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Review of Power Converters for Wind Energy Systems

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Abstract

The paper presents commonly used power electronic topologies in Wind Energy Conversion Systems. It discusses the main differences between partially and fully rated converters, their control methods and their application in large and small scale wind turbines. The paper also presents methods of tracking the optimal power point for permanent magnet synchronous generator based wind energy systems.

1. Introduction to wind energy conversion systems

A wind energy conversion system consists of a rotor that captures energy from the wind and converts it into mechanical energy as torque and speed. This energy is then converted to electrical energy using an electrical generator. In the majority of cases, generated electrical energy is fed to the grid at an appropriate voltage level.

1.1 Aerodynamic energy conversion

The power available in a wind stream P_{air} is given by Eq. 1, [1, 2].

$$P_{air} = \frac{1}{2}\rho A V_w^3 \tag{1}$$

where ρ is the air density [kg/m^3], A is area swept by the rotor [m^2] and V_w is the free wind velocity [m/s]. This power cannot be completely extracted and the conversion efficiency is dependent on the power coefficient C_P which is the ratio between the extracted power P_w and the available power P_{air} as defined by Eq. 2, [3].

$$C_P = \frac{P_w}{P_{air}} \tag{2}$$

This coefficient can have a maximum of 0.593, known as the Betz limit. It is a function of two variables: the blade pitch angle β and the tip speed ratio λ, which is given by Eq. 3 [1].

$$\lambda = \frac{\omega_{rot} R}{V_w} \tag{3}$$

where R is the radius of the rotor [m] and ω_{rot} is the rotational speed of the rotor [rad/s]. Hence, the power extracted by the rotor of a wind turbine is given by [1]:

$$P_w = \frac{1}{2} \rho A V_w^3 C_P(\beta, \lambda) \tag{4}$$

A typical variation of C_P as a function of the tip speed ratio for different pitch angles is shown in Fig 1. It can be observed that there is only one tip speed ratio value at each pitch angle that gives a maximum C_P. Therefore, by controlling the speed of the rotor (generator) to follow the tip speed ratio that maximises C_P, maximum power extraction can be achieved at different wind speeds [4]. This is one of the motivations for using variable-speed operation.

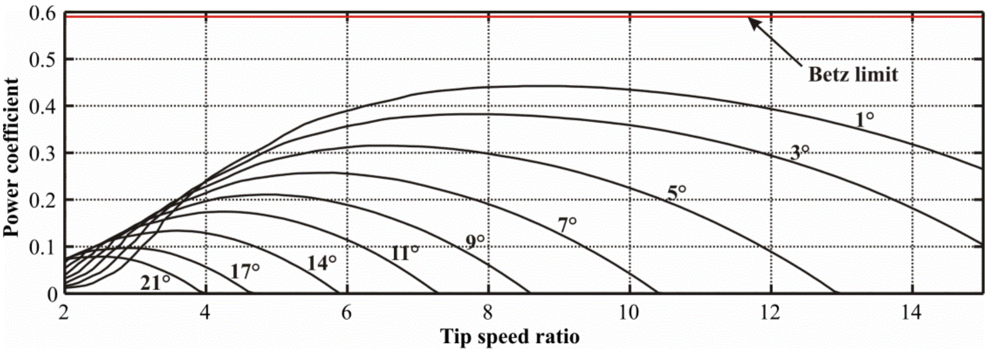

Fig 1: Variation of C_P as a function of the blade pitch angle β and tip speed ratio λ

1.2 Operating Regions of variable-speed wind turbine

A typical power *vs*. speed characteristic of a variable-speed wind turbine in per unit[1] is shown in Fig 2, where the optimal rotor speeds for maximum power extraction at different wind speeds are highlighted. Also as shown, the operating regions of a wind turbine can be divided into mainly three regions. The amount of wind power available in Region 1 is not enough to overcome the turbine losses and therefore it is unproductive. In this region, for large scale wind turbines the rotor is held stationary and the generator is disconnected from the utility grid until the cut-in wind speed is reached. Typical cut-in wind speeds vary between 3 to 5 m/s depending on the scale and turbine design [5-7]. In Region 2, the turbine is operated at variable speed to maximise the extracted power from the wind. This region ranges from the cut-in to the rated wind speed at which rated power is produced. Region 3 is mostly relevant for large scale wind turbines and is the constant torque region which ranges from rated to the cut-out wind speed, which for most turbines is 25 m/s. In this region, the rotor speed is controlled using the pitch mechanism to maintain rated power not to overload the turbine component design ratings. Above this region, the wind turbine is shut down for protection.

