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Review Article

Control Aspects for PMSG-Based Grid-Connected Wind Energy Conversion System- A Review

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Abstract *- Wind energy provides environmentally friendly and cost-effective power generation to meet the electricity demand across the country. This paper focuses on the power converter topology, control methodology, sensorless control strategy, and various methods used for maximum power extraction in a wind power conversion system based on a direct-drive permanent magnet synchronous generator. It also briefly reviews generator grid inner connection problems such as PMSG's frequency deviation, low voltage ride through, capacitor sizing, DC-link voltage fluctuations, and output power smoothing issues. The primary focus of this paper is to understand the optimal strategy for reducing frequency deviation in Wind Energy Conversion Systems (WECS), including both islanded and grid-connected modes, and optimize the capacitor size used.*

Keywords *- Frequency control system, Sensorless control, Maximum Power Point Tracking, Power converter control, Direct-drive permanent magnet synchronous generator, Virtual inertial support, Synchronous Reference Frame-Phase Locked Loop.*

1. Introduction

The rapid reductions in fossil fuels and environmental concerns have attracted primary concern due to electricity generation from renewable energy sources. Out of all the renewable energy sources, wind power is gradually catching up to conventional energy sources in popularity. Technological progress, cost reduction, and government incentive programs have mainly driven this inclination. The installed capacity of global wind energy reached up to 837 GW in the year 2022. In India, the total installed capacity of wind power generation is 41.93 GW, and solar power generation is 63.30 GW (as of 31st December 2022) [1]. The Squirrel-Cage Induction Generator (SCIG) is the base of the initial generation Wind Turbine System (WTS). For a seamless connection of the generator to the utility grid, the Power Converter (PC) is used as a soft starter. This system poses several substantial difficulties, including the need for an obligatory soft starter, the need for reactive power correction, and low-speed restrictions (one percent of synchronous speed).

Table 1. Types of WECS configurations [2, 3]

WECS	Advantages	Disadvantages
Type-1: WECS with SCIG, fixed-speed (±1%)	Simple, low initial cost, reliable operation, robust	Fixed wind speed, low energy conversion efficiency, additional hardware required for speed variation, high mechanical stress, and high power fluctuations
Type-2: WECS with WRIG, semi-variable speed (±10%)	High conversion efficiency, low mechanical stress, improved power quality	Rotor resistance loss, for reactive power correction soft starter used, converter losses, and cost, complex control system
Type-3: WECS with DFIG, semi-variable speed (±30%)	Enhanced dynamic performance, high energy conversion	Fault Ride-Through (FRT) is limited and requires regular maintenance
Type-4: WECS with SCIG, PMSG, or WRSG, fully variable speed (±100%)	The full-speed operation, FRT compliance without any external hardware	Full capacity converter, size, cost, and complexity

Numerous drawbacks, including low energy output under various wind speed conditions and significant stress on the turbine drive train, are associated with the restricted speed range. WECS has two principal parts: a wind generator and a converter. In this manuscript, four WECS configurations have been studied with the help of these two parts [2]. Table 1 shows the types of WECS configurations with their advantages and disadvantages.

Based on WRIG, a second-generation WTS is developed to address the above issues of first-generation WTS. To expand the speed limit to around 10% around synchronous speed, a small power converter is utilized in the rotor circuit to modify the rotor winding resistance. Due to variations in rate, a soft starter is necessary to regulate the reactive power.

To address the above issues, third-generation WTS was developed, where electricity is fed into a utility grid through both rotor and stator windings, thus using a Doubly-Fed Inductor Generator (DFIG). However, the convenient terminology has the same architecture as a WRIG. The wind energy sector mainly utilizes DFIG WT (over 50%). Slip power is converted by the power converter in a rotor circuit to enable variable-speed operation at a speed of about ±30% higher than synchronous speed.

A utility grid can be connected smoothly with the generator without a soft starter. Without any external reactive power correction devices, the power factor in the wind farm at the point of standard coupling is automatically adjusted. The fourth-generation WT is designed to operate at varied speeds across the whole wind speed range. It is named PMSG. The use of PMSG has several advantages, such as low maintenance, variable speed operation, high power density, and high precision.

The absence of a gearbox increases reliability. The PMSG wind power system may be connected to the grid through a bidirectional power flow Back-to-Back converter (BTB). As a result, the power converter's capacity increases from 30 to 100 percent.

The speed range of a full-scale power converter is 0 to 100 percent. These turbines have the highest energy yields. Research in turbine control has also been advancing at a high rate in recent years because of the increasing penetration of wind energy in electric power systems. Y. Errami et al. have operated the non-linear back-stepping approach of the Wind Farm (WF) driven Direct Drive Synchronous Generator (DDSG) for standard and voltage drop conditions [4]. For turbine and generator systems, variable pitch control and variable speed operation are developed to improve the efficiency and reliability of power generation systems. Most installed wind turbine generators are in the 1.5 to 5MW category, with gear drives DFIG-based WTs continuing to dominate the markets. Z. Q. Zhu et al. have a target of 5 to 10MW level [5] for large systems. For offshore wind farms, DD-PMSG with a full-capacity power converter has shown to be a more efficient choice than a DFIG-based system.

1.1. Comparison between PMSG & DFIG and their Limitations

In DFIG, reduced-capacity converters are used. A multistage gearbox is necessary. But in PMSG, full-capacity converters are used. By employing a large number of poles, the gearbox may be removed, allowing for greater efficiency. However, PMSG and DFIG-based WECS have many advantages and limitations; Table 2 compares PMSG and DFIG.

DD-PMSG has low maintenance costs, complete decoupling from the grid, wide speed limits, and increased fault-riding capability through operations.

2. Variable Speed Wind Turbine-Based Generator

Nowadays, PMSG is widely used as a generator in VSWTs. Mathematical Modeling of PMSG WECSs has been commonly discussed in the literature [2-5, 7].

2.1. Modeling of Wind Turbine

The shaft of a wind turbine drives a generator, which converts mechanical energy into electricity. The output power characteristics are used in the turbine model.

$$P_m = C_p\ (\lambda\ ,\beta).\tfrac{1}{2}\ \rho\ A v_w^3 \qquad (1)$$

$$\lambda = (\mathrm{R_{blade}} * \omega_r)/\mathrm{v_w}$$

The wind speed determines the mechanical output power in watts (Pm) (v_w), the performance coefficient (C_p), air density (ρ), and the turbine swept area (A). The kinetic energy in the air at a given speed v_w is equal to $\frac{1}{2}\ \rho\ A v_w^3$. The performance coefficient C_p (λ, β) defines how much of the kinetic energy of the wind can be collected by the wind turbine system and is dependent on the tip speed ratio λ and blade pitch angle β. $C_p\ (\lambda,\ \beta)$ is described by a non-linear model as follows:

$$c_p\ (\lambda\ ,\beta) = c_1(c_2 - c_3\beta - c_4\beta^2 - c_5)e^{-c_6} \qquad (2)$$

Here, c_1=0.5, c_2=116/ λi, c_3=0.4, c_4=0, c_5=5, c_6=21/ λi,

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\ \beta} - \frac{0.035}{\beta^3 + 1} \qquad (3)$$

R_{blade} and ω_r represent the blade radius and angular frequency of the turbine.

