

An Integrated Wind-Turbine Performance and Power-Quality Framework for Grid-Connected PMSG Wind Energy Conversion Systems Using Optimized LCL Filtering

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Abstract: *This study establishes a comprehensive assessment framework for variable-speed wind-energy conversion, originating from three increasingly connected levels of investigation: turbine-side operating variability, grid-side PMSG converter control, and passive LCL-filter design. The framework begins with a one-year SCADA power-curve analysis, proceeds to a MATLAB/Simulink grid-connected PMSG model with synchronous-reference-frame control, and ends with a comparative LCL-filter study. The power-curve analysis includes 50,530 samples of approximately 10-minute durations, reports a ratio of actual to theoretical power of 87.64% (with wind speed obviously still the primary driver of actual power, correlation coefficients $r = 0.913$ to 0.944 , and cross-correlation coefficient $r = 0.950$ between actual power and theoretical power), and yields the findings of a converter baseline synchronization at 50 Hz, a stable 181.7-182 V DC-link voltage, a 5-A nominal dq-axis current reference, approximately 180-200 W active power transfer, near-zero reactive power, near-unity power factor, and 5.89% current THD. The separate LCL comparison then concludes the 25-mH/10-F/8-mH case to be the lowest-THD among four simulated configurations, at 5.89% current THD and 6.15% voltage THD while reducing the total inductance from 47 mH to 33 mH. The main achievement of this study is not to claim a new dataset or a new connected simulation result, but rather to establish a traceable simulation-to-design cycle in which SCADA-derived wind power variability defines the converter operating domain, dq control embodies the grid-interface regulation, and LCL-filter optimization manages switching harmonics. The framework hence constitutes a validation protocol for future variable wind- and hardware-testing. The results indicate that wind-resource variability, converter control, and harmonic filtering should be examined as integrated engineering problems rather than isolated sub-systems.*

Keywords: PMSG, wind energy conversion system, SCADA, power curve, dq-axis control, DC-link voltage, PLL, LCL filter, THD, grid integration, power quality.

1. Introduction

Wind-energy conversion systems are more and more asked to deliver variable renewable energy to the electrical grid at a stable DC-link voltage, with controlled active and reactive power, with synchronization and within allowable harmonic content. Wind turbines are, by definition, variable, because the aerodynamic energy extracted from the air is strongly dependent on the wind speed, and the electrical interface has to deliver a grid-compatible power level. In this context, any credible evaluation of a wind energy system should go beyond the aerodynamic power curve and steady-state waveforms at the converter-architecture level, toward determining how the source-side variability relates to control requirements and to the design of the harmonic filter at the grid connection.

Three source studies support such an integrated perspective. The first study assesses the actual versus theoretical power of a turbine using 50,530 short-term SCADA observations across a year, averaging 87.64% actual-to-theoretical, with large temporal and directional variation. The second assesses the MATLAB/Simulink performance of a scaled grid-connected PMSG WECS by inclusion of a PLL, dq-axis

current control, DC-link regulation, and an L filter, and based on its baseline response finds stable DC-link voltage, near-zero q-axis current, and 5.89% total current THD. The third compares four sets of LCL-filter parameters, and based on all four sets compares 5.89% total current THD and 6.15% voltage THD of the 25-mH/10-F/8-mH combination with the total inductance reduced from 47 mH to 33 mH.

The research gap being filled here is thus a gap of integration. The analysis of power, power quality, and electrical response data is well understood when considered in isolation: turbine power-curve analysis describes the available and achieved energy; converter-control analysis describes the electrical response; filter optimization describes power quality. But they are applied separately. This paper brings them into a single engineering workflow: (i) quantify the wind-power operating envelope from SCADA data, (ii) connect representative power states to the PMSG grid interface, (iii) maintain the dq-axis control and PLL locking as the regulation layer, and (iv) choose an LCL filter on the basis of harmonic and component-size constraints.

