Impacts of Responsive Loads and Energy Storage System on Frequency Response of a Multi-Machine Power System

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Abstract: In recent decades, the power grid’s configuration is shifting towards a smart grid where responsive loads and energy storage systems (ESS) are finding an increased role in the power system operation. In the presented work, a mathematical formulation for frequency response analysis of a multi-machine power system is developed, considering the individual and combined roles of ESS and responsive loads. The validity of the developed model is demonstrated with the help of multiple case studies, which consider the various configurations of the power system. Moreover, different combinations of capacities of generation units, ESS and responsive loads are also simulated. With the help of mathematical model and simulation results, it is demonstrated that ESS and responsive loads may improve the economy and performance of the power system even during the failure of a certain portion of generation capacity. Though the case studies consider non-reheat turbines only, the mathematical model and conclusions are equally valid for other types of turbines as well.

Keywords: energy storage system; frequency response; load frequency control; multi-machine power system; responsive loads

1. Introduction

Amongst the primary requirements for a safe and reliable operation of a power system is a stable frequency response which depends on the balance between real power’s supply and demand. Though power supply and demand continually change in a power system, the power system frequency response is maintained within a specific operating range through a process known as frequency regulation. Traditionally, the frequency regulation is realized using spinning and non-spinning reserves during normal conditions; and, under-frequency or over-frequency load-shedding methods are adopted during emergency situations [1–3]. However, other methods of frequency regulation are also gaining the popularity due to environmental and financial concerns. Utilization of renewable energy resources, energy storage systems (ESS) and responsive loads are some of the famous methods for the frequency regulation [4–6].

In a smart grid environment, the responsive loads are integrated through demand response (DR) programs which are advantageous to consumers and utility [7,8]. Several strategies of integration of responsive loads and their benefits in enhancing the power grid’s performance and economy are reported in literature. The authors of Reference [9] developed a 2-layer strategy for microgrid frequency regulation with the help of responsive loads considering electric vehicles as a part of them and showed...
a better performance of the microgrid with the developed strategy. The authors of References [10,11] proposed a control mechanism based on manipulation of responsive loads for primary frequency regulation. In Reference [10], a modified load frequency control (LFC) model considering responsive loads for frequency regulation process is developed and verified by simulation results. This work presented in Reference [11] splits the microgrid operation into 3 modes depending upon the magnitude of frequency deviation. For each operating mode, different share of responsive loads takes part to minimize the frequency deviation and the overall scheme shows a promising role of DR in frequency regulation process. Similarly, the simulation results of work carried out in Reference [12] show the effectiveness of responsive loads for frequency regulation.

The use of ESS to enhance grid stability is also under increased consideration in recent decades. ESS makes an optimal fit to accommodate intermittent renewable energy resources in smart grids and can provide virtual inertia (VI) to overcome the low-inertia problem associated with renewable energy systems [13]. The literature shows the application of VI for frequency regulation services and it is expected that role of ESS will increase in future for power system’s stability [14,15]. A control scheme is proposed in Reference [16] to suppress the deviation in system’s voltage and frequency using VI. The study in Reference [17] proposed a virtual inertia control-based model predictive control for frequency regulation. In this work, the test system is exposed to a high share of intermittent renewable energy systems and the proposed scheme exhibits a robust performance. In References [18–20], detailed discussions on the mathematical modeling, control system development and experimental results involving hardware in the loop are presented.

Considering an escalated and simultaneous integration of responsive loads and ESS in smart grids, further research is needed to discuss their combined role. The authors of this work presented a modified LFC model considering responsive loads and ESS and discussed their individual and combined role in improving the frequency response [21]. In Reference [22], a droop controlled distributed generation framework integrated with DR is developed for frequency regulation with the objectives of emission reduction and cost minimization. The work presented in References [23,24] considers renewable energy resources and demand response in the context of a virtual power plant.

In comparison to our previous work and other literature, the contribution and highlights of this work are presented as follows:

1. In contrast to previously mentioned literature which either discuss DR [6–11] or ESS [16–20], this work considers their combined operation in a smart grid environment. Moreover, prevalent multi-machine power system is considered for mathematical modelling and simulation results instead of a single-machine power system [21–25].

