Power Generation Using Permanent Magnet Synchronous Generator (PMSG) Based Variable Speed Wind Energy Conversion System (WECS): An Overview

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Abstract

In the recent time, Permanent-Magnet Synchronous-Generator (PMSG) based variable-speed Wind-Energy Conversion-Systems (WECS) has become very attractive to many researchers. The research aim is to analyse different synchronous machine and compare them based on their maximum power generation. This paper reviews various aspects of PMSG such as topologies with controlled and uncontrolled rectifier, grid-connected and standalone mode of operation with various control methods of PMSG based WECS and recent optimization approaches. The performance analysis of PMSG can be enhanced by adopting a number of control mechanisms with the benefit of advanced optimization techniques. A comparative analysis is carried out based on the techniques used and their corresponding advantages and drawbacks are discussed.

Keywords: PMSG, WECSs, power generation, synchronous generator, grid-connected PMSG, standalone mode of PMSC, grid side converter (GSC), machine side converter (MSC).

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List of Abbreviations

PMSG – Permanent Magnet Synchronous Generator
WECS – Wind Energy Conversion Systems
BESS – Battery Energy Storage System
SG – Synchronous Generator
PM – Permanent Magnet
WT – Wind Turbine
HAWT – Horizontal Axis Wind Turbine
VAWT – Vertical Axis Wind Turbine
GSC – Grid Side Converter
MSC – Machine Side Converter
CSC – Current Source Inverter
MPPT – Maximum Power Point Tracking
RAPS – Remote Area Power Supply
PLL – Phase Locked Loop
PCC – Point of Common Coupling
FLC – Fuzzy Logic Controller
AFLC – Adaptive Fuzzy Logic Controller
ANN – Artificial Neural Network
DTC – Direct Torque Control
PSO – Particle Swarm Optmization
GA – Genetic Algorithm
BFO – Bacterial-Foraging-Optimization

1 Introduction

Nowadays, PMSGs are most popular for power-generation, as they have high efficiency [1–5]. For instance, the electrical efficiency of PMSGs is higher than the synchronous-generators (SGs) in the moderate-size power marine diesel gen-sets [6]. As PMSG don't comprise excitation control, voltage-regulation in island-operation is challenging. The flux-density of permanent magnet (PM) reduces with the rise in temperature, so voltage-control become complicates. Some of the difficulties of PMs are high cost and handling while manufacturing [7]. The variable-speed operation of the WECS is essential for extracting maximum wind power. A modern control based tracking of power or torque helps to achieve best utilization of wind-energy [8, 9]. Control strategies are developed based on wind-velocity to acquire required shaft speed. These schemes involve high cost and reduced reliability for a small scale WECS. The current-vector of an interior type PMSG optimizes the operation at variable wind-velocity, which needs control of six active switches [10]. Switch-mode rectifier is also designed for PMSM [11]. For standalone operation, load-side converter voltage needs to be controlled in terms of amplitude and frequency [12]. Grid connected PMSG based WECSs are also proposed and implemented. Probability to attain less pole-pitch permits the machine to run at low speed and removes the gearbox or allows using single-stage gear for more compact design. This paper reviews various PMSG techniques with the aim of maximum power generation [13, 14].

The objective of this paper is to discuss different methods and approaches for control of PMSG based WECS. In Section 2 of the paper, discussion about WECS and modelling of PMSG is carried out. Section 3 is presenting various topologies for the converters used for PMSG based WECS. In Section 4, method of control of grid connected pmsg based WECS are discussed. Section 5 presents discussion about standalone mode of operation of PMSG based WECS. In Section 6 some advanced control methods of PMSG based WECS are discussed. Section 7 presents recent optimization approaches for the system. Section 8, includes the conclusion with a comparative analysis of the diffenent methods and apporoaches discussed in the previous sections.

2 Wind Energy Conversion System (WECS) and Modelling

Non-conventional means of energy has become an alternative and or an additive for the conventional source of energy. With endless potential of wind energy and environmental-merits, it has become the most popular source of renewable energy. The WECS based on the wind-turbine (WT) is categorised as fixed and variable speed system. Initially fixed-speed WECS was popular one. Nowadays, variable speed generators are more effective. PMSG is more effective and efficient as compared to other generators and are best suited for WECS due to its high torque to size ratio, less maintenance required, omission of slip-rings, reduced overall-cos. Permanent magnets(PM) instead of electromagnets makes the stator direct-flux constant [65]. The modelling of wind based power generation system is discussed below.

2.1 Modelling of the Wind Turbine

The rotor-blades of WT converts the kinetic-energy of the wind into mechanical-energy. Then generator as an electrical-sytem transform mechanical-power into the electrical-power. WTs generally used for WECS are vertical-axis-wind-turbine (VAWT) and horizontal-axis-wind-turbine (HAWT). HAWT shows listed below advantages than VAWT.

- it offers flexible blade-pitch so that blades can operate at optimum-angle of attack, for extracting more wind-energy.
- it always captures efficient wind-energy from during the whole rotation as blade's rotation is perpendicular to the wind.
- it is self-starting, but VAWT needs initial starting-torque.

The kinetic energy, which is extracted from the wind, is penetrated on to the turbine blade area.

According to the principle of energy-mass conservation in wind, the maximum extracted wind power is given as [65];

$$\mathrm{P_{wind}} = \frac{1}{2}\,\rho \mathrm{A} v_{\mathrm{w}}^{3} \tag{1}$$

Where $\mathrm{v_w}$ is wind velocity, ρ is density of air, A is swept-area of turbine-blades.

