

# Grid-Scale Virtual Energy Storage to Advance Renewable Energy Penetration

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**Abstract**—It is now widely recognized that energy storage enables increased integration of renewable resources. One of the uses of storage is to provide synthetic inertia, making up for some of the inertia lost from displaced conventional generation, thereby maintaining frequency stability. However, energy storage systems continue to be very expensive, and this motivates the development of innovative approaches to mitigate some of the challenges posed by renewable resources. This paper presents a novel method called “grid-scale virtual energy storage” that harvests free energy storage from properties inherent to control of multi-area power systems, thereby increasing the amount of renewable generation that a system can tolerate before its frequency stability is compromised. The concept of virtual energy storage proposed here is based on the surplus of necessary energy that is required to restore the system frequency to within a safe range of the nominal frequency. In a dynamic sense, virtual energy storage is very responsive and is not limited by the operation time and capacity. Moreover, it can be exchanged easily among control areas and does not require installation and implementation expenses as it takes advantage of the existing diversity of area control errors in interconnected systems and employs an appropriate frequency control method. It also helps in reducing the reserve requirement, regulation capacity, transmission loading, and wear and tear on power system by functioning as normal energy storage. In this paper, the proposed new approach is explained mathematically, and its operation is analyzed using a mathematical model and simulation in order to validate its effectiveness.

**Index Terms**—Area control error, frequency regulation, frequency drift, grid scale virtual energy storage, interconnected system, load frequency control, renewable energy.

## I. INTRODUCTION

For decades, researchers have been interested in renewable energy resources (RERs) due to their environmental benefits and abundant supply [1], [2]. With recent technological advances in this area, the leveled cost of renewable energy production is becoming economically competitive with that of conventional technologies. According to a report [3] from the Agency International Renewable Energy Agency, RERs will contribute a significant portion to the total electricity generated in the coming years. With 26.2% of global energy consumption in 2018 came from RE, it is expected that the contribution of RERs will reach 45% by 2040 [4]. The International Energy Agency also predicts that RERs will become the largest sector of energy generation and will provide one-third of total energy demand worldwide by 2025 [5]. However, there are challenges associated with integrating RERs into the grid that need to be addressed in order to meet these objectives. The variability of most RERs creates several operational challenges that are well

understood. Other challenges with RER integration include reduced system inertia [6], [7], frequency regulation capacity [8], [9], transmission capacity violation [10], [11], reserve requirement [12], [13], voltage instability [14], [15], and small signal instability [16], [17].

To resolve the issues associated with RERs, many solutions have been applied such as energy storage [18], [19], virtual synchronous generator [20], virtual energy storage system [21], improved control of ESS [22], [23], advanced RER control strategies [24], [25], and advanced power electronic interfaces [26], [27]. Besides, coordination among control areas [28], RER prediction improvement [29], [30], seasonal diversity between RERs [31], the diversification of RERs [32], [33] and locations [34], [35] are among other solutions for RER integration. Among these solutions, energy storage, when equipped with a speedy response and high storage capacity [36], [37], is strongly capable of alleviating power instability. This makes it well suited for assisting with integration of RERs into the main grid. However, the installation of energy storage is expensive even though energy storage devices are constantly improving and becoming more affordable. To counter this economic drawback while retaining favorable features of energy storage, [28] has introduced a novel concept called “virtual energy storage”. This concept provides an innovative operation method for power systems by allowing period power to be freely exchanged among balancing authorities. Period power, which is the difference between the scheduled interchange and the constant schedule of control areas, is omitted from area control errors to create a reduction in regulation of the whole system. Hence, period power is considered “virtual energy” and each balancing authority is called “virtual energy storage”. To further expand the idea of “virtual energy”, this paper proposes a new concept called “grid-scale virtual energy storage”, which is based on the regulation of system frequency and the coordination of control areas. The fundamental concept is the combination of frequency drift within a safe specified limit and the diversity of area control error (ACE) in order to create virtual storage among control areas. The surplus of necessary energy to recover the frequency to nominal value to the required energy to bring the frequency back to the safe limits is the “virtual energy” that is “stored” in each control area. If the frequency deviates above the upper limit, the control areas are considered to be “charging” with virtual energy. Otherwise, the control areas are considered to be “discharging” virtual energy. This method does not require capital investment in storage devices and implementation. Moreover, as will be presented later in the paper, this method effectively reduces the amount of regulation for all control areas when the system is subjected to disturbances. The main difference between the concept of “virtual energy” in this

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work and the one in [28] is the nature of “virtual energy”. In [28] “virtual energy” is period power (which is related to the first term of ACE, i.e., the interchange differential), while in this paper, “virtual energy” is created by the deviation of actual frequency from its nominal value (which is related to the second term of ACE). The proposed operation of “virtual energy storage” that takes advantage of frequency deviation relaxation has never been presented in the previous works in literature. Four main contributions of this paper are as follows:

- The proposed “virtual energy storage” is not physical energy storage but a “virtual” form of energy storage based on the improved operating strategy of control areas that takes advantage of the existing diversity of area control errors in interconnected systems and employs an appropriate frequency control method. The importance of the proposed method is justified in the context of increasing distributed generation (especially RERs) in modern power systems which causes more random fluctuations in system frequency. “Virtual energy storage” supports power systems in responding to the disturbances and controlling frequency and therefore assists the system in advancing RER integration.
- The proposed “virtual energy storage” does not require any investment or installation on physical energy storage. Hence, “virtual energy storage” eliminates the expense of physical ESS as it requires no cost. Moreover, in the dynamic sense, physical ESS is not as responsive as “virtual energy storage” due to the limit of charging/discharging time and available capacity. However, the proposed “virtual energy storage” is very responsive and is not limited by the time and capacity. Moreover, due to the diversity of oscillations, “virtual energy storage” can be exchanged easily among control areas without any expense.
- The proposed “virtual energy storage” assists the system not only in reducing the cost associated with physical ESS but also effectively reducing the amount of regulation for all control areas when the system is subjected to disturbances. Hence, it helps in reducing the reserve requirement, regulation capacity, transmission expansion, and wear and tear on power system by functioning similar to normal energy storage. This in turn supports the economic operation of the systems.
- The proposed “virtual energy storage” has the advantage of not creating any negative impacts on the stability of system frequency compared to normal operation of load frequency control without the proposed virtual energy storage.
- The proposed “virtual energy storage” is controlled completely on the operators’ side, not on the client side as other approaches to “virtual energy storage” presented in the literature. This is the main difference of our proposed “virtual energy storage” in this paper.

This work proposes a means of harvesting free storage at a time when physical storage is very expensive. The free storage is harvested by exploiting features already present in existing systems. The means of such exploitation is brought

out through the development presented in the paper. The remainder of this paper is organized as follows. Section II explains the fundamentals of grid scale virtual energy storage (VES) and its mathematical formulation. Section III presents a fully-constituted control model with grid scale VES of one-area power generating unit. Simulation results and conclusion, potential challenges in realizing grid scale VES are covered in Section IV and V, respectively.

## II. GRID SCALE VIRTUAL ENERGY STORAGE

### A. Review of virtual energy storage methods

Application of virtual energy storage has been proposed in many previous works in literature. VES formed by heating ventilation and air conditioning was proposed for frequency service in [38]–[40]. The work in [41] also develops VES based on coordinating multiple groups of aggregated air-conditioner loads to manage distribution network loading. Similarly, the authors in [42], [43] have developed VES concept by utilizing the heat storage capability of the building and distributed electric loads with thermal storage where loads are treated as thermal cells. In [44], [45], operation of aggregated electric vehicles is modeled as VES for ancillary services in distribution grid. VES can also be results of the spatio-temporal coordination of hydropower as shown in [46]. To improve energy efficiency, a silo and the coal train are integrated into the operation scheduling of the conveyor belt to model VES [47]. The ability to control electric-driven water facilities as VES for renewable energy management to reduce ESS requirement was presented in [48].

Besides frequency control support, VES has been applied to support voltage stability. The work in [49] adjusts controllable loads including air conditioning loads and electric vehicles jointly and refers this as VES. Authors in [50] propose a hierarchical dispatch strategy for VES to support voltage stability of the low voltage grids with high RER integration with two control levels: VES are managed by the aggregators at lower level and aggregators are managed by the system at the upper level based on control objective. In [51], distributed real-time power management for VES using dynamic price to support voltage stability is presented.

In addition, VES has been shown to be effective in supporting integration of RERs. In [52], [53], VES using smart demand response management to mitigate the fluctuation of RERs. The operating revenue is set up as the objective, which includes operating cost and revenue, the unpredictable feature and cost of RERs [54].