2. A mathematical model is developed to include the role of responsive loads and ESS in multi-machine electric power system. For their integration, independent control loops for the DR and the VI powers are introduced, which provide a means of extra degrees of freedom for frequency regulation. Moreover, this approach provides a simpler structure to design the controllers.

3. The developed model is verified with the help of simulation results carried out under a comprehensive set of case studies. The case studies range from consideration of an individual machine to combined role of responsive loads and ESS in a multi-machine system. The results show that the responsive loads and ESS can play a vital role in frequency regulation in case of partial or temporary unavailability of generation resources.

The paper is organized as follows: In Section 2, a model for a multi-machine power system considering responsive loads and ESS is developed. Case studies are discussed in Sections 3 and 4 summarizes and concludes the paper.
2. Development of the Model

Figure 1 shows a general block diagram of the LFC model of a multi-machine power system. The system is equipped with primary or droop control (with droop control value represented by $R$ in Figure 1) and secondary control. Typically, the secondary control is a part of automatic generation control and provides an integral control action to diminish the steady-state frequency deviation. For the objective of frequency response analysis and control under a load disturbance ($\Delta P_d(s)$), Equation (1) models the frequency deviation as follows [1,2].

$$D\Delta f(s) + 2sH\Delta f(s) = \sum_{i=1}^{N} \Delta P^i_T(s) - \Delta P_d(s)$$

(1)

where, $D$ and $H$ are the damping coefficient and inertia constant of the power system, respectively, $\Delta P^i_T(s)$ is the incremental power from $i$-th turbine out of a total $N$ turbines. The system shown in Figure 1 considers general forms of turbines and governors. The transfer functions for governor and three commonly available turbine types (i.e. reheated, non-reheated and hydro turbines) are given in Equations (2) and (3), respectively [26].

$$T_{gov}(s) = \frac{1}{(T_g s + 1)}$$

(2)

$$T_{tur}(s) = \begin{cases} 
cT_{tr,h} s + 1 & \text{for reheated turbine} \\
\frac{1}{(T_{tr,h} s + 1)(T_t s + 1)} & \text{for non-reheated turbine} \\
\frac{1}{0.5T_w s + 1} & \text{for hydro turbine}
\end{cases}$$

(3)

where,
- $T_g$ : time constant of governor (sec)
- $c$ : Percentage of power generated in the reheat portion
- $T_t$ : turbine time constant (sec)
- $T_{tr,h}$ : turbine time constant of reheated turbine (sec)
- $T_w$ : turbine time constant of hydro turbine (sec)

Thus, a general form for $i$-th machine $M^i(s)$ is represented as:

$$M^i(s) = T^i_{gov}(s) \cdot T^i_{tur}(s)$$

(4)

Figure 1. Model of a multi-machine power system.
2.1. Responsive Loads

In the smart grids, responsive loads make an important part of the power system for long-term energy balance and to provide ancillary services. Integration of responsive loads is realized with the help of DR programs. There are two major categories of DR programs:

1. Dispatchable programs: where the system operator can manipulate the responsive loads according to power grid’s needs. For example, direct load control is a type of such programs and also considered in this work.
2. Non-dispatchable programs: the programs in which the customer is financially encouraged to manipulate the loads but the system operator does not have direct control over the responsive loads. Its examples of are real-time pricing and peak time rebate [27].

The concept of manipulation of responsive loads for the frequency regulation is easy to understand. After the inception of a negative (positive) frequency deviation, a portion of responsive loads is turned off (on) to improve the real-power balance. Once the balance between real-power supply and demand is achieved, the frequency profile is maintained within its allowed range. In general, DR control results in quicker frequency regulation in comparison with conventional methods where change in valve or gate position takes considerable amount of time [1,13]. The communication delay in DR control mainly depends on the communication infrastructure and size of the power system. With the modern fast-paced communication network in smart grids, a quicker restoration of frequency profile with the help of responsive loads is achievable [9–11,21].

