Analysis of Responsibilization within Primary Frequency Control

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***Abstract*—The emerging need to prioritize remedial frequency control measures closer to the source of an imbalance event, referred to as responsibilization, is being acknowledged. As responsibilization is inherent within secondary frequency control, novel primary frequency control (PFC) approaches to incorporate responsibilization are being proposed in literature. This contribution is aimed to enhance the understanding of responsibilization to enable further improvement and development of the concept. To this end, this paper extends the knowledge-base by presenting an analysis of responsibilization within conventional PFC and a responsibilizing PFC reported in literature. The analysis is undertaken by means of real-time simulation conducted on a six-area reduced model of the Great Britain power system.**

I. INTRODUCTION

The need to prioritize frequency response closer to the source of an imbalance event, within the first seconds of its occurrence to ensure stable operation in a future changing, constrained grid has been demonstrated in [1] and further discussed in [2], [3]. The temporal requirement of prioritization renders primary frequency control (PFC) as the most suitable existing service to address the need, otherwise development of new services might be considered. Acknowledging the emerging need to incorporate locational information for a targeted response to a power system imbalance, in [4], the term responsibilization is introduced as the prioritization of remedial control measures closer to the source of an imbalance event. The introduction of the term filled the gap in referring to an important concept and thereby supported the drive towards the new paradigm of greater decentralization of power systems.

Larger synchronous power systems are often divided into a number of smaller areas, for effective frequency control, referred to as load frequency control (LFC) areas [5]. The objective of PFC is to contain the frequency after an event and in synchronous power systems is designed such that each LFC area responds proportionally to their capacity based on the frequency droop slope set by the system operator [6], [7]. Introduction of responsibilization within PFC of synchronous power systems would refer to the enforcement of the LFC area with an event to contribute more PFC response to the event. Although responsibilization is inherent within secondary frequency control (SFC), the operation of PFC at a much faster timescale than SFC, presents a challenge for responsibilization to be incorporated. Responsibilization can be incorporated in PFC if the droop slopes of the LFC areas can be adapted in real-time, i.e., allocation of a lower frequency droop percentage (higher active-power response contribution) to the area with the event. A number of works in literature extensively discuss adaptive droops for microgrids [8], [9]. However, for the purpose of introduction of responsibilization within PFC, the droops can be adapted only if the location of the event can be detected within the timescale of operation of PFC.

In [10], a method to adapt droops for PFC of LFC areas is presented, where the droop slope of the areas is adapted by a fuzzy controller incorporating an event detection technique. The scope of the adaptation is to reduce PFC response when the imbalance event is outwith the area, i.e., somewhere else in the power system, while for the case when the imbalance event is within the area, the droop slope remains unchanged. Although the approach presents successful adaptation of droops for PFC, it does not introduce effective responsibilization. This is due to the fact that the PFC response of area with the imbalance event remains unchanged. It should be noted that the approach does not restrict increasing the contribution from the area with the imbalance, but has been identified to be out of scope of the study presented in [10]. Furthermore, the event detection in the aforementioned approach is centralized within the LFC area. This is acceptable for SFC where the conventional approach is either centralized at a synchronous system level or at the LFC area level. However, conventional PFC is fully decentralized and more decentralized solutions should be sought.

To address this need, in [4], a decentralized responsibilizing PFC is proposed where responsibilization is achieved by means of measuring a new observable referred to as the transient phase offset (TPO). The proposed approach is fully decentralized as it relies on local measurements only and requires no form of communication. Although methods to incorporate responsibilization within PFC have been proposed, a detailed analysis of responsibilization within conventional PFC and responsibilizing PFC has not yet been presented in literature. Therefore, this paper aims to address this gap and is organized as follows. Section II introduces the test network and system characteristics that will be utilized for the analysis. Section III presents the theory of conventional PFC followed by an analysis of its responsibilization. The principles

