Enhanced visualisation of fast frequency phenomena as exhibited in the GB transmission system

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***Abstract*—This paper investigates fast frequency phenomena as exhibited in the Great Britain (GB) transmission system as a consequence of the relationship of system disturbances to the changing inertia of the system. Fast frequency phenomena are studied with specific reference to real case studies associated with GB transmission system disturbances as recorded by Phasor Measurement Units located across the transmission system. The intrinsic behavior of the phenomena is investigated, observed and analyzed using enhanced 2D and 3D visualization tools. The novel visualization tools and techniques have been developed using Matlab and the impact area of system disturbances with regard to Rate of Change of Frequency and Vector Shift can also be observed and analyzed via the developed visualization tool.**

***Index Terms*-- System Inertia, Phasor Measurement Units, Loss-of-Mains protection, Distributed Generation**

I. INTRODUCTION

The mixture of electricity generation has changed significantly in recent years across the world, [1]. This is mainly due to the increasing amounts of renewable energy sources, such as wind and solar, that are being connected to power systems in parallel the decommissioning of conventional power stations, such as coal, for environmental reasons. This trend is expected to continue in coming years in order to meet environmental targets and legislation. As a consequence, the inertia of the Great Britain (GB) system has decreased and disturbances in the power system, such as line or generator tripping, can lead to larger frequency fluctuations across wider geographical areas, particularly a larger rate of change of frequency (RoCoF), when compared to historical situations where system inertia was higher. This fluctuation may when unmitigated in some cases have a similar behavior as are typical during the islanding and thus leads to issues including the malfunction of the Loss-of-Mains protection relays, cascade tripping of distributed generation, etc, [1].

A current research project at Brunel University London that is sponsored by National Grid Electricity System Operator (NGESO), as the GB Transmission System Operator, aims to investigate fast frequency phenomena associated with this decrease of system inertia in the GB transmission system.

II. GREAT BRITAIN TRANSMISSION SYSTEM

A. *Desctiption of transmission system*

The GB transmission system is an isolated synchronous system (cca. 60GW), with only HVDC connections to continental Europe and Ireland, Figure 1. The GB system currently faces challenges arising from low system inertia due to growing levels of renewables and HVDC integration. Larger systems such as continental Europe may face similar challenges in the future. The challenges of decreased inertia of the power system have already been studied in various power systems, including the continental European [2], South Africa, [3], Australia, [4], Great Britain, [5], [6].

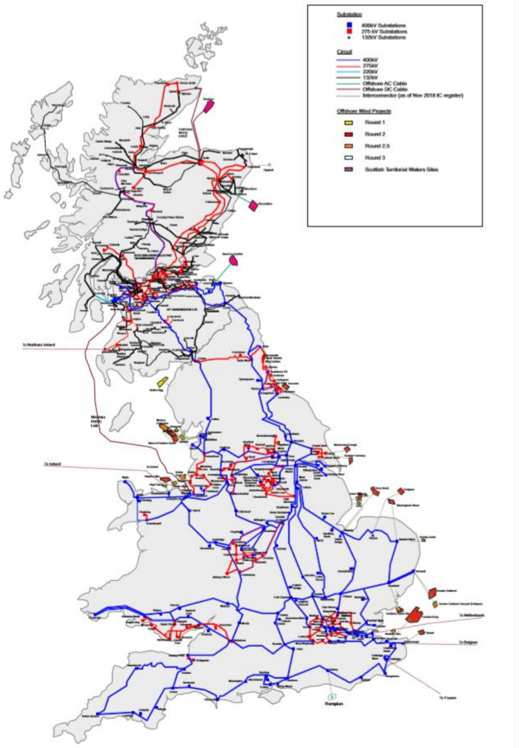

Figure 1 GB Transmission System 2018 [7].

B. Inertia development in the GB system

The total inertia of the power system comprises the sum of inertia of all synchronous generators as well as residual inertia (demand). The GB system in the past 20 years has experienced a rapid growth in renewable generation (solar and wind farms), Figure 2. This has resulted in reduction of the total system inertia as presented by a significant amount, in Figure 3.