Table 2.Comparison between PMSG & DFIG [6-8]

S. No.	Part/Parameters	PMSG	DFIG
1	Gearbox	Not required	It requires a bulky multistage gearbox, which generates lots of noise, mechanical losses, and mechanical loading.
2	Excitation current	It has a self-excitation system	Needs excitation current
3	Maintenance cost	low	high
4	Control methodology	simple	complex
5	Controllability of the system	full	partially
6	Overall efficiency, reliability	Both high	Both low
7	Operating range	Wide operating range	Limited operating range
8	FRT capability	Capable	Not capable
9	The capacity of power converters	The full-capacity converter (full-scale converter)	The capacity of the power converter is up to 30% (partial scale converter)
10	Speed	Operates at low and high speed	Only on high speed
11	Torque-to-weight ratio	High	Low
12	Power flow	Bidirectional power flows are obtained by inserting converters with nearly 120% generator rating between the stator and grid.	Bidirectional power flow is obtained by inserting converters with nearly 50% generator rating between the rotor and grid.
13	THD	Low	High
14	Grid side transformer	Less bulky	Bulkier
15	Blade diameter	It allows small blade diameter	It does not allow small blade diameter
16	Reactive power	Able to absorb/provide sufficiently	Able to absorb/provide limitedly
17	Grid code	Less limitation on grid code	Grid code limitation
18	Power factor	During start-up, it does not use grid current for magnetizing purposes	Low power factor problem because It obtains magnetizing current from the power grid
19	Installation cost	High	Low
20	Power converter losses	High	Low
21	Generator cost and size	High & heavy	Low & less bulky
22	Synchronization and voltage regulation at start-up	It could cause issues with synchronization and voltage regulation during start-up	No problem
23	Control of rotor flux	No control of rotor flux	It has a rotor flux control
24	Demagnetization of permanent magnets	Possible demagnetization of permanent magnets	No

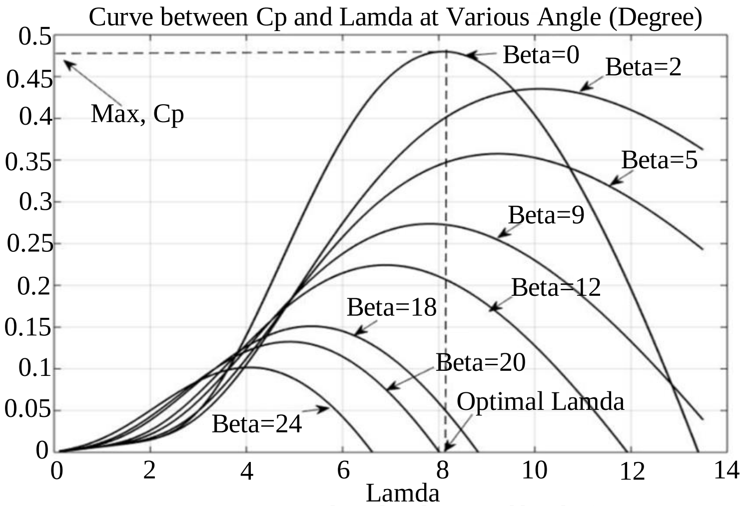
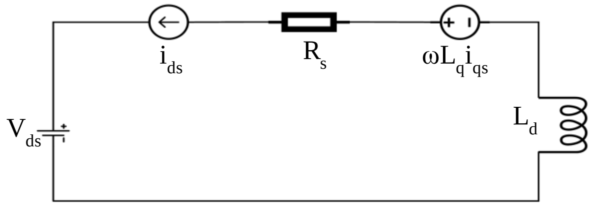


Fig. 1 At various pitch angles, the Cp and lamda (λ) curve

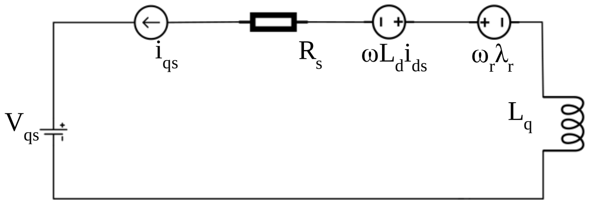
Figure 1 depicts the C_p-λ curve for this specific turbine type at various angles β, illustrating that to attain maximum C_p, at angles of $\beta = 0°$ and $\lambda = 8$.

2.2. *Mathematical Model of the Permanent Magnet of Synchronous Generator*

The *d-q* model of PMSG is extracted from the steady-state equation through vector space representation. The equations explain the d-q model of the PMSG, and Figure 2 depicts the analogous circuit for the PMSG d-q model.



(a) d-axis circuit



(b) q-axis circuit

Fig. 2(a, b) d-q model of PMSG in synchronous reference frame [2]

$$V_{ds} = -R_s\, i_{ds} + \omega_r L_q i_{qs} - L_d \frac{di_{ds}}{dt} \quad (4)$$

$$V_{qs} = -R_s\, i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q \frac{di_{qs}}{dt} \quad (5)$$

The model works for synchronous generators, including both salient and non-salient poles. The dq-axis synchronous inductances, L_d & L_q are the same for non-salient generators but differ for salient-pole generators. PMSG has a smaller d-axis synchronous inductance than the q-axis $(L_d < L_q)$.

The electromagnetic torque produced by the generator is,

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \{L_d - L_q\} i_{ds} i_{qs}\right] \quad (6)$$

The motion equation determines the rotor speed ω_r.

$$\omega_r = \frac{P}{JS} * (T_e - T_m) \quad (7)$$

For dynamic simulation of the generator, equations are rearranged.

$$i_{ds} = \frac{1}{S}(-V_{ds} - R_s\, i_{ds} + \omega_r L_q i_{qs})/L_d \quad (8)$$

$$i_{qs} = \frac{1}{S}(-V_{qs} - R_s\, i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r)/L_q \quad (9)$$

Where,

V_{ds}& V_{qs} : Stator voltages on the *d* & *q* axis.

i_{ds} & i_{qs} : Stator currents on the *d* & *q* axis.

λ_r& P : Rotor flux linkage, no of pole pairs, respectively.

ω_r & R_s : Rotor speed and stator winding resistance, respectively.

L_d& L_q : d and q axis synchronous inductances, respectively.

T_e& T_m : Electromagnetic torque and mechanical torque, respectively.

J & S : The moment of inertia & Laplace operator, respectively.

$\frac{1}{S}$: Represents an integrator.

3. Power Converters Used in Direct Drive PMSG

The power electronics converters adapt the generator to the grid's needs for frequency, voltage, active and reactive power, and harmonics [6]. Variable speed operation of PMSG WT systems includes two-level and multilevel converters. Open switch faults in the converter are increasing due to short circuit faults causing the IGBT rapture. As a result, maintaining the DC-link voltage of the power converter is difficult. Active power dissipation methods based on DC chopper technology can be used to sustain the DC link. Due to their low cost, great reliability, and ease of control, a 3-ϕ diode-rectifier and boost converters are often utilized for small-scale application WECS [7].

The voltage frequency controller is realized using two BTB-connected VSCs and one BESS. A high-pass RC filter is attached to the PCC to absorb the GSC's switching ripples. For load levelling, the battery is utilized on the DC link. PMSG concepts have been recently proposed without power converters between grids and generators. Power converters for PMSG WTs are mainly categorized into direct and indirect [8].

Indirect power converters utilize two-stage (AC/DC-DC/AC) or three-stage (AC/DC-DC/DC-DC/AC) power converters. In contrast, direct power converters use single-stage (AC/AC) power converters. It is again divided into Low-Voltage (LV) and Medium-Voltage (MV) systems, which are based on the output voltage level of PMSG [9]. The exciting power converters for MV and LV PMSG systems are four types shown in Figure 3.

