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Architecture for an Ultra-fast Power Response System to enable Low Inertia Systems

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Abstract—Introduced in this document is a combination of research published by our university cluster. It outlines the requirements for an ultra-fast response system to correct generation/load imbalances on timescales that could be considered virtual inertia. Much of the research is based on real power system measurements and lab experiments, supplemented by computational models. The work has been tailored to the Irish power system that is facing a low inertia threshold, limiting the utilization of renewable generation. Ireland is taken as a test case for the necessary road other power system will need to take as they integrate converter interfaced renewable generation. At present Ireland has the objective to decarbonize its power system by 2050; as anyone who has read the IPCC 2018 summary will appreciate, this is far too late and if preparatory research is not undertaken, projects may be rushed.

Keywords—PMU, Frequency Transients, System Stability, Wide-area Monitoring Protection and Control, Virtual Inertia

I. INTRODUCTION

The research presented details the requirements for an ultra-fast power response system that can preserve system stability. Aspects of this system are detailed, from rapid event detection, communication, decision making, control and response. This paper brings together different aspects of the authors and collaborators work to be considered as a whole. Event detection is derived from point on wave measurement devices, network communications are over optimised TCP/IP communications and control decisions implemented with BESS or demand response. A proposal is made for a staged implementation of the wide-area monitoring, protection and control (WAMPAC) system.

Power system stability services are particularly valuable when transitioning from a traditional high inertia grid to a low inertia grid and these have been explored in Ireland under the DS3 program [1]. The initial application of the proposed system is transient stability, however there are obvious applications to transient and oscillatory events. Throughout the paper it is argued that a drop in power system inertia is as much a solution as a problem, but during the transition problems inherent to synchronous generators are exposed.

The findings of the IPCC 2018 report [2] were very clear, globally carbon neutral by 2040, to stand any chance of abiding by the Paris Agreement, carbon neutral by 2055 to reduce the potential of catastrophic runaway global heating. It can be argued that developed countries should take the lead in ambitious carbon reduction targets, meaning domestically they should aim for net zero by 2030, or soon after. Furthermore, electrical power systems are one of the easiest energy supplies to decarbonise, when compared to heating and transportation. Therefore, it can be argued that power systems should target net zero emission of CO_2 by between 2025 and 2030. While these sorts of targets may seem politically unrealisable, they are a scientific reality and it falls to engineers to fill the gap.

There are a number of paths to decarbonising electricity power generation and most are heavily site dependent. Most paths, other than geothermal and hydro, also necessitate a significant reduction in power system inertia [3]. This criteria arises as power generation from converter interfaced generation (CIG) displaces conventional, synchronous generation. On some networks, such as California, CIG will be dominated by PV at certain times of the day, on other networks, such as Ireland, CIG will come from wind power.

The Irish power system is a useful test case for the transition from a high inertia system to a low inertia system [4]. At present the grid code stipulates that system non-synchronous penetration (SNSP) must not exceed 70%. However, the grid code also stipulates that power system inertia must not drop below 23 GWs [5]; therefore thermal plant is being constrained on, when it could be desynchronised, increasing cost and emissions, but preserving security of supply.

Ireland was ambitiously reducing its system inertia, but this stopped and has since reversed since 2013. Ireland is also the third highest per capita emitter of CO2 in the EU, missing even its own standards [6]. Therefore, in Ireland and on many other systems, a bolder vision is required to avoid catastrophic, run-away climate change in coming decades.

II. OVERVIEW OF THE RESEARCH CONTEXT

A. *The Irish Power system*

The Irish power system is a synchronously islanded power system, with two synchronised grids that can be separated; one is in the Republic of Ireland and on in Northern Ireland. The Irish power system now has a harmonised electricity market and unified services and grid codes. EirGrid, the

TSO in the Republic of Ireland, now owns SONI, the TSO in Northern Ireland, facilitating harmonisation on the Island.