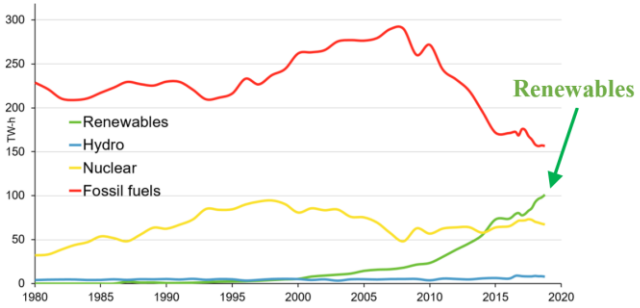

Figure 2 UK electricity production by source 1980–2018, [8].

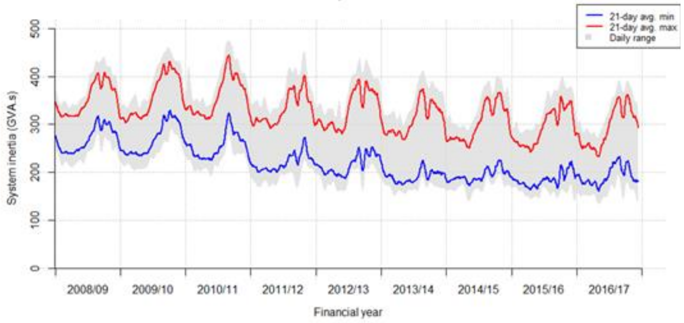

Figure 3 Historic system inertia of the GB system [9].

C. Phasor measurement units in Great Britain's transmission system

In order to analyze the Fast Frequency Phenomena in the GB transmission system, installed Phasor Measurements Units (PMUs) can be utilized. There are a number of PMUs installed across the GB system. These PMUs measure the parameters of the grid such as voltage and frequency, which are synchronized by GPS signals.

Approximately, 90 PMUs or Waveform Measurement units (WMU) spread across the country are currently installed in the GB transmission system, to monitor its behavior. The necessary infrastructure was built prior to this F2P-project, and is well described in one of the previous projects "VISOR": "**Visualisation of Real Time System Dynamics using Enhanced Monitoring**", [10]. Installations in the GB transmission system with the location of the PMUs, WMUs, data centre, Hub and communications can be seen in the following Figure 5. The project in this paper used the data obtained from these PMUs to investigate fast frequency phenomena.

The IEEE C37.118.1 standard on Phasor Measurements Units defines how the Frequency is estimated by the PMU, Figure 4. The frequency is estimated as a derivation of the positive sequence voltage angle. This may lead to the misinterpretation of some fast electromagnetic phenomena originated as Frequency phenomena [8].

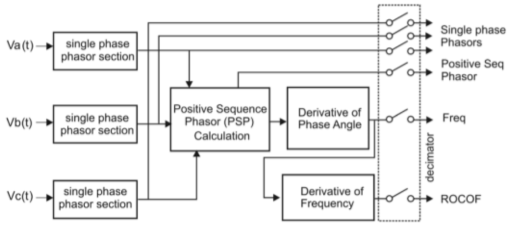

Figure 4 A PMU model using the positive sequence phasor. IEEE Standard C37.118.1™-2011 [11].

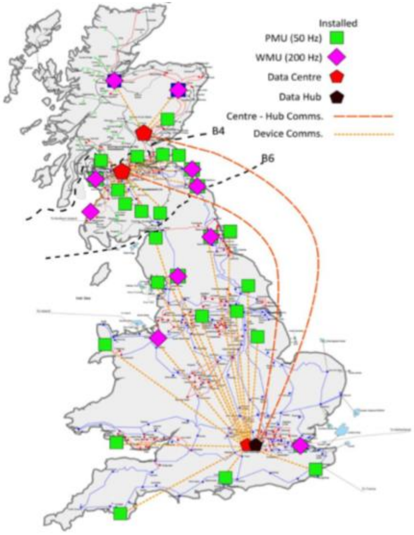

Figure 5 The WMUs and PMUs and communication, (VISOR) [10].

III. IMPACT OF LOW INERTIA

A. Response of the system with lower inertia

During the first seconds following a disturbance the power system frequency variation depends significantly on system inertia, because there is no time for traditional governors to react. The decreasing inertia of the power system leads to a faster system reaction. This fast frequency phenomenon propagates from the place of incident across the whole network. The same disturbance applied to the system will lead to different behavior depending on the actual inertia; for the lower system inertia, a faster reaction is to be expected together with a lower nadir, Figure 6.

