Inertia Estimation Methodologies vs Measurement Methodology: Impact on System Operations

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SUMMARY

The global energy sector has been undergoing a significant shift in recent years from being predominantly powered by synchronous, centralised fossil fuel plant to an energy mix characterised by a greater proportion of non-synchronous, decentralised generation. The increasing uptake of renewables, particularly wind and solar, necessitates a fundamental change in the way Transmission System Operators (TSOs) operate their networks and manage system stability.

Until recently, there was no known way to measure total power grid inertia, so it has always been estimated. When the grid was predominantly supplied by large, fossil fuel power stations all connected at the transmission level and demand patterns were predictable, TSOs could see which power stations were running and easily calculate transmission system inertia. However, as an increasing amount of power is being produced by renewable sources embedded at the distribution level, the level of generation connected to transmission level is decreasing, making any inertia calculation based on this shrinking portion of generation increasingly inaccurate. The GB system operator (National Grid ESO) for example, currently only has limited visibility of the source of over 20 GW of embedded generation connected to the distribution network, which is a significant system insight issue they have recognised. [1]

Currently, in a bid to mitigate the risks associated with lack of accurate inertia visibility, TSOs have little choice but to curtail renewable generation in favour of synchronous fossil fuel generation, which limits the speed of renewable uptake. Germany, a world leader in deploying wind and solar capacity, is showing growing levels of curtailment. A consistent pattern has emerged relating curtailment to renewable penetration: as the wind and solar share of electricity grew from 10% to 26%, the share of curtailed wind and solar energy grew from about 0.2% to around 1.8%. [2]

There are currently three ways of estimating inertia: summing inertia constants from transmission-connected generation, calculating Rate of Change of Frequency (RoCoF) during large frequency excursions and calculating inertia based on power events throughout the day. These estimation models provide static and historic views of system stability only. None offer a controllable, accurate and continuous view of inertia from transmission, distribution and demand – a view that TSOs require to safely integrate greater amounts of renewable generation and maintain system stability. For this reason, Reactive Technologies partnered with National Grid ESO to conduct an innovation trial in which a novel technology was proven to accurately measure system inertia in real time. This paper

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will provide a literature review of the existing inertia estimation methodologies and compare them to a patented measurement methodology pioneered by Reactive Technologies, and proven with National Grid ESO, and discuss the operational implications of the technological breakthrough for TSOs experiencing high levels of renewable penetration and greater system volatility.

KEYWORDS

Power grid inertia, system stability, renewables integration, energy transition, inertia measurements.

The Inertia challenge

As renewables become a greater proportion of the energy mix, they are inadvertently causing a serious challenge for Transmission System Operators (TSOs) globally in the form of declining system inertia.

Traditionally, TSOs have relied on fossil fuel power stations to provide inertia as their large rotating-mass turbines inject inertia directly into the electricity grid, helping to maintain system resilience in the face of a sudden imbalance or disturbance, such as a fault. Renewable generation however is unable to physically produce inertia and therefore does not positively contribute to grid stability.

Until recently, there was no known way to measure power grid inertia, so it has always been estimated. When the grid was predominantly supplied by large, fossil fuel power stations all connected at the transmission level, TSOs could see which power stations were running and easily estimate system inertia. However, as the supply mix is changing and increasing amounts of power is being produced by renewable generation embedded in the distribution network, greater proportions of the supply mix are becoming hidden from view to the TSO. For example, it is estimated that National Grid ESO currently only has limited visibility of the source of over 20 GWs of embedded generation connected to the distribution network. [1] And as renewable generation exponentially increases, the estimates that TSOs can make of system inertia become increasingly inaccurate.

Currently, in a bid to mitigate the risks associated with lack of inertia visibility, TSOs have little choice but to curtail renewable generation in favour of fossil fuel generation. Power grids can theoretically safely operate with up to 75% of system non-synchronous penetration from renewable sources. Once non-synchronous penetration exceeds 75% of the energy mix, system inertia is deemed too low to maintain stability. Without an accurate measurement of inertia, TSOs curtail renewable input below the 75% as a safety measure. For example, the Irish TSO Eirgrid currently imposes a system non-synchronous penetration limit of 65% and ERCOT imposes a limit of 100 GWs. [3]

Germany, a world leader in deploying wind and solar capacity, is showing growing levels of curtailment. A consistent pattern has emerged relating curtailment to renewable penetration: as the wind and solar share of electricity grew from 10% to 26%, the share of curtailed wind and solar energy grew from about 0.2% to around 1.8%. [2] The cost of constraints is ultimately recovered through consumers' bills. If each country followed the curtailment trend described, annual curtailment would amount to 128 TWh or 0.4% of total global generation. The value of this energy is worth ~$9 billion (assuming a value of $70/MWh).