Figure 2 shows the model of a multi-machine power system augmented with battery energy storage system (BESS) and responsive loads connected through DR programs. The term \( \varepsilon \) represents the share of power to be adjusted with the help of responsive loads by DR program. The value of \( \varepsilon \) depends upon several factors including the price of electricity, network conditions and customer-side aspects. With reference to Equation (1) and Figure 2, the presence of responsive loads for frequency regulation results in Equation (5) where \( \Delta P_{DR}(s) \) represents the power contribution from DR program.

\[
D\Delta f(s) + 2sH\Delta f(s) = \sum_{i=1}^{N} \Delta P_f(s) - \Delta P_d(s) + \Delta P_{DR}(s)
\]

Figure 2. Model of a multi-machine power system augmented with responsive loads and virtual inertia from BESS.

2.2. Energy Storage System

In the conventional power systems, massive machines of large power systems have inherent inertia which improves the system’s stability. On the other hand, renewable energy systems in smart grids have no, or very small, rotating masses which cannot provide sufficient inertia as compared to the traditional power plants. So, the increased penetration of renewable energy resources poses a
challenge to the grid stability. A successful solution to the low inertia problem is proposed in the form of a control system called virtual synchronous machine that provides virtual inertia (VI) [13,28]. Such a control system utilizes BESS as a source of power and other main constituents are a power converter and a controller, as shown in Figure 3. The idea behind a virtual synchronous machine is to imitate the dynamic model of a real synchronous machine to improve the grid stability. From the operational point of view, the nominal state of charge of BESS is kept at 60–70% of rated capacity during normal conditions. In this way, BESS can absorb or inject power during contingency or emergency events. Thus, there are two main operating modes of a virtual synchronous machine as follows:

1. Virtual generator mode: in this case, BESS provides power to the grid
2. Virtual load mode: in this case, excess power from the grid is stored to BESS

The transfer function \( T_{VI}(s) \) between frequency deviation \( (\Delta f(s)) \) and virtual synchronous machine’s power change (denoted by \( \Delta P_{VI}(s) \)) is calculated according to Equation (6) as follows [25].

\[
T_{VI}(s) = \frac{1}{(K_I s + K_P)}
\]  

(6)

where, \( K_I \) and \( K_P \) emulate the inertia and damper winding characteristic of a synchronous generator. The value of \( K_I \) is calculated such that the maximum defined rate of change of frequency makes the virtual synchronous machine to exchange its maximum power. In this study, maximum rate of change of frequency is considered as 1 Hz/s Hz. Similarly, the value of \( K_P \) is calculated in a way that \( \Delta P_{VI}(s) \) is maximum when the frequency deviation reaches a predefined maximum value (which is 2.5 Hz in this study) [13,19]. Equation (6) signifies that though a virtual synchronous machine does not have rotating masses, its electrical appearance is similar to an electromechanical synchronous machine from the grid point of view.

With reference to Figure 2, where the term \( \zeta \) represents the share of power to be adjusted with the help of VI mechanism, the power balance equation is calculated as Equation (7).

\[
D\Delta f(s) + 2sH\Delta f(s) = \sum_{i=1}^{N} \Delta P_{f_i}(s) - \Delta P_d(s) + \Delta P_{DR}(s) + \Delta P_{VI}(s)
\]  

(7)

Figure 3. Configuration of control system for utilization of BESS for frequency regulation.
2.3. Multi-Machine System with DR and ESS

The frequency deviation in a multi-machine power system augmented with DR and VI resources is calculated according to Equation (8) as follows:

\[
\Delta f(s) = \frac{1}{2Hs + D} \left[ \sum_{i=1}^{N} \Delta P_i^d(s) + \Delta P_{DR}(s) + \Delta P_{VI}(s) - \Delta P_d(s) \right]
\]

(8)

Referring to Figure 1 and Equation (4), \(\Delta P_i^d(s)\) is calculated as:

\[
\Delta P_i^d(s) = M_i(s) \left[ \Delta P_S^i(s) - \frac{\Delta f(s)}{R_i} \right]
\]

(9)

Combining Equations (8) and (9) and solving for \(\Delta f(s)\):

\[
\Delta f(s) = \frac{1}{\Phi(s)} \left[ \sum_{i=1}^{N} \left( M_i(s) \cdot \Delta P_S^i(s) \right) + \Delta P_{DR}(s) + \Delta P_{VI}(s) \right] - \frac{\Delta P_d(s)}{\Phi(s)}
\]

(10)

where,

\[
\Phi(s) = \sum_{i=1}^{N} \left( \frac{M_i(s)}{R_i} \right) + 2Hs + D
\]