In other works, controlling of ESS and VES can be coordinated to obtain maximum benefit and increase efficiency [39], [55]. This control strategy is also utilized to support the distribution network voltage to promote distributed generation installation [56]. In [21], [57], VES was developed based on coordination of demand response from conventional flywheel ESS and domestic refrigerators to support frequency response. These units are coordinated to support system frequency and at the same time minimize the charging/discharging cycles of VES. The authors in [51] have developed flexible VES that consists of battery energy storage system, flexible loads,

inflexible loads as well as RERs with the objective of optimal operation cost.

Besides, many research works have focused on improving the control strategy of demand response based VES to support frequency stability. A coordinated control strategy for the VES in [58] proposes an algorithm to enable ancillary frequency regulation services by grouping multiple aggregated VESs which are composed of thermostatic loads. The distributed model predictive control is developed so that VES can support primary frequency regulation with the constraints of switching time and indoor temperature. In [59], a model to enable virtual storage sharing among a group of users was proposed. A storage aggregator controls the central ESS by dividing it to separable virtual capacities and sells them to users.

Although various VES models have been investigated, most of the published research focuses on the demand response, especially thermal demands, management aspects of the consumption. VES is developed mostly based on operation of thermostatically controlled loads (air conditioners, refrigerators, heat pumps etc) and electric vehicles. In this paper, we propose a new control strategy that allows VES to support frequency control at grid level while reducing the stress on system regulation based on frequency drift, not demand response. Therefore, our proposed VES is based on the control of supply side. This distinguishes the proposed work in this paper from other methods in literature.

### B. Proposed virtual energy storage

Frequency is considered one of the principal indicators of stability in power systems. Frequency is maintained at a scheduled value (60 Hz in the US for example) in the long term by balancing generation and load. This nominal frequency has been accepted and enacted strictly since the 1930s. The NERC has prescribed bounds and established standards for frequency deviation and area control error and these are still in effect. However, the increasing penetration of renewable resources with low inertia poses challenges with frequency stability. To assist the penetration of RE, consolidation of balancing authorities, which increases the system rotational storage capacity, has been implemented increasingly in recent years. An alternative approach to support RERs is to mitigate its variability. As proposed in [60] a few years ago, the NERC had considered relaxing the frequency deviation standards. Although this has not yet been implemented, it is shown in this work that this could enable increased penetration of renewable resources. This is due to the fact that permitting frequency deviation over a period of time translates to absorption or depletion of rotational kinetic energy in conventional generators, and this would help mitigate the variability of RERs. The relaxation in frequency regulation is important to the establishment of grid scale VES. By allowing the frequency to deviate *slightly* from 60 Hz and by taking advantage of ACE diversity in different control areas, each control area can act as a VES for the others. An example depicted in Fig. 1 is used to illustrate the idea.

When control area 1 experiences a decrease (or increase) in load, the frequency of the interconnected system increases (or

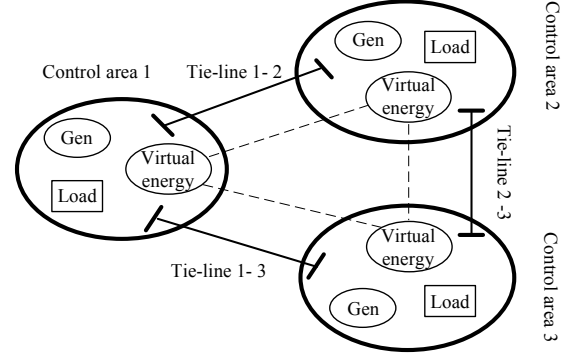


Fig. 1: Grid scale virtual storage in a multi-area system.

decreases). While the traditional regulation would restore the frequency precisely to the nominal value (60 Hz) in all areas, the new concept of slightly drifted frequency suggests that the implemented regulation should only bring the frequency back to a value within the allowed drift range. At the upward (or downward) drifted frequency, all areas will consume more (or less) energy than they do at nominal frequency. The difference between the amount of energy consumed at drifted frequency and at nominal frequency in each area is called the virtual energy area 1 stored in that area. Hence, it is said that the areas other than area 1 charge (or discharge) virtual energy. Such charged (or discharged) energy can be paid back to area 1 during the time when area 1 charges (or discharges) virtual energy for other areas or when other areas discharge (or charge) virtual energy for area 1. Because the difference between generation and demand in one control area can be positive or negative, other control areas that connect to it can charge or discharge virtual energy. This flexibility makes grid scale VES in the interconnected system operate in a more efficient manner.

The new method offers great economical and technical benefits because of the reduction in regulation, transmission, installation cost, ACE and of no cost in VES.

In preparing for the analysis and simulation of grid scale VES in the system, the mathematical model of VES and ACE in one control area is presented below.

Defining  $\epsilon$  as the frequency drift limit of the system, ACE and VES of control area  $i$  can be expressed as:

If  $f_{i,a} - f_{i,s} > \epsilon$ :

$$ACE_i = (P_{i,a}^{tie} - P_{i,s}^{tie}) - B_i(f_{i,a} - f_{i,s} - \epsilon) \quad (1)$$

$$E_i^{virt} = \int B_i \epsilon dt \quad (2)$$

If  $f_{i,a} - f_{i,s} < -\epsilon$ :

$$ACE_i = (P_{i,a}^{tie} - P_{i,s}^{tie}) - B_i(f_{i,a} - f_{i,s} + \epsilon) \quad (3)$$

$$E_i^{virt} = - \int B_i \epsilon dt \quad (4)$$

If  $|f_{i,a} - f_{i,s}| \leq \epsilon$ :

$$ACE_i = (P_{i,a}^{tie} - P_{i,s}^{tie}) \quad (5)$$

$$E_i^{virt} = \int B_i(f_{i,a} - f_{i,s})dt \quad (6)$$

where

- $f_{i,a}$  = the actual frequency of area  $i$
- $f_{i,s}$  = the scheduled (nominal) frequency
- $B_i$  = the frequency bias constant of area  $i$ , in MW/ 0.1 Hz
- $E_i^{virt}$  = virtual energy storage of control area  $i$
- $ACE_i$  = area control error of control area  $i$

These equations indicate that when control area  $i$ 's actual frequency  $f_{i,a}$  is lower (or higher) than the scheduled frequency  $f_{i,s}$ , control area  $i$  discharges (or charges) virtual energy.

Based on the above concept of grid scale VES and its mathematical model, the following section of the paper describes the implementation of load frequency control (LFC) with grid scale VES.

### III. LFC MODEL OF ONE CONTROL AREA WITH GRID SCALE VIRTUAL ENERGY STORAGE

#### A. Frequency regulation procedure

As stated earlier, if there is a difference between generation and demand, the frequency of the power system will experience a disturbance. Once this disturbance happens, the load frequency control will take action to bring the frequency back to the nominal value with the assistance of various resources. The LFC action consists of four main stages [61]: Inertial response, Primary control, Secondary control, and Tertiary control.

- 1) Inertial response: in this stage, the kinetic energy of rotating mass is immediately discharged or absorbed by synchronous generators to resist the change in frequency.
- 2) Primary control: this stage, which is invoked in the first few seconds following the disturbance, relies on governor action and load damping to stabilize the frequency. Once the governors sense the frequency deviation, they regulate the generators' output accordingly by adjusting the prime movers' input. On the other hand, load damping, which is the resultant speed change of motor loads in direct proportion to frequency excursion, helps to resist the frequency disturbance by changing the motor loads' power consumption.
- 3) Secondary control: the purpose of this stage is to further stabilize the frequency after primary control to the nominal value by means of Automatic Generation Control (AGC). AGC consults ACE and economic dispatch in order to determine the most practical output for each generator, then changes governor set points accordingly. This third stage is employed in minutes.
- 4) Tertiary control: this stage is the final level of frequency control. Its purpose is to restore reserve margin used for secondary control after secondary control is completed. The generators are rescheduled for future regulation. Tertiary control is not automatic. It is executed based on request from the grid operators.

Traditionally, LFC manages to regulate frequency deviation to zero at the end. However, in the new method with grid scale VES, the difference between frequency deviation and frequency drift limit would be controlled to zero instead.