The maximum and minimum demands on the Irish system are 6.53 GW and 2.42 GW [7], with 5.55 GW of nameplate wind and solar generation. Maximum demand occurs during winter months, when wind generation is highest. Minimum demand occurs during summer nights, as air condition is an insignificant load in Ireland. The TSOs expect Irelands demand to grow by 33% over the next 10 years, not due to electrification of heating and transport, but because of data centres. While attracting inward investment in data centres is a "business as usual" strategy, indifferent to climate change; these loads, with their associated UPSs, offer an interesting control opportunity, on a path to a low inertia power system.

Ireland has made significant strides into renewable energy integration, with 32.5% of electricity coming from renewables and 27.6% coming from wind in 2018 [6]. Unfortunately further progress is impeded by existing grid constraints [5] that exist for system security, this is discussed further in Section IIC. The renewable generation target for 2020 was 40% of electricity generation to come from renewable sources and this target will almost certainly be missed.

The renewable energy integration numbers are also misleading, as Ireland exports significant amounts of electricity, over HVDC interconnectors, when wind is high, but this is not factored into consideration. Finally, when the TSOs present their "addressing climate change" high ambition scenario, they talk about decarbonising electrical generation by 2050 [7]; in light of the IPCC 2018 report, this is an all too common failure of understanding and ambition.

B. The PMUs in Use

SONI/EirGrid use PMUs from a sole vendor, they are all of the same make and model and have the same firmware update cycle. These PMUs are well studied in QUB with known features and latencies. Discussed in Section IIE is the characteristic 40 ms to 60 ms delay in detecting a frequency deviation and a 20 ms to 40 ms delay in detecting the power response.

On request from the authors the PMU manufacture added a feature called network cross triggering; where-by the DFR in one PMU can send a TCP/IP message to a second PMU, triggering a DFR capture with POW measurements. The trigger is a relatively simple TCP/IP package.

Ultimately a deployed ultra-fast power response system would be sending signal to call for power or reduce demand. Before this deployment a development platform can send fast capture commands to these PMUs. The event capture will,

- Give precise latency measurements
- Provide wide-area POW measurements
- Identify how reliable the system is

This means that the staged deployment of a development platform results in incremental returns, as discussed in Section IV.

C. Challenges on the Irish System

The Irish power system needs to move towards a low inertia system if it is to gain maximum benefit from its renewable energy resource. This journey into a low inertia state is necessary to meet the Paris Climate Agreement [8] and the IPCC 2018 report [2]. However, Ireland's maximum, minimum and average inertia has remained largely unchanged inspite of increased renewable generation. This is understandable as a low inertia power system presents many novel problems for power system engineers [3].

Two of the major problems being addressed at present are frequency oscillations and frequency transients. The oscillations appear to arise from synchronous generators; as fewer remain on the system, low inertia appears to be exposing underlying instabilities that were previously damped [9].

Oscillation studies are quite complex, while under and over frequency transients are relative simple. A loss of generation or load causes a generation/load imbalance resulting in a frequency deviation. At any one time the largest potential loss of generation or load must be underwritten. Historically this was the largest generator, however now HVDC links present the largest potential loss or gain in power.

Shown in Fig. 1 is a power system response to a loss of 420 MW of generation. This plot is derived from PMU measurements of 60% of generation at the time and entire system response extrapolated from publically available metered generation data, as discussed in [10]. It can be noted that the inertial response replaces approximately 75% of the lost generation apparently instantly, with the mismatch resulting in the observed RoCoF. An ultra-fast distributed power response could arguably make this event much less sever, just as the observed step change from the HVDC vastly mitigates the effect of the transient.

Classical inertia is always taken as beneficial for both operation and when a transient event occurs. System inertia reduces the frequency of the power systems oscillatory common mode, during normal operation. During a frequency transient Inertia reduces the RoCoF, buying time for power system operations, such as the droop response, to come into effect. However, inertia works against control operations when attempting to arrest the frequency drop and