$\mathrm{C_p}$, power coefficient is defined as the ratio of turbine power to the extracted wind power.

$$\mathrm{C_p} = \frac{\text{Turbine power } (\mathrm{P_{turbine}})}{\text{Power obtained from wind } (\mathrm{P_{wind}})}$$

Hence the turbine-power is given by:

$$\mathrm{P_{turbine}} = \mathrm{P_{wind}} \mathrm{C_p} = \frac{1}{2}\rho \mathrm{A} v_{\mathrm{w}}^{3} \mathrm{C_p} \tag{2}$$

The turbine-power wrt wind transients is given by

$$\mathrm{P_{turbine}} = \mathrm{P_{wind}} \mathrm{C_p} = \frac{1}{2}\rho \mathrm{A} v_{\mathrm{w}}^{3} \mathrm{C_p}\,(\lambda, \beta) \tag{3}$$

Where λ is the tip-speed ratio of the turbine:

$$\lambda = \frac{\text{rotational speed of rotor } (\omega_{\mathrm{r}}) * \text{radius(r)}}{\text{wind velocity } (\mathrm{v_w})} \tag{4}$$

Where

$$\mathrm{C_p}\,(\lambda,\ \beta) = \mathrm{C_1}\left(\frac{\mathrm{C_2}}{\lambda_{\mathrm{i}}} - \mathrm{C_3}\beta - \mathrm{C_4}\right) e^{\frac{-\mathrm{C_5}}{\lambda_{\mathrm{i}}}} + \mathrm{C_6}\lambda \tag{5}$$

$$\lambda_{\mathrm{i}} = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^{3}+1}\right) \tag{6}$$

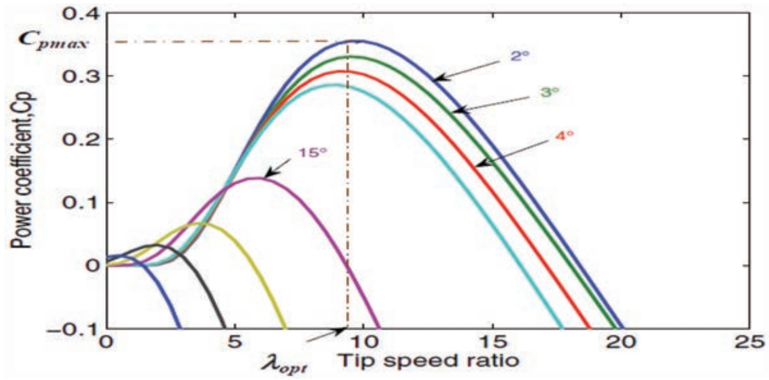

Figure 1 Power coefficient $C_p(\lambda, \beta)$ v_s tip speed ratio λ.

Where β stands for the blade pitch angle.

The coefficient C_1 to C_6 are: C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21, C_6 = 0.0068.

Figure 1 show the relationship between the power coefficient C_p and tip speed ratio λ

The governing formula for directly-coupled PMSG for the mechanical-analysis is given as,

$$\frac{d\omega_m}{dt} = \left(\frac{1}{J}\right)(T_m - T_{gen} - B\omega_m) \tag{7}$$

$$\omega_e = P\omega_m \tag{8}$$

Also

$$\int \omega_e \, dt = \theta_e \tag{9}$$

Where, θ_e = electrical angle (is required for abc↔d-q transformation), T_m = generated turbine mechanical-torque (Nm), T_{gen} (=T_e) = generated electromagnetic-torque (Nm), P = pole-pairs ω_m = the rotor mechanical speed (rad/sec), ω_e= rotor electrical speed in elec. rad/sec, J = inertia-moment (Kgm^2), B = viscous-friction coefficient (can be ignored for small WT).

2.2 Modelling of the PMSG

Figure 2 shows the d-q axes ‘park’ model. In PMSG rotor is made up of PM, not fed by external source for producing magnetic-field. Hence rotor voltage-equation need not be be developed as variation in rotor flux wrt time is not

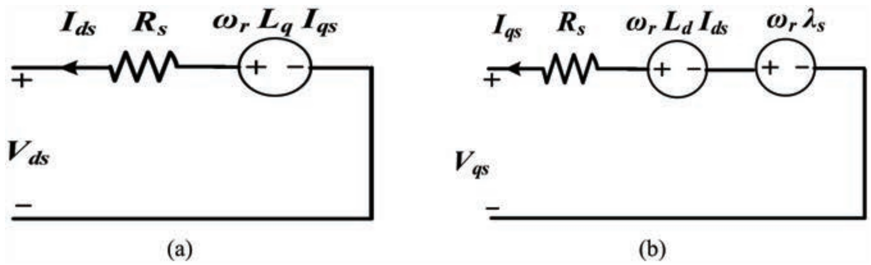

Figure 2 PMSG model (a) d (direct)-axis, (b) q (quadrature)-axis.

there. Stator voltageiequations are as follows [65]:

$$V_{sd} = R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_e \phi_{sq} \tag{10}$$

$$V_{sq} = R_s I_{sq} + \frac{d\phi_{sq}}{dt} + \omega_e \phi_{sd} \tag{11}$$

The stator fluxes are given by,

$$\phi_{sd} = L_d I_{sd} + \phi_m \tag{12}$$

$$\phi_{sq} = L_d I_{sq} + \phi_m \tag{13}$$

Where, R_s = stator-winding resistance, L_d = d-axis stator-inductance, L_q = q-axis stator-inductance, ϕ_m = flux linkage, V_{sd} & I_{sd} = d-axis stator voltage & current, V_{sq} & I_{sq} = q-axis stator voltage & current. From Equations 10–13:

$$V_{sd} = R_s I_{sd} + L_d \frac{dI_{sd}}{dt} - \omega_e L_q I_{sq} \tag{14}$$

$$V_{sq} = R_s I_{sq} + L_q \frac{dI_{sq}}{dt} + \omega_e L_d I_{sd} + \omega_e \phi_m \tag{15}$$

