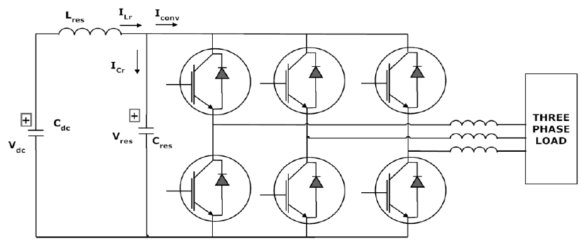

Fig.11. Resonant DC-link Converter

D. Matrix Converter for DFIG System

The matrix converter is capable of converting the variable AC from the generator into constant AC to the grid in one stage (Fig. 12). Two distinct advantages arise from this topology, the converter requires no bulky energy storage or DC-link and control is performed on just one converter. The utilization of a matrix converter with a DFIG has been explored [32, 12]. The use of a stator–flux oriented control was employed on the rotor matrix converter. The d-axis current was aligned with the stator–flux linkage vector Simple PI controllers can be employed to control the d–q-axis currents. The regulation of the d-axis current allows for control of the stator-side reactive power flow, where as the q-axis current helps regulate the stator-side active power [32].Another option is to control the rotor winding voltage, which consequently manipulates the power factor of the DFIG [12]. The matrix converter consists of nine bi-directional switches (18 total), arranged in a manner such that any input phase may be connected to any output phase at any time each individual switch is capable of rectification and inversion. The matrix converter is controlled using double space vector PWM, employing the use of input current and output voltage SVM. The details of this method exceed the scope of this paper and can be further examined in [12]. One of the major drawbacks of a matrix converter is that 18 total switches are required, causing an increase in converter semiconductor cost.

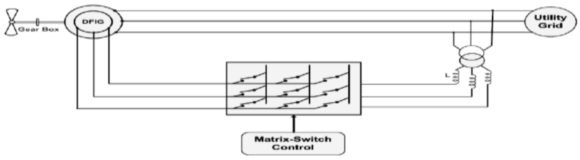

Fig12. Matrix Converter topology with DFIG

3.3. Converter topologies for PMSG System

Permanent magnet excitation is generally favored in newer smaller scale turbine designs, since it allows for higher efficiency and smaller wind turbine blade diameter In recent years, the use of PMs is more attractive than before, because the performance of PMs is improving and the cost of PM is decreasing. The trends make PM machines with a full-scale power converter more attractive for direct-drive wind turbines. Currently, Zephyros (currently Harakosan) and Mitsubishi are using this concept in 2 MW wind turbines in the market. A major cost benefit in using the PMSG is the fact that a diode bridge rectifier may be used at the generator terminals since no external excitation current is needed. Much research has been performed using a diode rectifier [33, 34, 35, and 3]; however, this leaves many options for the remainder of the power converter and its control

A.Thyristor supply-side inverter

Using a thyristor-based grid-side inverter allows continuous control of the inverter firing angle, regulating turbine speed through the DC-link voltage; hence, obtaining optimum energy capture [33].

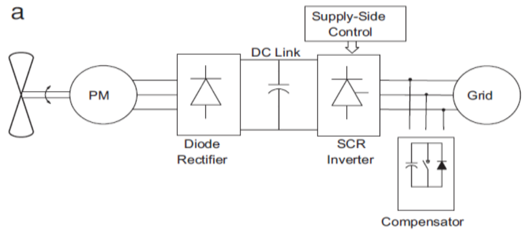

Fig 13.Blok Diagram of Thyristor supply side inverter

Advantages of this scheme include lower device cost and higher available power rating than hard-switched inverters. A major drawback to this inverter is the need for an active compensator for the reactive power demand and harmonic distortion created, as shown in Fig 13. A voltage source converter (VSC) is used for the compensator and the error signal between the reference and actual compensator current is used to drive the pulse width modulated (PWM) control [33].

B. Hard-switching supply-side inverter

A proposed control involves the manipulation of the modulation index of the reference sinusoidal signal applied to the PWM generator. This is achieved by determining the DC-link voltage by a power mapping technique that contains the maximum power versus DC voltage characteristic. The control system is further improved by using a derivative control on the stator frequency, since it also changes with change in DC-link voltage [4]. This control is compared with maximum power point tracking (MPPT), which Intermediate DC/DC converter stage Back-to-back PWM converters includes an anemometer, a wind prediction control scheme and a fixed-voltage scheme. The anemometer measures the wind speed and aids in providing the wind power reference to the MPPT controller. The reference power is compared with the actual DC power extracted in which the result is used to determine the new operating DC voltage. The current control loop of the inverter receives the new operating DC voltage and outputs an instantaneous driving signal for the PWM [4]. In wind prediction methods, autoregressive statistical models are commonly used. The system considers energy captured in the previous time frame to predict the wind speed value for the next time frame set. Under fixed-voltage control, the voltage of the inverter is fixed at a targeted optimum wind speed. In comparing the four control methods, the fixed voltage scheme was used as the reference since it was least efficient. The MPPT with anemometer setup proved to be superior, obtaining 56–63% of energy available. However, the proposed method using sensor-less control was not far behind, obtaining 55–61% of the total energy available from the wind.