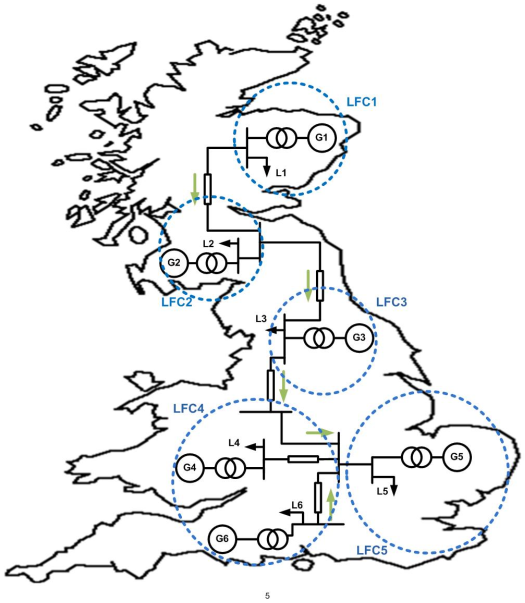


Fig. 1: Reference 5 area reduced GB power system.

of responsibilizing PFC utilized in this work are presented followed by a comparative analysis of its responsibilization with the conventional approach in Section IV. Section V concludes the paper.

II. Test System

For analyzing primary frequency control approaches, in this paper a reduced six-machine dynamic model of the GB power system has been chosen as the test grid. It is worthy to mention that the GB grid is a single synchronous area and has no LFC areas. However, in this paper buses of the reduced model have been grouped to represent LFC areas as shown in Fig. 1. These regions have been developed around major generation sources, power flow corridors and load centers [11].

A. Modeling

The six-machine model has been developed in RSCAD and simulated in real-time with 50 μs as time step using a digital real-time simulator from RTDS Technologies [12], with each area comprising at least one aggregated generator and an aggregated load. Each aggregated generator is modeled as a large synchronous machine connected to the transmission system via a step-up transformer (13.8/400kV). The rating of each generator is set according to the predicted GB 2017 load flow [11]. Each generator is controlled by the widely used IEEE type 1 static excitation system. A gas turbine and speed governor control the speed and input torque of each machine. The synchronous machine, excitation system and gas turbine parameters have been obtained from [5], while the governor speed control parameters are tuned against real recorded events as will be explained in the following sub-section. The transmission lines are modeled using Pi-sections with lumped resistance, capacitance, and inductance parameters calculated from the power flow data provided by the National Grid Electricity Ten Year Statement (ETYS) for 2017 [11] as per the methodology presented in [13]. The model parameters can be found in [14].

B. Validation

The model has been validated by means of two tests in [14]:

1) Load flow analysis: This test is to evaluate the steady-state performance of the model. The load flow simulation data of the six-bus test system closely matches the predicted data obtained from ETYS, for the winter peak of 2017 [11]. This includes the generation and demand data at each region and the power flow across the boundaries of the regions.

2) Dynamic frequency response evaluation: The dynamic response of the six-bus reference power system model is benchmarked against a number of real historic frequency deviation events data recorded by PMUs located at various points of the GB power transmission network. In [14], the event chosen was the trip of the England-France HVDC interconnector on 11th of January 2016 leading to a power loss of 900MW. In other words, the model represents the real-world GB network on the 11th of January, 2016. The total generation and demand of the model is adjusted to match the values on the day of the event (total demand=59.56GW). The inertia constant, the governor time constant, the droop percentage, and the load reference set-point parameters are tuned to ensure the model frequency response matches the frequency response (pre-disturbance, RoCoF and frequency nadir) obtained from the PMUs.

C. Adaptation

The model initial frequency in [14] was adjusted to match that of the real GB power network on the 11th of January 2016. However, as this work analyses primary frequency control, the load reference of the model was modified such that in steady state the model frequency is 50 Hz. It was further found that the synchronous generators utilized within the model were sized for a minimum droop value of 13% (the tuning of the governor during the dynamic validation of the reference power system yielded a droop value of 13%). To allow for exploring the performance of the system with lower droop percentages, the ratings of the synchronous generators were increased by 500 MW.