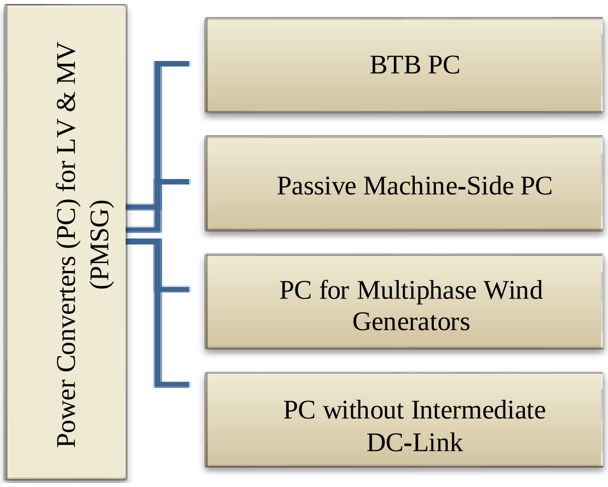


Fig. 3 Block diagram of Power Converters for LV & MV (PMSG)

3.1. Low Voltage Converters for PMSG

The low-voltage converter is effective at less than 3 MW. Because the power flow is bidirectional, PMSG can use Back-to-Back converters (BTB). Due to its higher performance, the BTB-linked converter architecture is ideally suited for grid-integrated variable-speed wind turbine systems. Low voltage >1 kV and medium voltage 1–35 kV are the two types of BTB converters. Low voltage grid Connections are 575 V and 690 V. The DC link capacitor makes decoupling the generator from the grid possible. As a result, the generator's transition is not apparent from the grid side. A common setup for all converters might be the DC-link to reduce cost and space. On the generator side, passive converters can be used instead of PWM active converters to make the system less expensive and complicated. PWM converters are intrinsically less reliable than diode rectifiers.

A diode rectifier, a two-level boost converter, and a two-level boost inverter are included in the PMSG for enhanced controlled independence. The boost converter enhances the uncontrolled DC voltage to a high level that can be used in a two-level voltage source inverter [6, 9]. The construction and control of the Two-Level Rectifier (2L-VSR) and Two-Level Voltage Source Inverter (2L-VSI) are identical. The wind industry supports distributed converters and multi-phase PMSG to boost power handling [2]. Multi-phase PMSG reduces the circulating current due to the harmonic filter's inherent electrical isolation in the winding.

3.2. Medium Voltage Converters for PMSG

For turbines with outputs more significant than 3 MW, WECS's MV operation is the most cost-effective, reliable, and suitable option. In [10], a comprehensive cost comparison was made between WT's LV and MV operations. According to the findings, MV operating reduces energy output costs by 2% to 4%. A two-level VSC can also be used for MV applications.

In the literature, BTB-linked Neutral Point Clamped (NPC) converters have been commonly employed [11]. Up to 6 MW and 3-4 kV voltage levels, BTB and NPC converters can be used without connecting switching devices in series or parallel. In high-level applications, multilevel methods based on H-bridge or neutral point clamping are commonly utilized. The NPC converter has a problem controlling neutral point voltage. External hardware can be used to ensure equal voltage between DC link capacitors.

A matrix converter is an AC/AC conversion system that does not require a storage capacitor in the DC stage, resulting in a unity power factor for any load [6]. For MV-PMSG WT, the Modular Multilevel Converter (MMC) is promising because of its compact size, modular construction, transformer-free operation, and excellent efficiency. A Current Source Converter (CSC) can be employed with MV PMSG. The three-stage boost converter controls maximum power extraction and neutral point voltage.

4. Control of PMSG Wind Turbines and Wind Farms

Various control schemes for the PMSG conversion system of the wind turbine, generator, grid integration, and protection system are specified. Figure 4 shows the schematic of grid interconnection with control schemes.

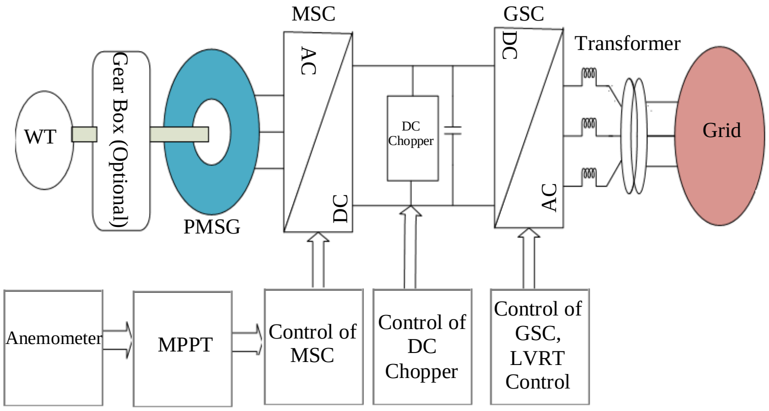


Fig. 4 Schematic of grid interconnection

4.1. Power Converter Control

Controlling converters, energy conversion systems, and variable speed drives with classical control techniques are well-established and widely used. Classical control methods include hysteresis and linear control with modulation. Hysteresis control is a non-linear control approach [2]. Hysteresis current control is one of the simplest and most reliable approaches because it involves no system settings, converter model, or previous user knowledge. The machine's back electromagnetic force, the converter's switching frequency, the load time constant, and the amount of DC-link voltage all impact the dynamic response time in this method. Direct Power Control (DPC) and Direct Torque Control (DTC) are sophisticated forms of hysteresis control.

The drive system's torque and flux are regulated in DTC, but the grid's active and reactive powers are directly controlled in DPC. Hysteresis controllers generate error signals. After that, switching signals for the converter are produced using a lookup table using the relative magnitudes of these error signals.

The linear control uses a cascaded control mechanism to linearize the non-linear power converter. The linear control system uses Pulse Width Modulation (PWM), Space Vector Modulation (SVM), and Selective Harmonic Elimination (SHE) with a fixed switching frequency determined by the carrier frequency. For power converters, Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) are typical modulation schemes. Due to its more excellent harmonic profile and more effective DC bus utilization, SVM is preferred to SPWM. The propagation of the harmonics spectrum can lead to resonance in some power converters because of the changeable switching frequency.

The power converter is treated as a linear model with PI controllers in the linear control with modulation stage. The motor torque and flux are controlled in a decoupled manner using Field-Oriented Control (FOC). This approach involves a modulation stage, two d-q-axis PI controllers, and reference frame transformations. The grid-connected converter is controlled using Voltage-Oriented Control (VOC), similar to FOC. In a decoupled way, VOC is used to manage the net DC-bus voltage and reactive grid power. In this method, the grid voltage harmonics degrade the control performance. Using linear and hysteresis control approaches, including system limits and technical requirements in the control scheme design, is difficult.

Vector control is commonly used to control Machine Side Converter (MSC) and Grid Side Converter (GSC) using traditional PI, fuzzy, sliding mode control, and many controllers such as port-controlled Hamilton systems, wavelets, neural networks, and feedback linearization, and many more. The converter's role (MSC and GSC) depends on the operating conditions, such as MPPT and LVRT power oscillation damping. To comply with the grid code, the GSC regulates the DC link voltage and reactive power flow to the grid.