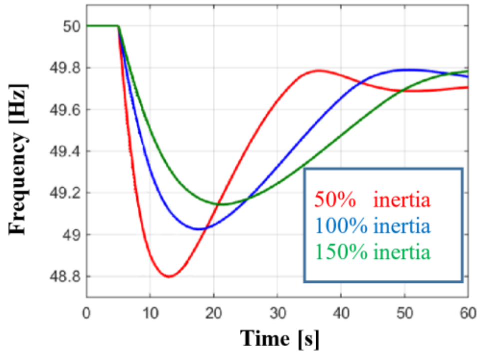

Figure 6 Response of the power system to a disturbance for different levels of inertia.

B. Impact of low inertia on Loss-of-Mains protection

Loss-of-Mains protection (LoM) is designed to safely disconnect embedded generation following islanding from the main power system. LoM works on one of two principles: RoCoF (Rate of Change of Frequency) or Vector Shift. In a low inertia system, the threshold values for RoCoF &/or Vector Shift given by the UK Engineering Recommendation G59 may be exceeded during a main system disturbance that does not involve islanding (e.g. the trip of a generator or HVDC interconnector or a correctly clear transmission fault). LoM protection may therefore malfunction, and the cumulative effect might be critical (cascade tripping of embedded generation in addition to the original disturbance). Originally the limits governed by G59 were 0.125Hz/s for RoCoF and 6 degrees for Vector Shift. Recently, during 2018, for new connections in the UK the RoCoF limit was increased to 1Hz/s and Vector Shift was no longer approved, however, the LoM protections installed in the past still operate at the old settings and thus the risk remains. An industry initiative is underway to update existing LoM protection to the new settings, but this will take some years and may not achieve full coverage of all embedded generation installations.

IV. A STUDY CASE

In order to demonstrate the Fast Frequency phenomena a study case is presented from the GB transmission system. The case presents a trip of a HVDC link connected in the South-East of the GB transmission system. In the presented case, an element of the HVDC tripped while importing 500 MW to the GB transmission system and thus the system frequency fell for about 10s after the event occurred (in this case between 20th and 30th second of recordings). This results in electromechanical response of the system represented by RoCoF (measured in all the stations) as a negative "DC" component together with some short time (local and inter-area) oscillation - about 1.5 Hz in the South and 0.5 - 0.6 Hz in North of the transmission system. This DC - RoCoF starts at -0.045 Hz/s and in 10 s reach 0 Hz/s, Figure 7 (left top and left bottom). This trip is also associated with a Vector Shift (especially nearby the location of an event) which is a reason for initially high RoCoF transient -1.8 Hz/s within 200ms after the fault. Figure 7.

V. TYPES OF RECORDED FAST FREQUENCY PHENOMENA

It is apparent from recorded historical events, that the Fast Frequency Phenomena (F2P) cannot be understood as a single type phenomena, but rather as 3 types, for the purpose of this study. Firstly there is an electromagnetic effect, which is a fast initial transient originated from the Vector Shift in the voltage waveform. The subsequent electromechanical responses present slower but longer lasting phenomena. The electromechanical components can be further dived into general behavior i.e. slowing down or speeding up of the generators ("DC components"), and the oscillations ("AC components"). The oscillations represent the local or inter-area mode oscillations, Figure 8. The first electromagnetic phenomena will naturally not depend on the inertia as it is not originated from the rotors mechanical behaviors, whilst the other two electromechanical phenomena will depend on the system inertia and its distribution, based on the swing equation.