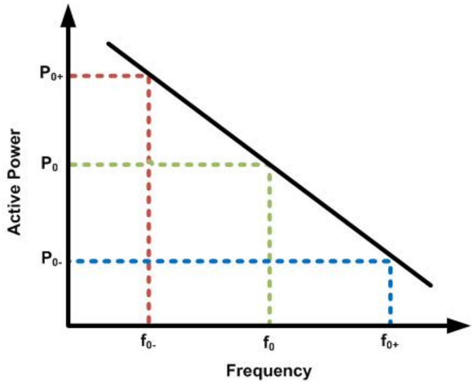
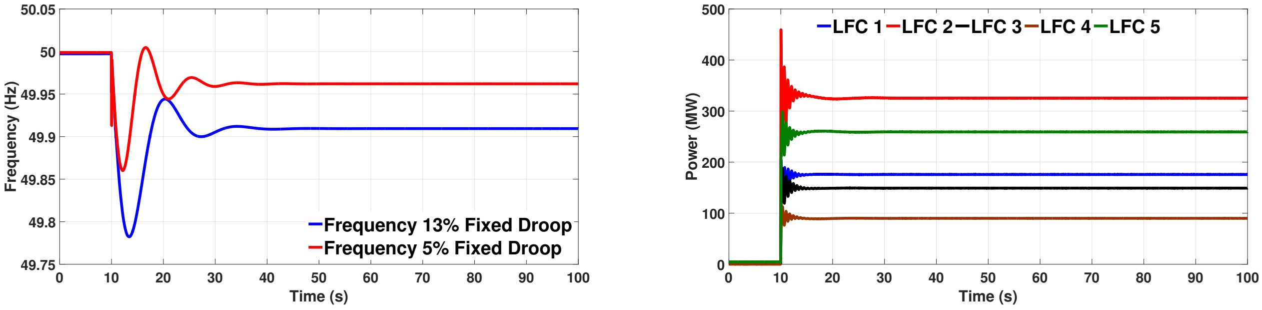
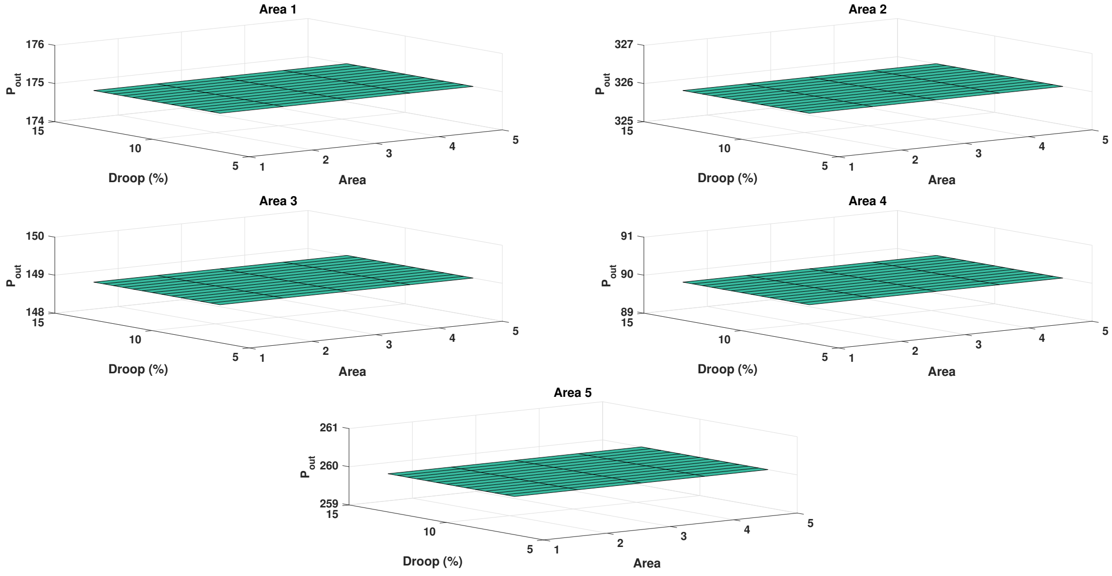


Fig. 2: Example conventional droop curve.