The MSC controls the PMSG output power/torque through the stator current regulation [12]. The rectifier and inverter are isolated via a simple DC-link or an intermediary DC/DC buck-boost or boost converter to improve system reliability [6]. Due to the delay in detecting grid disturbances and the inertia of the control system, the MSC cannot immediately react to a grid fault, and the Vdc may exceed the upper limit of the initial tens of milliseconds after grid disturbances. As a result of the MSC and GSC control functions being inverted, the converter must be configured differently. So, the conversion process's failure risk rises.

A feedback linearization controller for the direct-drive synchronous generator at GSC improves the function of traditional linear current controllers, allowing them to keep current levels within design limits even when the voltage sag is significant. A PMSG that runs at maximum torque per ampere is extremely efficient, resulting in minimal losses in the generator winding voltage source converter. It also leads to a reduction in the total V_{dc} rating. A low switching frequency operating in power converters is required at the high-power level to reduce switching losses and provide appropriate heat dissipation.

4.1.1. Machine Side Control in DD PMSG

FOC and DTC are standard machine-side control methods for the PMSG. For industrial drives, the FOC is generally preferred due to its simplicity. The FOC uses one outer-loop speed controller and two inner-loop current controllers to implement the synchronous reference frame concept. Zero d-axis Current (ZDC) and Maximum Torque Per Ampere (MTPA) control are used in the FOC.

Figure 5 shows the schematic diagram of the FOC zero d-axis control. The angle between the stator current vector and the rotor flux vector in the ZDC technique should be 90 degrees. To achieve that, the d-axis reference current (i_d^*) is zero and does not contribute to the torque production. In contrast, the q-axis reference current (i_q^*) is to be determined by the MPPT controller.

As a result, the magnitude of the stator current determines the generator torque. Typically, the ZDC approach controls the SPMSG with Id* =0. In contrast, the MTPA method controls the Interior Permanent Magnet Synchronous Generator (IPMSG) to provide the maximum torque with the least stator current. Because of surface-mounted multi-pole PMSGs are more accessible to manufacture and less expensive than IPMSGs, they are used in WECS and have identical inductances in the SPMSG.

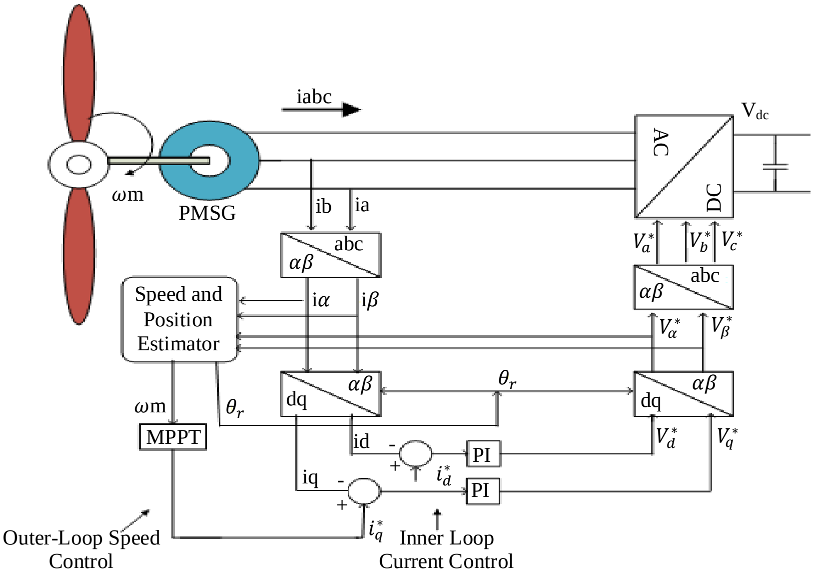


Fig. 5 Schematic diagram of sensorless FOC zero d-axis control for PMSG WECS

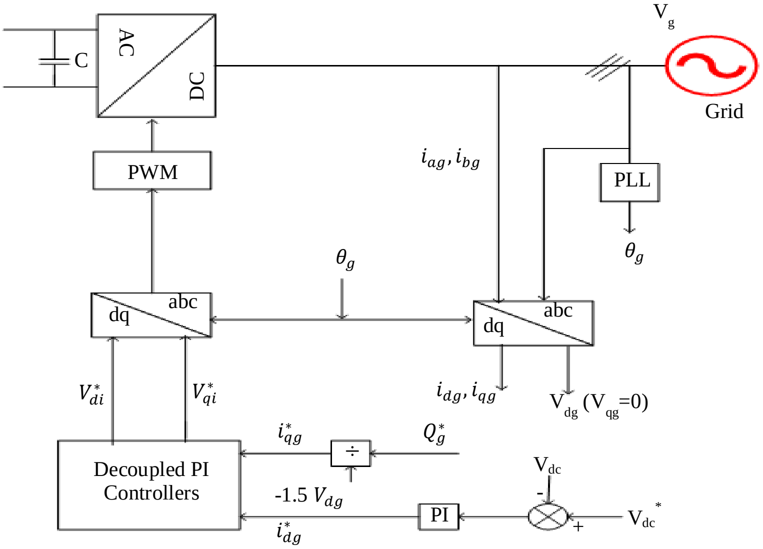


Fig. 6 Schematic diagram of GSC control in PMSG WECS

4.1.2. Grid Side Control in DD PMSG

Classical control methods of grid side control for the PMSG are VOC and DPC. Grid voltage orientation is used in both control systems, in which the synchronous reference frame's d-axis aligns with the grid voltage vector, resulting in zero grid voltage on the q-axis. In the PMSG wind turbine, the GSC maintains the net DC-link voltage and grid reactive power at these reference values. The DC link voltage and reactive power in the VOC are controlled by regulating the d-q axis grid currents [9]. VOC is similar to FOC in that the external control loop incorporates reactive power and DC link voltage control utilizing observed grid voltage. Figure 6 illustrates the grid-side control of PMSG, where PLL produces the grid voltage angle.The grid phase voltage multiplied by 3.06 is the reference DC link voltage, which provides a 20% margin for adjustment in the modulation index during the transient period [2]. Grid active and reactive powers are regulated by a lookup table and hysteresis comparator in the DPC approach, which is identical to DTC.

4.2. Maximum Power Point Tracing (MPPT) Techniques

The purpose of the MPPT method is to provide reference electromagnetic torque speed so that the machine side converters follow the Maximum Power Point (MPP) curve [13]. The two basic categories are wind rotational speed and sensorless control. Authors have also carried sensorless adaptive MPPT methods for small-sized PMSG wind turbine systems without anemometers [7]. Due to various features, such as the primary input of the techniques, pre-information of the wind turbine, the requirement of memory, controlling difficulty, controlling efficiency, and cost, the MPPT techniques vary. It can produce peak power at any wind speed. A brief description of several MPPT control techniques is as follows:

4.2.1. Tip Speed Ratio Control (TSR)

It is the simplest method widely used in the WECS industry. It does not require the wind turbine power characteristic. The MPPT control works effectively in different wind circumstances since the generator's wind speed is proportionate to the observed wind speed. The speed sensor increases the system's cost and complexity [3, 13, 14]. Because ultrasonic sensors give more precise and dependable wind speed information, they are promising for this control.

4.2.2. Power Curve-Based Control

The power versus wind speed curves are used in this method. This wind turbine power control measures the reference power at different wind speeds. Because both employ wind speed sensors, wind turbine Power Curve-based Control (PCC) is comparable to TSR control.

4.2.3. Optimal Torque Control (OTC)

Previously, costly wind speed sensors were used, and the data obtained was not always reliable. The generator speed sensor is used instead of the wind-speed sensor. In commercial wind turbine systems, the TSR and OTC control approach is commonly utilized.