(11)

The step load disturbance of magnitude \(\Delta P_d\) in time-domain, is mathematically written as Equation (12) by taking its Laplace transform as follows:

\[
\Delta P_d(s) = \frac{\Delta P_d}{s}
\]

(12)

Applying the final value theorem and solving for steady-state frequency deviation (\(\Delta f_{SS}\)):

\[
\Delta f_{SS} = \lim_{s \to 0} s \cdot \Delta f(s)
\]

\[
= \lim_{s \to 0} s \cdot \left[ \frac{1}{\Phi(0)} \left( \sum_{i=1}^{N} \left( M_i(0) \cdot \Delta P_S^i(0) \right) + \Delta P_{DR}(0) + \Delta P_{VI}(0) \right) - \frac{\Delta P_d(0)}{\Phi(0)} \right]
\]

\[
= \frac{1}{D + \sum_{i=1}^{N} (R_i)^{-1}} \left( \sum_{i=1}^{N} \Delta P_{SS,i} + \Delta P_{DR,SS} + \Delta P_{VI,SS} - \Delta P_d \right)
\]

(13)

where,

\[
\Phi(0) = D + \sum_{i=1}^{N} \frac{M_i(0)}{R_i} = D + \sum_{i=1}^{N} (R_i)^{-1}, \text{ frequency response characteristics}
\]

\[
\Delta P_{SS,i} = \lim_{s \to 0} s \cdot M_i(s) \cdot \Delta P_S^i(s)
\]

\[
\Delta P_{DR,SS} = \lim_{s \to 0} s \cdot \Delta P_{DR}(s)
\]

\[
\Delta P_{VI,SS} = \lim_{s \to 0} s \cdot \Delta P_{VI}(s)
\]

(14)

Equation (13) indicates that, in addition to power from conventional resources, there are other resources of power (i.e., responsive loads and ESS) which contribute to diminishing the effect of \(\Delta P_d(s)\). In other words, the system operator has extra degree of freedom to select the share between these three controls. The selection of each participant’s share depends on several factors including electricity rate, network situation, capacity of ESS and customer-side factors. If \(K(s)\) is the total effort to counteract the effects of load disturbance and \(\gamma, \epsilon\) and \(\zeta\) are respectively the shares of conventional, DR and ESS controls, then the mathematical representation of this distribution is provided as follows [21]:

\[
\gamma + \epsilon + \zeta = 1
\]

(15)
\[
\Delta P_{DR}(s) = \varepsilon \cdot K(s)
\]
\[
\Delta P_{VI}(s) = \zeta \cdot K(s)
\]
\[
\Delta P_S(s) = (1 - \varepsilon - \zeta) \cdot K(s)
\]

(16)

3. Case Studies

This section highlights the various features of the developed model with the help of numerical simulations performed on a 3-machine, 100MW-base test system whose parameters are shown in Table 1 [10,13,21].

Table 1. Parameters of test system and machines.

| Parameter       | Value                          |
|-----------------|-------------------------------|
| D               | 0.015 p.u/Hz                  |
| H               | 0.075 p.u sec                 |
| \( \Delta P_d \) | 0.05 p.u                      |
| Governor Deadband | \( \pm 0.6\% \)               |

| Machine-1 | Machine-2 | Machine-3 |
|-----------|-----------|-----------|
| R         | 3 Hz/p.u  | 2.4 Hz/p.u| 2.8 Hz/p.u |
| \( T_t \) | 0.4 sec   | 0.8 sec   | 0.5 sec    |
| \( T_g \) | 0.08 sec  | 0.3 sec   | 0.1 sec    |

| Controller | Transfer function |
|------------|-------------------|
| \( K_{DR}(s) \) | \( -\frac{6.1}{s} + 2.3 \) |
| \( K_{VI}(s) \) | \( \left( \frac{0.2}{s} + 0.4 + 0.1s \right), \) (Filter coefficient, \( N = 100 \)) |
| \( K_S(s) \) | \( -\frac{0.03}{s} \) |

Numerous simulations were performed to analyze the role of responsive loads and BESS on the system frequency response under a load disturbance of 0.05 p.u applied at \( t = 5 \) sec. A comprehensive description of 31 test cases is provided in Table 2.