(a) Frequency.

(b) PFC response.



(c) Individual LFC areas' contribution to PFC.

Fig. 3: System PFC response to 1000 MW generation loss.

III. CONVENTIONAL PRIMARY FREQUENCY CONTROL

A. *Theory*

The objective of PFC is to contain the frequency upon occurrence of load-generation imbalance. PFC response is provided in the first few seconds following a frequency change and is maintained until it is replaced by SFC action. PFC operates based on a droop curve (as shown in Fig. 2) that defines the relation between the measured frequency and the power output of resources participating in PFC. The fall or rise in frequency is arrested by means of increasing or decreasing the active power output of resources participating in PFC. This change in active power is based on defined droop characteristic represented as

$$P_{out} = P_0 + \frac{1}{R}\left(f_0 - f_{meas}\right) \tag{1}$$

where P_{out} is the active power output set-point of the participating resource, P_0 is the power set-point at nominal frequency f_0, f_{meas} is the measured frequency and R is the droop gain. In synchronous power systems, PFC is designed such that each Load Frequency Control (LFC) area responds proportionally to its capacity based on the droop slope set by the system operator. As can be observed from Fig. 2, when there is a decrease in system frequency from f_0 to f_{0-}, the power output set-point of the LFC areas increases from P_0 to P_{0+}. Similarly when the system frequency increases from f_0 to f_{0+}, the power output set-point of the LFC areas decreases from P_0 to P_{0-}.

B. *Analysis of Responsibilization Capability*

To analyze the responsibilization capability of conventional PFC, consider the response of the system to 1000 MW imbalance (net generation loss, referred to as reference event henceforth) within LFC area 2 for two values of droop gain: 5% and 13% (for all the LFC areas), shown in Fig. 3.

As can be observed from Fig. 3a, with no SFC response, the frequency settles at a new steady state value after the imbalance. In accordance with droop response, the frequency settles at two different values for the two different droop gains utilized. A 5% droop gain corresponds to a higher PFC response and therefore the frequency settles at a higher value than compared to that with a droop gain of 13%. However, it should be noted that although two different values of droop gains have been utilized, for a disturbance of reference magnitude, the contribution of active power from each of the LFC areas remains the same and proportional to the capacity of individual LFC areas as shown in Fig. 3b. For further evaluation, reference magnitude imbalance is emulated in each of the LFC areas individually with a variation in droop gain from 13% to 5%. The droop is varied in steps of 1% for all the LFC areas, i.e, if the droop value is 6%, it is 6% for all the LFC areas. The increase in power output of individual LFC areas, i.e., the PFC response of each LFC area, is presented in Fig. 3c. As can be observed, irrespective of the location of the imbalance event or the value of droop gain chosen (as long as it is the same for each area), the PFC response of each LFC area remains the same, i.e., proportional to the capacity of the LFC area.

From the analysis presented above, it can therefore be inferred that there is no inherent responsibilization within the conventional PFC as there is in conventional SFC.

IV. RESPONSIBILIZING PRIMARY FREQUENCY CONTROL

In this section, the alternative novel decentralized PFC as proposed in [4], where responsibilization is achieved by means of measuring the TPO within each of the LFC areas is briefly presented. This is followed by an analysis of its responsibilization capability.