#### B. Impact of renewable energy resources on LFC

Despite the intermittent nature of RERs, some types of RER generation have ability to provide partial inertia to support the grid [62], [63] by occupying some advanced control strategies [64]. However, this partial inertia is limited by the available output and the type of RER generators. When RERs gradually replace conventional generators, the total system inertia reduces while the equivalent regulation constant increases [6]. This leads to a reduction in the area frequency response characteristic. If the partial inertia that RERs can contribute to the grid is  $r_w$ , the reduction of inertia due to the replacement of conventional generation is  $r_r$ , the new inertia constant is determined as follows [6]:

$$H_i = H_{old,i}(1 + r_w - r_r) \quad (7)$$

Due to the presence of RERs, the equivalent regulation constant is also affected:

$$R_i = \frac{R_{old,i}}{1 + r_w - r_r} \quad (8)$$

Due to the increase in equivalent regulation constant, the updated area frequency response characteristic is as follows:

$$\beta_i = B_i = \frac{1}{R_{old,i}}(1 + r_w - r_r) + D_i \quad (9)$$

The change in  $R$  and  $\beta$  consequently changes the area control error in the interconnected system:

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i \quad (10)$$

Depending on each scenario of virtual energy storage in Section 2, ACE will be modified accordingly.

#### C. LFC mechanism of one control area with grid scale virtual energy storage

The combination of turbine-governor, rotating mass and load damping with VES is represented in the load frequency control model as shown in Fig. 2 below [65]. The effect of RER intermittency is taken into account by  $\Delta P_L$  based on the assumption that renewable energy is a negative load. The impacts of RERs due to their low inertia are described in subsection IIIB. Also, a dead zone is embedded in the model to allow the frequency to drift. The parameters of the described LFC model are as follows:

$$\begin{aligned} \Delta P_C &= \text{supplementary control} \\ \Delta P_P &= \text{primary control} \\ K(s) &= \text{LFC controller} \\ \Delta P_{load} &= \text{non-frequency-sensitive load change} \\ \Delta P_L &= \text{disturbance} \end{aligned} \quad (11)$$

$$\begin{aligned} T_{ij} &= \text{synchronizing torque coefficient} \\ &\quad \text{between area } i \text{ and area } j \\ H &= \text{equivalent inertia constant} \\ \Delta f &= \text{frequency deviation} \\ D &= \text{load damping constant} \\ GT_{ki} &= \text{turbine-governor} \\ \beta_i &= \text{frequency response characteristic of area } i \end{aligned}$$

$T_g$  = time constant of the governor  
 $T_t$  = time delay of turbine model  
 $\Delta P_{tie,i}$  = total tie-line power exchange between area  $i$  and other areas

$B_i$  = frequency bias factor in area  $i$ .

Assuming that the generators consist of non-reheat turbines and reheat turbines, the turbine-governor dynamic models are represented in equation (12) and (13), respectively [66]:

$$GT_{i\text{non-reheat}}(s) = \frac{1}{1 + T_{t,i}s} \frac{1}{1 + T_{g,i}s} \quad (12)$$

$$GT_{i\text{reheat}}(s) = \frac{1}{1 + T_{t,i}s} \frac{1}{1 + T_{g,i}s} \frac{1 + F_{HF,i}T_{RH,i}s}{1 + T_{RH,i}s} \quad (13)$$

where  $T_{RH}$  is time constant of reheater and  $F_{HF}$  is the fraction of turbine power generated by HP unit. The dynamic models of turbine-governor systems for these two generators are shown in Fig. 3 and Fig. 4 [66] where  $\Delta P_{RH}$  is intermediate reheat power signal.

The state-space of LFC dynamic model for control area  $i$  that includes  $m$  reheat steam turbine generators in the presence of wind power can be presented as follows:

$$\dot{x}_i = \hat{A}_i x_i + \hat{B}_i u_i + \hat{C}_i n_i \quad (14)$$

$$y_i = \hat{D}_i x_i + I m_i \quad (15)$$

where

$$\begin{aligned}
 x_i &= [\Delta f_i \ \Delta P_{ti} \ \Delta P_{gi} \ \Delta P_{tie,i} \ \Delta P_{RH,i}]^T \\
 \Delta P_{ti} &= [\Delta P_{t1i} \ \Delta P_{t2i} \ \cdots \ \Delta P_{tmi}] \\
 \Delta P_{gi} &= [\Delta P_{g1i} \ \Delta P_{g2i} \ \cdots \ \Delta P_{gmi}] \\
 \Delta P_{RH,i} &= [\Delta P_{RH1i} \ \Delta P_{RH2i} \ \cdots \ \Delta P_{RHmi}] \\
 y_i &= [\Delta f_i \ ACE_i]^T \\
 u_i &= [\Delta P_{C1i} \ \Delta P_{C2i} \ \cdots \ \Delta P_{Cmi} \ \epsilon]^T \\
 n_i &= [\Delta P_{Li} \ \sum_{\substack{j=1 \\ j \neq i}}^N T_{ji} \Delta f_j]^T \\
 m_i &= [0 \ -\epsilon \beta]^T
 \end{aligned}$$

Matrices  $\hat{A}_i$ ,  $\hat{B}_i$ ,  $\hat{C}_i$  and  $\hat{D}_i$  of a control area with one reheat steam turbine can be expressed as shown in (16):

$$\hat{A}_i = \begin{pmatrix} \frac{-D_i}{2H_i} & \frac{1}{2H_i} & 0 & \frac{-1}{2H_i} & 0 \\ 0 & \frac{-1}{T_{RH,i}} & \frac{F_{HF,i}T_{RH,i}}{T_{ti}T_{RH,i}} & 0 & \frac{T_{ti}-F_{HF,i}T_{RH,i}}{T_{ti}T_{RH,i}} \\ \frac{-1}{R_i T_{gi}} & 0 & \frac{-1}{T_{gi}} & 0 & 0 \\ 2\pi \sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{T_{ti}} & 0 & \frac{-1}{T_{ti}} \end{pmatrix} \quad (16)$$

$\hat{B}_i$  is a matrix with all zero except rows  $(m+2)$  to  $(2m+2)$  which corresponds to  $[\Delta P_{gi1} \ \cdots \ \Delta P_{gim}]$ . Let these nonzero rows be  $B_{i1}$ .

$$\hat{B}_{i1} = \begin{pmatrix} \frac{1}{T_{gi1}} & 0 & \cdots & 0 & 0 & \frac{-1}{R_i T_{gi1}} \\ 0 & \frac{1}{T_{gi2}} & \cdots & 0 & 0 & \frac{-1}{R_i T_{gi2}} \\ \vdots & & & & & \vdots \\ \vdots & & & & & \vdots \\ 0 & 0 & \cdots & 0 & \frac{1}{T_{gim}} & \frac{-1}{R_i T_{gim}} \end{pmatrix}$$

$$\hat{C}_i = \begin{pmatrix} \frac{-1}{2H_i} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -2\pi & 0 \end{pmatrix}^T$$

$$\hat{D}_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \beta_i & 0 & 0 & 1 & 0 \end{pmatrix}$$

The state variables of non-reheat turbine are similar to those of reheat turbine with the difference at the entries corresponding to  $\Delta P_{RH}$  which are omitted. Moreover, the entries corresponding to  $\Delta P_t$  are modified.

When a load disturbance occurs, the resultant frequency deviation will be filtered by the dead zone. That filtered frequency deviation and the tie-line power signal are captured as feedback in control system to generate ACE.

The filtered frequency deviation is determined according to the following mathematical model for the dead zone [67]:

$$u = \begin{cases} 0 & \text{if } -\epsilon \leq \Delta f \leq \epsilon \\ \Delta f - (-\epsilon) & \text{if } \Delta f < -\epsilon \\ \Delta f - \epsilon & \text{if } \Delta f > \epsilon \end{cases} \quad (17)$$

where

$-\epsilon$  = the start of the dead zone (lower limit)  
 $\epsilon$  = the end of the dead zone (upper limit)  
 $u$  = filtered frequency deviation, which is the output signal of the dead zone.

The three cases of filtered frequency deviation  $u$  could be accordingly divided into the following three case studies.