The electromagnetic-torque can be written as:

$$T_e = \left(\frac{3}{2}\right) P(\phi_m I_{sq} + (L_d - L_q) I_{sd} I_{sq}) \tag{16}$$

For surface-seated PMSG, we can assume $L_d = L_q$. Then T_e can be written as:

$$T_e = \left(\frac{3}{2}\right) P\left(\phi_m I_{sq}\right) \tag{17}$$

For steady-state condition, real power P_s and reactive power Q_s of PMSG are as follow:

$$P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \tag{18}$$

$$Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \tag{19}$$

3 Converter Topologies for Permanent Magnet Synchronous Generator (PMSG) BASED Wind Energy Conversion System (WECS)

PMSG is more popular among the synchronous and asynchronous generators due to its lower weight & size, self-excitation. Low maintenance-cost and no gearbox give high efficiency and power factor compare to wound-rotor synchronous generator (WRSG), squirrel-cage induction generator (SCIG), and doubly-fed induction generator (DFIG). DFIGs are the promising choice due to high wind power extraction capability with low converter losses [69]. PMSG with diode-bridge rectifier (AC/DC), boost-converter (DC/DC) & inverter (DC/AC) were proposed for power extraction. The DC/DC converter controls the machine's voltage. Cost and control complexity is reduced by diode-bridge rectifier [66]. Due to effect of diode commutation at more wind velocity and discontinuous- operation of DC/DC-converter at low wind-velocity, the extracted wind-power decreases. Therefore, for power in the range of 10s kW, back-to-back converter is the better choice, which leads to 5%–15% rise in power [67]. Various techniques are proposed and implemented by the researchers to enhance the performance of PMSG connected to variable speed WECS, such as PMSG with controlled and uncontrolled rectifier for grid connected or stand-alone system. Figure 3(a) shows a grid-connected PMSG through AC/DC-boost-DC/AC converters and Figure 3(b) shows a grid-connected PMSG through bidirectional (back-to-back) converter. Bidirectional-converter consists of 2 VSI-PWM converters and a dc-link capacitor. The MSC works as controlled-rectifier and grid-side-converter as inverter. Dc-link voltage can be made constant by controlling power flow of the GSC. MSC is controlled to suit the magnetization & the reference speed/torque. This topology provides decoupling-effect MSC & GSC through capacitor. Decoupling-effect helps for independent converters-control with some protection [68].

Figure 4(a) shows the schematic diagram for controlled rectifier based MSC, Figure 4(b) shows the MPPT control, and Figure 4(c) shows the phsed locked loop (PLL) to find angular velovity. Dynamic modelling of PMSG

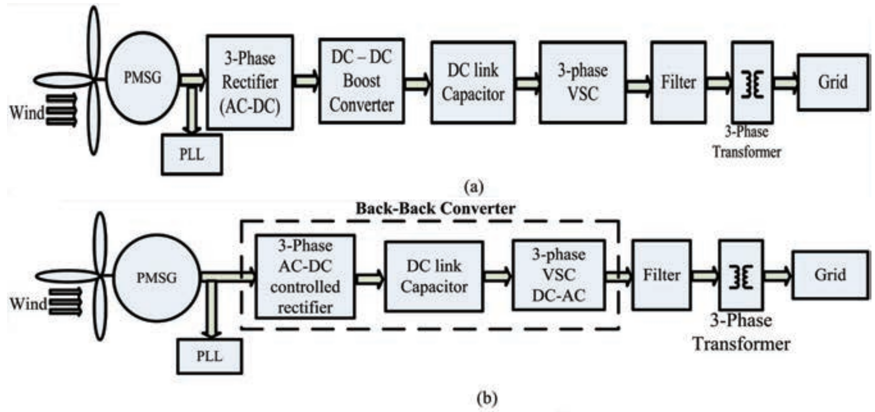

Figure 3 (a) WECS with uncontrolled diode rectifier, boost-converter, VSC; (b) WECS with controlled rectifier and VSC.

based WECS, and MPPT based controller design using fuzzy-logic controller (FLC) is presented for constant and variable wind conditions [16]. An Artificial-Neural-Network (ANN) based Reinforcement-Learning (RL) MPPT algorithm is proposed. Initially, MPPT-algorithm learns the ideal link among the rotor-speed & electrical-power of PMSG by the integration of ANN and Q learning algorithm. MPPT-algorithm is changed from the online-RL to relation-based online-MPPT. The online-learning scheme permits WECS to perform like an intelligent-agent (with memory) to learn from its specific knowledge, therefore enhancing the learning efficiency. The online RL algorithm is reenergised whenever genuine optimal-relationship diverges from the learned-one due to system aging [17]. Figure 5 [17] shows the Schematic diagram of the ANN-based RL algorithm. The major problem in a series-connected current-source-converter (CSC) is the insulation level, due to monopolar operation. Bipolar operation gives a half insulation requirement, is investigated to solve the degradation of the system. Paths for dc-link current produces a concern for appropriate operation of the bipolar system. Bipolar operation with the support of the optimized dc-link current control characterise lower insulation, higher reliability, efficiency and flexibility[18]. An inclusive analysis on power converter topologies with technical details for MW range PMSG-WECS, fault-ride-through compliance approaches and digital control approaches are presented in [19]. In WECS, traditional frequency-control techniques are imposing a severe stress on the system. Enhanced frequency-response scheme for PMSG-based WECS to control the frequency of Remote