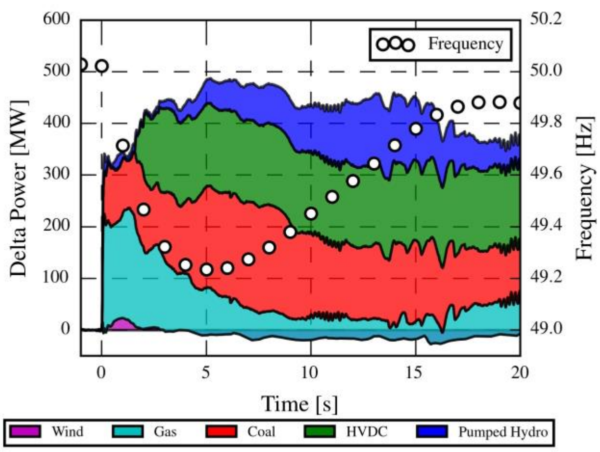

Fig. 1 Observed and extrapolated generation to a 420 MW loss of generation on the Irish power system

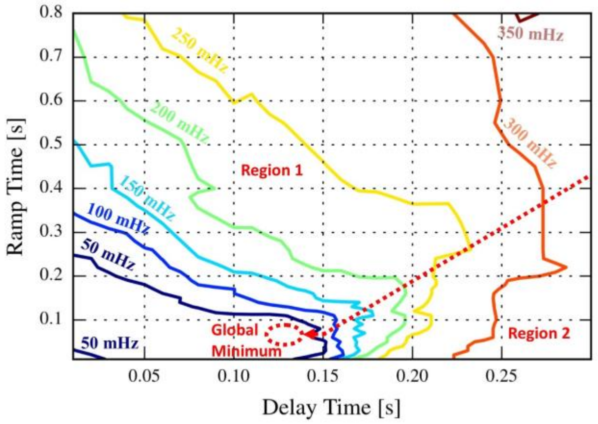

Fig 2, Effect of delay time and ramp time on RoCoF

Table 1, Equivalent delay and ramp for fast frequency response

Delay Time	Ramp Time	RoCoF	Example Application
20 ms	300 ms	80 mHz	Flow battery, at DRR
60 ms	210 ms	80 mHz	Slow response batteries
100 ms	115 ms	80 mHz	Lithium ion, distributed
150 ms	100 ms	80 mHz	Demand response

return the frequency to the deadband. Consequently a low inertia system is beneficial, when a fast acting power response is available, as the per unit effect of control assets is increased [10].

D. Solution to Under Frequency Transients

Engineers are often cautious when it comes to introducing a step, or impulse, response into an oscillating or rotating system as they can excite a wide variety of oscillatory modes. This problem is discussed in [11] and it is argued that it is not as big a problem as is supposed. It is noted that synchronous machines ramp at GW/s rates and this is considered the gold standard in inertia provision. On the Irish system a step change is observed on HVDC links to the UK [11] which only have positive consequences. Finally, there was no evidence of instability issues on the IEEE 39 Bus System in [11] when it was subjected to extreme ramps.

In [11] the requirements for delay time (in beginning a power ramp post event) and ramp time (zero to full power) are specified. In the case presented in Fig. 2, tuned to a real system event, various combinations of delay time and ramp time were investigated. Displayed in Table 1 is the combination of delay times and ramp times that reduced a RoCoF event from 320 mHz/s to 80 mHz/s.

Moving forward a delay time of 100 ms to 150 ms, from event start to trigger signal received, is considered the objective for this system.

E. Rapid detection of Under Frequency Transients

The inertial response of a synchronous machine, to a frequency transient, is taken as fact of nature in power engineering. Fig. 3 shows data captured by the combined PMU/DFR described in Section II B, with the point on wave data coming from the DFR and the PMU data streamed regularly. It was an unlikely circumstance that caused this fast capture of the synchronous machine response, but this type of recording would be achieved regularly as part of the staged deployment of the proposed platform. The delays in PMU power and frequency measurements are evident, these

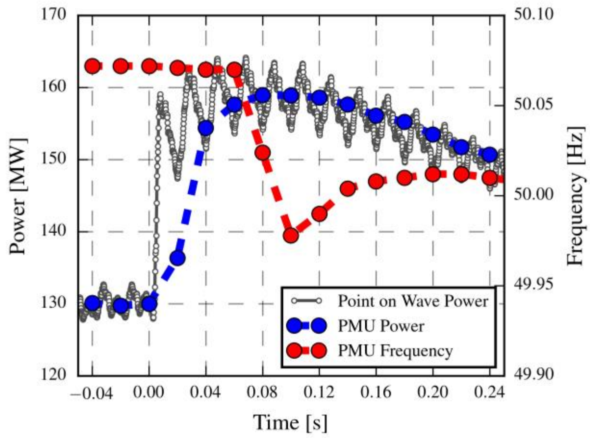

Fig 3, Capture of the initial response of a CCGT synchronous generator to a significant frequency transient.