[1] 1 pu speed and power denote the rated speed and power of a wind turbine

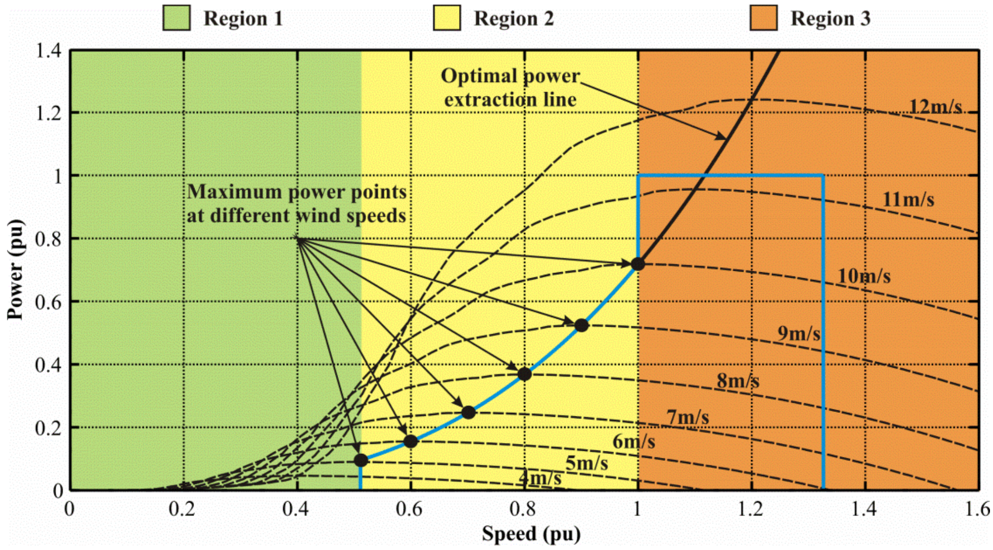

Fig 2: Power *vs*. speed characteristic of a variable-speed wind turbine

1.3 Variable-speed wind turbine architectures

The present techniques for converting mechanical to electrical energy in a wind turbine are shown in Fig 3. It shows different possible technological options such as with or without gearbox, using synchronous or induction machines and different power converter topologies. These concepts can be split into two groups according to their power converter rating: partially rated (PRC) and fully rated converters (FRC).

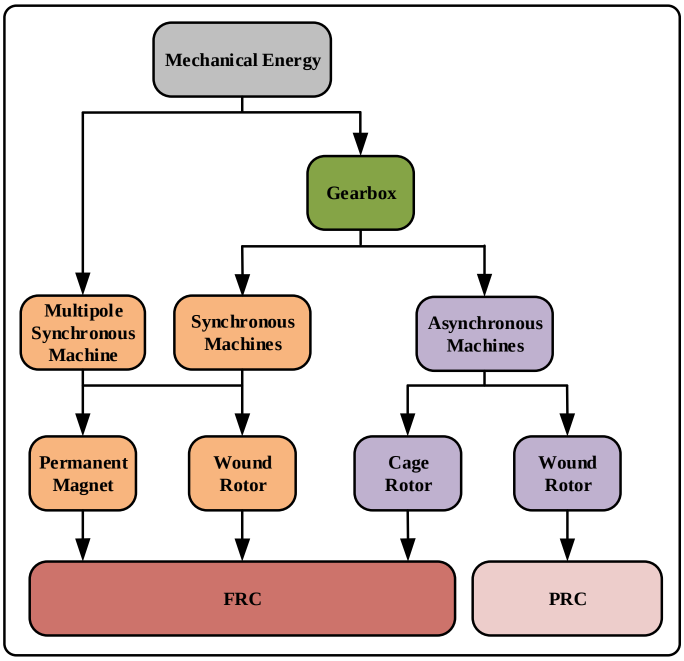

Fig 3: Wind energy conversion technology routes [8]

Wind turbines are generally divided into two broad categories, large scale and small scale systems. Large scale systems are intended to generate power in bulk to replace conventional generation. Energy yield and availability are then the main objectives. Small scale wind turbines are intended to supplement conventional generation or for remote areas. The design of such systems is driven by cost optimisation of the turbine components and the converter. Due to the different objectives, the adopted solutions are generally different with large scale systems driving the technology and small scale systems opting for the simpler alternatives.