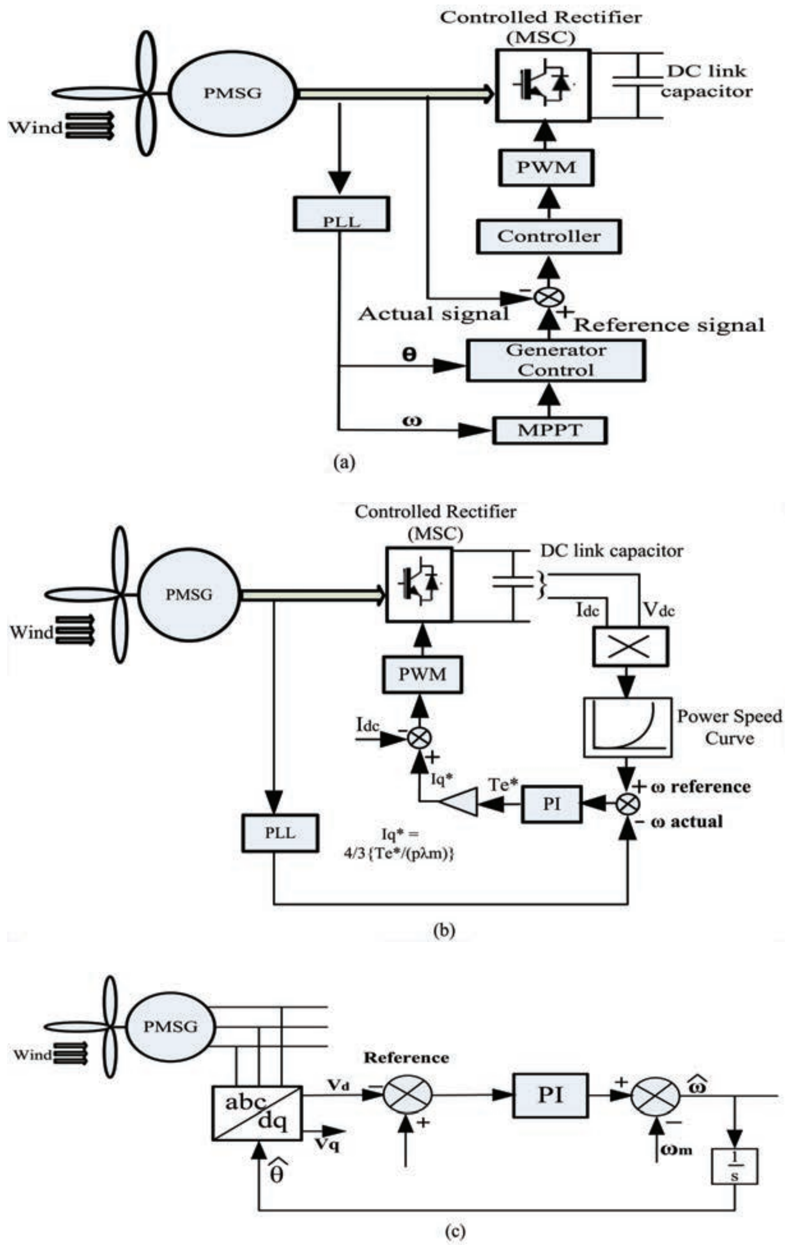

Figure 4 (a) Controlled rectifier based machine side converter, (b) MPPT control, (c) PLL.

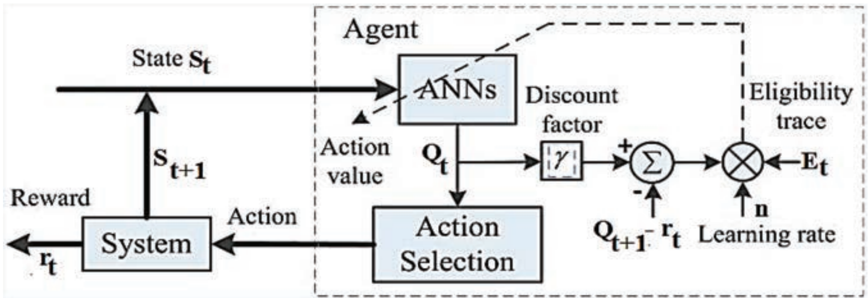

Figure 5 Schematic diagram of the ANN-based reinforcement learning (RL) algorithm.

Area Power Supply (RAPS) system with its combined ultra-capacitors is proposed [20]. Here frequency-response scheme is based on droop-control and virtual-inertial methods. It efficiently controls RAPS frequency with high rate of change of power. A Medium-Frequency Transformer (MFT) based WECS for offshore wind farms is proposed using current source converters [21]. This configuration includes a medium-voltage PMSG which is connected to a low-cost passive rectifier, onshore current source inverter and MFT-based cascaded converter. Both simulation and experimental results are achieved better performance is shown compared with conventional methods.

In [22], robust & reliable power system is proposed having a combination of a machine-side 3-switch buck-rectifier and a grid-side Z-source inverter as a bridge among the grid and the machine. Figure 6 shows the schemetic diagram of PMSG based WECS with Z-source converter. Space-vector modulation and Z-source network operation principles in utilized to develope the modulation scheme. Two control approaches such as unity-power-factor control and rotor-flux-orientation control are considered to develop the optimized proposed control. Decoupled active and reactive-power control is attained independently. MPPT is achieved through control of shoot-through duty cycles of Z-source network.

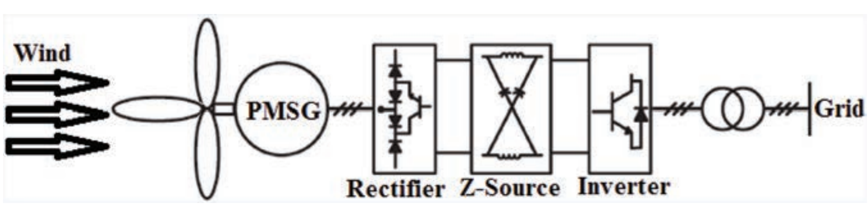

Figure 6 Schematic diagram of PMSG based WECS with Z-source converter.