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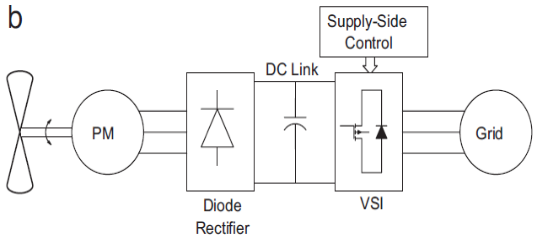

Fig. 14. Block diagram of hard switching supply side inverter

C. Intermediate DC/DC converter stage

The use of a voltage source inverter (VSI) accompanied by a DC/DC converter is investigated [39,40], depicted in Fig. 3c. This setup is also compared to the converter shown in Fig. 14 [37]. Incorporating an extra DC/DC converter gives the following advantages:

1. Control of generator-side DC-voltage through variation of the switching ratio,
2. Maintains appropriate inverter-side DC-voltage,
3. Allows for selective harmonic elimination (SHE) switching, giving reduced losses,
4. Inverter no longer needs to control DC-voltage, and has more flexible control.

The inverter power control can be achieved by regulating the magnitude of the fundamental line current and the phase angle between the line current and line voltage [17].The controller is configured such that the VSI is switched at the frequency of the triangular carrier signal and its output harmonics are well defined. For every shaft speed, optimum values of DC voltage and current can be identified corresponding to the maximum available turbine power [36]. The DC/AC voltage ratio and power angle are used as control variables that are tuned to control the power, and ultimately the speed of the generator. The inverter control can also be implemented to keep the DC-link constant and vary the reactive power in a manner that attains maximum real power transfer to the grid [36].Results show that the thyristor-based inverter with active compensator is best suited for strong AC systems since it relies on the system to ensure commutation [6]. However, both the VSI and DC/DC–VSI systems are capable of integrating with both strong and weak AC systems. Other control strategies have been discovered for this converter [40]. The DC/AC inverter can control the active and reactive power delivered to the grid via control of the q-axis and d-axis current, respectively [38]. The q-axis reference current is determined by the error in the DC-link voltage, and is then compared with the actual current. The phase angle of the utility, used in power factor control, is detected using software phase lock loop (PLL) in a d–q synchronous reference frame. Power factor control creates the d-axis reference current allowing it to be compared with the actual d-axis current. The error in both reference frame currents are used to create the d–q-axis reference voltages used in space vector PWM control. Using the voltage equation governing a boost-up DC/DC chopper and a proportional–integral (PI) controller, the duty ratio of the chopper switch may be determined for any particular optimum point [38].

The inverter-side DC voltage remains constant set by the grid voltage giving the advantage of flexible transfer of active and reactive power to the grid.

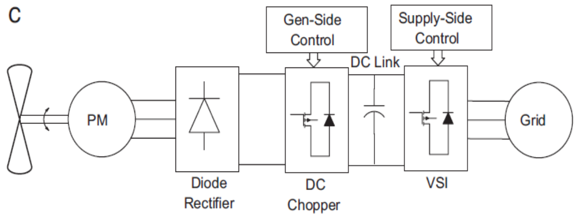

Fig: 15. Intermediate DC/DC converter stage

D. Back-to-back PWM converters

A reliable and consistent power source can be obtained by harnessing wind power and using the grid as a backup source for the promotion of extensive use of wind power, the overall cost of the system should be reduced without compromising on system reliability. This cost can be brought down by reducing the cost of the wind turbine, PMSG and power conditioner [37] .The cost of the power conditioner will come down if the number of switches used therein are reduced to 6. In order to realize the reduction in switch count, this power converter is considered. There are only eight switches and two dc link capacitors, instead of twelve switches and one dc link capacitor. The output power from PMSG is first converted into dc and then it is fed to the grid (frequency and magnitude of voltage are assumed to be constant). The MPPT extracts optimum power from the wind turbine for the wind speeds varying from cut-in to rated, by generating a suitable reference current to the rectifier. A separate controller generates the reference current for the inverter in such a way that the dc link voltage is maintained constant.

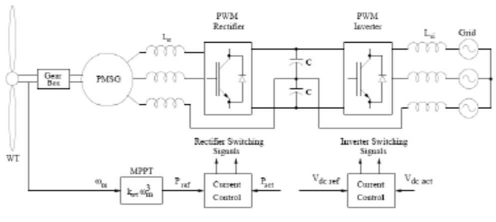

Fig.16. Schematic Diagram of Back-Back PWM converter

4. CONCLUSIONS

The paper provides an overview of different wind turbine concepts and possible generator types. The basic configurations and characteristics of various wind generator systems based on contemporary wind turbine concepts are described with their advantages and disadvantages. Converter topologies used in combination with PMSG, DFIG, IG, along with different control schemes has been described in detail.. There is a continuing effort to make converter and control schemes more efficient and cost effective in hopes of an economically viable solution to increasing environmental issues.

Wind power generation has grown at an alarming rate in the past decade and will continue to do so as power electronic technology continues to advance.

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