2. Large Scale Wind Energy Systems

Large scale wind turbines comprise systems whose power ratings exceed 100kW. Power ratings rise substantially up to 8MW, with current plans pushing the ratings up to 10MW. Such systems are generally located in prime wind locations, and due to the current energy prices, have also been installed offshore. Large scale systems are generally grid connected and are interfaced to the grid at high voltage levels. Apart from the active power control, they are also generally required to control the flow of reactive power. Different architectures, classed by the power converter topology are described below.

2.1 Wind Turbine Architectures

2.1.1 Wind turbine architectures with partially rated converters (PRC)

A wind turbine equipped with a wound rotor asynchronous machine with a PRC has been a very popular approach for achieving variable-speed operation. The advantages of this architecture are lower converter costs and losses, since the power converter handles only a fraction (20–30%) of the total power [9]. The disadvantages of such system is a limited variable-speed operation range and higher maintenance costs due to the slip rings required to access the rotor windings [10]. There are two variants of this approach: the variable-slip operation and the doubly-fed [8, 11].

Fig 4 shows the block diagram of a wind turbine equipped with a wound rotor induction generator (IG) configured for variable-slip operation. The wind turbine rotor is coupled to the generator through a gearbox since the rated speed of induction generators is usually higher than that of the wind turbines. The pitch control adjusts the angle of the blades to lower the power coefficient and limit the energy capture in Region 3. The three phase generator rotor windings are connected to external resistors through a power electronic converter. Variation in the effective rotor resistance will result in a variation of the generator slip, which ultimately affects the rotational speed [10]. The typical speed variation with the variable-slip operation is less than 10% [8, 9]. In this configuration the generator draws reactive power from the grid to build up the magnetic field. Therefore, capacitor banks are usually installed to compensate for the reactive power absorbed [10]. Moreover, a soft-starter is needed to limit the inrush current during start-up [11]. The system is interfaced to the grid through a transformer to step up the voltage level as required.

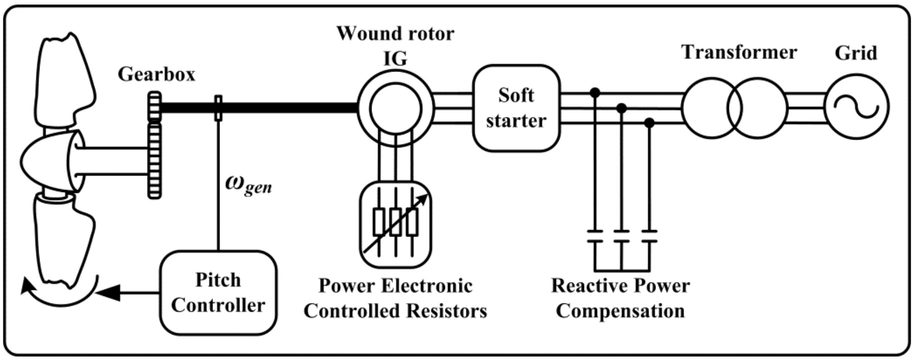

Fig 4: Wound rotor induction generator with variable-slip configuration

A typical configuration of a doubly-fed induction generator based wind turbine is shown in Fig 5. The mechanical interface to the turbine rotor and the pitch control is similar to that of Fig 4. The rotor of the wound rotor induction generator has its rotor connected to the grid through a PRC. The converter is typically a back-to-back voltage source converter with a typical rating of 30% of the rated power [8]. This converter decouples the rotor frequency from the grid frequency, hence enabling variable-speed operation [3]. The speed variation is directly related to the power of the rotor side converter and is typically ±30% of the synchronous speed [8, 10]. In this configuration, electrical power can be delivered to the grid through both the stator and the rotor depending on the generator speed. In the case of super-synchronous speed operation, electrical power is delivered to the grid through both the stator and rotor. On the other hand, when the generator is operating in sub-synchronous speed, electrical power is delivered to the grid through the stator only whilst the rotor side absorbs active power [3]. The crowbar protects the generator and the converter from any over-currents during grid failures.