**Case 1:** When  $-\epsilon \leq \Delta f \leq \epsilon$ , the frequency deviation is within the drift limit and the control signal  $u$  equals zero. Therefore, the primary control and part of secondary control have no effect on the system. The diagram of control system turns into Fig. 5 and the frequency deviation can be obtained as:

$$\Delta f_i(s) = \frac{1}{2H_i s + D_i} \left( \sum_{k=1}^m GT_{ki}(s) \Delta P_{Cki}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s) \right) \quad (18)$$

where

$$\begin{aligned}
 \Delta P_{Cki}(s) &= K(s) \Delta P_{tie,i}(s) \alpha_{ki} \\
 K(s) &= \frac{K}{s} \end{aligned} \quad (19)$$

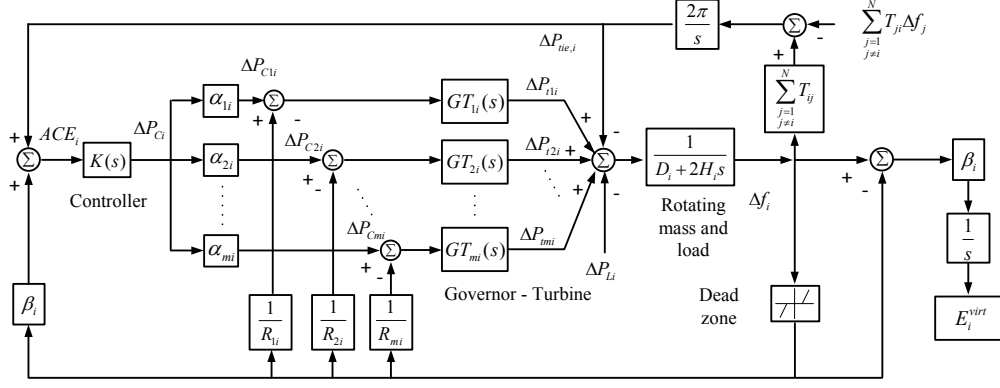


Fig. 2: Control area  $i$  in an interconnected system with grid scale virtual energy storage.

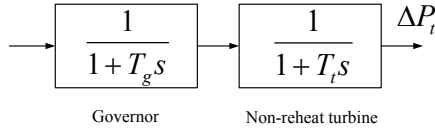


Fig. 3: Block diagram of governor with non-reheat turbine.

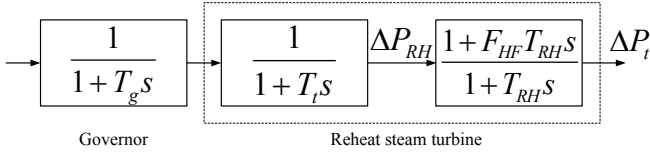


Fig. 4: Block diagram of governor with reheat steam turbine.

After applying equation (19) into (9) and moving  $\Delta f$  to the left hand side, the frequency deviation is given by:

$$\Delta f_i(s) = \frac{\sum_{k=1}^m GT_{ki}(s)K(s)\Delta P_{tie,i}(s)\alpha_{ki} - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_i s + D_i} \quad (20)$$

Final value theorem is employed to yield the steady state value

of the frequency deviation  $\Delta f_{i,ss}$  as in equation (21):

$$\Delta f_{i,ss} = \lim_{s \rightarrow 0} s \Delta f(s) = \lim_{s \rightarrow 0} s \cdot \frac{\sum_{k=1}^m GT_{ki}(s)K(s)\Delta P_{tie,i}(s)\alpha_{ki} - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_i s + D_i} \quad (21)$$

From the assumption that  $\Delta P_{tie,i}(s)$  moves toward zero as the system reaches the steady state, equation (21) turns out to be:

$$\Delta f_{i,ss} = -\frac{\Delta P_{L,i}}{D_i} \quad (22)$$

Equation (22) indicates that for the case when the frequency deviation is within the drift limit, it will be eventually settled to the value  $-\frac{\Delta P_{L,i}}{D_i}$ . The value of VES in this case has already been shown in equation (6).

**Case 2:** When  $\Delta f > \epsilon$ , frequency deviation raises above the drift limit, the control signal  $u$  equals  $\Delta f - \epsilon$ . All three LFC stages are engaged in the frequency control procedure. The system frequency deviation is given by:

$$\Delta f_i(s) = \frac{1}{2H_i s + D_i} \left( \sum_{k=1}^m GT_{ki}(s) [\Delta P_{Cki}(s) - \Delta P_{Pki}(s)] - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s) \right) \quad (23)$$

where

$$\Delta P_{Cki}(s) = K(s)(\Delta P_{tie,i}(s) + B_i(\Delta f_i(s) - \epsilon))\alpha_{ki} \quad (24)$$

$$\Delta P_{Pki}(s) = \frac{\Delta f_i(s) - \epsilon}{R_{ki}} \quad (25)$$

Substituting  $\Delta P_{Cki}(s)$  and  $\Delta P_{Pki}(s)$  by their corresponding right-hand side in (24) and (25), equation (23) can be rewritten into the following form:

$$\Delta f_i(s) - \epsilon = \frac{\sum_{k=1}^m GT_{ki}(s)K(s)\Delta P_{tie,i}(s)\alpha_{ki}}{2H_i s + D_i - \sum_{k=1}^m GT_{ki}(s)K(s)B_i\alpha_{ki} + \frac{\sum_{k=1}^m GT_{ki}(s)}{R_i}} - \frac{\Delta P_{tie,i}(s) + \Delta P_{L,i}(s) + \epsilon(2H_i s + D_i)}{2H_i s + D_i - \sum_{k=1}^m GT_{ki}(s)K(s)B_i\alpha_{ki} + \frac{\sum_{k=1}^m GT_{ki}(s)}{R_i}} \quad (26)$$

Fig. 5: Control area  $i$  in an interconnected system with grid scale virtual energy storage for case 1.

Applying final value theorem as in case 1 to find the steady state value yields the result:

$$(\Delta f_i - \epsilon)_{ss} = \lim_{s \rightarrow 0} s(\Delta f(s) - \epsilon) \quad (27)$$

As stated in case 1,  $\Delta P_{tie,i}(s)$  disappears at steady state, so equation (27) is equivalent to:

$$(\Delta f_i - \epsilon)_{ss} = 0 \quad (28)$$

Therefore:

$$\Delta f_{i,ss} = \epsilon \quad (29)$$

Equation (29) obviously shows that for the case when the frequency deviation exceeds the upper drift limit  $\epsilon$ , it will be finally regulated to that upper drift limit at steady state. The value of VES in this case has already been shown in equation (2).

**Case 3:** When  $\Delta f < -\epsilon$ , the frequency deviation falls below the lower drift limit, the control signal  $u$  equals  $\Delta f + \epsilon$ . This case is symmetric to case 2. A calculation similar to that in case 2 yields the frequency deviation at steady state:

$$\Delta f_{i,ss} = -\epsilon \quad (30)$$

The value of VES in this case has already been shown in equation (4).

In short, equation (31) summarizes the value of the system frequency at steady state under the regulation of the LFC model with grid scale VES:

$$\Delta f_{i,ss} = \begin{cases} -\frac{\Delta P_{L,i}}{D_i} & \text{if } -\epsilon \leq \Delta f \leq \epsilon \\ -\epsilon & \text{if } \Delta f < -\epsilon \\ \epsilon & \text{if } \Delta f > \epsilon \end{cases} \quad (31)$$

Based on the above theoretical analysis, a simulation model is implemented in section IV to evaluate the effectiveness of the proposed grid scale VES.

Dynamic stability of frequency in the presence of VER is analyzed based on sensitivity analysis to reduce the order of system equations. A low-order system frequency response was developed by Anderson in [68]. In this low-order frequency response model, it is assumed that the reheated steam turbine dominates the system. Anderson has shown that the most significant time constant in frequency response of reheat turbine is the reheater time constant  $T_{RH}$  which dominates the response of the largest fraction of turbine power output. The second dominant time constant is the inertia constant  $H$ . Moreover, inertia is doubled and that strengthens its impact. The third dominant constant is the regulation constant  $R$  that plays the role as a gain in the control model. Anderson also showed that the nature of the response to a variation in either  $\Delta P_L$  or  $\Delta P_C$  (supplementary control), is of the same form, but of different sign and phase [68]. These analyses led to the reduced order control model of LFC as shown in Fig. 6 below [68]. Applying VES, a filter is implemented in the feedback loop as shown in the dashed box in the figure.

Additionally, a sensitivity analysis in [69] using linear curve-fitting technique was implemented to shown how sensitive frequency deviation is to the change of governor parameters for the low-order LFC model presented by Anderson. The results of sensitivity is shown in the Table I below [69].

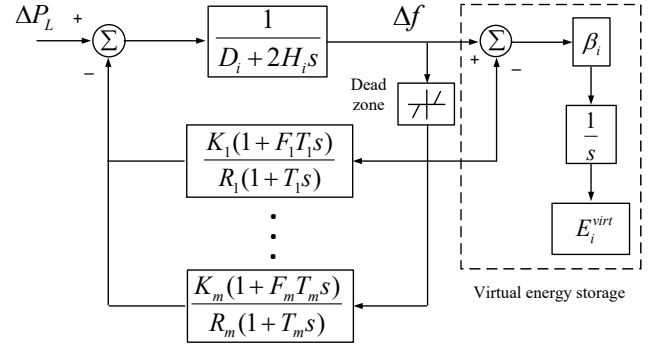


Fig. 6: Multi-machine LFC model [68], [69].