Table 2. Description of simulation cases.

| Single Machine | Multi-machine | Single machine with DR | Multi-machine with DR | Single machine with BESS | Multi-machine with BESS | Single machine with DR, BESS | Multi-machine with DR, BESS |
|----------------|---------------|------------------------|-----------------------|--------------------------|------------------------|-----------------------------|-----------------------------|
| Case           | Description   | A1 Machine 1           | A2 Machine 2           | A3 Machine 3             | A4 Machine 1,2,3        | G1                          | G2                          |
| Single machine with DR |          | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \varepsilon = 0.15 \) | y = 0.70, \( \varepsilon = 0.30 \) | y = 0.55, \( \varepsilon = 0.45 \) | y = 1.0, \( \zeta = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) |
| Multi-machine with DR |          | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \varepsilon = 0.15 \) | y = 0.70, \( \varepsilon = 0.30 \) | y = 0.55, \( \varepsilon = 0.45 \) | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) |
| Single machine with BESS |          | y = 1.0, \( \zeta = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) |
| Multi-machine with BESS |          | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) | y = 1.0, \( \varepsilon = 0 \) | y = 0.85, \( \zeta = 0.15 \) | y = 0.70, \( \zeta = 0.30 \) | y = 0.55, \( \zeta = 0.45 \) |

The numerical study has been divided into 4 categories, each having 2 subgroups considering various configurations of the test system. For a broader perspective, these cases include the results for single-machine and multi-machine system with and without the consideration of responsive loads
and energy storage systems. Machine-1 is utilized for the cases where a single machine operation is executed in the presence of responsive loads or ESS. The numerical simulations are performed in MATLAB/Simulink environment.

3.1. Conventional Model: Single- and Multi-Machine Cases

This case study considers a conventional multi-machine system and serves as a base case for comparison where responsive loads and ESS are not available for frequency regulation. A 3-machine test system equipped with non-reheat type turbines is shown in Figure 4. As detailed in Table 2, the response of individual and combined operation of machines is discussed in cases A1-A3 and B1-B4, respectively.

Figure 5a shows the frequency response for individual machines when a load disturbance ($\Delta P_d = 0.05 \ p.u.$) is applied to the system at $t = 5 \ sec$. The response of Machine-2 (Case-A2) is slower due to higher values of governor and turbines time constants as compared to other machines. Response of Machine-1 is the fastest as its governor and turbine have lower time constants.

The frequency response for two or all machines when a load disturbance ($\Delta P_d(s)$) is applied to the system is shown in Figure 5b. As expected, the lowest value for maximum frequency deviation is observed when all the three machines are operational as indicated by Case-B4.

![Figure 4. 3-machine test system for numerical simulations.](image)

![Figure 5. Cont.](image)
Figure 5. Frequency response for various configuration of the test system under load disturbance (a) frequency deviation for single-machine cases (A1-A3); (b) frequency deviation for multi-machine cases (B1-B4).

3.2. Conventional Model Augmented with Responsive Loads

In this case study, responsive loads are also considered for frequency regulation in addition to a single/multi-machine system. A description of the test cases is provided in Table 2 (i.e. C1-C4 and D1-D4). Figure 6a shows the role of DR when only Machine-1 is available in the system. The impact of responsive loads in the presence of all three machines is shown in Figure 6b. The summary of important observations from this case study is presented as follows:

1. The presence of responsive loads helps in improving the frequency profile depending on the share (ε) of responsive loads participating for frequency regulation under DR program.
2. Depending on the availability and amount of responsive loads, the need for (spinning and non-spinning) reserves reduces as responsive loads can be manipulated according to grid’s needs.

Figure 6. Frequency response under load disturbance when the test system has responsive loads (a) frequency deviation for single-machine and responsive loads cases (C1-C4); (b) frequency deviation for single-machine and responsive loads cases (D1-D4).
3.3. Conventional Model Augmented with ESS

A description of the test cases of this study is provided as E1-E4 and F1-F4 in Table 2. Here, ESS takes a part of frequency regulation in addition to a single/multi-machine system. The summary of important observations from this case study is presented as follows:

1. Figure 7a shows the role of ESS when only Machine-1 is available in the system. The presence of ESS improves the frequency profile in terms of maximum frequency deviation and settling time. Moreover, it can be deduced that the presence of virtual synchronous generator can reduce the size of conventional reserves.