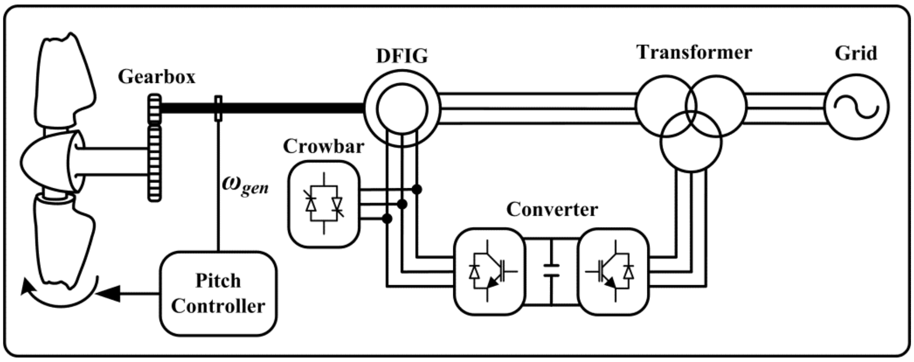

Fig 5: Doubly-fed induction generator configuration

2.1.2 Wind turbine architectures with fully rated converters (FRC)

A typical configuration of a FRC based wind turbine is shown in Fig 6. The FRC configuration is characterised by a broad variable-speed operation ranging from stand-still to the full rated speed [1]. This is one of the advantages of a FRC over the PRC based turbines. However, in this case the converter cost and losses are higher due to the full power rating [9].

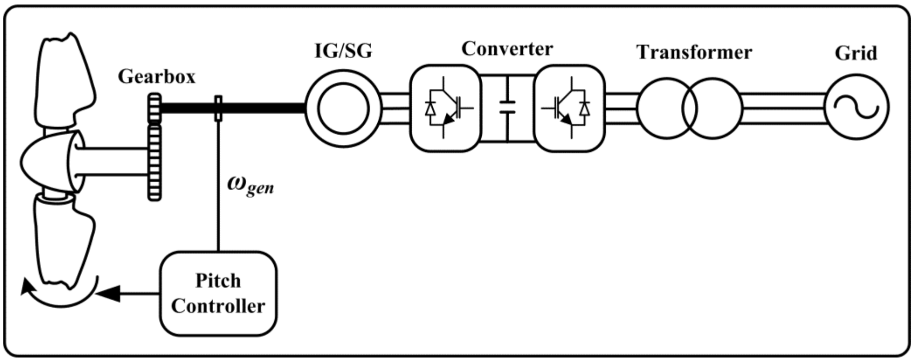

Fig 6: Fully rated converter configuration

In this configuration, the generator is connected to the grid through a back-to-back voltage source converter. Therefore, it offers complete decoupling of the generator from the grid frequency, thereby enabling variable-speed operation. Moreover, full control of the active and reactive powers is possible with this type of converter [10]. This is highly desirable in order to fulfil Grid-Code requirements [11]. As indicated in Fig. 6, the FRC configuration applies for both synchronous generators (SG) and IGs.

A SG has the ability to provide its own excitation on the rotor, either by having a wound rotor or by permanent magnets. The two generator variants are referred to as the electrical excited (EESG) and the permanent magnet synchronous generators (PMSG) respectively. Recently, PMSG are gaining more popularity particularly for offshore applications. SGs allow multipole construction that enable matching of the generator speed to the rotor speed. This allows direct mechanical connection between the rotor and the converter, hence eliminating the gearbox as shown in Fig 7.