In [23] the solutions based on diode rectifiers are found wrt the waveforms of electrical & mechanical quantities, efficiency, torque ripple, with various connections (6-pulse & 12-pulse rectifier). Rectifier with high no. of pulses can be utilized without using special shifter-transformers, makes them very useful for low-medium power applications. A scheme comprising of 3 individual thyristors and two 3-ϕ diode bridge is implemented for high-power variable speed PMSG [24]. Here each of diode bridge rectifiers is supplied by a 3-ϕ power-source and their outputs are connected in parallel. Three individual thyristors connects the corresponding input phases of the rectifiers. The rectifier's dc output voltage is equal to the output of a single diode bridge, if thyristors are off. The outputs of the two diode bridges are cascaded and total dc voltage becomes double, if the thyristors are controlled and turned on. This rectifier consists some important properties such as low power loss, low cost, simple control, and more efficient [24]. The effect of Vienna-rectifier voltage-vectors on PMSG torque & stator-flux are derived by Direct torque control (DTC) [25]. In [26], operational challenges of 3-ϕ surface-mount PMSG connected to a diode-rectifier are evaluated and by using analytical steady-state model of the system, maximum power transfer is obtained. In [27] a linearized average dynamic-model of the WECS including PMSG, diode-rectifier, boost-converter is presented. Also relationship between electromagnetic torque & converter current is extracted; then system's control-loops are developed using linearized model. Then small signal stability of the overall system is presented. Here the effect of speed-controller on the stability of the system is observed theoretically and with simulations. In [28] a novel scheme with fuzzy fractional order proportional integral + I (FFOPI+I) controller for grid-connected PMSG based variable-speed WECS is proposed. The controller is employed to control system with nonlinear load through a bidirectional-converter. The MSC aims to extract maximum-power under fluctuating wind speed. The controller develops a FLC in parallel with Fractional Order PI (FOPI) and conventional PI controllers. The initial parameters of FFOPI+I controller is computed using a frequency approach to produce a search space then particle-swarm-optimization (PSO) algorithm is applied to choose optimal-parameters. The performance evaluation of FFOPI+I controller is estimated under the steady-state and transient conditions. The simulation results demonstrate the effectiveness of FFOPI+I over FOPI and enhancing the grid-side power factor for a wide range of wind speed. Figure 7 shows the schematic diagram of the control scheme with FFOPI+I controller [28].

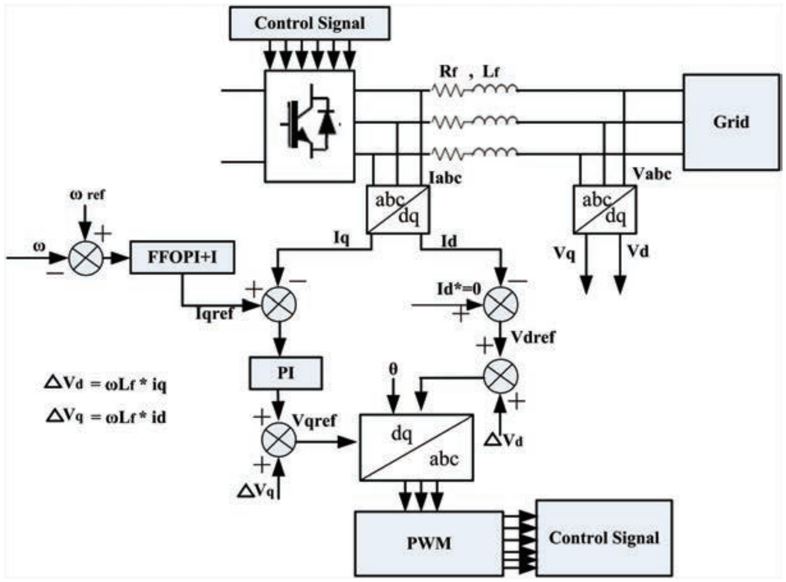

Figure 7 Schematic diagram of the control scheme with FFOPI+I controller.

4 Grid Connected Permanent Magnet Synchronous Generator (PMSG) Based Wind Energy Conversion System (WECS)

In [29], intelligent controllers are proposed for a Switched-Reluctance Generator (SRG) based WECS to obtain the maximum-power. These controllers are based on of fuzzy-logic (FL) controller and ANN techniques. Controller adjusts WT rotational-speed by fixing the turn-on angle and varying the turn-off angle of SRG. Simulation results shows the effectiveness of ANN-controller in terms efficiency & accuracy than FL-controller. In [30] a model-predictive-control is proposed, which provides better dynamic-response and permits flexible-operation of parallel-connected generators by removing the dependency of voltage & frequency synchronization. Scheme shows operational-ability of the micro grid under islanding from distribution-grid. An enhanced rapid dynamic-system for regulating Matrix-Converter (MC) is proposed with modified-hysteresis-current-controller and optimal-tuning-PI-controller in [31]. Also enhanced Bacterial-Foraging-Optimization (BFO) algorithm is applied for active & reactive currents control of PMSG to achieve maximum-power. Using BFO, active & reactive powers can be supplied to the grid at normal and fault situations. Dynamic limiter with

BFO-controller controls the injected reactive-power to grid and improves the system stability. Also pitch angle controller with rate limiter is developed for WECS protection from mechanical-damage. An overall control technique for hybrid-wind/PV distributed generation system is presented [32].

Various energy sources are integrated using DC bus into the utility grid. Meta-heuristic Firefly algorithm (FA) based controller is utilised for voltage & frequency control at point of common coupling (PCC). The gains of PI & PID controllers are concurrently improved by powerful FA and their performance is evaluated. The dynamic responses of PID controller shows the better performance compare to PI controller. A Maximum-Power-Extraction Algorithm (MPEA) is proposed for a grid-connected PMSG based WECS and it is feasible to implement in practical without any mechanical sensors for WECS via a PMSG [33]. Comprehensive models have been proposed to analyse power & voltage fluctuations, which depends on the grid-parameters. Flicker emissions can be reduced by activating the developed voltage regulation loop [34]. The q & d axis current controls the active & reactive power respectively. Utility-voltage phase-angle is identified by software PLL in synchronous-reference-frame. This method provides high quality & low cost power conversion for WECS [35]. Figure 8 shows the control scheme of a grid connected PMSG system.