2. The impact of ESS in the presence of all three machines is shown in Figure 7b and depends on its share ($\zeta$). Generally, higher the value of $\zeta$, better the frequency response. Moreover, the response of ESS is quicker in comparison to the responsive loads and conventional schemes as well.

![Figure 7](image)

\textbf{Figure 7.} Frequency response under load disturbance when the test system is equipped with ESS (a) frequency deviation for test cases (E1-E4); (b) frequency deviation for test cases (F1-F4).

3.4. Conventional Model Augmented with Responsive Loads and ESS

This test study involves both the responsive loads and the ESS with their various shares as detailed in Table 2. The observations for this study are in-line with the already discussed cases. The frequency response for these simulation cases are shown in Figure 8. In addition to frequency response, the changes in machine, DR and VI powers are also shown in Figure 9. The summary of important observations from this case study is presented as follows:

1. Due to presence of responsive loads and ESS, the response in this scenario is better than conventional control only and between the two already discussed cases.

2. Figure 9a shows the simulation results for Case-H1 where 3 machines contribute their powers to balance the impact of load disturbance. The slower response of Machine-2 as already discussed is again visible here. In this case, there is no contribution from responsive loads and ESS resources, hence their powers are zero.
3. Figure 9b shows the simulation results for Case-H4 where 50% contribution comes from responsive loads and ESS. The ESS has the fastest response as shown in Figure 9b. The contribution of powers from machines, DR and ESS at steady-state agrees with the model developed in Section 2. For example, the contribution of DR is calculated as: \( \varepsilon = 25\% \Rightarrow \Delta P_{SS}^{DR} = 0.25 \times 0.05 = 0.0125 \text{p.u.} \), which agrees with the results shown in Figure 9b. Similar calculations are valid for a power contribution from machines and ESS.

![Figure 8](image1.png)

**Figure 8.** Frequency response under load disturbance when the test system has responsive loads and ESS (a) frequency deviation for test cases (G1-G4); (b) frequency deviation for test cases (H1-H4).

![Figure 9](image2.png)

**Figure 9.** Change in power (p.u) for machines, demand response (DR) and virtual inertia (VI) resources (a) Case-H1 with 3 machines only; (b) Case-H4 with DR and VI resources in addition to 3 machines.
3.5. Comparison

Figure 10 highlights the contribution of DR and ESS in a comparative sense as explained below:

1. Figure 10a compares a 2-machine case (Case-B3) with a single machine system augmented with DR (Case-C4). The results show that the responsive loads can effectively handle the load disturbances even when there is partial shortage of conventional supply resources. It is notable that responsive loads cannot fully replace a generation unit if the magnitude of load disturbance is very high. Moreover, despite their benefits, DR programs affect the consumers’ comfort level, so their contribution is limited. However, the presented comparison highlights the fact that responsive loads can play a vital role in frequency regulation in case of partial or temporary unavailability of generation resources.

2. Figure 10b compares a 3-machine case (Case-B4) with a single machine system augmented with ESS (Case-E4). The results show that the ESS can quickly restore the frequency deviation. Similar to the previous discussion, it is once again observed that a virtual synchronous machine can efficiently handle the load disturbances in the presence of limited generation resources.

![Figure 10](image-url)  
(a)  
(b)

**Figure 10.** Comparison of various configurations (a) comparison of a 2-machine system case (B3) with a single machine system augmented with responsive loads (C4); (b) comparison of a 3-machine system case (B4) with a single machine system augmented with ESS (E4).

4. Conclusions

Modern power systems will have increased penetration of responsive loads under DR programs and VI provided by ESS. In the literature, there is limited work that focuses on the combined role of DR and VI in a multi-machine power system. The presented work adds the DR and VI loops to the basic model of a multi-machine system for the objective of frequency response analysis and control. The mathematical formulation for DR and VI powers and their role in steady-state frequency control is provided. It is observed that the DR and VI controls have the potential to provide the system operator with additional capabilities of frequency regulation with minimum time delays. Moreover, the results indicate that the ESS and responsive loads can possibly handle the load disturbances during
a temporary or partial shortage of conventional power resources. It is, however, notable that due to socio-technical reasons, the ESS and responsive loads cannot replace a major part of the generation. These reasons include stochastic nature of DR programs and customers’ participation factor; expanding demand for electrical energy; efficiency and operational life of ESS and so on. For future research, the distribution of power shares among conventional, DR and VI controls can be optimized under various constraints.