4.2.4. Power Signal Feedback Control

This approach combines the properties of a wind turbine power curve and OTC techniques. The generator speed sensor is used instead of the wind speed sensor, and reference power is calculated using power curves. The Power Signal Feedback Control (PSFC) calculates the reference power using the measured generator speed.

4.2.5. Generator Signal Feedback Control (GSFC)

The reference generator speed is calculated using the generator output power computed. It's comparable to the optimal torque control method and tip speed ratio.

4.2.6. Speed Sensorless Control (SSLC)

It removes the requirement for wind and generator speed sensors. The wind speed is estimated using the WECS's autoregressive statistical model based on the measured generator frequency in this method.

The reference power is calculated in the same way as the wind turbine power curve based on the turbine power against the wind speed curve once the wind speed has been predicted. Based on the expected wind speed, achieving sensor-less optimum tip speed ratio control is also feasible. Although this method eliminates the requirement for speed sensors, it does raise the MPPT control's overall complexity.

Table 3 gives a comparison of various control methods for MPPT control. TSR and OTC are primarily used in industry and are more straightforward than all other methods [7, 9]. Fast-tracking MPPT algorithm uses a matrix converter for a wind energy conversion system. Currently, the maximum power tracker changes the rotating speed to maximize the output power of the wind turbine. The active and reactive power flows in this system are bidirectional. The isolated power generator regulates the amplitude and frequency of the load voltage, harmonic removal, and load balancing.

For the generator-side voltage source converter, MPPT is achieved using the OTC method. Inertial support is provided by extracting the accumulated kinetic energy from the spinning mass of the WT. Mechanical stress might increase when the wind turbine generator's MPPT curve is diverted to an inertial support curve operating in a suboptimal Power Point area [16]. The traditional droop control is used in both grid-connected and islanded operating modes. However, there is no support for MPPT during regular operation; instead, it uses a grid synchronization mechanism. TSR and OTC control methods give the optimum balance of complexity and performance. However, the WECS industry often uses sensorless control.

Table 3. Comparison of various control methods for MPPT control [14]

Features	TSR	PCC	OTC	PSFC	GSFC	SSLC
Primary Input	V_w	V_w	ω_m	ω_m	$V_s I_s$	f_s
Pre-Information about Wind Turbine	No	Yes	Yes	Yes	Yes	Yes
Requirement of Memory	No	Yes	No	Yes	Yes	Yes
Controlling Difficulty	Very less	Medium	Less	Medium	Medium	High
Controlling Efficiency	Highest	Highest	High	High	High	Moderate
Cost	More	More	Moderate	Less	Less	Very less

5. Sensorless Control Techniques

If the Sensorless method is adopted, the SPMSG will become more popular globally. It is possible to avoid problems such as electromagnetic interference in position signals and sensor failures. The DD-SPMSG wind power conversion system increases reliability and reduces maintenance requirements [5]. MPPT requires the generator's speed, measured through a mechanical sensor. The motorized sensor is noisy, has maintenance problems, and is unsuitable for an extended period. Figure 7 displays many generator speed-based approaches to make SPMSG sensorless for obtaining position and speed [15].

The fundamental model-based sensorless control technique is the most efficient for high and medium generator speeds. Voltage or current variables are utilized to estimate the back EMF or flux. Generators with low pole pairs are used in this method. If this method is used for low-speed operation, the rotor angle collapses drastically because of variations in machine parameters. The generators used in saliency tracking-based sensorless control systems often include extremely high pole pairs appropriate for low speed and a standby generator. The fundamental PWM excitation and High-Frequency (HF) signal injection techniques are used in saliency-based sensorless control systems. However, the HF signal injection method is challenging with specific oscillations and power loss from the controller [17].

Due to restrictions on control time, the bandwidth limit can only be slightly extended in the fundamental PWM excitation approach. The step load state provides highly reliable results [15]. The two approaches mentioned above are widely used for commercial and industrial reasons. Using various strategies, several researchers worked to create sensorless systems. Typically, the arctangent function is used to establish the state of position using stator flux component estimations.

However, the presence of harmonic noises hampers the estimation accuracy. Sreejith et al. used the Sliding Mode Observer (SMO) approach based on a Dual-Second-Order Generalized Integrator Frequency Lock Loop (DSOGI-FLL) for sensorless speed and position estimation. Noise occurs in the picture because of the presence of SMO [18].

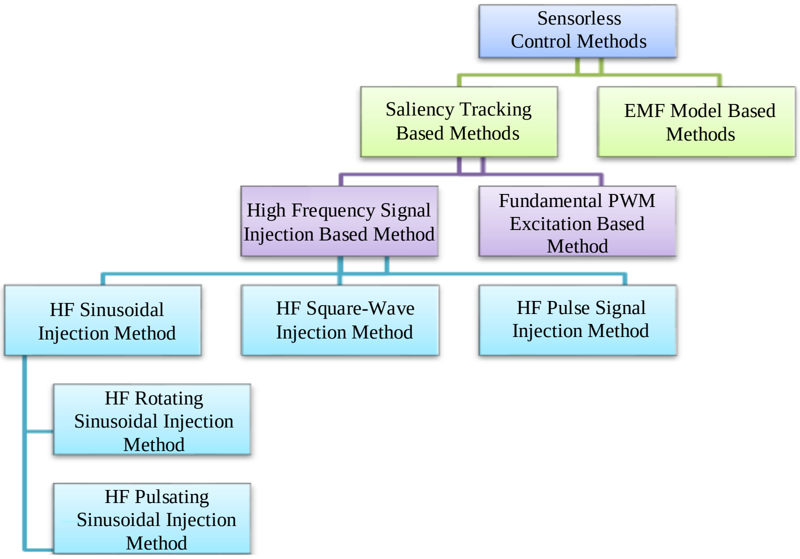


Fig. 7 Sensorless control methods for SPMSG

To mitigate this noise, a Synchronous Reference Frame-Phase Locked Loop (SRF-PLL) estimates speed and angle. The SRF-PLL performs best in non-linear and distorted circumstances. The Second-Order Generalized Integrator Quadrature Signal Generator (SOGI-QSG) is a widely utilized and reliable tool for estimating the system's frequency. However, a low pass filter on feedback is necessary to stabilize the system in the transient situation since stability is somewhat compromised. The filtered signal becomes harmonic-free when SOGI-QSG is used. The grid frequency is extracted using a SOGI based on PLL and FLL. The grid frequency is extracted using a Modified SOGI (MSOGI) version, which can also remove the DC offset present in SOGI-QSG-based PLL and FLL systems [19].

A direct DSOGI-PLL is used to improve the performance of the PLL when the grid voltage is unbalanced or asymmetrical. To remove the negative sequence current and keep the output power constant, the active/reactive current decoupling method is utilized; it is based on positive and negative sequence voltage orientation. Gating pulses for the VSC and actual recent extraction are provided using an Improved Third-Order Generalized Integrator-based control method (ITOGI). Control parameters are determined by adopting the pole-zero plot technique. This method has improved dynamic performance for both higher and lower-order harmonics [20].

Low pass filters are used to mitigate harmonic load, but they generate errors due to time delays. Therefore, SOGI is used to eliminate the time delay, but it does not remove the DC offset component in load currents. It is introduced during dynamic load fluctuations. A TOGI-based control may eliminate the DC offset present in the load current and filter harmonics components [21]. It is a notch filter with minimum attenuation for the DC offset current component. A fourth-order generalized integrator combined with two Second-Order blocks (SO-SOGI) effectively reduces the DC offset component but cannot remove lower-order harmonics. So, ITOGI is better because parameter selection is made through pole-zero plots.