TABLE I: Sensitivity of frequency nadir to governor parameters

| Parameters  | $T_{RH}$ | $H$  | $F_H$ | $D$  | $R$   |
|-------------|----------|------|-------|------|-------|
| Min         | 4        | 3    | 0.1   | 0    | 0.03  |
| Max         | 11       | 9    | 0.35  | 2    | 0.08  |
| Sensitivity | -0.01    | 0.03 | 1.35  | 0.05 | -9.14 |

The table shows that the sensitivity of frequency deviation to the governor time constant is very small. Therefore, it is reasonable to assume that the governor time constants for the system governors are identical [69]. The order of frequency response is decreased without significantly compromising the system accuracy.

When applying the proposed VES concept to the reduced control model in Fig. 6, the frequency in equation (26) would be simplified as followed:

$$\Delta f = \frac{\frac{\Delta P_L}{s} + \epsilon \sum_{l=1}^m \frac{K_l(1+F_l T_{RH} s)}{R_l(1+T_{RH} s)}}{D_i + 2H_i s + \sum_{l=1}^m \frac{K_l(1+F_l T_{RH} s)}{R_l(1+T_{RH} s)}} \quad (32)$$

With the assumption that the governor time constants for the system governors are identical, equation (32) can be rewritten as a second-order system:

$$\Delta f = \frac{\Delta P_L(1 + T_{RH} s) + \epsilon(R_T + F_T)}{2H_i T_{RH} s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (33)$$

where

$$\omega_n = \sqrt{\frac{1}{2H_i T_{RH}}(D_i + R_T)} \quad (34)$$

$$\zeta = \frac{1}{2} \frac{2H_i + T_{RH}(D_i + F_T)}{\sqrt{2H_i T_{RH}}(D_i + R_T)} \quad (35)$$

$$F_T = \sum_{l=1}^m \frac{K_l F_l}{R_l} \quad (36)$$

$$R_T = \sum_{l=1}^m \frac{K_l}{R_l} \quad (37)$$

The second-order response in equation (33) is a function of  $\zeta$  which is different from zero with two poles  $-\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1}$ . As these two poles belong to quadrants II and III, the frequency deviation will reach the stable condition

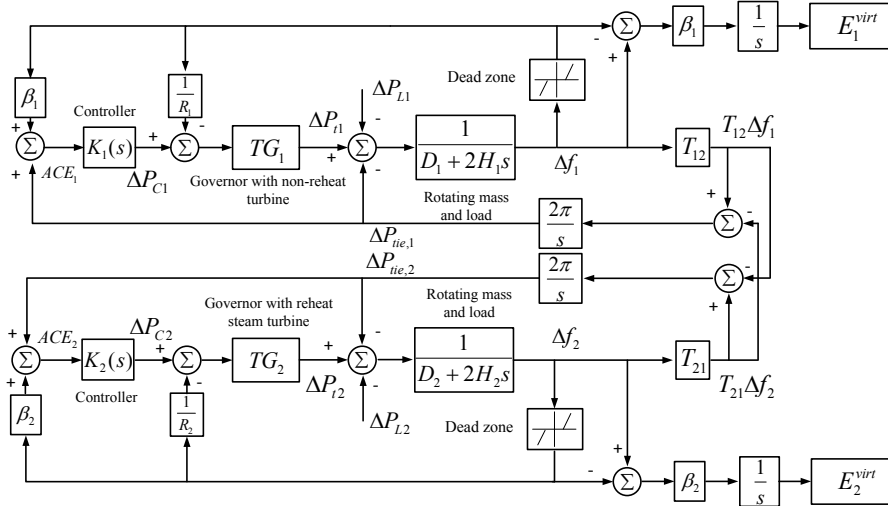


Fig. 7: Two control areas with one non-reheat turbine and one reheat turbine unit.

and the speed of reaching stability depends on  $\zeta$  which is a function of system regulation capability ( $H, D, T_R, F_T, R_T$ ), not a function of  $\epsilon$ . This result, which is based on the reduced order system, is reasonable for equation (26) because the presence of  $\epsilon$  due to the filter in equation (26) in the numerator only impacts its zeros, not the poles. Therefore the filter does not have a detrimental effect on the stability of frequency response. This is another advantage of the proposed method.

#### IV. SIMULATION AND RESULTS

In order to observe the quantitative benefit of grid scale VES to frequency control in multi-area power system, a simulation model that includes two interconnected control areas is developed under the following settings and assumptions:

- The two areas are strongly connected; transmission constraints and losses are ignored.
- One non-reheat turbine and one reheat turbine configuration is employed for area 1 and 2, respectively.
- The LFC model of the studied system is developed as in Fig. 7, where  $\Delta f_1$  and  $\Delta f_2$  are respectively the frequency deviations in area 1 and area 2, in Hz.
- Load disturbance is simulated by a step function. Area 1 is subject to the load disturbance in order to observe the operation of VES in control area 2.
- The parameters of the investigated systems are given in Table II [65], [70]. It is assumed that these parameters have already taken into account the change in inertia, equivalent regulation constant and frequency response characteristic due to the impact of renewable energy integration.

TABLE II: Simulation parameters for two interconnected control areas

| $K$  | $D$<br>(pu/Hz) | $2H$<br>(pu.s) | $R$<br>(Hz/pu) | $T_g$<br>(s) | $T_t$<br>(s) | $B$<br>(pu/Hz) | $T_{ij}$<br>(pu/Hz) | $T_{RH}$<br>(s) | $F_{HP}$ |
|------|----------------|----------------|----------------|--------------|--------------|----------------|---------------------|-----------------|----------|
| -0.3 | 0.015          | 0.167          | 3.00           | 0.08         | 0.4          | 0.348          | 0.2                 | 0               | 0        |
| -0.4 | 0.008          | 0.167          | 2.4            | 0.08         | 0.3          | 0.42           | 0.2                 | 10              | 0.5      |

A dead zone is employed to specify the frequency drift limit between  $-0.05$  Hz and  $0.05$  Hz. This frequency drift limit follows the recommended safe range  $\pm 0.2$  Hz for frequency deviation under normal condition without event disturbance [71], [72].

Three simulation scenarios are developed based on the three case studies described in section III. A fourth scenario that does not employ grid scale VES is also included in the simulation in order to highlight the difference introduced by grid scale VES. The fifth scenario is a combination of all previous scenarios to show the operation of VES in a continuous, quasi-realistic manner.

In the first scenario, the load disturbance in control area 1 is set up in such a way that it yields a frequency deviation within the drift limit of the dead zone. A  $0.001$  pu load disturbance is chosen to produce such outcome. This scenario observes a zero value in control signal  $u$  and no primary control. The frequency deviations, rate of change of frequency (ROCOF), energy that area 1 stores in area 2, and the ACE following the disturbance are shown in Fig. 9, Fig. 10, Fig. 11 and Fig. 12, respectively.

In the second scenario, the load disturbance is arranged so that the resultant frequency deviation is greater than the upper limit of the dead zone. The application of  $-0.03$  pu load disturbance could meet that requirement. The control signal  $u$  is  $\Delta f - \epsilon$  in this case. The frequency deviations, rate of change of frequency (ROCOF), energy that area 1 stores in area 2, and the ACE following the disturbance are respectively depicted in Fig. 13, Fig. 14, Fig. 15 and Fig. 16.

In the third scenario, the arrangement for the load disturbance in control area 1 is opposite to that in the second scenario. The resultant frequency deviation should be smaller than the lower limit of the dead zone and the value of control signal  $u$  is  $\Delta f + \epsilon$ . A load step disturbance of  $0.03$  pu is employed. The frequency deviations, ROCOF, energy that area 1 stores in area 2, and ACE following the disturbance are respectively depicted in Fig. 17, Fig. 18, Fig. 19, and Fig. 20.