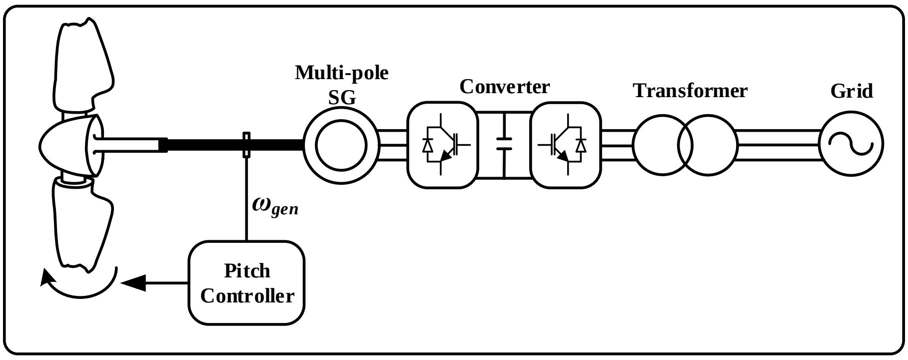

Fig 7: Gearless configuration

In the case of a SG, the voltage source converter on the machine-side can be replaced by a diode rectifier as shown in Fig 8. This makes the converter cheaper; however, the control of the whole system becomes more difficult. A boost converter is normally used to increase the DC link voltage more than the grid line to line voltage in order to achieve full control of the grid current [12].

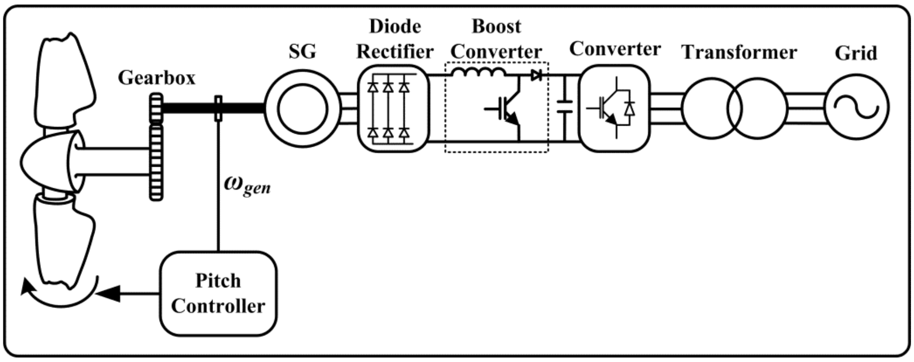

Fig 8: Fully rated converter with diode rectifier configuration

The EESG based wind turbine configuration is shown in Fig 9. It can be observed that in addition to the FRC there is a diode rectifier to provide the DC excitation current to the rotor. In the EESG, the rotor is often a salient pole type which is typically used for low speed applications. This configuration is attractive for direct-drive applications [9].

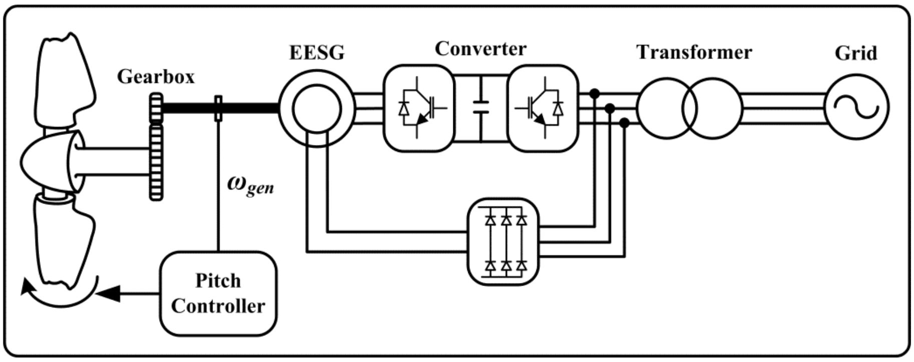

Fig 9: Electrically excited synchronous generator configuration

2.2 Wind turbine control

Large scale wind turbines have several layers of control [13]. These can be classified into three categories: Supervisory, Power production and Safety. The supervisory control is responsible for starting, stopping and emergency stops sequences, braking, yawing and health monitoring of the turbine. The power production aim is to maximise power below rated wind speed and controlling the rotor speed above the rated wind speed. An additional control task in this category is load alleviation. The safety system ensures that the turbine is kept within the normal operating limits if the supervisory control fails. Therefore, this control system has to be independent of the other systems and must have its own power source.

3. Small Scale Wind Energy Systems

Wind turbines whose power rating do not exceed 100kW are known as micro or small scale wind turbines. The different designs that are presently available can be generally of two types: Horizontal Axis (HAWT) or Vertical Axis Wind Turbines (VAWT).