The inertia of European electricity grids is forecast to continuously decrease under all modelled scenarios. For this reason, on 2nd of August 2017, the European Commission passed a regulation for TSOs to address the decreasing levels of inertia. [4] The regulation (Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation) places an obligation on all TSOs to determine if minimum inertia is a concern. While modelling and estimations will give a view to this, to actively manage the issue, real time inertia measurements are required.

Inertia: estimation and Measurement methodologies

There are currently three ways of estimating inertia: summing inertia constants from transmission-connected generation, calculating Rate of Change of Frequency (RoCoF) during large frequency excursions and calculating inertia based on power events throughout the day. These estimation models provide static and historic views of system stability only. None offer a controllable, accurate and continuous view of inertia from transmission, distribution and demand – a view that TSOs require to safely integrate greater amounts of renewable generation and maintain system stability. There is also a newer method of directly and continuously measuring inertia invented by Reactive Technologies and proven alongside National Grid ESO. This section provides an overview of the known inertia estimation methods as well as the measurement method developed by Reactive Technologies.

A) Synchronous Generators Only: Summation of inertia constants across all generators.

The inertia constant (H) is known for large central generators from manufacturer specifications. The inertia constants of all online plant (known by recording the breaker status in the SCADA system) can be summed together, giving some insight into inertia in the power system. This gives a continuous result, however it ignores any demand side inertia, such as that from CHP engines or directly-connected motors. In the UK, demand side inertia can currently be up to about 30% of the total inertia in the system – neglecting this, or assuming it is a fixed constant, leads to significant errors on the inertia value.

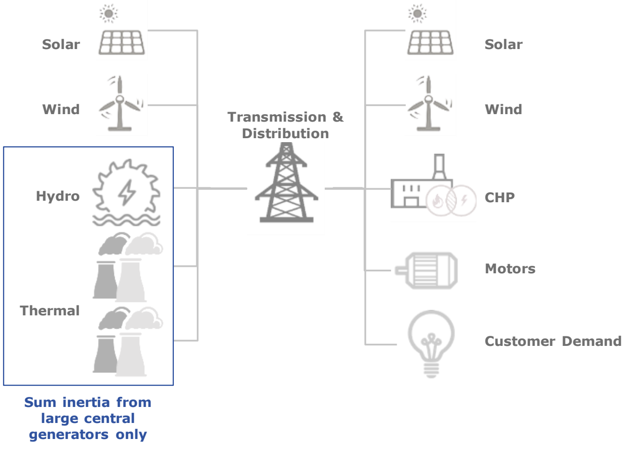

Figure 1 : Visual representation of 'Synchronous Generators Only: Summation of inertia constants across all generators' inertia estimation method.

B) Calculation During Frequency Event: Measurement of Rate of Change of Frequency (RoCoF) during a large frequency excursion.

During a large frequency excursion, inertia can be calculated from the MW power loss and the resultant Rate of Change of Frequency (RoCoF) using the Swing Equation methodology. This takes into account any demand side inertia, however will only give a 'snapshot' of what total inertia is on the power system at a given time.

For this methodology to work, there must be an instantaneous MW loss (otherwise governor control influences RoCoF) and it can be difficult to determine precisely when a frequency event starts, influencing the RoCoF and subsequently the inertia calculation.

This technique is useful for testing the accuracy of other approaches but does not provide a continuous measurement of inertia because this can only be calculated when these infrequent events occur.

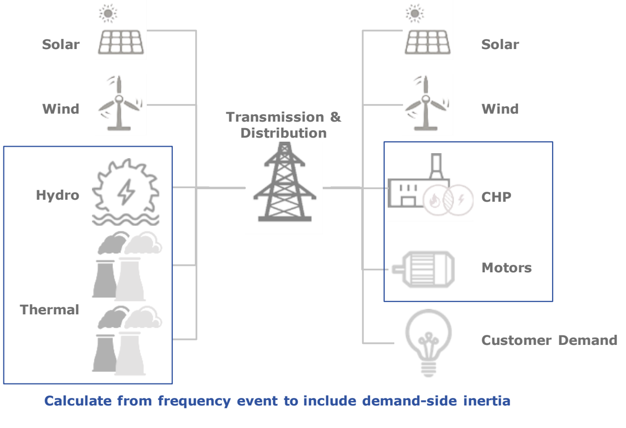

Figure 2 : Visual representation of 'Calculation During Frequency Event: Measurement of Rate of Change of Frequency (RoCoF) during a large frequency excursion' inertia estimation method.

C) Estimation based on power events throughout the day

A third method for estimating inertia has emerged in an academic publication and in some utilities' practices where the inertia can be estimated in a similar manner to method (B) but uses small perturbations that occur throughout the day. [5] This method commonly uses widespread PMU installation for frequency measurement and depends highly on the extensive measurement of power within the SCADA system.