In the fourth scenario, the dead zone is eliminated from the LFC model while the load disturbance arrangement is the same

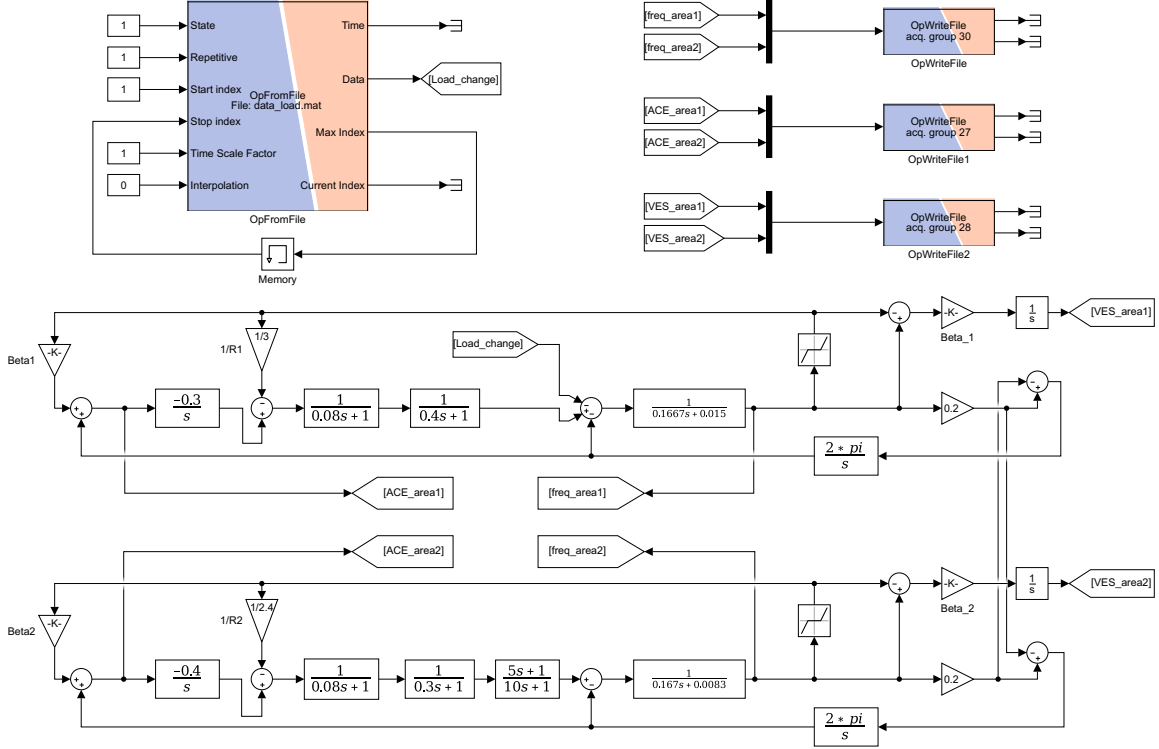


Fig. 8: The real-time simulation model in OPAL-RT for scenario 6.

as in the third scenario. The frequency deviations, ROCOF, and the ACE following the disturbance in control area 1 are shown in Fig. 21, Fig. 22, and Fig. 23 respectively.

In the fifth scenario, the disturbances are random and model the combined variation of load and RER prediction error. For the purpose of simulation, these disturbances take random values in the range  $[-0.03; 0.03]$  p.u and follows a normal distribution [73]. The sampling time of these random disturbances is 30 seconds. The total time of simulation is 8970 seconds (300 samples). The frequency deviations, energy that area 1 stores in area 2, and the ACE following the disturbances in control area 1 are shown in Figs. 24, 25, and 26 respectively. These figures only show the results from 4000 seconds to 5500 seconds for the sake of clarity.

In the sixth scenario, RER integration is performed with three different levels: 0%, 20%, and 30%. Two cases are implemented: a step load disturbance  $-0.03$  pu and random disturbances as in the fifth scenario. For clarity, frequency deviation, energy that area 1 stores in area 2, and the ACE following the disturbance in control area 1 are shown for the step load disturbance but only VES and ACE are shown for the random disturbances.

To provide additional validation, the sixth scenario is also implemented in the real-time simulator in the OPAL real-time simulator (OPAL-RT) as shown in Fig. 8. The software used is the OPAL-RT Linux (x86-based) RT-LAB (workbench) version: 2019.3.0.228 and the simulation is performed in the software synchronized mode. The model is implemented using two blocks, the sc-user interface block, and the sm-

computation block. The waveforms obtained from the real-time simulation were identical to those shown in Figs. 27–31, and are not repeated here.

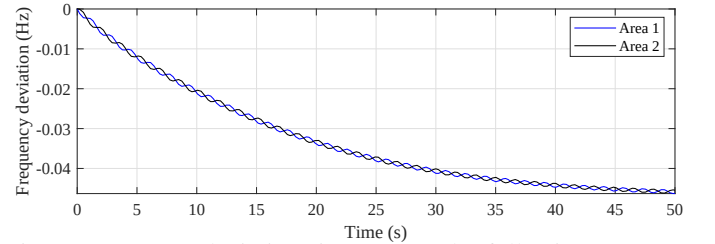


Fig. 9: Frequency deviations in area 1 and 2 following a 0.001 pu load step disturbance in control area 1.

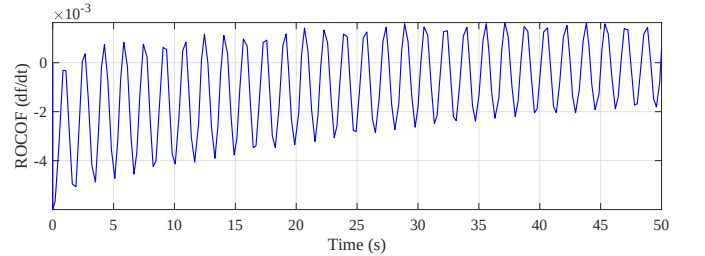


Fig. 10: ROCOF in area 1 following a 0.001 pu load step disturbance in control area 1.

From the graphical simulation results, some observations can be made:

- 1) Following a load disturbance in the control area 1 in the three simulation scenarios with grid scale VES, the

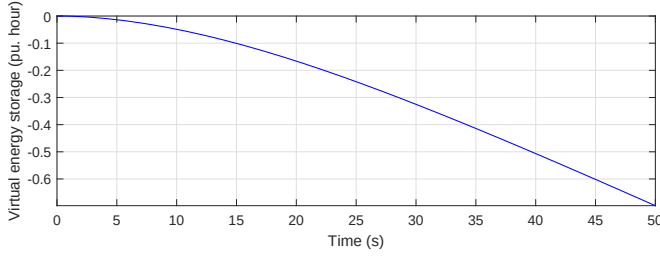


Fig. 11: Energy stored in area 2 following 0.001 pu load step disturbance in control area 1.

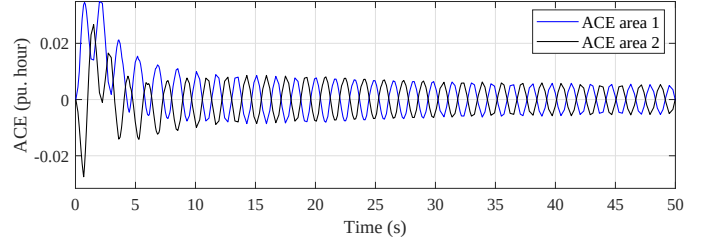


Fig. 16: ACE in area 1 and 2 following a  $-0.03$  pu load step disturbance in control area 1.

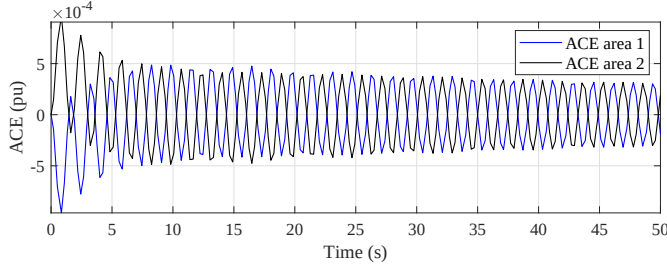


Fig. 12: ACE in area 1 and 2 following a 0.001 pu load step disturbance in control area 1.

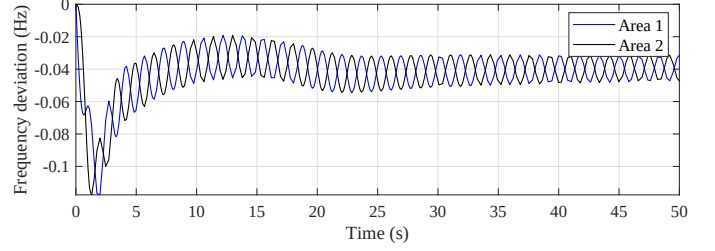


Fig. 17: Frequency deviations following a 0.03 pu load step disturbance in control area 1.