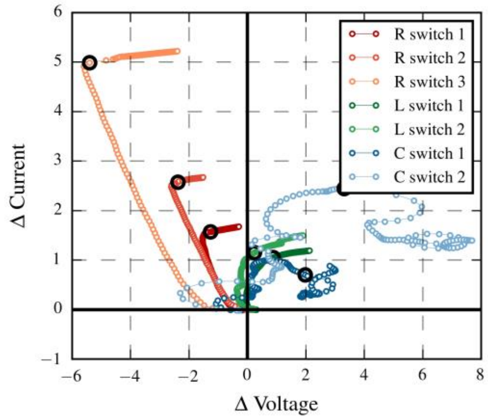

Fig 4, Change in voltage and current output from a laboratory synchronous generator during the first 20 ms post transient events [12] (the black circle marks 10 ms post event)

result from differing frequency and phasor estimation algorithms.

The start of the event is detected by the obvious step change in power, observed in Fig. 3. A threshold of 3 standard deviations from background noise, this is exceeded after 4 measuring points in Fig. 3; this is equivalent to 0.156 ms at a reporting rate of 128 samples per second on a 50 Hz system. The power was simply calculated by multiplying line currents by phase voltages, this results in the obvious noise. The noise can be reduced though various computational techniques, including removing the DC component, but this was not deemed necessary at this point.

When using active power measurements to directly detect a frequency transient, power responses caused by other system operations and faults must be categorised or eliminated, this is discussed in [12]. In this paper Fig. 4 is presented and it shows the progression of a frequency transient over 20 ms, measured on a laboratory synchronous subjected to transients. The data presented comes from the fast capture function of the PMU. It is evident that the capacitor and inductor switching operations differ markedly from the surprisingly linear frequency transients. It is worth noting that an alpha filter was applied to the measurements in Fig. 4 to reduce noise.

Fig. 4 displays voltage deviation and current deviation from measurements averaged over the previous seconds. The progression of voltage deviation and current deviation have interesting features at characteristic time points. It is proposed that messages be sent at these time points.

The first message would be sent at t = 0 (0.156 ms), when the power event effectively started. The second time point is at 10 ms post event, when voltage drop should reach an inflection point; between 0 and 10 ms dI/dV should be approximately a constant and negative. At 20 ms a third message is sent, between 10 and 20 ms dI/dV should be largely constant and positive. Similarly between 20 and 30 ms dI/dV is constant and similar to the 10 to 20 ms value.

These reports can continue every 10 ms so a false detection can be ruled out, aborting a power rapid response. Multiple reports also increase the certainty of a detection from a single device, then multiple matching reports from devices at differing locations cross validate and aid in fault location.

F. Generation loss matching

Ideally when a generation/load imbalance occurs the balance would be replaced as quickly as possible and with a response equivalent to the imbalance [11]. Furthermore, it is preferable that the power response be located as close to the source of the imbalance as possible. These objectives require a knowledge of the power loss/gain and event localisation.

If a rapid detection device is located at a generator, HVDC or load that suddenly disconnects, then all required information is available. On the Irish power system this is feasible with the low numbers of generators, but might be more difficult on larger systems [13]. If the lost unit is not being monitored, or the event removes the rapid detection device, then power loss and location need to be estimated. The location can be estimated from the rapid detection devices that are affected the most. The severity of the imbalance can be estimated from the progression of the dV and dI; Fig. 4 shows three frequency events of differing severity. With real-time knowledge of system inertia, the approximate magnitude of the imbalance could be estimated.