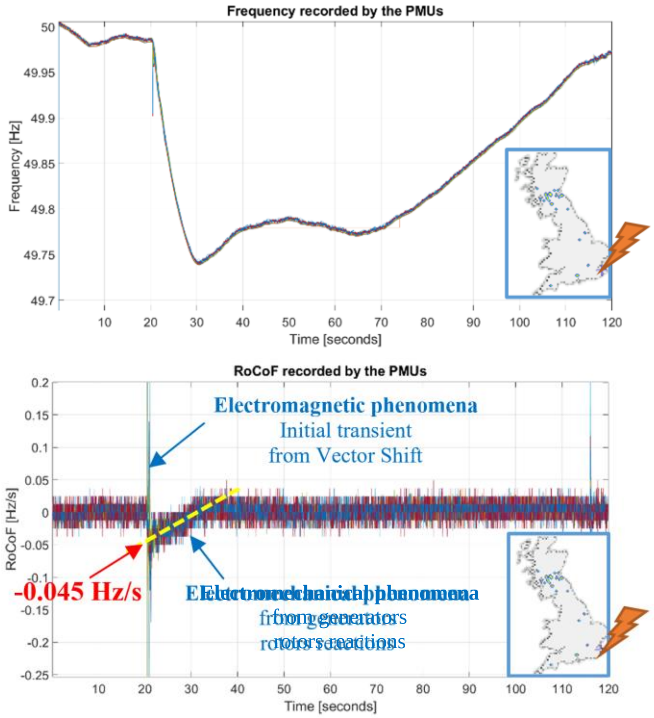

Figure 7 All PMUs during the HVDC trip event 20.4.2018. Location of the disturbance shown on a map with red arrow.

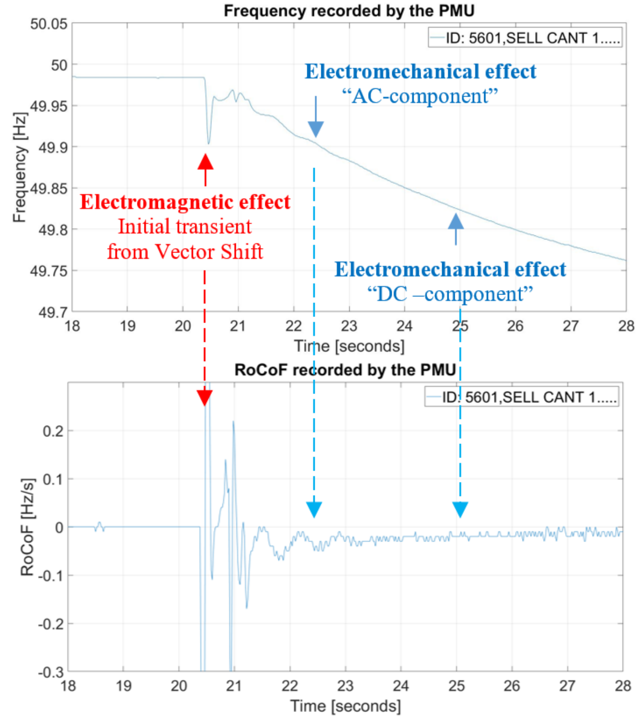

Figure 8 A 3 types of F2P investigated in this study. Case HVDC trip, 20.04.2018. PMU data of substation, where HVDC is connected.

