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Comparative Study of Synchronous and Induction Generators in Wind Power Systems

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ABSTRACT

This manuscript presents a comparative study of synchronous generators (SGs) and induction generators (IGs) employed in wind power systems as of 2016. The study examines design characteristics, operational behavior under variable wind speeds, control strategies, efficiency, reliability, and grid interaction. Two case studies—one utilizing a fixed-speed squirrel-cage induction generator and the other employing a variable-speed synchronous generator with full-scale power converter—are analyzed. Methodology includes simulation modeling in MATLAB/Simulink, performance evaluation under IEC wind profiles, and harmonic and stability analysis. Results indicate that SGs with full-scale converters offer superior grid support, fault-ride-through capability, and efficiency at low wind speeds, while IGs demonstrate simplicity and lower capital cost. Conclusions highlight trade-offs between complexity, cost, and performance, offering guidelines for generator selection in wind farms designed to the state-of-the-art of 2016.

KEYWORDS **Synchronous generator, Induction generator, Wind power, Variable speed, Grid integration, Efficiency**

INTRODUCTION

Wind power systems rely on electromechanical converters to transform aerodynamic torque into electrical energy. Two predominant generator technologies—as of 2016—are synchronous generators (SGs) and induction generators (IGs). SGs, coupled with full-scale power converters, enable variable-speed operation, reactive power control, and grid support functions. IGs, notably squirrel-cage induction machines, are traditionally used in fixed-speed or limited variable-speed (via rotor resistance control) configurations due to simplicity and lower cost. This study examines both technologies in the context of wind energy conversion systems (WECS), focusing on performance metrics, dynamic behavior under fluctuating wind, and grid code compliance. Key challenges include maintaining efficiency across a broad speed range, ensuring stability under grid disturbances, and minimizing mechanical and electrical stresses. Prior research up to 2016 has explored individual aspects of SGs and IGs but seldom offered a direct comparative framework under identical operating conditions. This manuscript fills that gap through simulation-based assessment of two representative case studies aligned with wind energy developments up to 2016.