A Strengthened Dual Third-Order Generalized Integrator (SDTOGI) using the SRF-PLL method is presented for estimating the position and speed of the observed stator current of the generator. It requires less settling time to attain the estimated speed. It enhances system stability more than others.

6. LVRT Control of PMSG Wind Energy Conversion System

Disconnection of large-scale wind turbines and wind farms can be caused by grid disturbances such as grid voltage sag/swell. Due to its capability and flexibility in active and reactive power regulation with a full-capacity converter, the PMSG-based wind power conversion system is appropriate for LVRT. Many countries have established new grid codes to ensure the safe operation of the electrical system. The essential grid code is LVRT, which supports wind turbine operation during grid faults and provides reactive power support according to grid voltage sag. Grid codes are described by voltages, indicating the minimum time required to connect during system voltage dips.

The instability of PMSGs usually results in severe grid fault conditions due to the limited LVRT capability of PMSGs. During voltage sag, the grid voltage drops below 0.9pu, and the LVRT function must commence within 20ms (one cycle) and deliver 1pu reactive power for grid voltages between 0.5 and 0.6pu; for every 1% voltage drop, the WECS requires 2% reactive current.

External devices can improve the PMSG's LVRT performance despite several grid faults. However, it adds to the control system's complexity. There are many LVRT methods in PMSG; one is modifying PMSG controllers using other external devices. Pitch angle and BTB converters have been used in Modified PMSG controllers; they are less expensive but less effective in LVRT improvement. During modified controller schemes, there can be difficulties with matching and switching between normal and LVRT modes.

A Braking Chopper (BC), an Energy Storage System (ESS), STATCOM, and a DVR are all common external devices [22]. However, due to additional hardware devices such as matching converters, the cost of these devices has grown, and the control process of these devices has also increased the complexity of PMSG. Because of their low price, fast LVRT performance, and compact configuration, braking chopper systems are extensively employed; however, frequent switching of the BC causes the DC voltage to oscillate.

The Superconducting Magnetic Energy Storage (SMES) and Superconducting Fault Current Limiters (SFCL) have the potential to increase the LVRT capabilities of wind farms. The transient performance of PMSG wind turbines with DC microgrids has also been improved using a resistive superconducting fault current limiter. However, the overspeed, mechanical stress, rapid ageing of the spinning elements of the generator and the overcurrent of the MSC are the major causes of PMSG failure with the DC microgrid.

SMES is implemented on the wind turbine generator system's DC link to smooth the wind turbine generator's output power and increase LVRT capability. SMES-SFCL-based cooperative control schemes increase PMSG's LVRT capability to reduce the capital cost of superconducting devices and parameter estimation. Recently issued rules constitute that wind power plants must participate in the quality of the power system at a steady state (frequency and voltage variations) and low voltage right through during the transient state.

The maximum active power that the GSC can send to the grid is reduced in proportion to the grid voltage in the event of a grid fault. Another LVRT control approach was developed for wind turbine generating systems. In a system in which V_{dc} is controlled by MSC instead of GSC, the surplus power is stored in system inertia during LVRT by raising rotor speed, allowing additional circuits to be eliminated.

However, with delays in grid disturbance detection and inertia of the control system, the MSC may not immediately respond to the grid fault, and V_{dc} still exceeds the upper limit in the initial tens of milliseconds. As a result of the conversion of MSC and GSC control functions, the converter must be reset, which raises the conversion process’s risk of failure. For MW class PMSG-based wind turbine generating systems, this overall control mechanism of LVRT is used. An over-voltage DC link capacitor will result from a mismatch between the power generated and the grid-connected power, and the generator may be destroyed by overcurrent. As a result, during LVRT, V_{dc} must be kept below its maximum value. It is essential to either minimize the amount of energy generated or consume additional energy.

Crowbar circuits are often used for LVRT because they are low-cost and easy to regulate. However, it causes heating problems and makes the converter’s design and heat dissipation design more challenging; regular maintenance includes adding an energy storage device to the DC link. The energy storage system, on the other hand, is both complex and costly.

In the literature, there have been several techniques to deal with surplus power during grid faults, such as (i) Pitch angle control techniques, (ii) Using the rotor inertia of a turbine generator, (iii) Using DC-link energy dissipation, (iv) Using of compensation devices, and (v) At the wind farm, wind turbine, and power converter level, control systems are used [11]. Because of its quick response time and low initial cost, DC-chopper propagation of surplus energy is the most extensively used mechanism in PMSG wind turbines.

7. Pitch Angle Control or Inertia Control for Frequency Regulation

Frequency regulation in power systems is a significant challenge as VSWT is controlled by MPPT control methods to achieve maximum power; VSWT is connected to the grid via a BTB converter, which decouples the rotating speed of VSWT and system frequency. Naturally, power systems consider VSWTs coupled to the power grid via VSCs as inertia-less. Variations in generation or load may create a deviation in frequency due to the low inertia, possibly causing instability in the system. With the increase of wind energy, the inertia decreases. So, it creates a frequency stability problem. Turbines and generators with variable pitch control and variable speed operation have already been used to increase the efficiency and reliability of power systems.

To improve the primary frequency contribution of a grid-connected VSWT generator, a reloaded wind turbine generator is used to provide relief to the grid during depressed frequency conditions using variable droop control. Deloading is the concept of operating VSWTs at a lower power level than their maximum power point. The overall performance increases the primary frequency support using variable instead of fixed droop [23].

Most research has focused on extensive systems with 5 to 10 MW capacities. Pitch angle control and variable speed wind turbine inertia are used to smooth output power. However, the blade tension of the VSWT becomes more extensive, and the pitching of the blade also increases. Figure 8 illustrates the traditional pitch angle control scheme. For output power smoothing, simple coordinated control of the DC link voltage and a pitch angle of the WECS with the PMSG is often used.

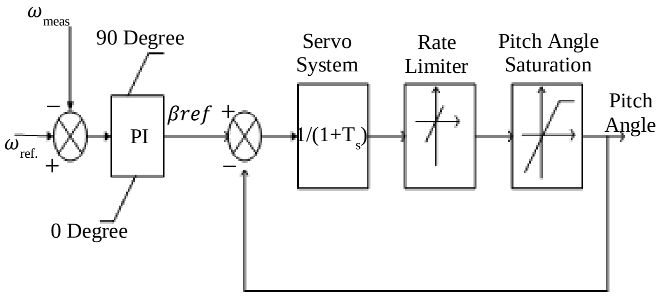


Fig. 8 Schematic diagram of conventional pitch angle control

The WECS’s output power variations in the low and high-frequency domains are smoothed by pitch angle and DC-link voltage regulation, respectively; however, the response is sluggish. A synchronous generator provides inertial support during frequency disruptions. However, it responds slowly to high-frequency events.

The system’s stability has been maintained using various control techniques, including voltage and frequency regulation. Energy storage devices can be used to provide inertial support for frequency control. System users often have concerns about the cost and control of storage devices. A high-power density supercapacitor is directly connected to the Wind Turbine Generator’s DC-link (WTG) to reduce wind energy variations [24]. The block diagram of the PMSG-based WECS using the frequency support system in the loop of the DC voltage controller is shown in Figure 9.

