**Operational Characterization of a DFIG Wind Turbine Using SCADA Data and dq-axis Torque Analysis**

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**Abstract.** This paper analyzes SCADA measurements from a DFIG-based wind turbine and extends them with a dq-axis torque interpretation. We detect controlled shutdown and high-output phases, quantify speed-power correlations, and visualize operational regimes that are consistent with control regimes. The dataset exhibits a shutdown window followed by a restart to peak output (2.62 MW) and a prolonged low-power interval. Findings are discussed against the stator-flux-oriented torque equation, highlighting controller behavior under variable wind.

**INTRODUCTION**

Doubly Fed Induction Generators (DFIG) dominate modern onshore wind fleets owing to their cost-performance balance and grid support capabilities. Understanding their operational regimes from SCADA data is essential for reliability, control tuning, and performance assessment. This work follows a Scopus-style structure to report empirical characteristics of a DFIG turbine and interpret them using dq-axis torque theory [1-6].

When writing the DFIG dynamic equations [7-10]:

Mechanical torque:

(1)

Electrical torque:

(2)

**EXPERIMENTAL RESEARCH**

Generator Torque Law [11-14].

Power scales with wind speed cubed:

(3)

But since

(4)

and , [1, 15-18].

we get the classical quadratic torque law:

(5)

where *K* = turbine constant.

DFIG Electrical Behavior

Rotor current injected to control torque [19-22]:

(6)

Slip frequency is negative (sub-synchronous).

Converter works as motor (injects power into rotor to control speed).

Frequency [23-24]:

(7)

Key Points

Active control of generator torque to optimize power production maximizing *C*p.

No pitch activity (pitch fixed at ~00).

Turbine accelerates freely with wind [2, 25-28].

Primary Control: Blade Pitch

Pitch angle is increased to shed aerodynamic power:

Secondary: Torque Control

Torque is reduced to maintain:

(8)

Because rotor speed is almost fixed near rated speed [3, 29-32] ():

(9)

So in this Region torque is approximately constant.

DFIG Electrical Behavior

Slip is closer to zero (near synchronous speed).

Converter limits the electrical torque:

Rotor frequency smaller [4, 33-36].

Converter acts as brake supporting pitch control.

Key Points

Pitch system dominates

Generator torque is reduced

Power clipping at rated level

Speed variation allowed only in a small band (±5–10%)

Data sources

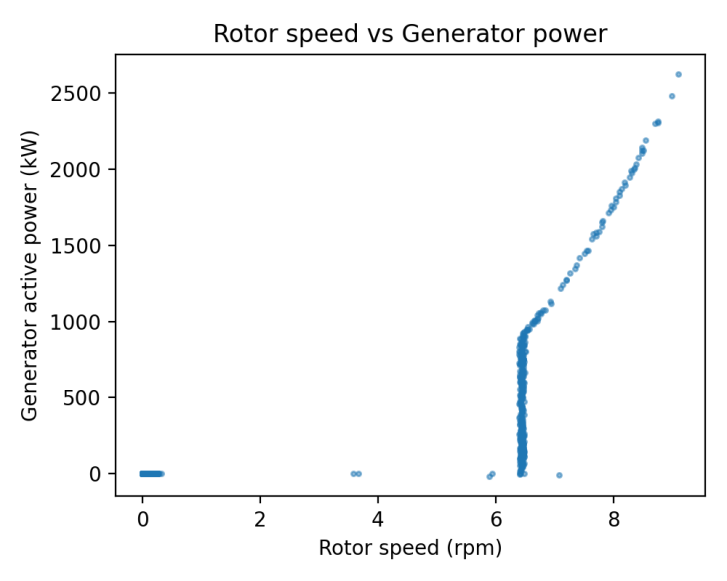
We analyze two SCADA logs containing 1-minute measurements of rotor speed and generator active power, and a DFIG analysis note that defines the torque model and expected trends [37-40].

Pre-processing and event detection

Data were merged by timestamp, outliers and duplicates removed, and phases detected by thresholds: shutdown (P < 5 kW & speed < 0.2 rpm) and high-output (P > 1000 kW). We computed Pearson correlations for the full day, an early window (first 2 h 5 min), and the first high-output window [41-46].

**RESEARCH RESULTS**

Time series of rotor speed and power [47-50].