Validation is conservative in this work. The provided converter study is without any plant-side electrical data, and

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the Kerala Pugalur-Thrissur project data set has transmission ratings not wind-farm measurements. The integrated paper is thus not producing an experimental validation nor generating new transient results, but is relying on existing data as traceable baseline evidence and a new simulation/experimental methodology for next stage work.

2. Related Work and Research Work

Power-curve analysis is common practice for: wind-turbine monitoring, energy assessment, and performance evaluation. The source SCADA investigation indicates SCADA power often correlates with the theoretical power, but a significant amount of deviation occurs in mid-range wind-speed bins and at certain times or directions. Deviations might be caused by site operations, curtailment, shutdowns, turbulence, wakes, control activity, generator, and converter losses, and other field phenomena. Power alone, however, cannot determine which electrical defect causes an underperformance event if no other monitoring data exists.

On the electrical side, the PMSG configuration applies an abc-dq synchronous reference frame (current on the d-axis is used for active-power transfer and current on the q-axis is used for reactive-power control), such that a zero q-axis reference is used for a unity-power-factor operation. The grid angle needed for the abc-dq and dq-abc transformation is provided by a PLL. The outer DC-link voltage loop produces the d-axis reference current needed to make power transfer and is optimized independently from reactive-power control. The other constraint of the baseline converter is its L filter. LCL study indicates an LCL structure can achieve similar or better harmonic performance with greatly reduced total inductance, when the resonant frequency and damping are carefully chosen. Current optimization techniques comprise analytical design, passive damping, particle-swarm optimization and multi-objective optimization. The missing link in practice is how to relate the real turbine operation variability to the filter choice. The new framework fills this gap in knowledge in both a conceptual sense and a quantitative manner through the three evidence streams provided.

3. Proposed Integrated Framework

3.1 Overall Architecture

The structure presented has four interconnected tiers as illustrated. The first is the turbine and wind-resource layer (represented by the wind speed, wind direction, real active power and ideal power), this forms the real-world wind farm. The second layer is the PMSG power conversion, where the mechanical input is converted to electrical power and passed via the DC link. The third layer; grid-side controls that include the DC-link PI regulator, dq current controllers, PLL and PWM voltage-source inverter. The fourth is the grid-interface filter, where an LCL topology is tested against the baseline of an L-filter configuration.

Wind speed / direction turbine power envelope PMSG rectifier DC link dq/PWM inverter LCL filter grid

3.2 Wind-Turbine Operating Envelope

The aerodynamic input is represented by the standard wind-power relation and the power coefficient. The tip-speed ratio links rotor speed and wind speed. These relations provide a physical basis for interpreting the SCADA power curve.

$$P_w = 1/2 \rho A V^3 \quad (1)$$

$$\lambda = \omega R / V \quad (2)$$

$$P_m = C_p(\lambda, \beta) P_w \quad (3)$$

$$T_m = P_m / \omega \quad (4)$$

Here, ρ is air density, A is rotor swept area, V is wind speed, ω is rotor angular speed, R is blade radius, C_p is the power coefficient, β is blade pitch angle, and T_m is mechanical torque.

3.3 SCADA-Based Performance Indicators

The source analysis compares actual and theoretical power using the power deviation, performance ratio and percentage loss. For observations with positive theoretical power, the instantaneous performance ratio can be represented as:

$$PR = P_{actual} / P_{theoretical} \quad (5)$$

The source dataset contains 50,530 observations. The mean actual power is 1307.684 kW and the mean theoretical power is 1492.175 kW. The reported overall actual-to-theoretical output ratio is 87.64%. The error metrics are MAE=195.479 kW, RMSE=465.792 kW and $R^2=0.884$. These values provide a quantitative source-side benchmark for the proposed integrated framework.

3.4 PMSG and Grid-Side dq Control

In the supplied model, wind energy is converted to mechanical torque by the turbine and then to electrical power by the PMSG. A three-phase diode rectifier transfers generator-side power to the DC link. The DC-link capacitor provides energy buffering, and the grid-side voltage-source inverter synthesizes the controlled AC waveform.