The movement of power needs to be accurately measured as any error in power measurement leads to an error in inertia calculation. Since power movement comes from multiple locations on the network, this requires widespread high-speed power measurements that are often expensive to attain as they require prevasive PMU installation. Furthermore, the larger movements of power mean that the frequency control loops (such as Automatic Generation Control and governing) can be active leading to further error due to the mismatch in electrical and mechanical power.

Some research suggests the use of pattern recognition algorithms helps to reduce the error on such estimations however all pattern recognition algorithms require good training data in order to be effective. Large events that provide adequate training data are infrequent and other data sets (such as from small perturbations or model results) are inherently biased by the data source. This means any improved accuracy yielded by such methods should be used with caution since the calculation is not deterministic but rather calibrated through targeted operation and therefore will remain biased once implemented in the system even when the system changes.

D) Direct Inertia Measurement

Reactive Technologies has developed a signalling technology which uses a small power change in the network (<10 MW) to alter frequency to a minute degree (e.g. 0.0005 Hz). For the measurement of inertia, a 'Modulator' alters the frequency of the power system slightly and high-speed measurement units distributed around the grid observe the minute changes in the system frequency and report the raw data to an Analytics Server via a secure cloud connection - this data includes frequency and voltage magnitude.

This small power change and minute frequency change are used to continuously and directly measure grid inertia from both the generation and demand side. These signals are heard louder in areas with lower inertia meaning that the more unstable the system, the more accurate the data.

This method uses the same Swing Equation methodology however it also incorporates communications and signal processing innovations to read and interpret these miniscule frequency changes.

This method does not rely on existing PMUs nor does it require further investment in PMUs. It does however necessitate a smaller investment in a modulator, or energy storage device.

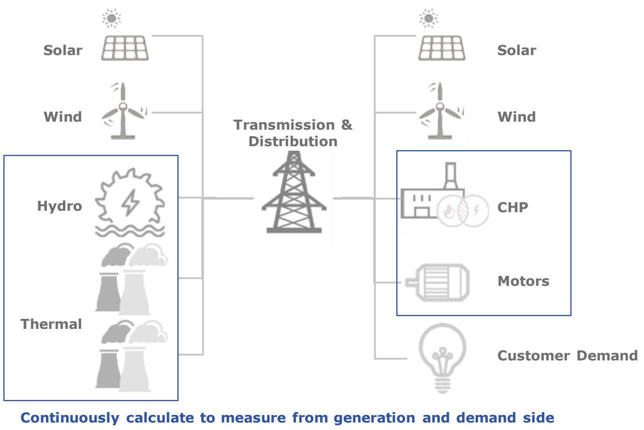

Figure 3 : Visual representation of 'Direct Inertia Measurement' method.

Proven Technology – Case Study

Reactive Technologies and National Grid ESO partnered on a regulator sponsored innovation System Inertia Measurement ("SIM") project, which was successfully completed in July 2017. [6] [7] Project SIM demonstrated that GridMetrix can be used to directly measure the inertia of the electricity grid in a safe, reliable, and cost-effective manner. Reactive performed a number of "blind measurement" campaigns without access to, or knowledge of, National Grid ESO's own estimated inertia values. The results were then compared after-the-event and the results clearly proved that Reactive had directly measured system inertia - a world first. Reactive's patented method enables TSOs to directly, systematically, and accurately measure how both production and consumption inertia change at any time.

Reactive's GridMetrix was built on an earlier technological breakthrough called Grid Data Measurement System (GDMS) trialled as part of another innovation project (SAMUEL) with National Grid ESO. [8] Reactive developed GDMS to enable the transmission of digital messages through an electrical grid using the grid itself as the communications channel. GridMetrix was the next stage in developing this innovation and used the communications technology to gain visibility into grid conditions and to accurately and continuously measure system inertia. GridMetrix receives frequency data from the measurement units and decodes the signal itself to learn about conditions on the grid, and in doing so can directly measure system inertia. This data is analysed and visualised for the TSO to allow them to better understand what is happening across their network in real-time.

For system operators, the results and learnings gained from Project SIM will be vital in better enabling them to manage the transition to a greener energy mix. GridMetrix enables TSOs to have enhanced visibility of critical data points such as inertia, regional frequency, RoCoF, sub-synchronous oscillation, system event analysis, voltage and phase angle within the electricity system. GridMetrix supports ultra-low latencies from taking the grid measurement to the data being in Reactive's cloud platform, ultimately enabling system operators to optimise their spend on critical grid infrastructure and balancing services. GridMetrix can handle large volumes of data, with measurement devices collecting and transmitting up to 48,000 samples of frequency per second. GridMetrix is the first and only technology capable of accurately and directly measuring system inertia, replacing the current practice of estimating inertia which is no longer fit for purpose.