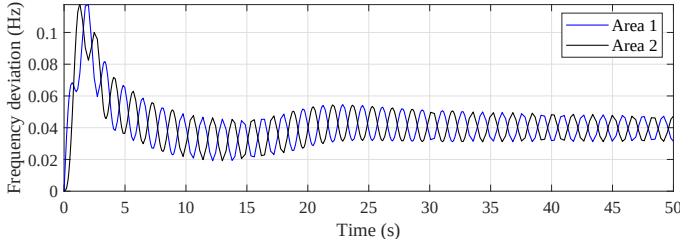


Fig. 13: Frequency deviations following a  $-0.03$  pu load step disturbance in control area 1.

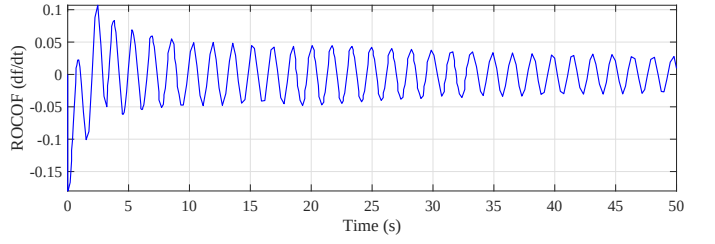


Fig. 18: ROCOF in area 1 following a 0.03 pu load step disturbance in control area 1.

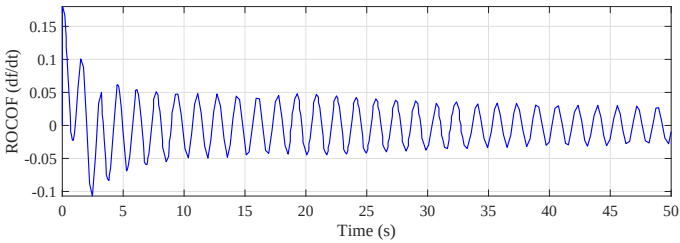


Fig. 14: ROCOF in area 1 following a  $-0.03$  pu load step disturbance in control area 1.

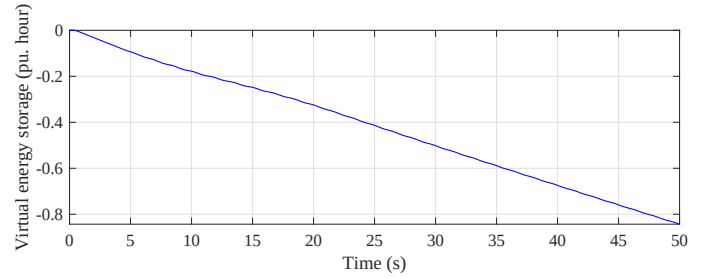


Fig. 19: Energy stored in area 2 following a 0.03 pu load step disturbance in area 1.

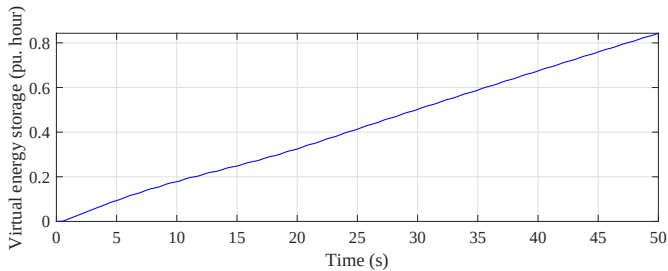


Fig. 15: Energy stored in area 2 following a  $-0.03$  pu load step disturbance in area 1.

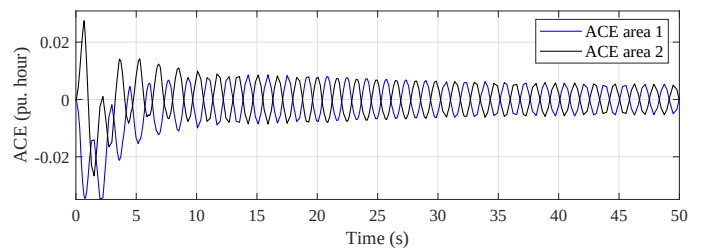


Fig. 20: ACE in area 1 and 2 following a 0.03 pu load step disturbance in control area 1.

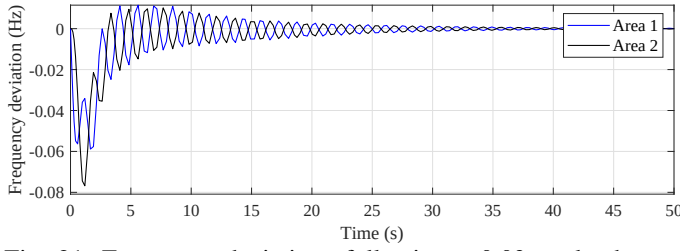


Fig. 21: Frequency deviations following a 0.03 pu load step disturbance in control area 1 without virtual energy storage.

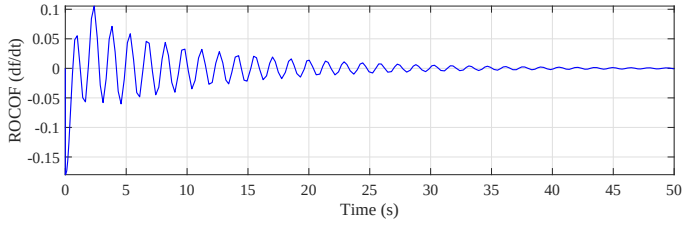


Fig. 22: ROCOF in area 1 following a 0.03 pu load step disturbance in control area 1 without virtual energy storage.

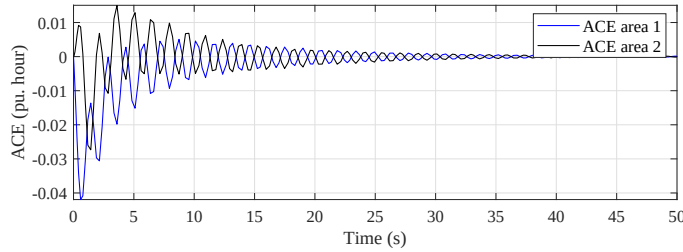


Fig. 23: ACE in area 1 and 2 following a 0.03 pu load step disturbance in control area 1 without virtual energy storage.

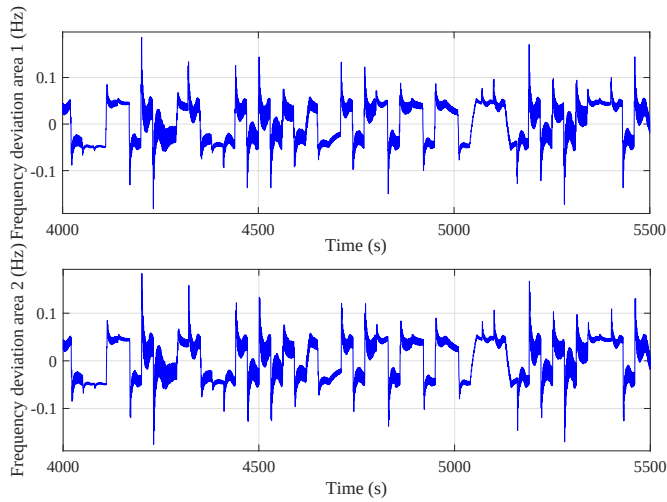


Fig. 24: Frequency deviations in areas 1 and 2 following random load step disturbances in control area 1.

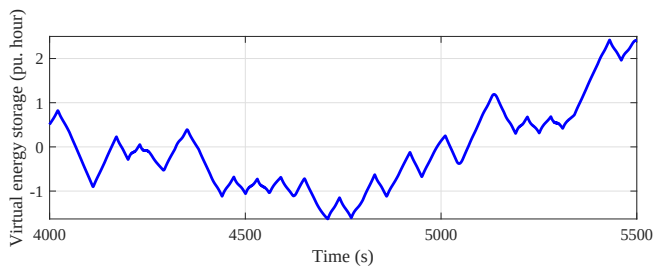


Fig. 25: Energy stored in area 2 following random load step disturbances in control area 1.

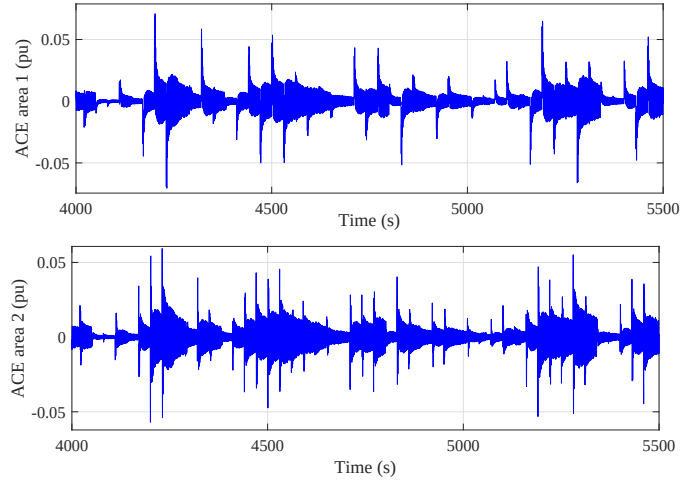


Fig. 26: ACE in areas 1 and 2 following random load step disturbances in control area 1.