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**Abbreviations and Acronyms**

| Symbol | Description |
|--------|-------------|
| $\gamma$ | Share of conventional control |
| $\epsilon$ | Share of demand response control |
| $\zeta$ | Share of energy storage system control |
| ESS | Energy storage system |
| $c$ | Percentage of power generated in the reheat portion |
| $D$ | Damping coefficient of the power system |
| DR | Demand response |
| $H$ | Inertia constant of the power system |
| $K_{DR}(s)$ | Demand response controller |
| $K_s(s)$ | Supplementary controller |
| $K_{VI}(s)$ | Virtual inertia controller |
| LFC | Load frequency control |
| $R$ | Droop characteristics |
| $T_g$ | Time constant of governor (sec) |
| $T_{geo}(s)$ | Transfer function of governor |
| $T_r$ | Time constant of reheated turbine (sec) |
| $T_t$ | Time constant of turbine (sec) |
| $T_{tur}(s)$ | Transfer function of turbine |
| $T_w$ | Time constant of hydro turbine (sec) |
| VI | Virtual inertia |
| $\Delta f(s)$ | Frequency deviation |
| $\Delta P_{d}(s)$ | Load disturbance |
| $\Delta P_{T}(s)$ | Change in turbine power |

**References**

1. Anderson, P.M.; Fouad, A.A. *Power System Control and Stability*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
2. Kundur, P. *Power System Stability and Control*; McGraw-Hill Education: New York, NY, USA, 1994; ISBN 978-0-07-035958-1.
3. Power Systems Relaying Committee. IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration. *IEEE Std. C 2007*, 37, c1–c43.
4. Shahid, K.; Altin, M.; Mikkelsen, L.M.; Løvenstein Olsen, R.; Iov, F. ICT Based Performance Evaluation of Primary Frequency Control Support from Renewable Power Plants in Smart Grids. *Energies 2018*, 11, 1329. [CrossRef]
5. Pieroni, T.; Dotta, D. Identification of the Most Effective Point of Connection for Battery Energy Storage Systems Focusing on Power System Frequency Response Improvement. *Energies 2018*, 11, 763. [CrossRef]
6. Zaman, M.S.; Bukhari, S.B.A.; Haider, R.; Hazazi, K.M.; Kim, C.H.; Ashraf, H.M. Demand Response Augmented Control with Load Restore Capabilities for Frequency Regulation of an RES-Integrated Power System. In Proceedings of the 2018 International Conference on Electrical Engineering (ICEE), Lahore, Pakistan, 15–16 February 2018; pp. 1–5.

7. Hussain, A.; Bui, V.-H.; Kim, H.-M. Impact Analysis of Demand Response Intensity and Energy Storage Size on Operation of Networked Microgrids. *Energies* 2017, 10, 882. [CrossRef]

8. Haider, Z.M.; Mehmood, K.K.; Rafique, M.K.; Khan, S.U.; Lee, S.-J.; Kim, C.-H. Water-filling algorithm based approach for management of responsive residential loads. *J. Mod. Power Syst. Clean Energy* 2018, 6, 118–131. [CrossRef]

9. Nisar, A.; Thomas, M.S. Comprehensive Control for Microgrid Autonomous Operation with Demand Response. *IEEE Trans. Smart Grid* 2017, 8, 2081–2089. [CrossRef]

10. Pourmousavi, S.A.; Nehrir, M.H. Introducing Dynamic Demand Response in the LFC Model. *IEEE Trans. Power Syst.* 2014, 29, 1562–1572. [CrossRef]

11. Pourmousavi, S.A.; Nehrir, M.H. Real-Time Central Demand Response for Primary Frequency Regulation in Microgrids. *IEEE Trans. Smart Grid* 2012, 3, 1988–1996. [CrossRef]

12. Delavari, A.; Kamwa, I. Virtual inertia-based load modulation for power system primary frequency regulation. In Proceedings of the 2017 IEEE Power Energy Society General Meeting, Chicago, IL, USA, 16–20 July 2017; pp. 1–5.