3.1 Wind Turbine Architectures

3.1.1 Horizontal Axis Wind Turbines

HAWTs follow similar designs used for large scale wind turbines. Due to the overriding cost considerations, they generally do not include sophisticated pitch and yaw control mechanisms. Typical solutions for orienting the rotor into the wind generally vary from the use of a tail vane for upwind to self–aligning designs for downwind turbines. The tail vane mechanism can also include features of furling of the rotor above rated wind speed. The power extraction in Region 3, identified in Fig 2, is also limited by furling, where the blades are appropriately designed to lower the conversion efficiency at such wind speeds.

3.1.2 Vertical Axis Wind Turbines

The HAWTs are popular in rural areas, have a higher C_P than the vertical type, however they do not operate efficiently in turbulent winds [14]. VAWTs are ideal for installations where wind conditions are not consistent, such as in built up areas as they do not need a yaw mechanism to turn the rotor into the wind. The VAWTs can be of three types: Savonius, Darrieus and H-Rotor type as shown in Fig. 10. The Savonius is a drag-type turbine and is the least efficient of the three vertical types, on the other hand the Darrieus is complicated to manufacture and can suffer from starting problems. The H-rotor is a derivative from the

Darrieus and requires less complex control. To date, the HAWT remains the most popular turbine due to its greater efficiency and ease of control.

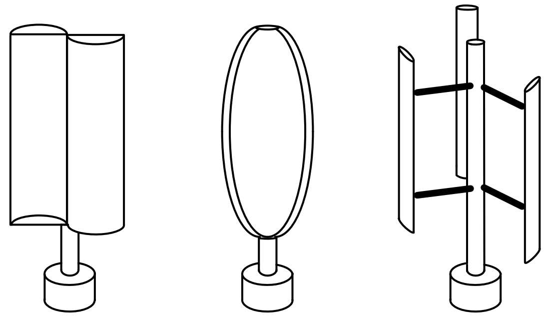

Fig. 10: Types of Vertical Axis Wind Turbines

3.2 Converter Topologies for Micro-Wind Turbines

Micro wind turbines normally make use of a PMSG as the means of converting the mechanical rotational power into electrical power. As identified before, the main advantage of this type of electrical machine is that the magnets on its rotor provide the magnetic field (self excitation). Although there can be plenty of power converter topologies used for PMSG power extraction and transfer to the electrical grid, the two most common systems set-ups follow those of Fig 7 and Fig 8. In the case of the latter figure, for a small wind turbine there is no gear box or pitch control, moreover for both figures, the connection to the grid is generally at low voltage, single phase and not three phase.

The most common set-up found in commercial micro-wind systems consists of a diode-bridge rectifier, a boost converter and a voltage source converter (VSC) as shown in Fig 8. The rectifier converts the PMSG three phase output into a DC voltage and the boost converter is used to control its power operating point. A braking chopper is installed on the DC link to limit the voltage during wind gusts and grid faults. The grid-connected inverter is a current controlled VSC which transfers power to the electrical grid.

For micro-wind applications, the set-up shown in Fig 7 is more expensive than that of Fig 8 however it allows for better generator speed control and higher quality of the machine’s currents [15]. This system consists of two back-to-back converters which allow bidirectional power flow. The machine-side converter acts as an active rectifier and can be controlled to achieve a sinusoidal current output from the generator which is of superior quality to the non-linear output current achieved by the rectifier in Fig 8. The DC link voltage needs to be higher than the peak of the grid voltage at all times, this voltage is kept constant by proper control of the grid-side converter.

4. Control of FRC PMSG based Wind Turbines

The FRCs shown in Fig 11 and Fig 12 make use of a machine-side and a grid-side converter. Both converters have their own individual control; this section shall focus mainly on common methods of control of the machine-side converter.

In Fig 11, assuming a fixed or zero pitch angle, the maximum power point tracking (MPPT) strategy uses a wind speed reference to determine the optimum tip speed ratio for maximum power coefficient (Fig 1). From this ratio the optimum rotational speed of the generator’s rotor can be deduced, this type of control is sometimes called Tip Speed Ratio Control [15,16]. The wind speed can be directly measured or estimated. The outer speed loop is used to determine the torque current reference (I_q^*). The other current, (I_d^*), also known as the field current, is used for field weakening however this is normally set to zero. Using field oriented vector control, the two dq-current demands are used as reference for the inner current control loops which generate the V_d and V_q references. These are transformed to the equivalent three phase reference voltages (V_a,V_b, V_c) which control the machine-side converter.