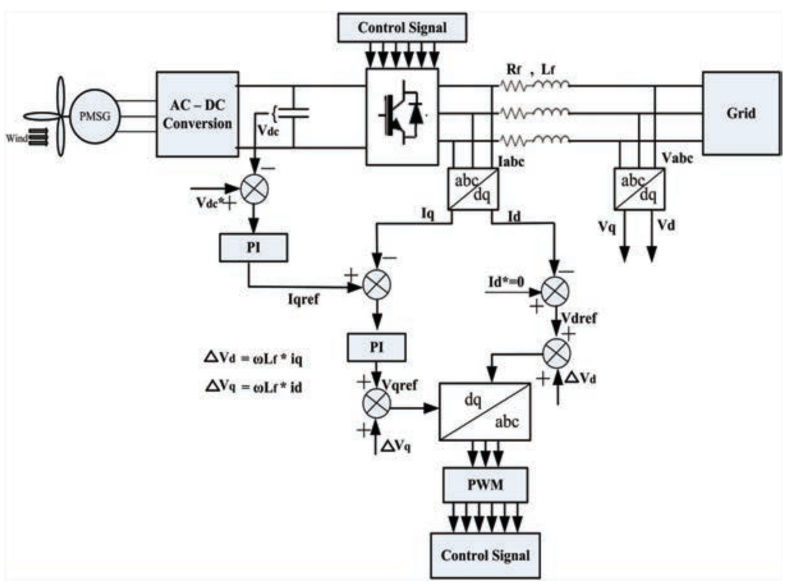

Figure 8 Control scheme of grid side converter (GSC).

In [36], two control schemes, based on sliding-mode control and classical PI controllers, to control both MSC & GSC for wind farms (WF) using PMSG connected to a DC-bus system are proposed. Control scheme integrates a pitch control method and MPPT to achieve more power from WF. In [37], hardware implementation of 3-parallel connected PMSGs based WECS is proposed, which minimizes the converters rating, shows better performance compared to traditional schemes.

5 Standalone Permanent Magnet Synchronous Generator (PMSG) Based Wind Energy Conversion System (WECS)

Figure 9 shows a PMSG based standalone WECS. Here PMSG is connected to a load via a 3-phase ac/dc converter, BESS, and a 3-phase dc/ac converter. Generally standalone WECS are supported by BESS and or super-capacitor/ultra-capacitor.

In [38] an Effective-Energy-Management algorithm for standalone PMSG using dc link voltage is proposed. Here variable-speed WECS with PMSG includes battery, dump load and fuel cell. By maintaining constant dc-link voltage to its reference value, constant inverter output is gained. An effective control scheme developed based on PWM-technique provides balanced line voltages at PCC for unstable load also. Also, control method for battery with DC/DC converter is developed to minimize the torque-pulsation of machine. Scheme maintains MPPT. In [39], controller for voltage & frequency is implemented using a battery-energy-storage-system (BESS). BESS controls the frequency and provide load levelling for varying wind velocity. Machine voltage control is achieved by supplying reactive power at variable loads & wind velocity. The performance of the system is verified as a harmonic compensator, a load-balancer & leveller and a voltage & frequency controller. An adaptive-control method based on Neural-network-identifier (NNI) for MPPT

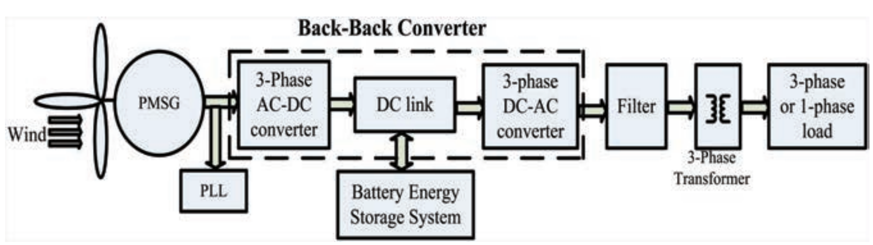

Figure 9 PMSG based Standalone WECS.

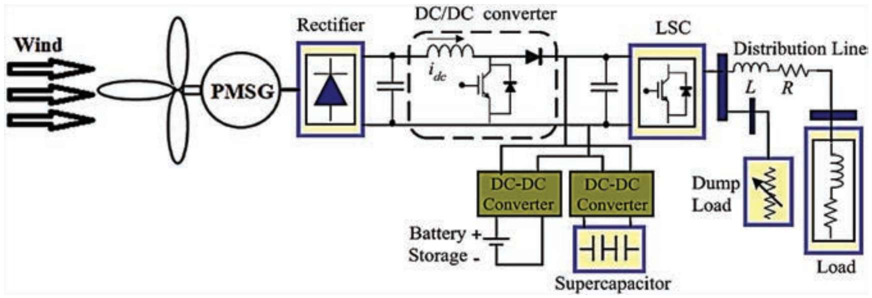

Figure 10 PMSG based standalone WECS with BESS and supercapacitor [41].

of stand-alone PMSG based WECS is proposed [40]. This method provides accurate mechanical torque signal and off-line training is not required to acquire its optimal-parameter-values. A block-back-stepping controller is also proposed to attain optimal rotor-speed. In [41], energy-management-algorithm (EMA) for enhancing the performance of hybrid-energy-storage-system along with super-capacitor is discussed. Figure 10 shows a PMSG based standalone WECS with BESS and supercapacitor. Synchronous-condenser offer reactive-power and inertial-aid to the system. Here developed coordinated-control manages the active & reactive power flow between system elements. The results achieved with the robust voltage and frequency regulation, effective management and maximum wind-power extraction.