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VI. GEOGRAPHICAL VISUALISATION OF FAST FREQUENCY PHENOMENA

A. Fast Frequency Phenomena Visualization program

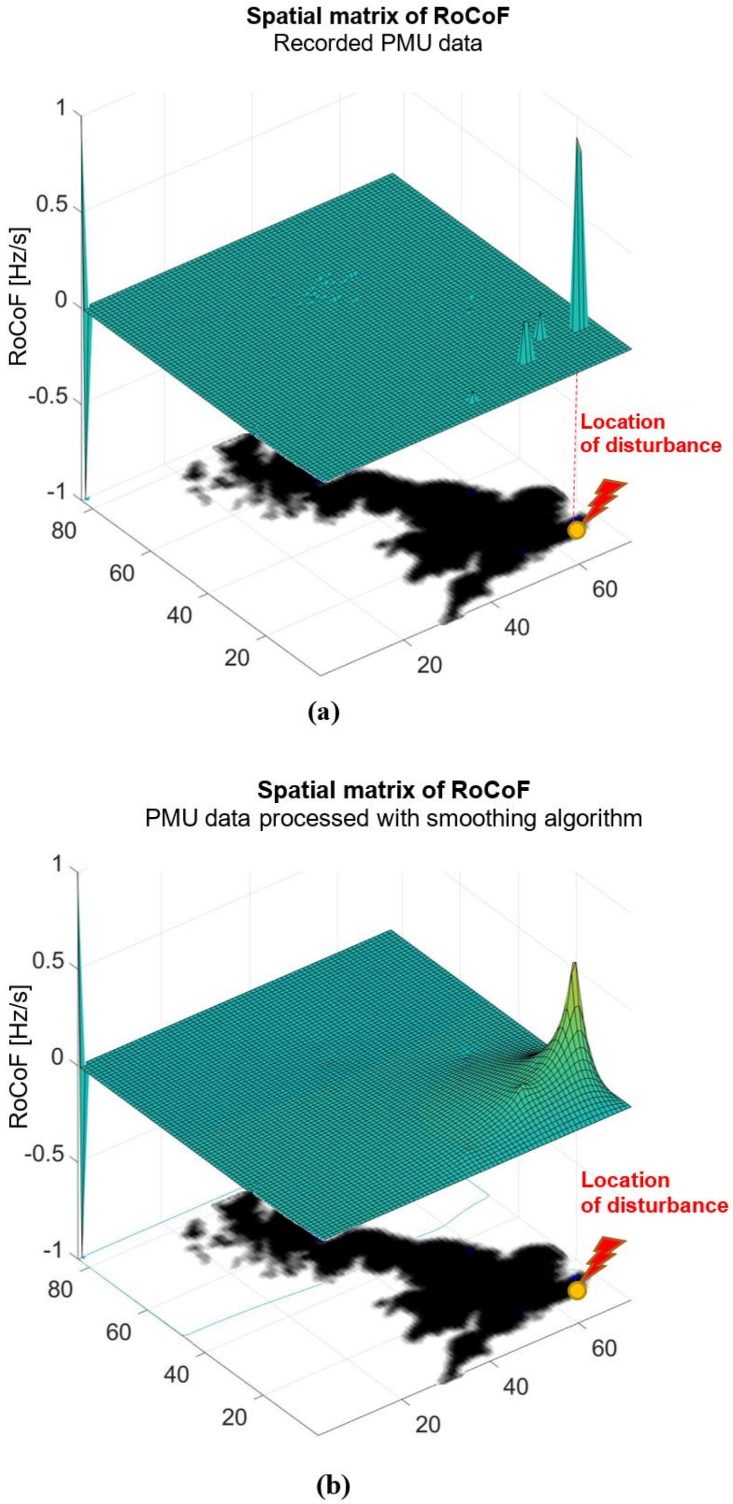
To assist in the study of fast frequency phenomena a visualization tool has been developed at Brunel University London. The visualization tool presents the spatial distribution of the critical parameters such as RoCoF and Vector shift. Typical historical events were identified in the two main categories of this work, i.e. Vector Shift and RoCoF. The spatial data were processed and displayed using with the implementation of a novel moving average algorithm, [8]. Using the available measurements the algorithm estimates RoCoF or Vector Shift values in places with no measurement. An impact area is also estimated where the RoCoF values exceed the 0.125Hz/s

B. A study case analysis

An example of fast frequency phenomena was demonstrated in the visualization tool, and displayed here, using the example of a trip of an HVDC link in the south east of the UK. An example of 3D visualization is presented in Figure 9, which also shows a good correlation between data estimated by the implemented smoothing algorithm and that recorded by the PMUs. Separately, the spatial distribution of RoCoF is plotted in 2D, Figure 10 and Figure 11. The impact area in this case (yellow color) will, however, not cause actual tripping because the transient's duration, lasting for about 200ms, is shorter than the G59 minimum time limit value of 500ms. The trip will not be caused in this case even by the electromechanical phenomena, as the RoCoF does not exceed 0.125 Hz/s for 500ms, Figure 8. However, the impact area where the instantaneous thresholds values are exceeded is a significant part of the transmission system

