Enhanced Fast Frequency Control Scheme and Wide-Area Monitoring for Low Inertia Power Systems

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Enhanced Fast Frequency Control Scheme and Wide-Area Monitoring for Low Inertia Power Systems

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Abstract— **Rate of change of frequency (RoCoF) increases with high share of converter-interfaced generations in modern low-inertia power systems. Consequently, system operators will have system stability challenges if they rely on classic frequency control schemes. This study demonstrates an innovative fast frequency control scheme and wide-area monitoring system developed for low-inertia grids. This can acquire precise frequency data at a zonal level, estimate the required rate and volume of fast response and then enable the initiation of this response within 0.5 seconds of a system frequency disturbance. The effectiveness of the proposed interim frequency control scheme against two methods in literature is verified based on a 36-zone Great Britain power system developed in DIgSILENT PowerFactory. Further, sensitivity analysis is used to investigate the impact of different parameters like RoCoF measurement time and communication latency. The proposed scheme allows low-inertia grids to operate with increasing volumes of non-synchronous generation.**

Index Terms— **Fast frequency response, Low inertia systems, Rate of change of frequency, Wide-area monitoring and control.**

I. INTRODUCTION

Incentivized by environmental concerns and energy security risks, converter-interfaced generation (CIG) and a fleet of renewable energy sources have been extensively penetrated over the last decade around the world. This reduces system inertia and gives rise to an increase in the volume and speed of frequency response [1]. Additionally, maintaining rate-of-change-of-frequency (RoCoF) and voltage angle within satisfactory boundaries is so critical to prevent unnecessary triggering of protection relays, what can result in cascading failures, violated system security, or even a drastically system blackout [2]. Thus, the motivation of this paper is to derive a new enhanced frequency control strategy.

In the case of frequency control, the inertial response and droop-based primary frequency regulation and control using available spinning reserves are inherently deployed in conventional power plants to arrest and recover sudden frequency deviations [3]. However, rotating masses of CIG units like wind energy conversion systems and industrial variable frequency drives are electromagnetically decoupled from the rotating parts on the grid side [4]. In addition, the photovoltaic (PV) systems do not have rotating mechanical parts and they are just connected to the grid over inverters [5]. The same is valid for battery storage systems. Thus, these units, by themselves, neither achieve the inertial response nor participate in frequency regulation mechanisms.

On the other hand, there is a growing motivation for loads to participate in frequency regulation under demand response framework [6]. Traditionally, under-frequency load shedding (UFLS) is commonly deployed as the simplest demand response to prevent frequency decrement after incident [7]. It is exposed that in low inertia power systems, 1 MW load resources with under frequency relays providing full response within 0.5 second after dropping frequency to a preset value is up to 2.35 times more effective than 1 MW PFR from the generation side [8]. In [9], the voltage dependency of the loads for adjusting the adaptive UFLS schemes is taken into account to utilize as much as possible the primary frequency support.

Past control system models typically represent the effects of national balancing services measuring national frequency change to deliver against national frequency containment. However, in the timescales that fast frequency response is now required, in less than 1 second, the enhanced frequency control capability (EFCC) project has demonstrated the phenomena of zonal frequency and zonal RoCoF using wide-area monitoring and control scheme (WAMCS) [10]. It is therefore necessary that any fast frequency response control system model accounts for zonal frequency variation. This approach considers the effectiveness of a frequency response solution by not requiring frequency data from across the network in real-time to inform its frequency response function. This approach, exactly as before, is based on performing a national frequency and RoCoF derivation. However, in this approach, that derivation comes from taking the zonal frequency and RoCoF value within the zone and deriving from the relative inertia locations across the network prior to the event and delivering frequency response proportional to that distribution of inertia. Unlike the above modes of operation, this approach would not require wide-area, real-time availability of phasor measurement unit (PMU) data to inform frequency and RoCoF measurement during an event, nor the infrastructure to communicate this to centralized or distributed points of national calculation. Comparison of the effectiveness of this approach against other alternatives is used to identify periods of future operation which could be satisfied

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by the interim approach and therefore requires less extensive infrastructure.

