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Modelling of PMSG Based Wind Power Generation

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Abstract: *This work grants a general modelling and simulation outline for wind control generation structures based on Permanent Magnet Synchronous Generators (PMSG). The model integrates wind turbine aerodynamics, mechanical drive train dynamics, and detailed electrical modelling of the PMSG in the d-q reference frame. It also includes the implementation of power electronic converters and control strategies such as Maximum Power Point Tracking (MPPT) and vector control for efficient energy extraction and grid integration. Developed in a simulation environment, the model supports performance analysis, control development, and system optimization under variable wind conditions, making it a valuable tool for both academic research and industrial applications..*

Keywords: Wind turbine, PMSG, WECS, MPPT, Power Converter, Drive Train Dynamics

I. INTRODUCTION

The global transition toward renewable energy sources have placed wind power at the forefront of sustainable electricity generation. Wind energy offers an abundant, clean, and environmentally friendly alternative to conventional fossil fuel-based power, making it a key component in reducing greenhouse gas emissions and achieving long-term energy security. To harness wind energy efficiently, the design and control of Wind Energy Conversion Systems (WECS) have become a significant area of research and development.

Among various generator technologies used in wind turbines, the Permanent Magnet Synchronous Generator (PMSG) has gained considerable attention, particularly in variable-speed wind turbines. PMSGs offer several advantages, including higher efficiency, compact size, reduced maintenance, and the elimination of the external excitation system due to the use of permanent magnets. These characteristics make PMSGs especially suitable for offshore and direct-drive applications, where reliability and efficiency are paramount.

The modeling of PMSG-based wind power systems involves the integration of several subsystems, including the aerodynamic behavior of the wind turbine, mechanical coupling through the drive train, and the dynamic response of the generator. Furthermore, power electronic converters are employed for controlling the generator and ensuring proper integration with the grid. Advanced control strategies such as Maximum Power Point Tracking (MPPT) and vector control are implemented to optimize performance under varying wind conditions.

This paper aims to develop a detailed and dynamic model of a wind power generation system using PMSG. The model will incorporate all essential components and control techniques required for realistic simulation and analysis. Such modeling serves as a foundation for performance evaluation, control system development, and grid compliance studies, ultimately contributing to the efficient and stable operation of modern wind energy systems.

II. MODELLING

2.1 Wind Turbine Modelling

2.1.1 Aerodynamic Model

The wind turbine captures wind energy and converts it into mechanical torque.

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2.1.2 Mechanical Power Extracted:

$Pm=\frac{1}{2}\rho ACp(\lambda,\beta)V_w^3$

Where:

ρ: Air density (kg/m³)

A: Swept area of the blades = πR^2

C_p: Power coefficient, function of tip speed ratio λ and pitch angle β

V_w: Wind speed (m/s)

2.1.3 Tip Speed Ratio (TSR):

$\lambda=\frac{\omega_t R}{V_\omega}$

2.2 Drive Train Modelling

This connects the turbine rotor to the generator shaft. Typically modelled with a two-mass system (turbine and generator sides).

Equations:

$J_t\frac{d\omega_t}{dt} = T_m - K_s(\Theta_t - \Theta_g) - D_s(\omega_t - \omega_g)$

$J_g\frac{d\omega_g}{dt} = K_s(\Theta_t - \Theta_g) + D_s(\omega_t - \omega_g) - T_g$

Where:

J: Inertia

θ: Angular displacement

ω: Angular velocity

T_m: Mechanical torque from turbine

T_g: Electromagnetic torque from generator

K_s, D_s: Shaft stiffness and damping

2.3 PMSG Modelling

The PMSG converts mechanical energy to electrical.

2.3.1 d-q Axis Model (rotating reference frame):

$v_d= R_s\, i_d + L_d\frac{di_d}{dt} - \omega_e L_q\, i_q$

$v_q= R_s\, i_q + L_q\frac{di_q}{dt} + \omega_e L_d\, i_d + \omega_e \lambda_f$

$T_e =\frac{3}{2}\, p\, \{\lambda_f\, i_q + (L_d - L_q)\, i_q\, i_d\}$

Where:

V_d, V_q : Stator voltages

I_d, i_q: Stator currents

R_s: Stator resistance

L_d,L_q: d-q inductances

λ_f: Permanent magnet flux

ω_e: Electrical angular speed

p: Number of pole pairs

2.4 Power Electronics Interface

Usually includes:

Back-to-back converter (generator-side and grid-side converters)

DC link capacitor

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2.4.1 Control Goals:
Generator-side: Regulate torque/speed (MPPT)
Grid-side: Sustain DC linkage power, accomplish control current, reactive power governor
Control strategies include:
Field-Oriented Control (FOC)for generator
Vector Governor or Straight Power Regulator for grid line

2.5 Maximum Power Point Tracking (MPPT)
The system should operate at the optimal TSR λopt to maximize power.
Reference Speed:
$\omega_{ref}=\frac{\lambda opt}{R}.V_w$
Control the generator torque to track this speed.