III. Requirements for Transient Suppression

As with any control system, the basic parts are detection, communication, decision, communication and implementation. Each of these steps are detailed, with a specific objective of signaling devices to respond with within 100 ms to 150 ms (delay time in Fig. 2), so they have in the region of 100 ms to implement the control decision (ramp time). The control decision must be robust against false positives and ideally the power response would match the lost generation.

A. Rapid Transient Detection

Most transient detection methods work by detecting a deviation in frequency, however there is an inherent delay in frequency estimation, especial under dynamic conditions [14]. The frequency is then differentiated to give RoCoF, amplifying inaccuracies. Fitting a sinusoidal wave to fewer than two cycles is very error prone, preferably five, increasing the detection time to an unacceptable point.

```
{"Report":  0-3
"ID":      name
"P":       {"initial": MW,    "delta": dMW, "rmse": 0-∞},
"Q":       {"initial": MVar, "delta": dMVar, "rmse":0-∞},
"V":       {"initial": V,      "delta": Dv,     "rmse": 0-∞},
"I":       {"initial": I,       "delta": dI,      "rmse": 0-∞},
"Time":  {"start": ms, "delta": ms, "error": ms},
"SID":    ########           }
```

Fig. 5, Content of rapid detection device report in JSON format

The detection method being developed utilises the hardware employed in the OpenPMU [15]. This hardware has a development environment and an ADC that can sample at 12.8 kHz and higher. This hardware is naturally TCP/IP as it is a PMU. Therefore this device has the necessary sensory applications, processing power and networking abilities to develop the hardware application. The device would carry out the detection and continued monitoring and reports described in Section II E.

The device should optimally detect and report the initial power deviation with 2 ms. The subsequent reports should then be sent within 2 ms of being measured i.e. before 12 ms, 22 ms, 32 ms etc.

B. Device to Server Communication

Four types of generator reports were discussed in Section II E. The messages will likely be in the form shown in Fig. 5, though this format is intended to contain information that relates to Fig. 4. The first message sent, reporting the power response, will likely not contain the voltage and current information.

In Fig. 5 the ID term is the identification given to the unit. A root mean square error (rmse) term is added, this is used to quantify the degree of linear fit observed during the time window. Time quality information is added to the absolute time, this is common practice with PMU synchrophasor data. Finally, a security ID field has been added for subsequent development.

The message in Fig. 5 is in JSON format which the authors have employed for PMU communication. In this context only TCP/IP communication methods are considered explicitly, but the method should be transposable onto most communication methods. Multiple mainstream and emerging network practices exist to reduce latency these include maintaining an open connection between devices, software defined networking and GOOSE messages in IEC 61850 [16]. The industry that has most explicitly worked to reduce communication time is of course the banking industry and methods from this industry should be leveraged.

Often customers have limited control over the latency between two devices, however techniques can be used to reduce latency. The simplest option is to employ a LAN, a proprietor owned WAN or route all traffic through a single ISP. Furthermore techniques such as software defined network and maintaining an active connection (with optimal routing) can be used to reduce latency further. Using these strategies latency should be reduced to the region of 10 to 50 ms.

C. Server Processing

The server will receive messages from multiple devices, which may or may not include the generator that was lost. These communications must be unpacked, analysed, processed and verified in the minimum necessary time, again methods from banking, but particularly financial trading, can be employed.

Financial trading often utilises stream analysis techniques to reduce computational time. However, within our university we have employed an MQTT broker with a hierarchical topic structure to achieve a type of stream analysis on PMU data. The asynchronous nature of the MQTT publish/subscribe system makes it ideal for handling these types of trigger signals with minimal data content. MQTT brokers are under constant development with some specialising in latency reduction. While MQTT servers may not be suitable for a production environment, they serve as an excellent development platform that should have low enough latencies to meet the necessary criteria.

The server must first determine that the message came from the proprietor's device, before acting on the data. The server will then need to build its confidence that an event is occurring as multiple reports come in. The necessary logic should result in significantly less than 10 ms of processing time. Speed of response could be improved by dispatching multiple messages that progressively increase the power system response. As information on power loss and location increase with time, the remedial action can become significantly more targeted.