Across all of the above control approaches, the weighting of each zone's frequency and RoCoF consider perfect foresight of the inertia available and its distribution across the GB network ahead of any event. The models are however capable of being modified to examine the effect of zonal and national forecast inaccuracies. In practice, PMU coverage as illustrated across the visualization of real time system dynamics using enhanced monitoring (VISOR) [11] and massive integration of power electronic devices (MIGRATE) [12] projects may complement improved definition of zonal inertia in real time and effectiveness of above simulation approaches in reality.

The simulation models on 36-zone Great Britain (GB) network also feature user definable fields enabling a variety of real-time operational considerations and settings. The setting of parameters like data synthesizing window periods and communication delay allows different strategies to implementation and control of a real network to be considered and behavior of those real networks to be closely emulated.

This paper is organized as: In Section II, the proposed enhanced frequency control method is discussed. Simulation results are presented in Section III. Final remarks and future works are given in Section IV.

II. ZONAL ENHANCED FREQUENCY CONTROL CAPABILITY

The zonal EFCC scheme is an evolving frequency control method developed in this paper to improve frequency stability of low-inertia systems with high integration of renewables. As explained in Fig. 1, the zonal controller is a crucial component deployed in this scheme, which directly makes decisions and accordingly deploys resources to stabilize frequency after a disturbance. In this case, if there is a pre-event data of the zonal inertia, the proposed scheme will be triggered to deploy frequency responses available in a zone considering its zonal inertia against the whole system inertia. Otherwise, the within zone mode will be activated instead only according to frequency and RoCoF which results in a slower and smaller frequency control response.

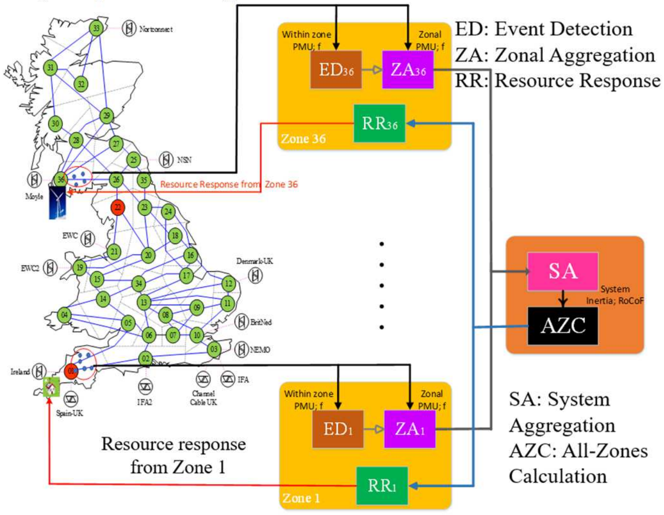

Figure 1. Proposed enhanced fast frequency control scheme and wide-area monitoring system

The zonal-based EFCC scheme demands zonal controllers to operate using only zonal information during the event itself, in which it responds to the local measurements, without accessing the data from an all-zones calculation (AZC). This AZC performs as a brain to the EFCC scheme in all-zones mode only in its communication ahead of the event of the system inertia distribution. The AZC calculates global center-of-inertia (COI) RoCoF to determine global power mismatch. While the zonal controllers estimate zonal power imbalances based on zonal COI RoCoF.