2.6 Grid Integration
Comprises a filter (usually L or LC) and a transformer.
Ensure: Wind turbines must match the grid's voltage and frequency to ensure stable and safe operation when connecting or operating with the power grid. Wind turbines may need to supply or absorb reactive power to help regulate grid voltage and maintain power quality, especially during fluctuating load conditions.Wind turbines must remain connected and stable during short-term grid disturbances (like faults), and recover without tripping offline, ensuring grid reliability.
Tools used for Simulation: MATLAB/Simulink– most common for detailed dynamic simulation

III. MPPT CONTROL TECHNIQUES
MPPT (Maximum Power Point Tracking) control techniques are essential in photovoltaic (PV) systems to ensure that the solar panels operate at their **maximum power point** (MPP) under varying environmental conditions. There are several MPPT algorithms developed with different levels of complexity, tracking speed, and efficiency. Here's a breakdown of the **common MPPT control techniques:**
3.1. Perturb and Observe (P&O)
Concept: Intermittently perturbs (deviations) the functional voltage and observes the conversion in control.
Pros: Simple, low-cost, widely used.
Cons: Can fluctuate about the MPP and might way in the incorrect path beneaths wiftly altering irradiance.

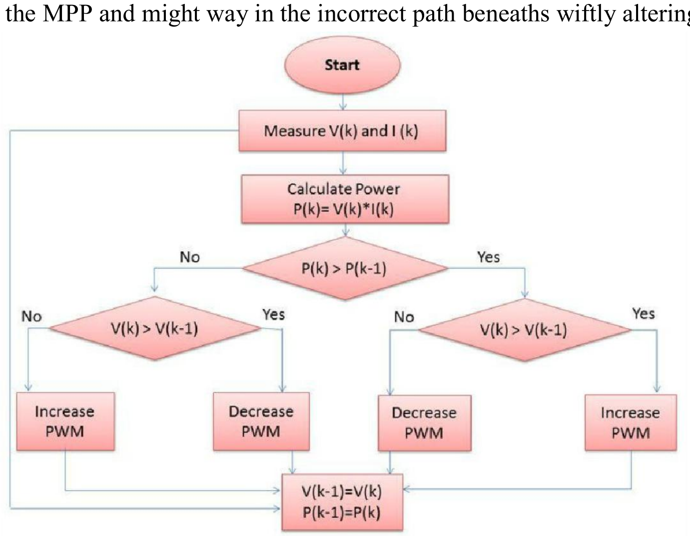

Fig.1: MPPT algorithm modelling

3.2 Incremental Conductance

Concept: Uses the fact that at MPP, the derivative of power with respect to voltage is zero:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V}$$

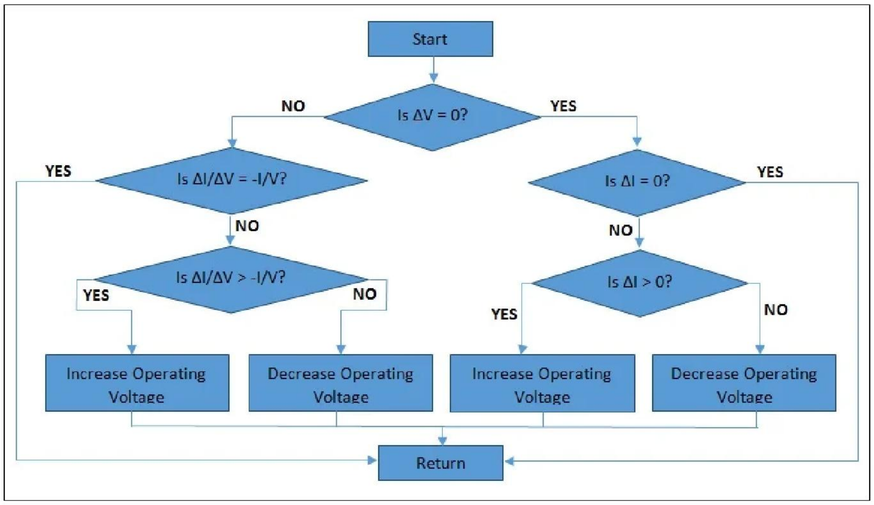

Fig.2: Flow chart for Incremental Conductance

Pros: More accurate under fast-changing conditions than P&O.
Cons: Slightly more complex to implement.