D. Server to BESS communication

It is anticipated that the same latency issues, timescales and optimisation procedures discussed in Section II B will also apply in this context. Therefore, a latency of 10 to 50 ms is again considered. Further to this a message similar to that in Fig. 5 will be sent to the device, either as a trigger signal, containing very little information, or containing power set point information. Similarly, security precautions should be considered from the start.

E. Implementation of the control signal

A BESS is used in this context as it provides ideal flexibility, being able to import and export power; however, demand side management, HVDC and other suitable technologies are equally valid. Many BESS suppliers claim that they can implement a ramp from zero to full power within 100 ms, and such operation has been observed on the HVDC links in Ireland (Fig. 1). The issue for BESS manufacturers is that they lack the confidence in control decisions to implement such aggressive responses. It is proposed that TSOs take responsibility for this measurement and control problem and implement an operation such as a static reserve response [5] or demand side management. In the interests of moving forward a ramp time of 100 ms is considered for this aspect of the operation.

IV. Overall Latency

The combined low time for a low confidence triggered response is 124 ms (2ms detection, 10ms communication, 2ms server, 10 ms communication, 100 ms ramp). This type of operation is incredibly quick and may be suitable for a initiating a low level response, e.g. 20% of estimated lost load.

A medium communication network with a moderate to high confidence of detection may take 174 ms (22 ms detection, 25 ms latency, 2 ms server, 25 ms latency, 100 ms ramp). This type of operation is still extremely favourable in terms of the results presented in Fig. 2

A high latency communication network coupled with a high degree of confidence may take 232 ms (30 ms detection, 50 ms latency, 2 ms server, 50 ms latency, 100 ms ramp). Even at this upper length, optimal RoCoF reductions are being achieved.

V. Staged Implementation

Power system operators are understandably conservative in their approach to new technologies, given the consequences of failure. Therefore, a staged implementation of the proposed project has been considered.

A. Stage 1

Installation of a single rapid detection device at a power station with a network connection to the PMU described in Section II B. This rapid detection device would trigger the DFR functionality of the PMU, recording a manual capture event, whenever any power excursion occurred. The data contained in this file would inform the developer of delays in detecting the onset of an event. There would also be valuable information regards false triggering and fault identification. A nice outcome of this installation would be point on wave measurements of a synchronous machines response to transient events.

B. Stage 2

Once stage 1 is validated the rapid event recorder would send reports to the central server; these reports would be sent every 10 ms, post event, as described in Section III E. The server would then process these reports and attempt to only trigger the fast capture recordings when a frequency transient occurred. Once this was refined the trigger signal would be sent to multiple PMU/DFR to record wide-area point on wave measurements; these should be invaluable for fault analysis.

C. Stage 3

Multiple rapid event detectors are installed at multiple generators. The reliability of event detection should increase substantially, reducing the time requirement to positively identify the onset of a frequency transient. Logic will need to be developed to handle asynchronous arrival of reports caused by network delays. Development of algorithms that estimate power loss can begin, either with or without of system inertia; these can be validated with subsequent knowledge of power loss.

D. Stage 4

Once the system has been thoroughly tested and reached acceptance by the TSO it can start to be used to trigger power system operations to alleviate frequency transients.

VI. Conclusion

The IPCC and the UN Emissions Gap Report tell us that we have 10 years to substantially pivot out economies to be low CO_2 emitters, or we will face precipitous and irreversible global warming. We have known this was the case for the past three decades, but have not reduced global emissions. We will need relatively daring schemes if we are to realise the necessary goals, because we have left this transition so late. In this case it is engineer's responsibility to start doing the research and building the knowledge and infrastructure, before the public start demanding it.

Presented in this paper is the staged development of a rapid frequency transient detection system with the requirements to implement a control decision in sufficient time. It is demonstrated that a full control operation could be delivered in less than 250 ms following a generation/load imbalance. It was demonstrated in previous research and presented in this document that this timescale provides excellent RoCoF reductions. This type of operation will be useful on ultra-low inertia systems, for example if a HVDC link is lost. But this technology will be vital as we incrementally lower the inertia of our power system, as the problems with synchronous machines are exposed, when there aren't others to compensate for them.

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