A. *Fast Event Location Detection by Transient Phase Offset*

Any sudden imbalance between generator mechanical power and load leads to a perceived change in frequency, in high or low inertia systems, due to the changing phase angles across network impedances, as active power flows change. The local Rate of Change of Frequency ($RoCoF$) in response is an estimate of local double derivative of the phase angle ϕ over the window T, obtainable by:

$$f = \frac{d\phi}{dt} \tag{2}$$

$$RoCoF = \frac{df}{dt} = \frac{1}{360}\left(\frac{d}{dt}\left(\frac{d\phi}{dt}\right)\right) = \frac{1}{360}\left(\frac{d^2\phi}{dt^2}\right) \tag{3}$$

The TPO of a system relative to a stable frequency can be estimated as [5]:

$$\phi_o = 360\int\left(\int(RoCoF\cdot dt)\right)\cdot dt = 180\cdot RoCoF\cdot t^2 \tag{4}$$

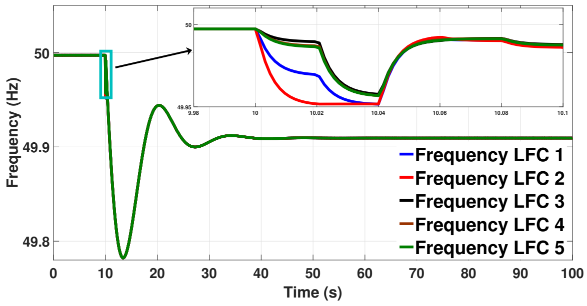
In Equation 4, the local deviations of phase are estimated from a linear phase ramp by means of extrapolation from pre-event values. The double differentiation allows for removal of any pre-event non-zero values of phase and frequency and allows for reconstruction of true local phase deviation by double integration.

The TPO when measured upon occurrence of an event is larger geographically closer to the event than further away. Therefore, in synchronous power systems that are divided into a number of LFC areas, a local TPO measurement can quickly and autonomously indicate if an area should contribute more PFC response than other areas. To illustrate this further, consider the response of reference power system subject to reference magnitude loss of generation in LFC area 2 presented in Fig. 4. One frequency measurement is taken in each of the LFC areas, and Fig. 4b shows that the observed TPO is the largest in LFC area 2. In a similar manner, the next largest observed TPO is for LFC area 1 that is next closest to the event (Fig. 1).

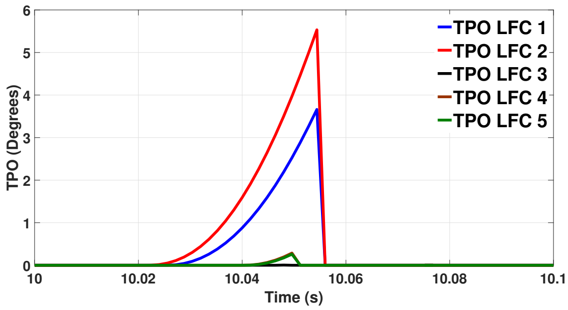
B. *TPO based Responsibilization*

Having the event detection explained, it is important to design a droop curve that would work based on TPO and introduces responsibilization. The droop curve for the proposed control is presented in Fig. 4c and is designed as follows:

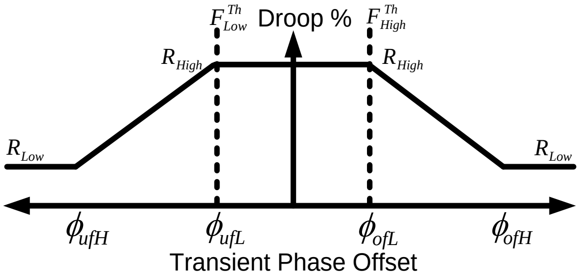
1) the lower and higher frequency thresholds beyond which the droop is adaptive are defined as F^{Th}_{Low} and F^{Th}_{High}



(a) Frequency.