As such the proportionate zonal response can be deduced from the proportion of resources that are in that zone and the zone's inertia. To this end, the zonal controller and its interim control system works under an "event trigger" mechanism, where the corresponding detection block will constantly receive the zonal RoCoF and frequency signals measured in a given period. Considering the measurement window, the zonal controllers can respond accordingly to secure the largest infeed loss. The zonal controllers determine the required power response based on the COI and zonal RoCoF measurements. The available resources in the control area, typically wind and solar energy sources, will then be dispatched by the corresponding zonal controller, according to the calculation results, to restore frequency. One of the prerequisites for this mechanism is that zonal controller has the knowledge of maximum power imbalance ΔP deployment prior to the fault in its pre-determined configuration (amongst resources are armed and available to meet the largest infeed loss. This depends on the RoCoF values and the location of the frequency response resources. If there are no sufficient resources in a zone, the other zones can potentially assist to secure system stability.

To better explain the EFCC scheme, the demonstration examples presented in this paper are assumed to purely adopt a demand reduction action, instead of renewable generations. However, it can be easily applied on other service providers based on the same principles. The objective of the simulation on the proposed EFCC is to see if this simplified system, which is less reliant on wide-area comms and real-time calculations but performs on a basis of zonal RoCoF values, is capable of deploying enough response and acting fast enough in practice.

III. SIMULATION RESULTS

A. 36-Zone GB Test System

The single line diagram of GB test system is depicted in Fig. 2 where in the generations and demand are concentrated on the southern part. As a matter of this fact, the zones are numbered from bottom to top. The simulations are conducted in DIgSILENT PowerFactory. It is supposed that the system demand is supplied by 70 power stations including gas, nuclear, biomass and hydro generations across the system and pump storage units located in 36 zones. The excessive power generation is transferred to other countries through eight HVDC links. The lowest and highest amounts of loads i.e., 57 MW and 3,541 MW are in zones 31 (Northern area) and 8 (near to London), respectively. The 36-zone GB network can

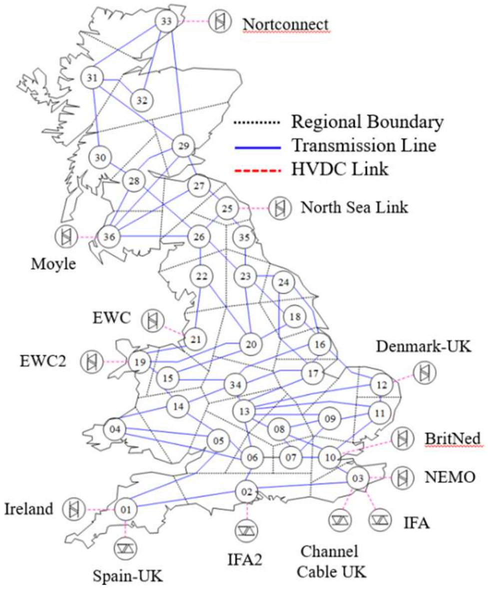

Figure 2. Single line diagram of 36-zone GB system

be approximately divided by three parts of bottom, middle and top where 58%, 32% and 10% of the system demand is consumed in them, respectively. In the zonal EFCC scheme, the following criteria have been considered:

1) Proximity EFCC: Resources closest to event are deployed as priority by All-zone control.
2) Equality EFCC: Resources are equally distributed across the whole system, by All-zone control.
3) Interim EFCC: Response is zonally provided by the proposed zonal controller, based on the zonal RoCoF.

It is to be noticed that this provides a pathway for the EFCC scheme to be mapped and the effect of the wide-area monitoring system to be simulated. Additionally, the proposed interim control has the potential to be an interim stage of EFCC deployment. It works on the following principles of:

i) If a "picture" of an event is needed beforehand, it can be accurately projected forward and reacted with confidence.
ii) With enough information it can still be acted. The proposed interim has a low infrastructure requirement.

B. *Marginal Cases*

This case is constructed from the plant dispatch for the consumer power minimum condition in the 2016 System Operability Framework (SOF) document data tables [13]. This dispatch is applied on the 36-zone GB test system. Inertia values by technology type are then applied based upon existing plants on GB capabilities and demand inertia assumptions for the events. The corresponding criteria can be considered as follows:

1) Zonal RoCoF values, measured with window of 0.5s, should be lower than 1.0 Hz/s
2) Zonal frequency nadir, measured in any zone, should be greater than 49.5 Hz.