The DC-link error is defined as the difference between the reference and measured DC-link voltage. A PI controller generates the d-axis current reference. The q-axis reference is set to zero for near-unity-power-factor operation. The PLL estimates grid phase angle and frequency for the coordinate transformations.

$$e_v = V_{dc,ref} - V_{dc} \quad (6)$$

$$i_{q^*} = 0 \rightarrow Q \approx 0 \rightarrow PF \approx 1 \quad (7)$$

The baseline simulation operates at 50 Hz and reports DC-link voltage near 181.7–182 V, a d-axis current reference near 5 A, active power around 180–200 W, reactive power close to zero, balanced three-phase currents, approximately unity power factor and current THD of 5.89%.

3.5 LCL Filter Model and Design Variables

The proposed integrated framework replaces the baseline L filter with an LCL design space consisting of inverter-side inductance L_1 , shunt capacitance C and grid-side inductance L_2 . The filter must attenuate switching-frequency

components while avoiding excessive resonance amplification. The source LCL study evaluates four configurations under fixed switching, modulation and PLL conditions.

$$f_{\text{res}} \approx (1/2\pi) \sqrt{(L1 + L2)/(L1 L2 C)} \quad (8)$$

The damping resistor is recalculated for each configuration in the source study so that the resonance is suppressed without introducing excessive passive loss. The key design principle is that component reduction is acceptable only when the resulting resonant frequency remains appropriately separated from the fundamental and switching sidebands.

4. Data and Methods

4.1 Source Data Streams

Layer	Source evidence	Main variables	Role in integrated framework
Turbine/SCADA	50,530 observations, one year	Wind speed, actual power, theoretical power, direction	Defines operating envelope and performance variability
PMSG converter	MATLAB/Simulink baseline	V _{dc} , I _d , I _q , P, Q, PF, current THD	Defines grid-interface control baseline
LCL design	Four comparative configurations	L1, C, L2, current THD, voltage THD	Defines harmonic/filter design benchmark
Kerala grid context	Pugalur–Thrissur project data	50 Hz, ±320 kV, 2,000 MW	System-level transmission context only

4.2 SCADA Analysis Procedure

Convert wind speed group into those used by the study: <3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9, 9-10, 10-12, 12-15, 15-20 and >20 m/s. Determine the average actual power, average theoretical power, deviation and performance ratio for each interval. Where theoretical power is positive & actual power is zero, and where actual power is less than 10% of theoretical power.

Evaluate monthly and eight-sector wind-direction behavior. To do 1. Calculate Pearson correlations, MAE, RMSE and R between real and theoretical power.

4.3 Converter Evaluation Procedure

The converter is assessed at the baseline operating point that was submitted in the MATLAB /Simulink tutorial. Performance figures are V_{dc}, I_d, reference, I_q, P, Q, power factor, grid-current balance and current THD. The assessment separates the steady-state baseline outcome from the subsequent disturbance experiment.

4.4 LCL Comparative Procedure

Configuration	L1 (mH)	C (μF)	L2 (mH)	Total L (mH)	Current THD (%)	Voltage THD (%)
Baseline	35	8	12	47	5.96	6.34
Case 1	25	10	8	33	5.89	6.15
Case 2	20	12	10	30	5.96	6.28
Case 3	15	15	5	20	5.95	6.36

The source LCL study holds load, modulation index and PLL parameters constant. The modulation index is 0.85, the PLL settling behavior is approximately 50 ms, and harmonic evaluation is performed after the transient using a 20-cycle 50-Hz observation window with harmonics evaluated through the 50th order.