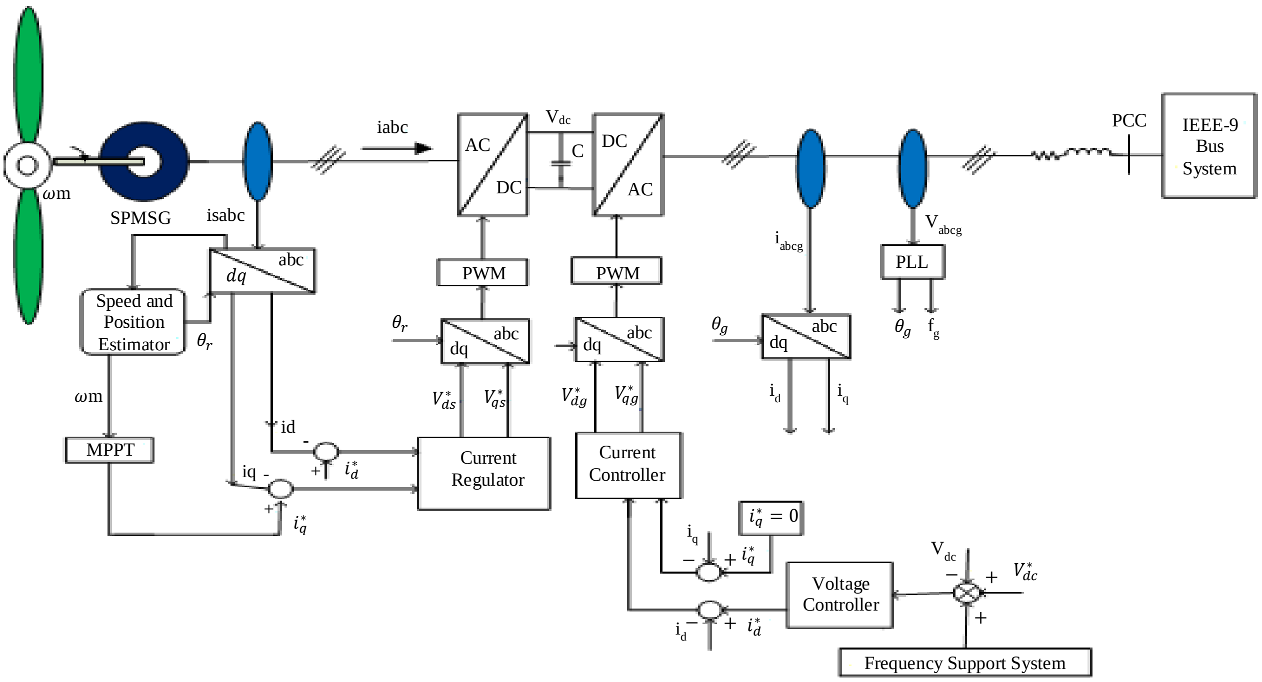


Fig. 9 Block diagram of SPMSG WECS

Fast response times during a frequency event are achieved via VIS, which provides unlimited inertial support at all times, quick recovery times, and mechanical stress reduction from the generator [25]. In WECS, rotational mass, DC-link capacitors, energy storage, and different VIS have been widely used.

Inertial support is provided by extracting stored kinetic energy from the spinning mass of the WT. However, this is a transient process followed by a reduction in rotor speed and a secondary frequency drop, further reducing grid stability. When an MPPT curve is converted into an inertial support curve, this operation might increase the mechanical load on the wind turbine generator. During the frequency disturbance, a VIS-based DC-link capacitor provided the initial support. However, this strategy increases the capacitor size to enable temporary inertial support for a short duration.

Before integrating energy storage into the electrical network, suitable energy storage, optimal sizing, and a control method must be examined. Because various energy storage system technologies behave differently in electrical networks, not all energy storage devices are suitable for VIS. Energy storage must have a high-power density for inertial support to respond rapidly during frequency changes, for example, supercapacitors and flywheel energy storage.

Battery Energy Storage (BES) provides VIS during frequency disruptions. However, battery energy storage has a shorter life cycle and lower power density [26]. A fuzzy logic-based frequency controller optimizes the primary frequency response for low inertia hybrid power systems incorporating battery energy storage.

On the other hand, the continuous charging and discharging operation of BES reduces battery performance and requires greater maintenance levels. A supercapacitor-based frequency support system has been used to improve the frequency response approach for remote field power supply and kinetic energy extraction from a wind turbine. On the grid side support, in [27], authors implemented a Frequency Control System (FCS) based VIS with supercapacitor. The FCS system is more capable of controlling frequency dips and rises. It has less settling time and a better Rate of Change of Frequency (RoCoF).

8. Grid Connected (AC Grid & DC Grid) & Islanded Mode Requirement and Problem

Onshore wind farms have lower costs, lower maintenance, and less power loss in the transmission line. The choice of HVAC and HVDC for grid integration of wind farms is determined by the distance to the utility grid near the wind farm and the power to be delivered. Reactive power compensators, such as static compensators, are used in HVAC transmission to improve transmission efficiency on both sides of AC cables. DC-link voltage fluctuations must be avoided since they can damage DC-link capacitors and cause power transmission failure. Most existing research focuses on improving frequency support capability for PMSG-based wind turbines through control design [28]. However, researchers must utilize frequency control techniques to remove DC link voltage oscillations.

To efficiently reduce the variations in DC link voltage under grid frequency disturbances, a current feed-forward control strategy for the PMSG wind power conversion system is used. Open switch faults are a severe type of fault in converters and should be considered in designing a robust and fault-tolerant electrical drive system. Variable-speed wind turbines with non-synchronized grid connections and free-running operating modes enhance output power variations, causing a security risk to the power system.

Frequency variations, system instability, reactive power loss variation, and voltage flicker from the PCC to the primary grid can all be caused by sudden fluctuations in wind power generation. Wind energy fluctuations also cause additional technical and economic problems. The amplitude and frequency of the load voltage are kept constant for balanced/unbalanced linear and non-linear loads. PI controllers are robust and capable of controlling wide-range stability margins. However, PI controllers are sensitive to immediate changes and system non-linearity.

A DC link capacitor over-voltage will result from a mismatch between the power generated and the power connected to the grid. Overcurrent might potentially harm the generator. A substantial non-detection zone in the passive islanding approach transfers from grid-connected to islanded mode. There is no provision for MPPT during regular operation, but the grid synchronization mechanism is used. When power fluctuations occur, it creates additional operational issues, particularly in islanded power systems. It has a low inertia and a weak system [29].

9. Future Research

The wind generator has a better power density; hence, PMSG raises the 10–15 MW class. Multi-phase PMSG is good; they provide fault-tolerant operation. MV power converters are an excellent alternative for high-power levels in the electric drive market. CSC is a viable option for the MV operation of PMSG wind turbines. More advanced measures might be proposed to increase the performance of MPPT control. Future trends in wind power conversion systems, such as fault diagnosis tolerance control and transformer-less concept, should be discussed.

Over the past years, open switch faults in the converter for electric drives have received attention. Synchronization, an issue in PMSG WECS with the grid, is also needed research. Investigation for cost reduction of PMSG WECS should be a concern for future research. The main problem is optimizing the capacitor size used in WECS and investigating the loading conditions to maintain constant DC-link voltage. Because of the lower total inertia and primary frequency regulation capabilities, extensive penetration of PMSG-WTG systems tends to worsen grid frequency stability. So, future research should be more concerned with virtual inertia for output power smoothing and frequency stability of a WECS.