VII. CONCLUSION

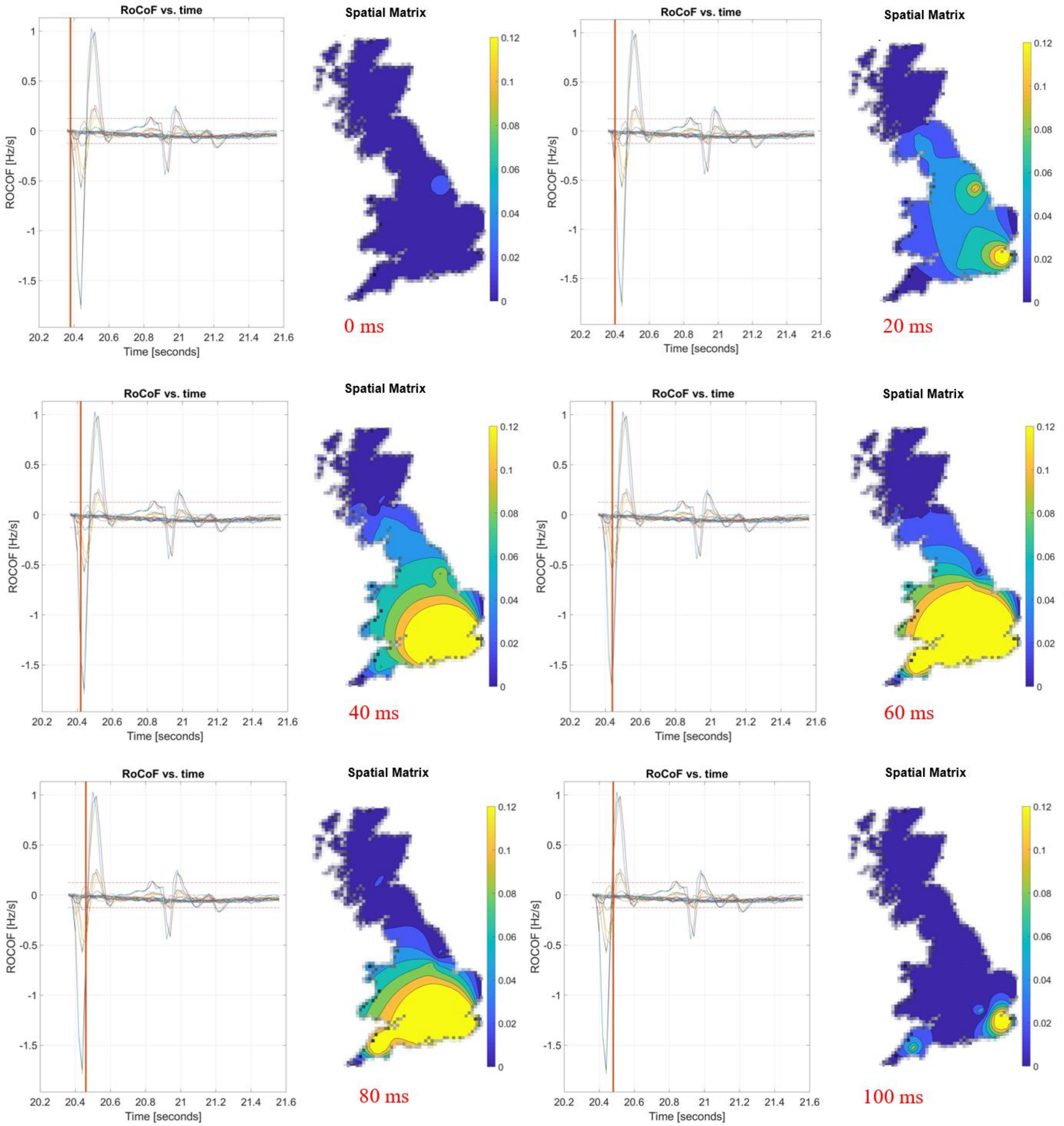
In this paper fast frequency phenomena as exhibited in the GB transmission system was studied to better understand the risk of Loss-of-Mains protection maloperation due to fast and regional phenomena. The historical data of real events as recorded by NGESO were used for the analysis. The historical data was analyzed using the developed visualization techniques. The visualization techniques indicate how fast frequency phenomena propagates across the GB transmission system and also compares the impact area against Loss-of-Mains relay operating thresholds as displayed and analysed. The proposed visualization techniques increase understanding of the fast frequency phenomena across the GB transmission system, furthermore, they also provide accurate estimations of the impact areas, where relay operating thresholds may be approached or exceeded. Further research will involve validation and potential enhancement of relevant GB transmission models (DigSilent PowerFactory, [12]) with a view to comparing them against such results as reported here. Furthermore, the project plans to use a range of GB transmission system models for Hardware-In-the-Loop studies using the OPAL RT real time digital simulator, and will involving testing a variety of Loss-of-Mains relays that are typically connected on the UK system.



(a)

(b)

Figure 9 - An example of 3D visualization of F2P (RoCoF), HVDC trip. (a) Recorded PMU data. (b) PMU data processed with smoothing algorithm. Spatial matrix dimensions 84x72.