This dispatch case has then flexed the size of the largest infeed loss simulated by re-allocating active power across the following zones:

1) Test 1: Zone 1 – Where Hinkley Point C as the largest infeed loss risk ultimately emerges, and the discrepancy between the system COI frequency and the zone's instantaneous frequency is maximum.
2) Test 2: Zone 22 - Heysham area, where there is a lot of existing generation, some maximum loss candidates, and has the smallest discrepancy between the COI frequency and the zone's frequency.

The marginal cases based on the above criteria are defined in Tables I and II for years 2020/21 and 2025/26. The respective system inertia is tabulated in Table III. All the EFCC sensitivities recover the frequency effectively for larger losses than are possible without EFCC. Up to 2025/26, interim EFCC mode is most effective; however, all approaches deliver acceptable results. Furthermore, with any of these three approaches being used under EFCC for the disturbance occurred in zone 1, a maximum system loss between 850MW and 395MW larger than possible without EFCC can be accommodated for scenarios 2020/21 and 2025/26, respectively. Further, the size of infeed loss required to reach RoCoF of 1.0Hz/s in the case of 2020/2021 are 645MW and 1290MW for zones 1 and 22, respectively.

Zone	Frequency Nadir 49.5 Hz	With EFCC implemented
1	710 MW	1560 MW
22	725 MW	1685 MW

TABLE I. MARGINAL CASE FOR DCENARIO YEAR 2020/21

Zone	Frequency Nadir 49.5 Hz	With EFCC implemented
1	710 MW	1560 MW
22	725 MW	1685 MW

TABLE II. MARGINAL CASE FOR SCENARIO YEAR 2025/26

Scenario year	Base Power S (MVA)	System Inertia (MVA.s)
2020/21	27,350	83575
2025/26	27,260	48602

TABLE III. SYSTEM INERTIA

C. *Comparison of Interim, Equality and Proximity EFCC Schemes for Scenario Year 2020/21*

All the following simulation results are associated with an infeed loss of 1,560 MW occurred in Zone 1 in which frequency nadir reaches its limit of 49.5 Hz.

1) System COI Frequency

Figure 3 compares the system COI frequency for the proposed interim EFCC scheme against the other two methods subject to an infeed loss of 1560 MW. The proximity EFCC has the lowest frequency nadir; however, the equality EFCC results in almost same frequency change. On the other hand, the interim EFCC has the lowest frequency deviation due to less communication delay. It is clear-cut that the proposed interim EFCC can efficiently enhance the zonal frequency responses, since it does need the zonal frequency data without communicating with other zones. Thus, the disturbance size will be quickly calculated and the required frequency response within zone will be quickly triggered. This performance can be highlighted even more for test systems with fewer number of zones. Furthermore, there are many parameters like frequency filtering time constant, RoCoF sampling windows that can be properly tuned to highlight the superiority of interim EFCC. This sensitivity analysis is discussed in the next subsection.

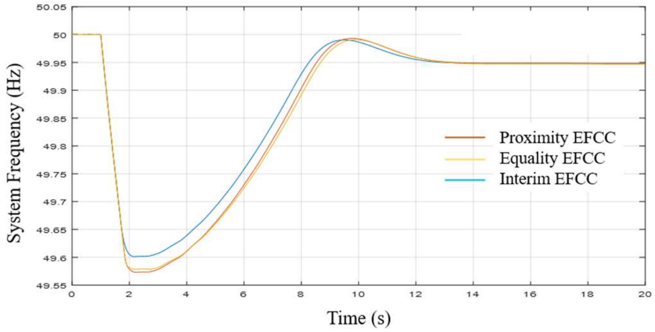

Figure 3. The system COI frequency for three different EFCC schemes with an infeed loss of 1560 MW in zone 1 in 2020/21

2) *System COI RoCoF*

The system COI RoCoF with the three EFCC schemes has been shown in Fig. 4. Based on the system swing equation ($H = \frac{\Delta P \cdot f}{2RoCoF}$), the total system inertia excluding the tripped generator is 72,500 MW.s, with $\Delta P, f, RoCoF$ equal to 1450 MW, 50 Hz and -0.5 Hz/s, respectively. The estimation error in infeed loss size estimation is about 7%). All EFCC methods have similar performance in terms of system COI RoCoF.