5. Results

5.1 Turbine-Side Performance

Indicator	Reported value
Observations	50,530
Mean actual power	1307.684 kW
Mean theoretical power	1492.175 kW
Overall actual/theoretical output	87.64%
Median performance ratio	0.888
Mean performance ratio	0.811
MAE	195.479 kW
RMSE	465.792 kW
R ²	0.884
Zero actual power	10,781 observations (21.34%)
Positive theoretical power but zero actual	3,497 observations (6.92%)
Actual <10% of theoretical	3,788 observations (7.50%)

The wind-speed analysis also confirms that actual power is consistently higher with rising wind speed. The largest absolute power differences are recorded at middle wind-speed intervals, but performance ratio approaches one as wind speed goes into higher ranges. At wind speed levels beyond 15 m/s, quoted performance ratios are 0.971 at 15–20 m/s and 0.992 above 20 m/s.

Directional resolution indicates some anisotropic behavior as well. A performance ratio as low as 0.620 is observed in the northwest direction, while a performance ratio as high as 0.889 is observed in the south direction. Since the provided data does not contain hill and wake information, fault and repair data, these differences cannot be attributed to a single physical reason.

5.2 Converter Baseline

Performance variable	Reported baseline result	Engineering interpretation
Grid frequency	50 Hz	PLL synchronization
DC-link voltage	≈181.7–182 V	Stable after startup
d-axis current reference	≈5 A	Active-power regulation
q-axis current	≈0 A	Reactive-power suppression
Active power	≈180–200 W	Controlled power injection
Reactive power	≈0 VAR	Near-unity PF operation
Power factor	≈1	Unity-PF operating point
Current THD	5.89%	Baseline harmonic performance

5.3 LCL Filter Results

Case 1 yields the lowest measured current and voltage THD of all four studied configurations. Total inductance drops from the 47-mH reference to 33 mH (a decrease of nearly 29.8%). Current THD drops from 5.96% to 5.89%, and voltage THD drops from 6.34% to 6.15%.

Case 2 drops total inductance to 30 mH, but return current THD to 5.96%.

Case 3 reduces total inductance further to 20 mH, but voltage THD increases to 6.36%, and the source study notes its resonance approaches the switching-sideband frequencies more closely.

5.4 Integrated Interpretation

Together, the three evidence streams define a consistent operating chain. From the SCADA analysis, turbine power is variable, and the actual power deviates significantly from the theoretical power. From the converter results, the grid interface can find and maintain a stable DC-link, control active power with the d-axis, cancel reactive exchange with the q-axis, and synchronize to the 50-Hz grid. The filter study confirms that the harmonic interface may be redesigned without simply increasing the inductance. When taken together, these three pieces of evidence encourage a design method where the converter and filter requirements are assessed in terms of the turbine's previously observed power states rather than at only a single nominal operating point.

Secondly, the simulation outputs are not combined in a constructed new simulation. This 87.64% turbine performance ratio, 5.89% baseline converter THD, and 5.89%/6.15% Case-1 LCL THD are all various different studies. The added value from this paper is the methodology to connect them and how the new combined simulation should be run.

6. Discussion

Existing turbine data show the converter system must be capable of supporting a large variation in power states. The power level is low at low wind speed, high in the power-growth region and near rated in the near-rated region. Such differences are of concern to the converter controller since the d-axis current reference is ultimately linked to active-power transfer. A converter controller optimized for a single steady-state condition must therefore be verified when the wind speed increases and decreases.

The baseline PMSG test shows the anticipated decoupling of active and reactive control in the synchronous reference frame: the q-axis current is nearly zero and the reactive power is nearly zero. This provides a useful baseline for a variable renewable interface. But it should not be taken as indicative of performance under weak-grid, voltage-sag or frequency disturbance conditions since those tests were not provided.

The LCL study is highly comparable to the 5.89% baseline current THD. The Cases 1 current THD values are identical to the baseline PMSG study, but since the 5.89% values are from separate simulations this should not be implied to be from the same experiment. Instead, the filter study contains a design target for an LCL configuration to minimize the size of the inductive components at the same steady-state harmonic level.

The Kerala transmission context offers a system-level incentive for further expansion. The Pugalur-Thrissur project is recognized as a 320-kV, 2,000-MW VSC-HVDC system with 50-Hz AC interfaces. The study supplied is explicitly considered as a grid-integration context instead of using measured offshore-wind data. The simulated 181.7-182-V DC-link and 180-200-W power transfer are control-level values, and thus not comparable to project rating.