0 ms

20 ms

40 ms

60 ms

80 ms

100 ms

Figure 10 Spatial behavior of the Fast Frequency Phenomena (0 to 100 ms, with step 20 ms) across the GB network in 2D. An absolute value of RoCoF is plotted. Limits set to +/-0.125Hz/s – yellow color.

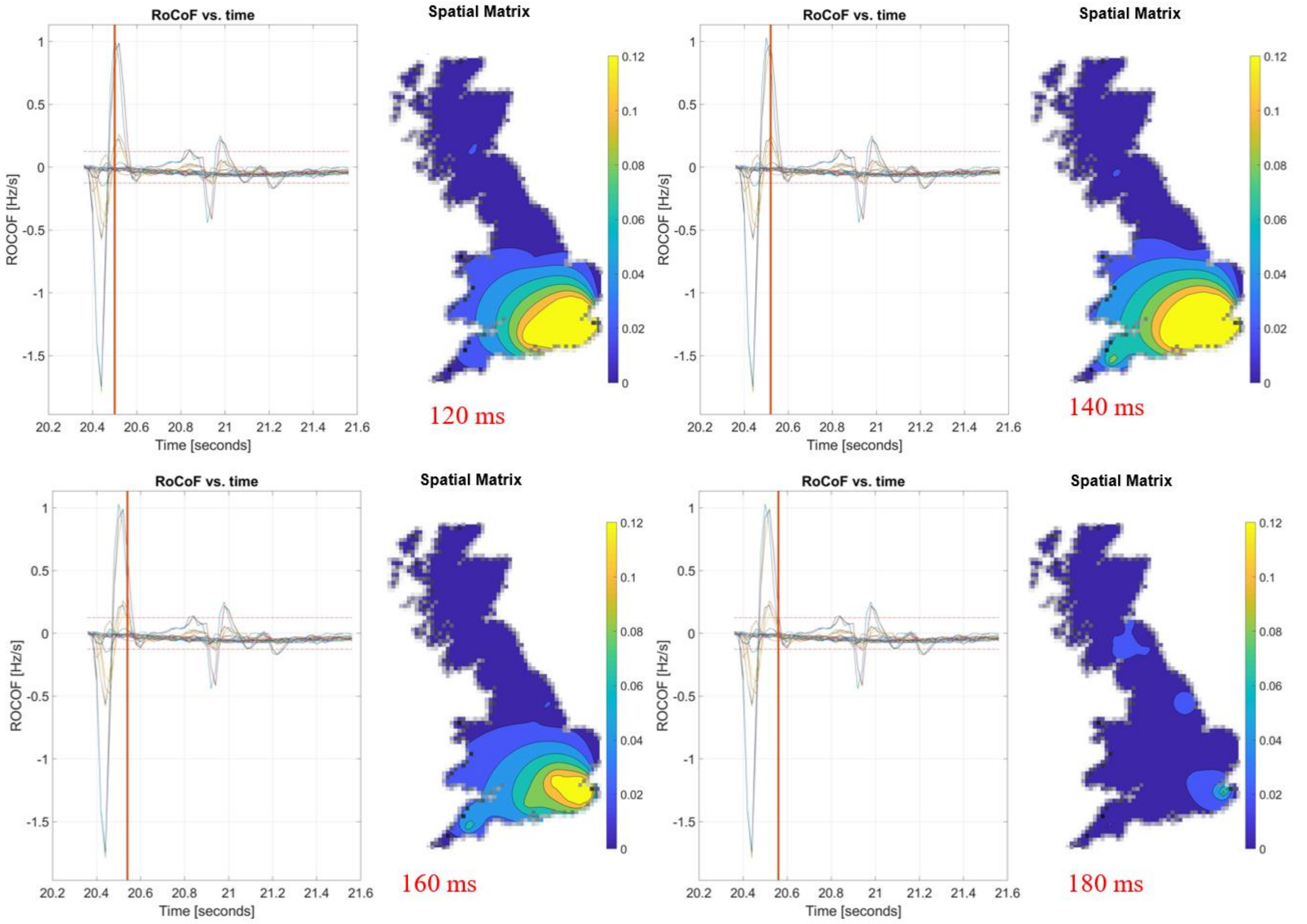


Figure 11 Spatial behavior of the Fast Frequency Phenomena (120 to 180 ms, with step 20 ms) across the GB network in 2D. An absolute value of RoCoF is plotted. Limits set to +/-0.125Hz/s – yellow color.

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