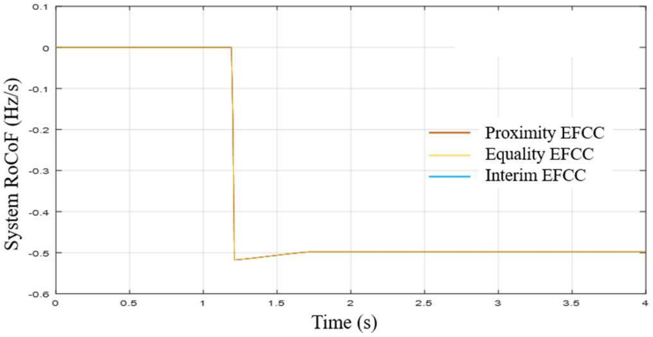

Figure 4. The system COI RoCoF for three different EFCC schemes with an infeed loss of 1560 MW in zone 1 in 2020/21

3) *Zone 1 Frequency*

Figure 3 compares the frequency measured in Zone 1 for the proposed interim EFCC scheme against the other two methods subject to an infeed loss of 1560 MW. As can be seen, the interim EFCC has better frequency nadir due to less communication delay. The proximity based all-zone EFCC has the worst frequency nadir. Unlike the equality and proximity modes of operation, the interim EFCC approach would not require wide-area, real-time availability of PMU data to inform frequency and RoCoF measurement during an event, nor the infrastructure to communicate this to centralized or distributed points of national calculation.

4) *Resource Response from Each Zone*

Fig. 7 compares the delivered frequency responses for the three different EFCC schemes, in each zone. In the proposed Interim EFCC, the zonal power responses are dependent to their corresponding zonal RoCoF. The higher the RoCoF is, the greater frequency response is. For instance, the zonal frequency response burden on zones 23, 12 and 10 is higher as compared to other zones since their RoCoF values are greater. With the proximity EFCC, each zone has a different degree of influence, because their electrical distance is considered. The closer to the disturbance location, the greater the response is. For example, zone 1 has higher response as the infeed loss is occurred in this zone. In equality EFCC, each zone principally shares the same responsibility for frequency response. With proximity and equality schemes, all zonal resources are

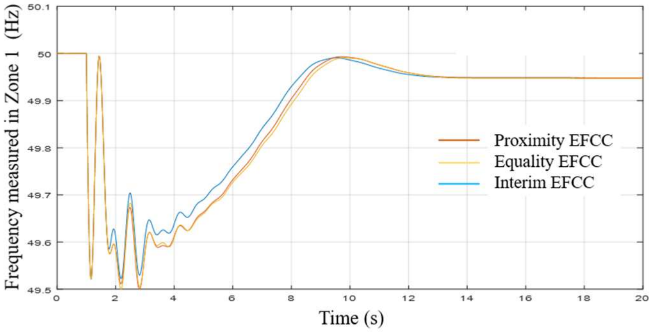

Figure 5. The frequency measured in Zone 1 for three different EFCC schemes with an infeed loss of 1560 MW in zone 1 in 2020/21