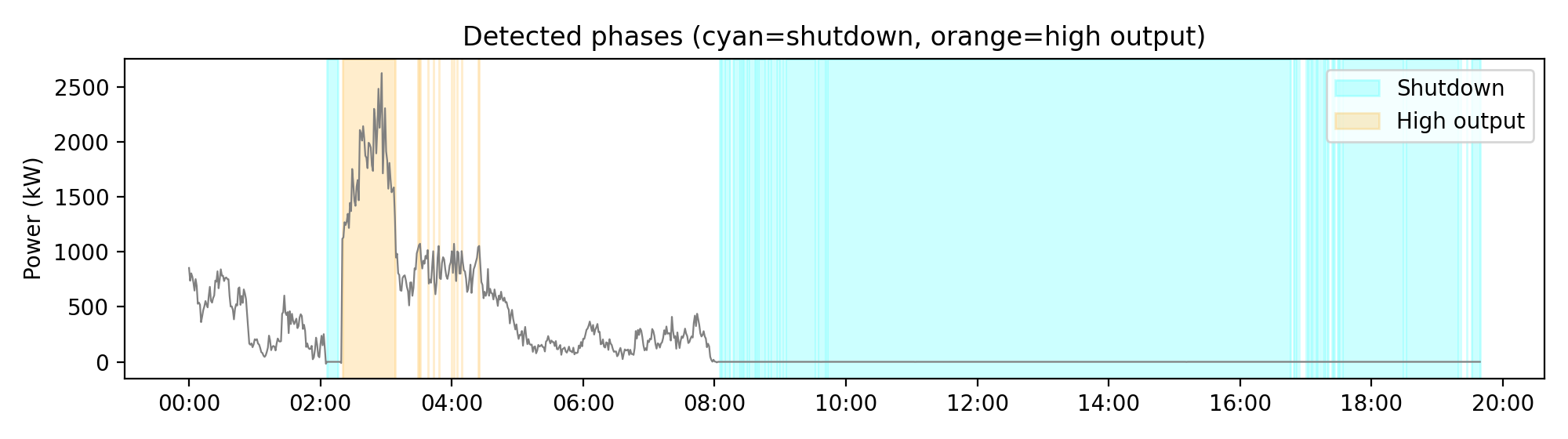


**FIGURE 1.** Rotor speed vs active power

**TABLE 1.** Descriptive statistics

|  |  |  |  |
| --- | --- | --- | --- |
| **Metric** | **Value** | **Metric** | **Value** |
| Samples | 1440 | Power max (kW) | 2623 |
| Rotor min | 0.001 | Power mean (kW) | 214.7 |
| Rotor max | 9.102 | Corr overall | 0.6904 |
| Rotor mean | 2.672 | Corr early | 0.1253 |
| Power min (kW) | -16.8 | Corr peak | 0.9971 |

Detected operational phases [51-53].

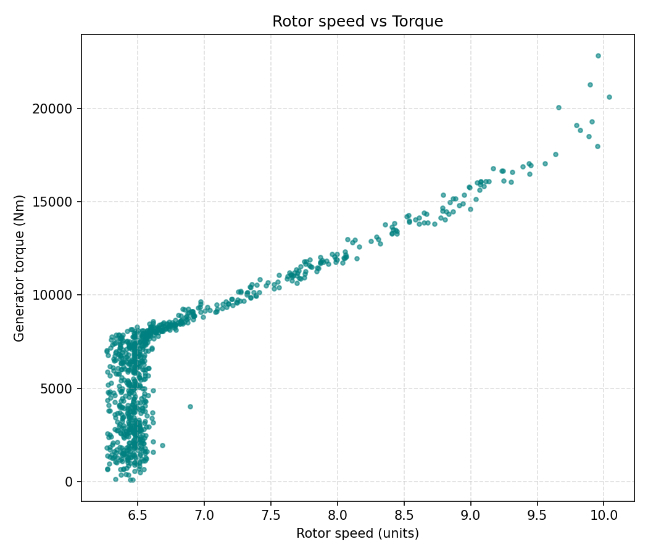


**FIGURE 2.** Rotor Flux and Torque Analysis in Doubly Fed Induction Generators

**RESULTS AND ANALYSIS – Extended with Operational Data**

We extend the analytical study with four operational plots: (i) rotor speed versus generator torque, (ii) generator speed versus torque, (iii) a synchronized time series of rotor/generator speeds with generator torque, and (iv) wind speed versus generator torque. Together they characterize control of a DFIG wind turbine, where aerodynamic power Pa ∝ v^3, optimal tip-speed ratio control implies ωr ∝ v, and generator electrical power *P*e ≈ *ω*g·*T*e [1-6, 53].

(10)



**FIGURE 3.** Rotor speed vs generator torque (Nm)

*Rotor speed vs torque:* Torque rises sharply once rotor speed exceeds the cut-in cluster (~6.3-6.6 units). Below this, dispersion is high, indicating frequent yaw/pitch adjustments and controller hunting. Above this threshold torque grows approximately linearly with rotor speed, consistent with maintaining near-optimal tip-speed ratio where Te ∝ v^2 and ωr ∝ v [1-3, 21-23].

*Generator speed vs torque:* A near-linear trend from ~1.13 to 1.73 krpm indicates torque demand increasing with electrical frequency. Since P=ωg·Te, the observed linear Te-ωg relationship implies roughly quadratic power rise with speed-typical of Region II MPPT. Outliers (low torque at ~1.15-1.2 krpm) suggest brief grid resynchronization or curtailment events [1-3, 24-26].