10. Conclusions

It has been concluded that DD-PMSGs are superior in most aspects compared to other wind turbine generators. The synchronous reference frame model is better for the mathematical Modeling of DD-PMSG. Two-level BTB VSCs are used for PMSG, such as WTs with a capacity of 3 to 5 MW, while MV multilevel converters, such as 3 or 4-level BTB NPC voltage source converters, are preferred for WTs with a power of 5 to 10 MW. From the control point of view of MSC & GSC in direct drive PMSG, vector control is better. The FOC for MSC and VSC for GSC are preferred in vector control mode. Stator voltage and current-based methods have been proven effective for VSWT systems due to their ease of implementation and non-intrusive nature.

The PLL-based sensorless control is preferred to sense rotor speed and angle for MPPT. An improved advanced PI controller that controls the MSC and GSC control reduces the error signal given to the PI controller. WT output power fluctuates with wind speed, causing grid frequency disruptions. This problem can be solved by controlling pitch angle or inertial and DC-link, but blade stress and losses may increase. Supercapacitors are preferred for virtual inertial support over DC-link capacitors and rotating mass. The supercapacitors provide infinitely inertial support with a short response time. PMSG WECS uses its energy reserve margin control to relieve the grid during depressed frequency conditions using the variables droop control method.

So, it is clear that for the PMSG wind power conversion system, the VIS concept and the variable droop control are desirable. PMSG is expected to be used efficiently in the future wind energy industry to obtain technological and economic benefits.

References

[1] Global Wind Energy Council (GWEC), Global Wind Report: Annual Market Update, 2023. [Online]. Available: https://gwec.net/globalwindreport2023/

[2] Bin Wu et al., *Power Conversion and Control of Wind Energy Systems*, Wiley-IEEE Press, 2011. [Google Scholar] [Publisher Link]

[3] Venkata Yaramashu, and Bin Wu, *Model Predictive Control of Wind Energy Conversion Systems*, Wiley-IEEE Press, 2017. [Google Scholar] [Publisher Link]

[4] Youssef Errami et al., “Power Extraction Control of Variable Speed Wind Turbine Systems Based on Direct Drive Synchronous Generator in All Operating Regimes,” *Journal of Electrical and Computer Engineering*, vol. 2018, pp. 1-17, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[5] Z.Q. Zhu, and Jiabing Hu, "Electrical Machines and Power-Electronic Systems for High-Power Wind Energy Generation Applications: Part II – Power Electronics and Control Systems," *COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 32, no. 1, pp. 34-71, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[6] Catherine Nasr El-Khoury et al., "A Review of Matrix Converters Applied to PMSG Based Wind Energy Conversion Systems," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, pp. 7784-7789, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[7] Ratna Ika Putri et al., "Maximum Power Extraction Improvement Using Sensorless Controller Based on Adaptive Perturb and Observe Algorithm for PMSG Wind Turbine Application," *IET Electrical Power Applications*, vol. 12, no. 4, pp. 455-462, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] Shuhui Li, Timothy A. Haskew, and Ling Xu, "Conventional and Novel Control Designs for Direct Driven PMSG Wind Turbines," *Electric Power Systems Research*, vol. 80, no. 3, pp. 328-338, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[9] Venkata Yaramasu et al., "PMSG-Based Wind Energy Conversion Systems: Survey on Power Converters and Controls," *IET Electrical Power Applications*, vol. 11, no. 6, pp. 956-968, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] W. Erdman, and M. Behnke, "*Low Wind Speed Turbine Project Phase II: The Application of Medium-Voltage Electrical Apparatus to the Class of Variable Speed Multi-Megawatt Low Wind Speed Turbines*," National Renewable Energy Laboratory (NREL), Technical Report, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[11] Salvador Alepuz et al., "Use of Stored Energy in PMSG Rotor Inertia for Low-Voltage Ride-through in Back-to-Back NPC Converter-Based Wind Power Systems," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 1787-1796, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[12] Rachid Errouissi, Ahmed Al-Durra, and Mahdi Debouza, "A Novel Design of PI Current Controller for PMSG-Based Wind Turbine Considering Transient Performance Specifications and Control Saturation," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 11, pp. 8624-8634, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] Zakariya M. Dalala et al., "Design and Analysis of an MPPT Technique for Small-Scale Wind Energy Conversion Systems," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 756-767, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[14] Abdullah M.A. et al., "A Review of Maximum Power Point Tracking Algorithms for Wind Energy Systems," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3220-3227, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[15] Gaolin Wang, Maria Valla, and Jorge Solsona, "Position Sensorless Permanent Magnet Synchronous Machine Drives - A Review," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 7, pp. 5830-5842, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jian Chen et al., "Design of Robust MPPT Controller for Grid-Connected PMSG-Based Wind Turbine via Perturbation Observation Based Non-Linear Adaptive Control," *Renewable Energy*, vol. 134, pp. 478-495, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] C. Silva, G.M. Asher, and M. Sumner, "Hybrid Rotor Position Observer for Wide Speed-Range Sensorless PM Motor Drives Including Zero Speed," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 2, pp. 373-378, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[18] R. Sreejith, and Bhim Singh, "Sensorless Predictive Current Control of PMSM EV Drive Using DSOGI-FLL Based Sliding Mode Observer," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 7, pp. 5537-5547, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Saeed Golestan et al., "Modeling, Tuning, and Performance Comparison of Second-Order-Generalized-Integrator-Based FLLs," *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10229-10239, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Vineet P. Chandran, Shadab Murshid, and Bhim Singh, "Improved TOGI-Based Voltage and Frequency Control for PMSG Feeding Single-Phase Loads in Isolated Pico-Hydro Generation," *IETE Journal of Research*, vol. 67, no. 6, pp. 882-898, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[21] Zhen Xin et al., "An Improved Second-Order Generalized Integrator Based Quadrature Signal Generator," *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8068-8073, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[22] M. Nasiri, J. Milimonfared, and S.H. Fathi, "A Review of Low-Voltage Ride-through Enhancement Methods for Permanent Magnet Synchronous Generator Based Wind Turbines," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 399-415, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[23] K.V. Vidyanandan, and Nilanjan Senroy, "Primary Frequency Regulation by Deloaded Wind Turbines Using Variable Droop," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 837-846, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[24] Yujun Li, Zhao Xu, and Kit Po Wong, "Advanced Control Strategies of PMSG-Based Wind Turbines for System Inertia Support," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3027-3037, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[25] Siqi Wang, and Kevin Tomsovic, "Fast Frequency Support from Wind Turbine Generators with Auxiliary Dynamic Demand Control," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 3340-3348, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[26] Ziping Wu et al., “Coordinated Control Strategy of Battery Energy Storage System and PMSG-WTG to Enhance System Frequency Regulation Capability,” *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1330-1343, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] Changqing Chen et al., “Virtual Inertia Coordination Control Strategy of DFIG-Based Wind Turbine for Improved Grid Frequency Response Ability,” *Electric Power Systems Research*, vol. 216, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[28] Jun Yao et al., “Frequency Regulation Control Strategy for PMSG Wind-Power Generation System with Flywheel Energy Storage Unit,” *IET Renewable Power Generation*, vol. 11, no. 8, pp. 1082-1093, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[29] Xue Lyu et al., “Coordinated Control Strategies of PMSG-Based Wind Turbine for Smoothing Power Fluctuations,” *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 391-401, 2019. [CrossRef] [Google Scholar] [Publisher Link]