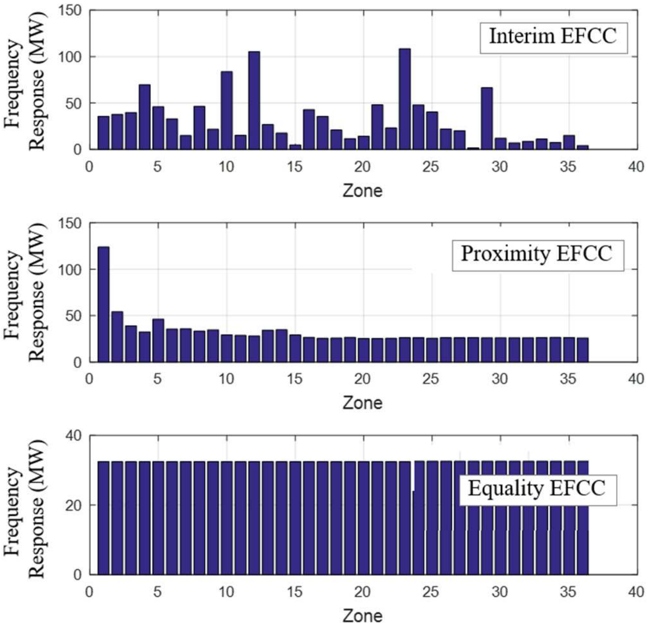

Figure 6. The zonal frequency responses with three different EFCC schemes with an infeed loss of 1560 MW in zone 1 in 2020/21

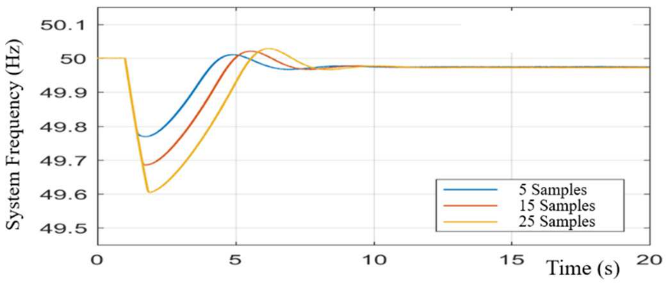

Figure 7. Comparison of System COI frequency with different Samples for RoCoF Calculation with infeed loss of 1560 MW in zone 1 in 2025/26.

activated at the same time based on the system RoCoF. However, the zonal controllers of interim EFCC are activated based on the zonal RoCoF to efficiently allocate required response on the frequency resources.

IV. CONCLUSION

In this paper, a Enhanced Frequency Control Capability (EFCC) method is proposed called Interim EFCC. It efficiently allocates the frequency responses between the armed resources using zonal frequency and RoCoF. Its effectiveness is compared to two schemes of fast frequency controls; the Proximity EFCC (where deployment of resources are prioritized based on the vicinity to the event location), and Equality EFCC (where deployment of resources are evenly spread across those available, irrespective of the location of the event). These three cases respectively enabled modelling a wide-area monitoring and control system (WAMCS) capability, and the sensitivity of not relying on the wide area communication in real-time during the event itself. These algorithms are designed with a flexible user interface allowing settings to be implemented. Whilst deployment of resources close to the event is beneficial, it has identified that up to 2025 this is not essential so that the proposed interim control is sufficient. This approach is not dependent on real-time frequency and RoCoF other than zonally received but which does need a wide-area picture of the system's state prior to an event. Approaches allow researchers to see the zonal and global frequency, identify how and to what extent zonal resource is important and how best to combine EFCC with other forms of frequency response. Across the period of study, a benefit of increasing the maximum infeed loss that the system could otherwise provide between 400MW and 850MW of additional maximum infeed loss capability to the GB grid, avoiding the need to intervene into the GB energy market to constrain down the maximum infeed loss.

As a future study, the simulation techniques used for fast frequency response can be incorporated into the full GB system model with the support of the optimization technique. This will coordinate and initiate all the service providers that are armed to arrest the frequency deviation over a time scale of seconds. Furthermore, the capabilities of resources which EFCC may seek to deploy for frequency control to deliver rapid and inertial responses can be appended into the proposed EFCC schemes.

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