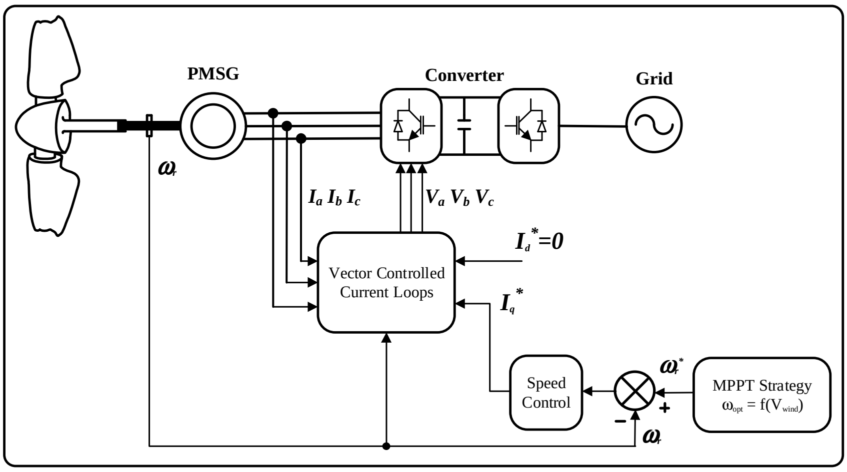

Fig. 11: Tip Speed Ratio Control of PMSG side inverter

The second type of control shown in makes use of a predetermined wind turbine power curve. During commissioning this curve is derived as a function of the rotor angular speed (rather than the actual wind speed) and stored in a look-up-table (LUT). This eliminates the need of wind speed measurement or its estimate. The output of the LUT gives the maximum power point value for a given rotational speed, which is used to obtain the torque current reference (I_q^*) as shown in Fig 12. As in the former case the field current (I_d^*), is normally set to zero.

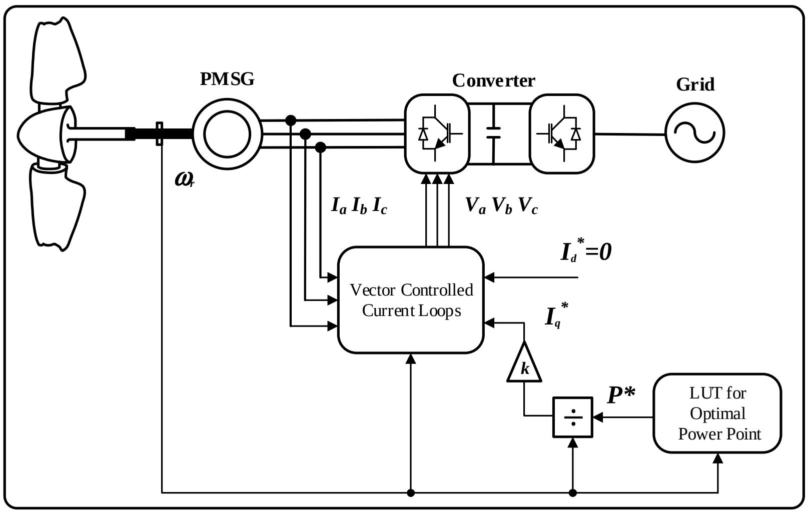

Fig. 12: Power Control of PMSG side inverter

Although not shown in Fig 11 and Fig 12, the grid-side converter also requires a control mechanism. This converter allows for the flow of both active and reactive power to the grid.

The grid-side converter control scheme ensures that the DC link voltage remains constant and at the same time controls the converter to absorb/produce grid reactive power whilst allowing the maximum active power to be supplied to the grid.

4.1 Control of Small Scale Wind Turbines

The control strategies described previously apply to both small and large scale wind systems. However due to cost considerations, strategies that require the use of speed or wind sensors are not usually applied. The common configuration for commercial systems is the set-up shown in Fig 13. The rotational speed of the PMSM is controlled indirectly through variation of the DC link voltage (V_{dci}) at the input of the boost converter. A LUT is used to map the optimal DC link voltages to output power levels. During operation, the output power is measured and used to select the optimal setting of the dc link voltage. This is then forced through the controller, which adjusts the duty ratio of the boost converter as shown in Fig 13. The variation in the input DC link voltage causes the rotor to accelerate or decelerate accordingly until the operating point converges to the maximum power point (MPP), where the power output and the set DC link voltage match.