In [42], a hybrid system is proposed which includes PMSG & DFIG integrated with a battery-storage. The simulation results varifies both the systems capabilities of voltage & frequency control. In [43] a parameter-independent-intelligent-power-management-controller, includes MPPT & power-limit-search (PLS) algorithm for standalone PMSG, is proposed. PLS algorithm helps to reduce surplus-energy production and minimize the heat-dissipation needs by finding optimal operating resulting required-power at the place of maximum-power.

6 Advanced Control Technique for Permanent Magnet Synchronous Generator (PMSG) Based Wind Energy Conversion System (WECS)

In [44], a systematic formula of loss using quadrature-direct axis current and speed and evaluation of loss model of high-speed PMSG is proposed. Total loss is concave function based on d-axis current and speed. Therefore, the mathematical derivation of solving the extreme value is employed and then the explicit expression of the two independent variables direct axis current and speed for the minimum-loss-point is accomplished. As the effect of the maximum current limitation of the circuit on the system speed operation mode, the minimum loss speed and direct current combined control strategy are raised. Proposed algorithm enhances the efficiency by 16.91% compared to conventional algorithms. Next, a power-control technique for PMSG based WECS is proposed. At sub-synchoronos speed, with rotor dynamic-characteristics, optimal reference-torque is found without wind velocity sensors. At super-synchronous speed, with flux-weakening helps to use maximum-torque under specific current & voltage. SVM-based direct-torque-control (SVM-DTC) helps to generate the torque angle & flux references [45]. Direct-model-predictive-control (DMPC), without extra-modulator, takes care of power converter's switching-non-linearity. Its nature of one-switching-vector/control-interval causes big ripples in the control-variables. To overcome this issue, multiple-vector-direct-model-predictive-power-control (MV-DMPPC) is presented for GSC based on FPGA [46]. Here, MV-DMPPC shows improved performance than DMPPC with duty-cycle-optimizations. Three methods of current control for MSC are presented based on rotor-flux-oriented-control [47]. Integral-sliding-mode-controller (ISMC), consist of two integral-switching-functions for stator d-q axis currents and controls the currents in synchronous-reference-frame. Then finite-control-set-model-predictive-control (FCS-MPC) controls the stator-currents and replaces ISMC. In FCS-MPC, switching action reduces a predefined-cost-function required for next sampling. At last, conventional PI is developed to evaluate new controllers. In [48] a feedback-linearization based partical swarn optimization (PSO) for selecting optimal working for MPPT of WECS based on PMSG is proposed and verified. A Vienna-rectifier based MPC, measures the possible eight voltage-vectors of the rectifier and enhance the performance of the WECS based on PMSG [49]. Cost-function measures the optimized voltage-vector, used for ripple-minimization. Selection of final switching-set is based on neutral-point voltage-unbalancing issue consideration. Output-power smoothing in low & high-frequency regions, based on coordinated-control of DC-link-voltage and pitch-angle of a WT is proposed [50]. WT blade-stress is alleviated as the pitch-action for high-frequency less and for low frequency; DC-link-capacitor size is reduced without its charge/discharge action. A new method for voltage & frequency control for a stand-alone WECS handling variable load is proposed [51]. Scheme controls GSC for maximum power extraction from wind. Dynamic illustration of dc bus and small-signal analysis is also obtained. In [52], predictive-current-control for the prediction of the generator-behaviour using a mathematical-model is proposed. These parameters may differ from their actual values, leads to inaccurate prediction, so deteriorate predictive algorithm. Extension of the proposed algorithm to enhance the prediction accuracy is presented, which decreases the current-ripple and improves robustness of the system against parameter uncertainties. A new sliding-mode-observer (SMO) to obtain the sensorless control of PMSG is proposed in [53]. An observer is constructed based on back EMF model and accuracy of estimation of rotor-position & speed is achieved. In [54], the output-power-control based on combined high-order-sliding-mode (HOSM) controller is proposed for PMSG based WECS integrating a stand-alone hybrid-generation-system with BESS and some other generation-subsystems. Figure 11 shows the control scheme proposed. Controller presents chattering-free behavior, simplicity & robustness wrt disturbances.

In [55], direct-current based d–q vector control method integrating fuzzy, adaptive and conventional PID control is proposed, which enhances the system optimal-performance. A PMSG-control based on dc-vector-control-process for MSC & GSC is proposed to gain maximum-power from wind [56]. This system achieves excellent performance under various conditions. A integrated power-control is presented for PMSG based WECS operating in various grid

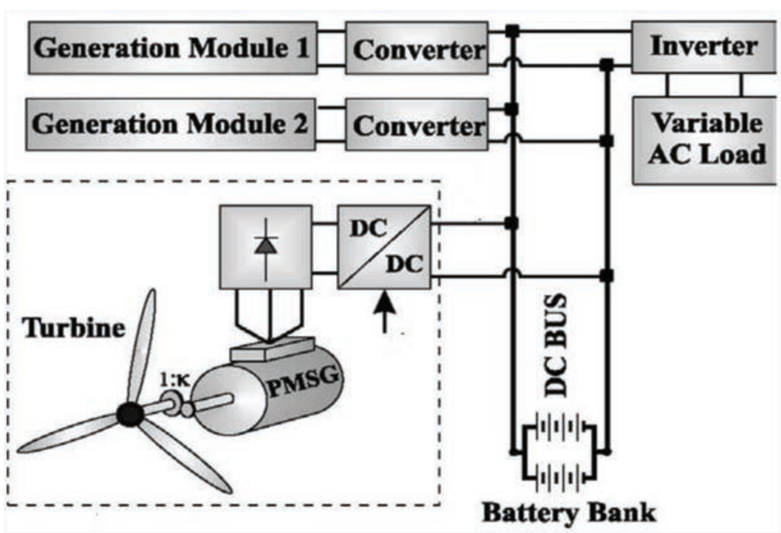

Figure 11 Schematic diagram for combined high-order-sliding-mode (HOSM) control [54].

conditions [57]. The designed scheme is more quicker and accuracy power responses than the variable structured control scheme that is advantageous to the grid recovery. A prototype version of the mechanical sensorless control technique of a 20-kW PMSG for maximum power tracking is proposed [58].