13. Bevrani, H. *Robust Power System Frequency Control*; Power Electronics and Power Systems; Springer International Publishing: Berlin/Heidelberg, Germany, 2014; ISBN 978-3-319-07277-7.

14. Tamrakar, U.; Shrestha, D.; Maharjan, M.; Bhattarai, B.P.; Hansen, T.M.; Tonkoski, R. Virtual Inertia: Current Trends and Future Directions. *Appl. Sci.* 2017, 7, 654. [CrossRef]

15. Stein, K.; Tun, M.; Musser, K.; Rocheleau, R. Evaluation of a 1 MW, 250 kW-hr Battery Energy Storage System for Grid Services for the Island of Hawaii. *Energies* 2018, 11, 3367. [CrossRef]

16. Hirase, Y.; Abe, K.; Sugimoto, K.; Sakimoto, K.; Bevrani, H.; Ise, T. A novel control approach for virtual synchronous generators to suppress frequency and voltage fluctuations in microgrids. *Appl. Energy* 2018, 210, 699–710. [CrossRef]

17. Kerdphol, T.; Rahman, F.; Mitani, Y.; Hongesombut, K.; Küfeoğlu, S. Virtual Inertia Control-Based Model Predictive Control for Microgrid Frequency Stabilization Considering High Renewable Energy Integration. *Sustainability* 2017, 9, 773. [CrossRef]

18. Van, T.V.; Visscher, K.; Díaz, J.; Karapanos, V.; Woyte, A.; Albu, M.; Bozelie, J.; Loix, T.; Federenciuc, D. Virtual synchronous generator: An element of future grids. In Proceedings of the Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Gothenburg, Sweden, 11–13 October 2010; pp. 1–7.

19. Karapanos, V.; de Haan, S.; Zwetsloot, K. Testing a virtual synchronous generator in a real time simulated power system. In Proceedings of the International Conference on Power Systems Transients (IPST), Delft, The Netherlands, 14–17 June 2011.

20. Albu, M.; Calin, M.; Federenciuc, D.; Díaz, J. The measurement layer of the Virtual Synchronous Generator operation in the field test. In Proceedings of the 2011 IEEE International Workshop on Applied Measurements for Power Systems (AMPS), Aachen, Germany, 28–30 September 2011; pp. 85–89.

21. Saeed Uz Zaman, M.; Bukhari, S.; Hazazi, K.; Haider, Z.; Haider, R.; Kim, C.H. Frequency Response Analysis of a Single-Area Power System with a Modified LFC Model Considering Demand Response and Virtual Inertia. *Energies* 2018, 11, 787. [CrossRef]

22. Rezaei, N.; Kalantar, M. Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework. *Energy Convers. Manag.* 2015, 92, 287–301. [CrossRef]

23. Lu, Z.; Guo, K.; Yan, G.; He, L. Optimal Dispatch of Power System Integrated with Wind Power Considering Virtual Generator Units of Demand Response and Carbon Trading. *Autom. Electr. Power Syst.* 2017, 41, 58–65.

24. Abbasi, E. Coordinated primary control reserve by flexible demand and wind power through ancillary service—Centered virtual power plant. *Int. Trans. Electr. Energy Syst.* 2017, 27, e2452. [CrossRef]

25. Bevrani, H. *Virtual Inertia-Based Frequency Control*. In *Robust Power System Frequency Control*; Bevrani, H., Ed.; Power Electronics and Power Systems; Springer International Publishing: Berlin/Heidelberg, Germany, 2014; pp. 349–376. ISBN 978-3-319-07278-4.
26. Sondhi, S.; Hote, Y.V. Fractional order PID controller for load frequency control. *Energy Convers. Manag.* **2014**, *85*, 343–353. [CrossRef]

27. Shariatzadeh, F.; Mandal, P.; Srivastava, A.K. Demand response for sustainable energy systems: A review, application and implementation strategy. *Renew. Sustain. Energy Rev.* **2015**, *45*, 343–350. [CrossRef]

28. Zhong, Q.-C.; Weiss, G. Synchronverters: Inverters That Mimic Synchronous Generators. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1259–1267. [CrossRef]