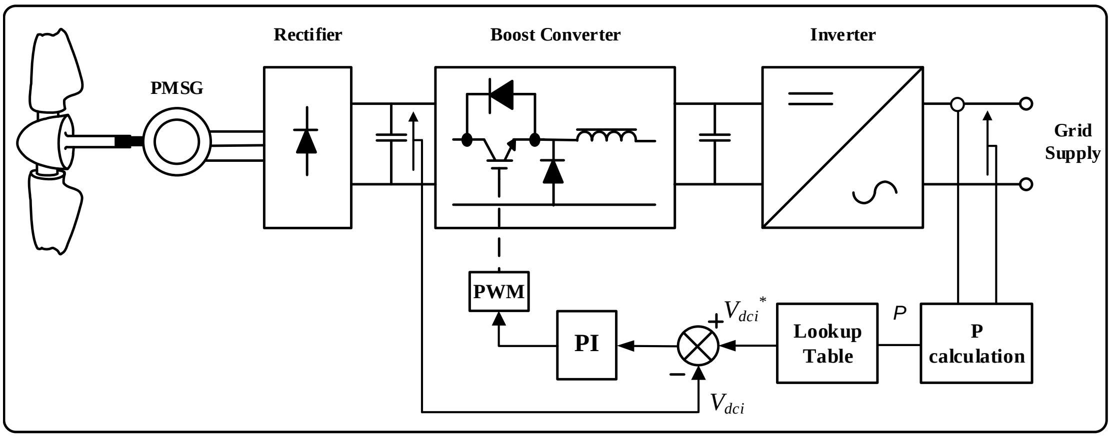

Fig. 13: MPPT Control of Boost Converter for Single Phase Micro Wind Turbine System

Another control strategy that can be applied on the topology of Fig 13 is the Hill Climb Technique. The technique continuously searches for the MPP condition by introducing small perturbations in the DC link voltage set–point and the resulting output power is compared to the previous value. If there is an increase in power, the perturbations are continued with the same polarity, otherwise their polarity is reversed. This process is shown in Fig 14. It can be observed that starting from both sides of the desired point leads to small changes in the rotational speed until subsequent convergence at the MPP. Refinements to the algorithm include the use of variable perturbation to avoid oscillations around the desired operating point. This technique is based on the assumption that although the wind varies highly with time, the generated power varies slowly because of the dynamics of the wind turbine and interconnected generator [17]. The same topology as shown in Fig 13 can be used, where the reference for the dc link voltage is obtained through the algorithm instead of the lookup table.

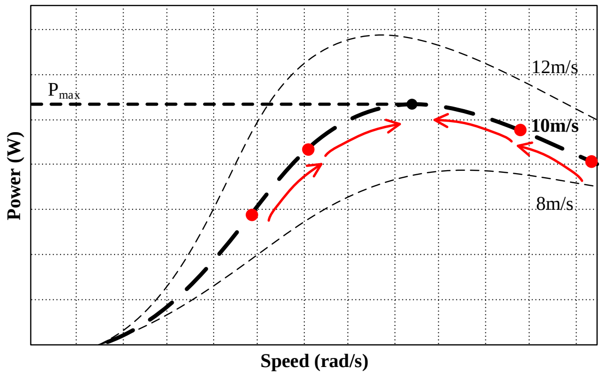

Fig. 14: Hill Climb Technique

5. Conclusion

This paper presented a review of the power electronic configurations for large and small scale wind energy systems. The paper described the basics of wind energy conversion, how to obtain the maximum power point according to the wind speed and tip speed ratio and how this can be implemented in practice. The paper also discussed the difference between geared wind turbines and direct drive systems using partially and fully rated converters. The different types of small scale horizontal and vertical axis wind turbine configurations and the difference in their performance were described briefly. To conclude, a description of the commonly used fully rated power converter topologies and the control mechanisms for permanent magnet synchronous generator based wind turbines were presented.

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