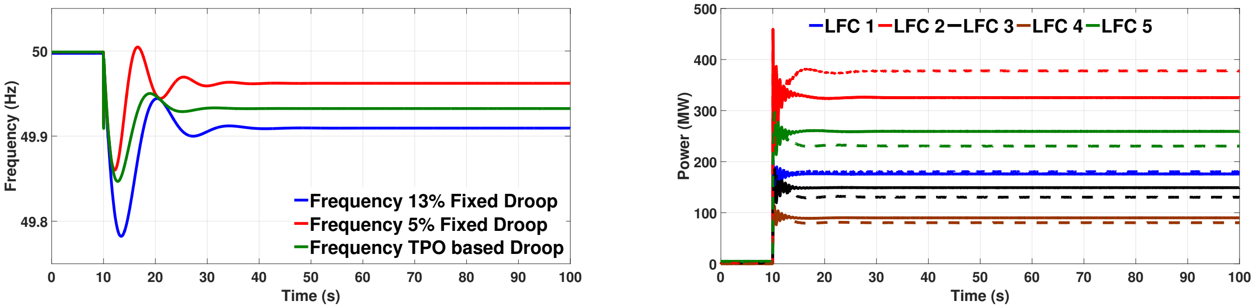


(b) TPO.



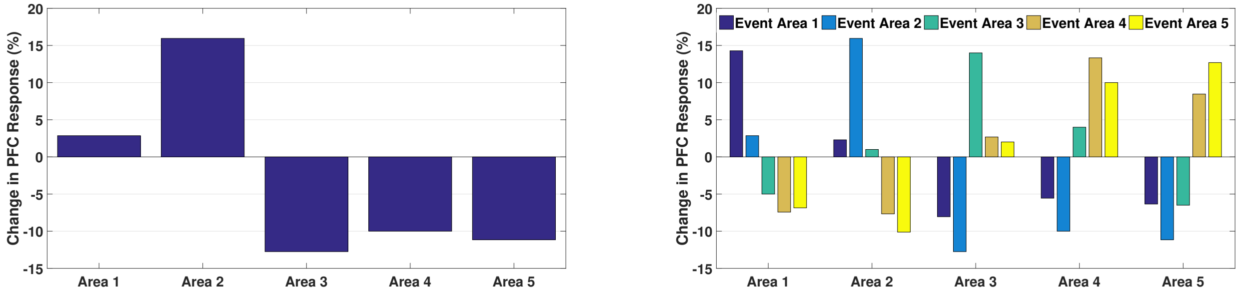
(c) Proposed droop curve for primary frequency control.

Fig. 4: System Response to 1000 MW Generation Loss.



(a) Frequency response.

(b) PFC response comparison.



(c) Percentage change in PFC response.

(d) Change in PFC response for events in individual LFC areas

Fig. 5: System Response to 1000 MW Generation Loss.

respectively

2) the lower and the higher droop percentages are defined as R_{Low} and R_{High} respectively

3) the smallest and largest event size accommodated within this design are defined as P_{Low} and P_{High} respectively

4) the TPO thresholds (ϕ_{Uf}^{Th} for under frequency events and ϕ_{Of}^{Th} for over frequency events) are then determined as:

$$\phi_{Uf}^{Th} = \begin{cases} \phi_{ufL} = \dfrac{\sum_{i=1}^{n} \phi_o^i}{n} & , \quad P_{Low}^{+} \\ \phi_{ufH} = \dfrac{\sum_{i=1}^{n} \phi_o^i}{n} & , \quad P_{High}^{+} \end{cases} \tag{5}$$

$$\phi_{Of}^{Th} = \begin{cases} \phi_{ofL} = \dfrac{\sum_{i=1}^{n} \phi_o^i}{n} & , \quad P_{Low}^{-} \\ \phi_{ofH} = \dfrac{\sum_{i=1}^{n} \phi_o^i}{n} & , \quad P_{High}^{-} \end{cases} \tag{6}$$

where n is the total number of LFC areas, ϕ_o^i is the TPO observed in LFC area i with an event of defined size. P^{+} indicates an increase in net load and P^{-} a decrease. Therefore, the TPO is continuously monitored within all the LFC areas and upon occurrence of an event that causes a deviation in frequency beyond F_{Low}^{Th} or F_{High}^{Th}, the droop value based on the observed TPO is utilized. This value of droop is latched until the frequency of the system is restored within the error margin (ε) defined. An increase in droop percentage corresponds to a decrease in response.