7 Optimization Approach for Permanent Magnet Synchronous Generator (PMSG) Based Wind Energy Conversion System (WECS)

Intelligent techniques, using two AFLC and PSO, to enhance DTC performance of PMSG based-WECS are proposed in [59]. AFLC replaces the traditional-comparators & switching-table and regulates real time PI-parameters. PSO keeps switching frequency constant, is used as an alternative to regulate PI parameters. Controllers help to reduce flux & torque ripples and improves dynamic & steady state efficiency. Pitch-control along with optimization, delay-perturbation-approximation, and signal-compensation methods is proposed [60]. Direct-search-optimization based controller provides delay-free pitch model. Delay-estimator calculates the perturbation due to delay. Signal-compensation method eliminates the effect from delay-perturbation to the turbine output. A multi-physics design optimization of

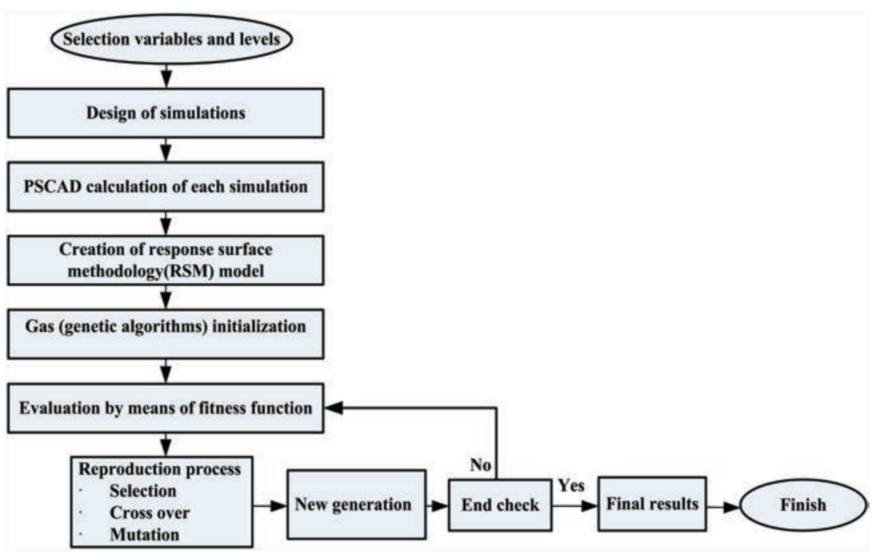

Figure 12 Flowchart of optimum design process.

PMSG is proposed, where goal is to reduce cost [61]. Multi-physics machine model, cost, and loss models are considered under design. Converter's control scheme, affects the system cost, is analysied. Here, optimization leads to describe the phase-angle of the generator-current. Fuzzy-sliding-mode loss-minimization control and an efficient on-line-training radial-basis-function-network (RBFN) for turbine-pitch-angle-control is presented [62]. MPPT algorithms for optimal wind energy capture using RBFN and torque-observer-MPPT-algorithm is proposed [63]. Here, efficient RBFN (based on back-propagation) and a modified-PSO regulates the controller for a sensorless control of PMSG. In [64] an optimum design procedure for parameters of PI controllers of frequency-converter using genetic-algorithms (GAs) is presented. Figure 12 shows the control algorithm for GA. GA enhaces the fault-ride-through also.

8 Conclusion

In this paper, various PMSG topologies such as with controlled & uncontrolled rectifier, grid connected operation; stand-alone operation, different control algorithms, and optimization technique for PMSG have been discussed based on their maximum power generation. Each technique is determined according to the required specification in terms of the parameters used. Also, comparative analysis of various PMSG based variable-speed WECS techniques is studied with advantages and future recommendations and is shown in Table 1. This comparison table provides advantages and research gap of each glitch reduction technique. The performance measure of PMSG can be enhanced by adopting several control mechanism with the aid of advanced optimization techniques. This research study helps as an advantageous knowledge for future research direction.

Table 1 Comparative analysis of PMSG techniques

Sl. No.	Paper Title	Topology Used	Outcomes	Research Gap
1	A medium-frequency transformer-based WECS used for current-source converter-based offshore wind farm [18].	PMSG with controlled & uncontrolled rectifier	Low power loss, low cost, simple control, and more efficient Achieved better performance.	More complexity

(*Continued*)

Table 1 Continued

Sl. No.	Paper Title	Topology Used	Outcomes	Research Gap
2	Experimental enhancement of fuzzy fractional order PI+I controller of grid connected variable speed wind energy conversion system [28].	Grid connected PMSG	Improved the grid-side power factor for a wide range of wind speed.	Average cost and high complexity.
3	A novel online training neural network-based algorithm for wind speed estimation and adaptive control of PMSG wind turbine system for maximum power extraction [40].	Stand-alone PMSG	It provides good accuracy.	More time consumption due to training phase in neural networks.
4	A Control Approach for Small-Scale PMSG-based WECS in the whole wind speed range [45].	control techniques	10 kW wind turbine for commercial applications.	High cost.
5	A comparative experimental study of direct torque control based on adaptive fuzzy logic controller and particle swarm optimization algorithms of a PMSG [59].	Optimization approach	Keeps a constant switching frequency which enhances the PMSM drive system control performance.	More time consumption.

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