3.3 Constant Voltage (CV) or Fractional Open Circuit Voltage (FOCV)

Concept: Accepts MPP energy is a continual segment (usually ~76%) of the open-circuit voltage.
Pros: Very simple, no need for current measurement.
Cons: Not very accurate, needs periodic open-circuit voltage sampling.

3.4 Constant Current or Fractional Short Circuit Current (FSCC)

Concept: Undertakes MPP contemporary is a stable section (usually ~90%) of the short-circuit current.
Pros: Easy to implement.
Cons: Less accurate, requires short-circuit current measurement which may disturb system operation.

3.5 Fuzzy Logic Control

Concept: Uses fuzzy logic rules and membership functions to determine control action.
Pros: Up right recital below restricted covering and changeable situations.
Cons: Requires tuning and expertise in fuzzy logic.

3.6 Neural Networks and Machine Learning

Concept: Trained models predict the MPP based on system inputs like irradiance and temperature.
Pros: Highly efficient under dynamic and partial shading conditions.
Cons: Complex, needs large training datasets and computational resources.

3.7 Ripple Correlation Control (RCC)

Concept: Utilizes the ripple components in voltage/current to guide toward MPP.
Pros: High efficiency, can be used without sensors.
Cons: More suitable for analog circuits; less common in digital systems.

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IV. POWER CONVERTER OPERATION

Why Converters Are Needed?

PMSG (Permanent Magnet Synchronous Generator) produces **variable-frequency, variable-voltage AC** power depending on wind speed. Most electrical loads or the grid require **constant-frequency, regulated voltage AC power**. Therefore, a **power electronic converter system** is used to condition the output.

4.2. Typical Converter Topology

A **two-stage back-to-back converter** is commonly used, consisting of:

4.2.1 Machine-Side Converter (MSC)

Function: Controls the generator output, especially the generator speed and torque.
Control Goals:
Maximize power extraction using **MPPT** (Maximum Power Point Tracking).
Regulate the generator's operating point.i
Frequently executed using **vector governor** or **field-oriented controller (FOC)**schemes.

4.2.2 DC Link

Function: Acts as an energy buffer between the MSC and GSC.
Maintains a **stable DC voltage** to ensure smooth power transfer.

4.2.3 Grid-Side Converter (GSC)

Function: Converts the DC link voltage back to AC and synchronizes with the grid.
Control Goals:
Maintain constant output voltage and frequency.
Ensure power quality and power factor control.
Control **active and reactive power** injection to the grid.

4.3 Control Strategy Overview

MPPT algorithm on the MSC side to track optimal wind energy.
Current control loops and **PWM techniques** (like SPWM or SVPWM) for regulating output.
DC-link voltage control and **grid synchronization** via Phase Locked Loop (PLL) on the GSC side.

4.4 Grid-Connected vs. Standalone Operation

Grid-connected: GSC confirms management and grid program acquiescence.
Standalone: GSC regulates voltage and frequency locally, often with added storage or load management.

4.5 Benefits of Using Converters in PMSG Systems

Enables **variable-speed operation** for higher energy capture.
Ensures **stable and high-quality output power**.
Supports **reactive power compensation**.
Enhances **fault handling** and **system protection.**

V. CONCLUSION

The modelling of PMSG-based wind power generation systems demonstrates their strong potential for efficient and reliable renewable energy conversion. PMSGs offer significant benefits, including high efficiency, low maintenance, and compatibility with variable-speed operation, making them ideal for both grid-connected and standalone applications. Accurate modelling enables better control strategies, improved system performance, and enhanced integration with hybrid and off-grid systems. While the simulations confirm the viability of PMSG technology, further research is encouraged in areas such as real-time implementation, grid compliance, and advanced fault-handling capabilities to fully harness its potential in future wind energy solutions.

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