C. Analysis of Responsibilization Capability

To analyze the responsibilization capability of the decentralized responsibilizing PFC, the system is subject to loss of generation of reference magnitude. In addition, its responsibilization capability is compared to that of conventional PFC. To aid the assessment, one key indicator, Percentage Change in Primary Frequency Control Response (ΔP_{PFC}), is defined. ΔP_{PFC} is the percentage change (increase or decrease) in PFC response of individual LFC area subject to an imbalance event compared to that of conventional PFC approach where fixed droops for all LFC areas are utilized and can be calculated as:

$$\Delta P_{PFC} = \frac{\Delta P_{PPFC} - \Delta P_{CPFC}}{\Delta P_{CPFC}} \cdot 100\% \tag{7}$$

where ΔP_{PPFC} is the PFC response with proposed PFC and ΔP_{CPFC} is the PFC response with conventional PFC. The parameter of the control remain the same as in [4].

The system response subject to reference magnitude generation loss at t=10s is presented in Fig. 5. The system frequency response is shown in Fig. 5a to be stable and between fixed droop response of R_{Low} and R_{High}. The PFC response, i.e., the active power contribution of each LFC, is presented in Fig. 5b. The solid line represents the system response with fixed droop and the dotted line represents system response with the proposed control. LFC area 2 increases its PFC response contribution to the event, demonstrating greater responsibilization. In a similar manner, LFC area 1 (that is next closest to the imbalance event) increases its PFC response while all the other LFC areas decrease their PFC response. The percentage change in PFC response of all the areas is shown in Fig. 5c.

To further evaluate the performance of the proposed control and to demonstrate its applicability, the imbalance event is emulated in each of the LFC areas individually. The change in PFC response of each LFC area for the above scenarios are shown in Fig. 5d. Within a synchronous area $\mathcal{A}$ and for an area under consideration i, defining the neighborhood as $\mathcal{NH}_i = \{i, \mathcal{AN}_i\} \subseteq \mathcal{A}$, with $j \in \mathcal{AN}_i$ as adjacent areas coupled over tie-lines with breaker state δ_{ij}, it can be observed that for an event in area i, in most cases there is increase in PFC response from $\{i, j\}$ and a decrease from $\{\mathcal{A} - \mathcal{NH}_i\}$.

D. Comparison with Centralized Approach

This section presents a qualitative comparison of the proposed approach with the centralized approach presented in [10]. Responsibilizing approaches need to be fast acting, within the first second of the disturbance to contribute towards frequency stability as has been highlighted in [15]. When centralized approach, as in [10], is employed, the values of adapted droop need to be communicated to the participating devices within the network. This would entail communications delay that needs to be taken into consideration. The performance of the communications networks that connects a control centre to the end devices for demand side applications has been analyzed in [16] and the results show that the latency expected is between 1-4.5 seconds. As is evident, unless more dedicated communications are deployed that can guarantee latency under a second, the centralized approach will not effectively contribute towards frequency stability. The proposed decentralized approach does not rely on communications and therefore responds as soon as the event has been detected. In this work, conventional generators have been utilized, however, the use of faster acting devices such as energy storage systems would further improve the performance of the proposed control.

V. CONCLUSIONS

In this paper, first, an analysis of responsibilization capability of conventional PFC is presented. It has been shown that the conventional PFC does not exhibit any responsibilization, contrary to conventional SFC where responsibilization is inherent. This is followed by analysis of responsibilization within a decentralized responsibilizing PFC. The control achieves responsibilization by means of fast and autonomous event detection and droop adaptation of LFC areas in real-time. The droops of LFC areas are adapted based on a bilinear droop curve with a dead-band. Simulation results show that the droop curve enables effective responsibilization, where the PFC response of areas closer to the imbalance event is increased. This work presents a stepping stone towards greater decentralization and distributed operation of power systems, supporting and enabling future power system architectures such as the Web-of-Cells [17]. Future work includes the exploration of further observables that would allow for faster responsibilization, to develop and incorporate wide area knowledge for a more coordinated response where necessary.

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