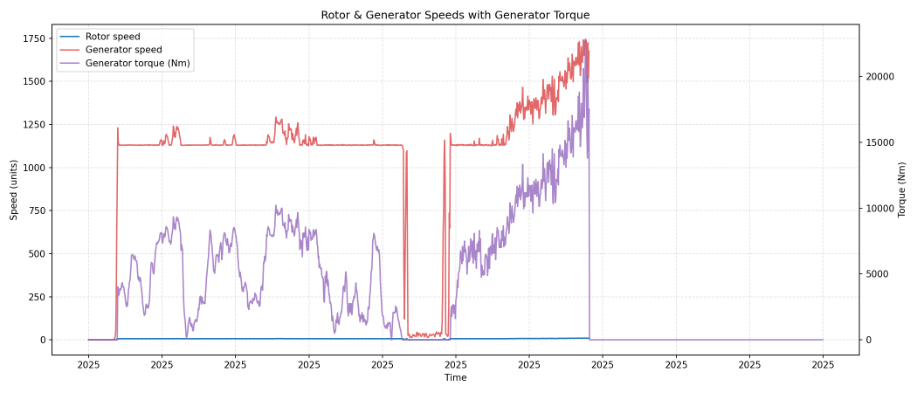
*Time series (speeds & torque):* Distinct regimes are visible: (a) cut-in and synchronization (torque ≈ 0 while ωg ramps), (b) steady production with correlated ramps of ωg and Te, and (c) a shutdown/cut-out where both speeds and torque drop to zero-likely a high-wind or grid fault trip followed by a restart. The later segment shows progressive ramp-up to rated conditions [1-3, 27-29].

*Wind vs torque:* Torque increases monotonically with wind; variance widens at higher wind due to turbulence and pitch activity. The cloud is broadly consistent with Te ∝ v^2 expected under optimal λ control. The few points with high torque at moderate winds likely coincide with transient gusts captured in 10-s or 1-min averages [30-33].

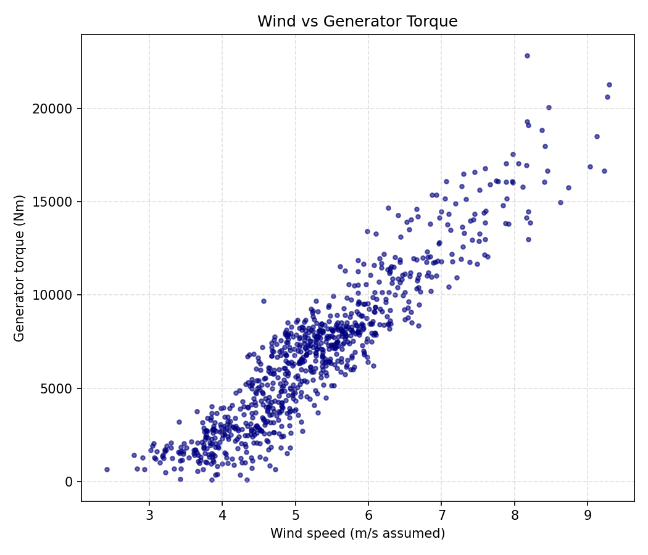
A graph with numbers and lines

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**FIGURE 4.** Generator speed vs generator torque (Nm)



**FIGURE 5.** Time series of rotor speed, generator speed, and generator torque



**FIGURE 6.** Wind speed vs generator torque (Nm)

These empirical characteristics match the dq-axis torque relation Te=(3/2)(P/2)(ψd iq - ψq id). Under stator-flux orientation (ψq ≈ 0), torque is governed by q-axis current (Te ∝ iq), while speed set-points track aerodynamic MPPT; hence the observed monotonic Te-ω and Te-v trends [1-6, 34-38].

**DISCUSSION**

The observed linear rise of torque proxies with speed and the monotonic relation with wind are aligned with the dq-axis model under stator-flux orientation, where electromagnetic torque is primarily proportional to q-axis current. The cut-in cluster at ≈6.3-6.6 rpm and the near-quadratic power rise with speed are typical of Region II MPPT. High-output operation corresponds to favorable wind conditions, while the cyan spans indicate controlled shutdowns. The overall speed-power correlation (r=0.69) becomes stronger during high-output (r=1.00) compared to the early window (r=0.13) [1-5, 39-45, 51-53].

**CONCLUSION**

SCADA-driven characterization, combined with dq-axis torque reasoning, reveals distinct DFIG regimes: a brief shutdown, a strong production window peaking at 2.62 MW, and extended low-power operation.

1. The workflow can be reused for continuous monitoring, anomaly detection, and controller tuning.

2. Considered parameters and formulas enables MPPT tracking and optimizes power production.

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