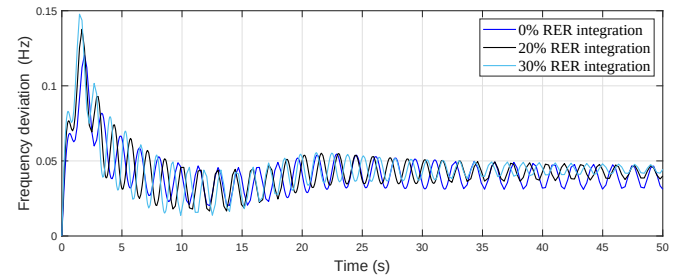


Fig. 27: Frequency deviations in area 1 following -0.03 load step disturbances in control area 1 in the presence of RERs at different integration levels.

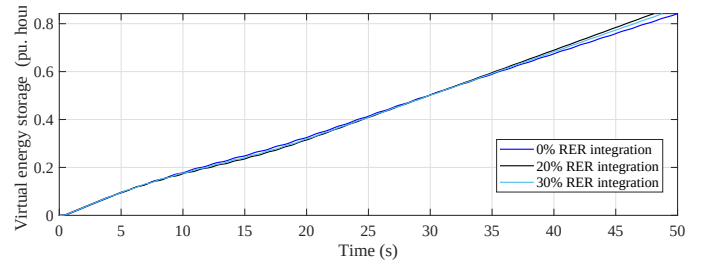


Fig. 28: Energy stored in area 2 following -0.03 load step disturbances in control area 1 in the presence of RERs at different integration levels.

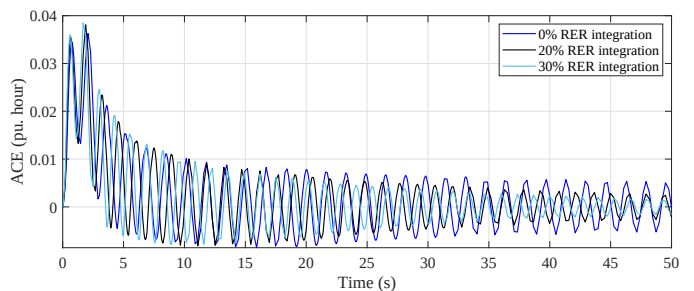


Fig. 29: ACE in area 1 following -0.03 load step disturbances in control area 1 in the presence of RERs at different integration levels.

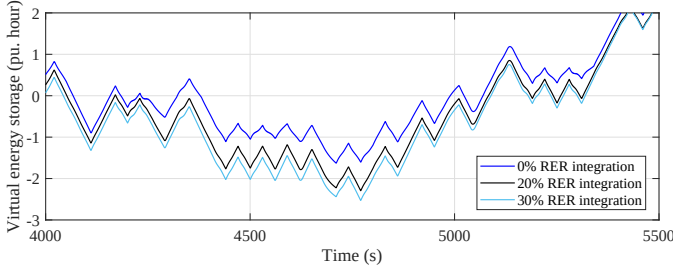


Fig. 30: Energy stored in area 2 following random disturbances in control area 1 in the presence of RERs at different integration levels.

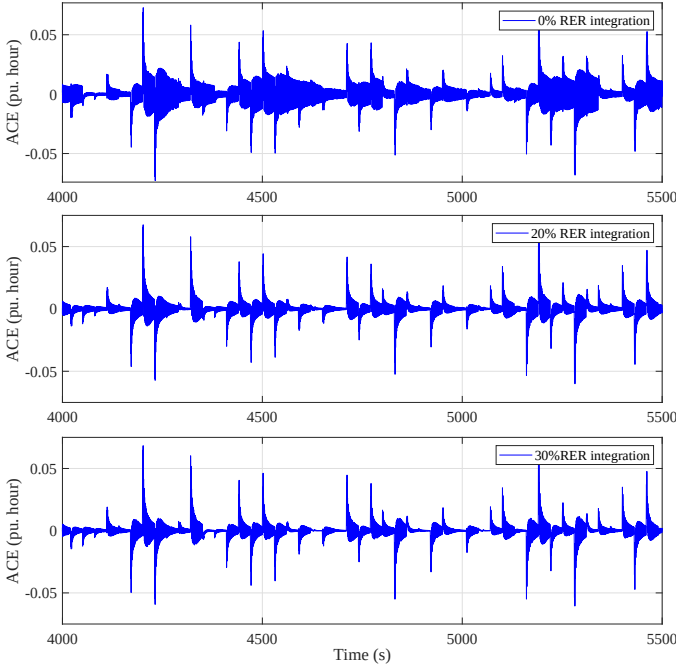


Fig. 31: ACE in area 1 following random disturbances in control area 1 in the presence of RERs at different integration levels.

frequency of the interconnected system experiences a transient instability and returns to the values within the drift limit under the regulation of LFC.

- 2) In the first simulation scenario, none of the control actions was invoked. The system frequency oscillated inside the drift limit until it reached a stable value. Area 2 discharged energy.
- 3) In the second simulation scenario, the frequency of the interconnected system was stabilized at the upper boundary of the frequency drift limit which was above the nominal frequency. As a result, VES in area 2 was positive, implying that area 2 charged virtual energy.
- 4) In the third simulation scenario, the frequency of the interconnected system at the steady state stayed at the lower boundary of the frequency drift limit which was below the nominal frequency. As a consequence, VES in area 2 was negative, indicating that area 2 discharged energy.

- 5) In all three scenarios that utilized grid scale VES, the ACE regulation requirement was markedly less stressful than that in the fourth scenario where the traditional LFC mechanism did not include grid scale VES. This distinction is obvious when observing Figures 16, 20 and 23. The rapid vanishing of ACE signal to sharp zero value in Fig. 23 and the gradual attenuation of ACE signal in Fig. 16 and Fig. 20 verifies that the effort to settle down the ACE spent by the traditional LFC was more intensive than the effort spent by the LFC with grid scale virtual energy. The fourth scenario also shows that the ROCOF does not experience a significant change compared to third scenario.
- 6) The fifth scenario models quasi-realistic operation with both positive and negative step changes in load and RERs. Therefore, the frequency of two control areas increases or decreases from nominal value accordingly. As a result, VES in area 2 is positive (charged) when frequency increases over the upper boundary of the frequency drift limit or negative (discharged) when frequency decreases below the lower boundary of the frequency drift limit or keeps constant otherwise. Area 2 lends area 1 virtual energy when it discharges and area 1 pays back area 2 virtual energy when area 2 charges.
- 7) The sixth scenario shows that the integration of RERs deteriorates the frequency response of the system. However, the presence of VES still reduces the stress for system regulation as shown in results of ACE. These results are consistent with the results from real-time simulation in OPAL-RT simulator.

The flexibility in system frequency at steady state allows an area to borrow virtual energy (e.g. when its demand increases) from other control areas and pay the charged virtual energy back to other control areas (when its demand decreases). This flexibility and significant reduction in ACE regulation requirement explained above are advantages of grid scale virtual energy that enable power system operators to save a considerable investment in reserve, transmission, regulation, wear and tear facilities.

## V. CONCLUSION

This paper presents the concept of grid scale virtual energy, which is a novel broadening of the virtual energy concept, as a new promising feature that can be integrated into the load frequency control model, and validates it with a detailed mathematical analysis and simulation. The VES model is developed based on the surplus of required energy to bring the system frequency deviation to zero to the required energy to bring the system frequency to the drift limited. This led to the reduction in area control error regulation. Therefore, virtual energy can be exchanged between control areas easily and be very dynamic in responding to system disturbances. Simulation results confirm the effectiveness of the proposed model in restoring the frequency as well as economic benefit in reducing regulation expense without introducing additional installation or implementation costs. However, one technical problem, which should be examined carefully during the

realization of grid scale VES, is how to determine a good frequency drift limit. Higher flexibility in frequency drift limit facilitates the operation of grid scale VES, but that may have an adverse impact on the service quality and the safety of the power system. The optimal frequency drift limit varies in each interconnected system; in particular, that drift limit heavily depends on the individual system configuration and ability of the system to resist disturbances. Once the technical subtleties have been properly resolved, the mechanism of grid scale VES can potentially enable increased integration of renewable energy in the power grid.

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