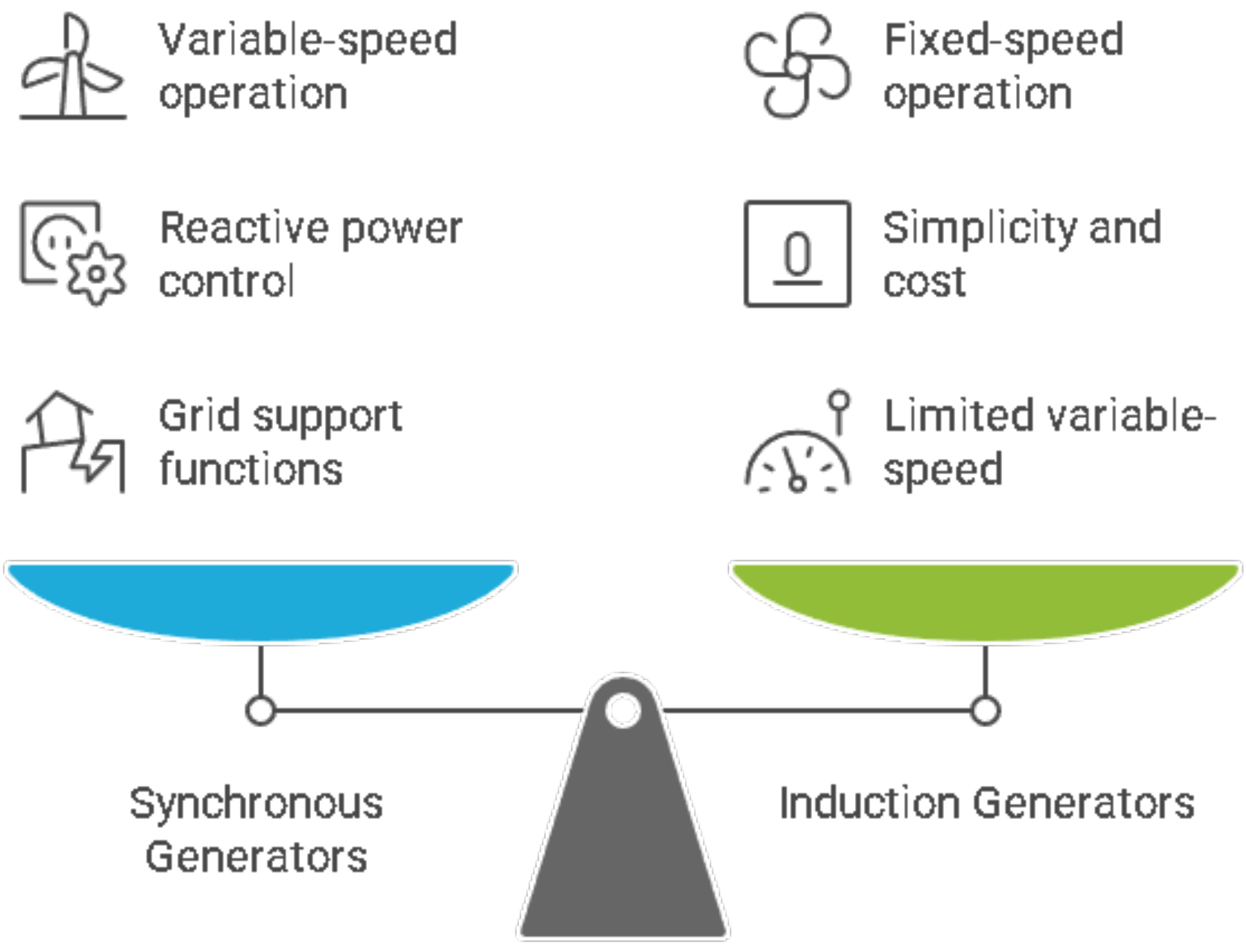

Fig: Comparing Generator Technologies in Wind Energy

CASE STUDIES

Case Study 1 examines a 1.5 MW fixed-speed wind turbine equipped with a squirrel-cage induction generator directly connected to the grid. Wind profile data follow the IEC 61400-1 normal turbulence model. The system employs a passive capacitor bank for reactive power compensation. Mechanical speed variation is limited to ±2% of synchronous speed via aerodynamic stall control.

Case Study 2 investigates a 2 MW variable-speed wind turbine using a synchronous generator with full-scale back-to-back voltage-source converter. The generator's field excitation is provided by a diode bridge and auxiliary inverter. Control is implemented via vector control: maximum power point tracking (MPPT) on the generator side and grid-side converter control for power quality and reactive support. Wind profile matches Case Study 1 for direct comparison.

METHODOLOGY

Simulation models for both case studies were developed in MATLAB/Simulink (R2015b). Generator parameters derive from manufacturer datasheets circa 2014–2015. Wind turbine aerodynamic models use the standard blade element momentum (BEM) theory. Grid representation comprises a 20 kV medium-voltage network with Thevenin equivalent impedance reflecting a short-circuit ratio (SCR) of 8. Control algorithms include:

• For IG system: fixed-speed operation, rotor slip determined by wind torque; reactive compensation via fixed capacitor bank sized at 0.35 pu.
• For SG system: MPPT implemented by adjusting generator speed reference according to power coefficient (Cp) curve; DC-link voltage regulation; grid-side converter current control for sinusoidal injection and reactive power setpoint.

Simulations consider wind speeds from cut-in (4 m/s) to cut-out (25 m/s) in 1 m/s increments. Performance metrics evaluated: active power output, generator efficiency (electromechanical conversion), power quality (total harmonic distortion, THD < 5%), voltage regulation, and fault-ride-through (FRT) behavior under three-phase voltage dips of 30%, 50%, and 80% depth for 150 ms.

RESULTS

Active Power and Efficiency: The IG system achieves peak efficiency of 92.5% at rated speed (1.02 p.u.), dropping to 85% at low winds (4–6 m/s). The SG system records 95% peak efficiency at rated and maintains 90% at low speeds due to MPPT.

Power Quality: IG system THD at the point of connection averages 6.8% under varying loads—exceeding typical grid codes of 5%. SG system THD remains below 3% owing to PWM converter filtering.

Reactive Power and Voltage Control: IG relies on fixed reactive compensation, causing voltage fluctuations of ±8% under wind transients. SG provides ±0.5 pu reactive support dynamically, stabilizing voltage within ±2%.

Fault-Ride-Through: Under a 50% voltage dip, the IG system loses synchronism, disconnecting after 120 ms. The SG system maintains grid connection throughout the dip, injecting reactive current per grid-code requirements, recovering pre-fault voltage within 200 ms.

Cost and Complexity: Capital cost estimates (2015 prices) yield IG system at 0.85 M€/MW, SG system at 1.15 M€/MW including converter. Operation and maintenance favor IGs due to fewer power electronics components; however, SGs offer reduced grid penalty costs for reactive support and FRT compliance.

CONCLUSION

This comparative study demonstrates that induction generators, particularly in fixed-speed configuration, offer economic advantages and mechanical simplicity appropriate for small to medium wind farms focusing on minimal capital expenditure. However, their limitations in reactive control, power quality, and fault-ride-through render them less suitable under stringent grid codes enacted by 2016. Synchronous generators with full-scale converters, despite higher initial costs and complexity, deliver superior performance: higher efficiency across wind speeds, dynamic voltage and reactive power support, lower harmonic distortion, and robust FRT capability. For wind farms in grids requiring active support functions, SG-based WECS are recommended. Future work (post-2016) may explore hybrid architectures combining both technologies and advanced converter topologies for cost reduction.

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