Using Reactive Technologies' signalling and measurement technology in a blind test, inertia was directly measured on the grid. The table below shows the results from Project SIM. The yellow trend represents National Grid ESO's synchronous generator only inertia estimate whilst the Red trend represents National Grid ESO's total inertia estimate which incorporates a scaling factor to include the effect of inertia embedded within the distribution system (this is around 30% on average). The Blue trend represents Reactive Technologies' inertia measurement based on a 2.4 MW modulation signal.

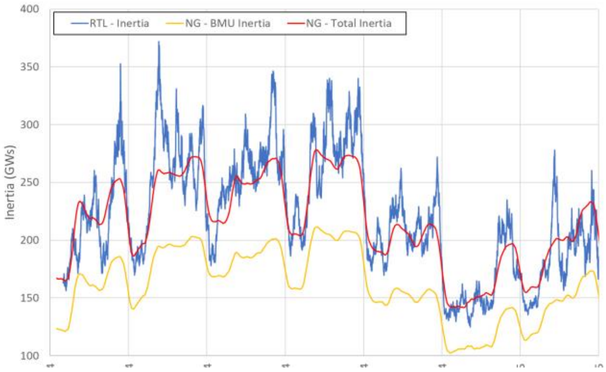

Figure 4: Blind test results from Project SIM [9]

Of particular interest is the Bank holiday shown in the zoomed in portion of the chart below – here the inertia is low and the measurement is more accurate since the modulator has greater effect at low inertia periods. The green shaded portions highlight where National Grid ESO's inertia estimate was conservative and savings could potentially be made in terms of purchasing reserve; the red shaded portion however shows where National Grid ESO's inertia was overly optimistic and therefore hiding risk. The measurement technique provides value in both cases either by revealing potential cost savings or by highlighting potential risk.

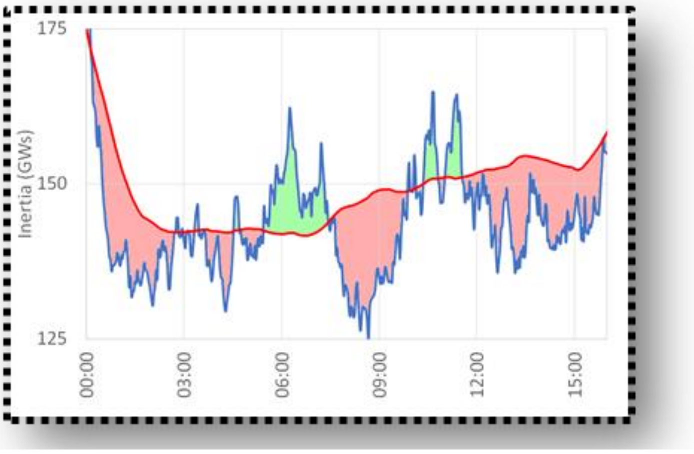

Figure 5: Bank holiday blind test results from Project SIM [9]

By simply moving from power grid estimates to direct accurate measurements of inertia, TSOs will experience decreased costs of procuring balancing services, more efficient operational decisions and the ability to more safely and effectively integrate an increased amount of renewable generation.

Benefits of Moving from Estimates to Inertia Measurements

There are a number of operational benefits TSOs will experience when they move from inertia estimates to accurate measurements:

- Increased ability to integrate renewable generation: Inertia measurements enable system operators to safely integrate more renewables while maintaining security of supply. By measuring inertia, Reactive has calculated that system operators could increase their renewable integration limit which would result in a dramatic reduction in renewable generation curtailment from 15% to 7% by 2020. This would allow renewable generators to operate nearer their full capacity, helping them maximise their earning potential in a non-subsidy regulatory landscape.

- Decreased procurement spend on surplus reserve services: Reactive has calculated that if inertia is overestimated by between 10% and 30% in Great Britain alone, the cost of in/out feed curtailment and un-optimised reserve services would range between be £30m - £100m annually by 2020. With inertia measurements, system operators have a substantially clearer picture of their networks off the back of real data points, allowing them to more accurately and efficiently procure reserve services.

- Number, risk and duration of islanding events and blackouts are mitigated: Blackouts occur when the frequency deviates beyond a critical point. The critical frequency deviation is related to system inertia such that blackouts are more likely to occur in power systems with high renewables penetration and low inertia. The societal value of loss of load is estimated at £17,000/MWh by National Grid ESO. [10] Even short duration blackouts result in a societal cost of £100s millions. By monitoring the actual inertia level of a grid, system operators can make much better-informed decisions to take action in order to avoid blackouts.

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