7. Proposed Simulation-to-Experimental Validation Matrix

Case	Condition	Main disturbance/reference	Primary outputs	Metrics
C1	Constant wind	Baseline operating point	Vdc, Id, Iq, P, Q	Settling time, overshoot, SSE, PF, THD
C2	Wind increase	Step increase in wind speed	P, Vdc, Id	Settling time, overshoot, SSE, PF, THD
C3	Wind decrease	Step decrease in wind speed	P, Vdc, Id	Settling time, overshoot, SSE, PF, THD
C4	DC-link reference	Vdc reference step	Vdc, Id	Settling time, overshoot, SSE, P, Q
C5	Active-power reference	P reference step	P, Id, Vdc	Settling time, overshoot, SSE, PF, THD
C6	Reactive-power reference	Q reference step	Q, Iq, PF	Settling time, overshoot, SSE, PF
C7	Voltage disturbance	Temporary grid-voltage reduction	PLL, Vdc, Id, Iq, P, Q	Recovery, THD, PF
C8	Frequency disturbance	Small grid-frequency deviation	PLL angle/frequency, P, Q	Tracking error, recovery, THD

These are test plan cases, not experiment results. A credible follow-on experiment should simulate the combined MATLAB/Simulink model for all 8 cases against the SCADA-manipulated operating envelope, then do them all over with the chosen LCL filter, then do the same cases on the lab platform. Simulated and measured waveforms should be compared at the same operating points, with MAE, percentage deviation, settling time, overshoot, steady-state error, power factor and THD. If the transient tests were repeated at least three times, then repeatability could be reported.

8. Future Research Directions

In subsequent work, the fully-integrated control architecture should be coded in MATLAB/Simulink with the steady-state wind input replaced by wind speed profiles representing the degree of turbulence observed from the SCADA data. The four LCL filtering strategies can then be tested under the same wind forces to compare their harmonic performance, DC-link power fluctuations, active-power control and filter loading at the low, intermediate and rated power states.² A third phase can then vary the grid impedance and weak grid load to evaluate interactions with the PLL, current controller and LCL filter resonance.

A third stage should look at the comparison between the above converter structures with different levels within the same wind-power envelope. This would directly challenge the source study's claim that multilevel conversion may give some advantages for waveform quality, switching stress and scalability. Laboratory measurements should be performed with a wind or motor-generator emulator and a programmable grid source with the same measurement window and FFT definition used in the simulation.

9. Conclusion

This paper has highlighted a complete integrated multi-level analysis of wind-energy conversion from the turbine operating level through to the grid power-quality level. Actual generated power from the source SCADA analysis of the source data shows that actual turbine power is in line with theoretical power, with an overall actual-to-theoretical ratio of 87.64%, but significant temporal variation, directional variation and under-performance has been identified. The PMSG converter analysis provides evidence that dq-axis controller along with PLL synchronization and DC-link regulation is able to deliver a steady grid interface at the scaled operating point reported, with the present 5 A d-axis current reference, active power of 180-200 W, nearly zero reactive power, unity power factor and 5.89% current THD. The LCL investigation for the device under test revealed that the 25-mH/10-F/8-m H network configuration achieves 5.89% current THD and 6.15% voltage THD while eliminating the 47-m H total inductance.

The main contribution is a traceable engineering procedure from source-side wind field characteristics, through grid interface specifications, to harmonic filter design. This paper refrains from asserting the three numerical study datasets constitute a single new experiment. They are, instead, suggestive of the precise next experiment the researchers should do: rerun the PMSG model using SCADA wind profiles, compare the L and LCL interfaces side-by-side on equal terms, measure the grid disturbances and weak grid effects, and experimentally verify the waveforms. This will enable the current synthesis to become a truly new, quantitatively defensible research result, without requiring any secondhand measurements.

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