Effects of Modified Inertia Constant and Damping Coefficient on Power System Frequency Response

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Abstract- The configuration of modern power system is drastically changing due to integration of distributed energy resources (DER) and responsive loads. Despite their advantages in terms of eco-friendliness and reliability enhancement, DER and responsive loads pose several challenges to the grid's operation and stability. Amongst these challenges are the modification in two critical system parameters: inertia constant (H) and damping coefficient (D). Typically, these parameters are considered unchanged during the operation of a power system. However, the high penetration of responsive loads and BESS may alter their values from the calculated or presumed values. In this work, an analysis of power system frequency response is presented considering the modifications in these two parameters. After explaining how DER and responsive loads modify these parameters, it is demonstrated that a mismatch between actual and presumed values of these parameters may degrade the reliability and economy of the power system. The study considers two typical configurations (i.e., with and without automatic generation control) of the power system, and highlights the importance of accurate calculation of H and D when DER and responsive loads have significant shares.

Keywords Battery energy storage system (BESS); demand response (DR); distributed energy resources (DER), frequency deviation; load frequency control (LFC) model; power system frequency response

Abbreviations and Acronyms

AGC	Automatic generation control
BESS	Battery energy storage system
c	% of power generated in the reheat portion
D	Damping coefficient of the power system
D'	Modified damping coefficient
DER	Distributed energy resources
DR	Demand Response
H	Inertia constant of the power system
H'	Modified inertia constant
$K_s(s)$	Supplementary controller
LFC	Load frequency control
R	Droop characteristics
T_g	Time constant of governor (sec)
T_r	Time constant of reheated turbine (sec)
T_t	Time constant of turbine (sec)
T_w	Time constant of hydro turbine (sec)
VISMA	Virtual synchrounous machine
$\Delta f(s)$	Frequency deviation
$\Delta P_d(s)$	Load disturbance
$\Delta P_m(s)$	Change in turbine power
σ	Relative change in damping coefficient

1. Introduction

One of the primary requirements for a secure and reliable operation of a power system is a stable frequency response which ultimately depends on the balance between supply and demand of the real power. Though a power system constantly experiences the fluctuations in power generation and demand, however, the power system frequency response is maintained within a pre-set operating range. 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, considering the environmental and financial concerns, other methods of frequency regulation are also gaining the popularity. Integration of DER (e.g. renewable energy systems, energy storage systems) and utilization of responsive loads (through demand response (DR) programs) are two famous methods for the said purpose [4]–[9].

In the modern power systems, an increased penetration of DER and DR programs helps addressing the environmental and financial concerns. However, their advantages are not a free lunch as they also offer several challenges to the grid operation [10]–[12]. Specifically, the load manipulation due to DR programs and DER may alter the load-damping characteristics (D) and inertia constant (H) of the power system, respectively [13]–[16].

Massive machines of large power systems have inherent inertia which improves the system's stability [13]. However, DER have no or very small rotating masses and, therefore, they do not provide sufficient inertia as compared to the traditional power plants. The solution to the low inertia problem of DER is proposed in the form of virtual synchronous machine (VISMA) which provides virtual inertia [13], [17]. The control system of a VISMA utilizes battery energy storage system (BESS) to improve the stability of power system. The studies show the application of VISMA for frequency regulation services, and an improved role of VISMA for the power system's stability is expected in the future [18]–[20]. In [21]–[23], a comprehensive discussion on the mathematical modelling, control system development, and experimental outcomes are presented considering VISMA hardware in the loop. These studies discuss the application of VISMA for power system stability improvement but do not provide details about the impacts of VISMA on system parameters. A report on prevailing topologies for VISMA and their comparison is presented in [24]. In [25], a model predictive control based on virtual inertia is presented for frequency restoration. The developed control system shows a good performance even in the presence of a high share of intermittent renewable energy. Similarly, a control scheme is proposed in [26] to suppress the deviation in system's voltage and frequency using VISMA. The above-mentioned studies, however, considers VISMA for frequency support without providing details of its effect on values of system parameters which affected due integration of large capacity energy storage system.

On the other hand, special types of DR programs, known as dispatchable programs, are also utilized to improve the power system's stability [27], [28]. In [29], power system frequency is controlled by dynamic demand response in a decentralized manner. Adaptive methods for frequency regulation are proposed in [30]–[34] where the manipulated responsive load is directly proportional to the magnitude of frequency mismatch to quickly restore the frequency. In the mentioned literature, power system's stability is achieved with the help of DR programs which dynamically affect the large part of responsive loads. The responsive loads may also include the frequency-sensitive loads such as motors (which have a significantly different load-damping coefficient than the rest of the loads). Manipulating such loads through DR programs modifies the frequency-related load-damping coefficient D , but this effect of DR is usually not considered properly.

Comparing to the previous work, the contribution and highlights of this work are presented as follows:

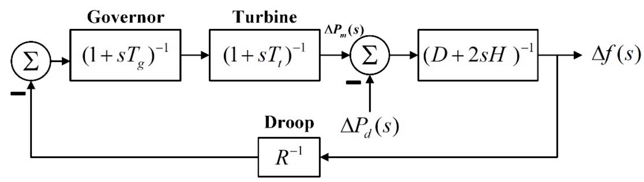
1. In contrast to the referenced literature which either discuss VISMA [13], [17]–[19], [21]–[26] or DR [27]–[34], this work considers both of them. Moreover, the above mentioned research discusses the design and applications of VISMA and DR for frequency regulation but does not shed sufficient light on the power system's behavior when the actual values of D and H are different from the calculated values due to increased integration of DER and DR.
2. It is demonstrated that manipulation of frequency sensitive loads through DR programs and integration of energy storage system for VI affects these system parameters. Moreover, two typical configurations (i.e. with and without AGC) of the power system for mathematical modelling and numerical simulation are considered.
3. The results show that an error in values of D and H can result in maloperation of safety devices and/or increased operational cost. The findings of this study necessitate the accurate calculation of these parameters.

The paper is organized as: In Section 2, it is explained that how BESS and DR affect D and H . The parameters of test system and simulation results are discussed in Section 3. Finally, Section 4 summarizes and concludes the paper.

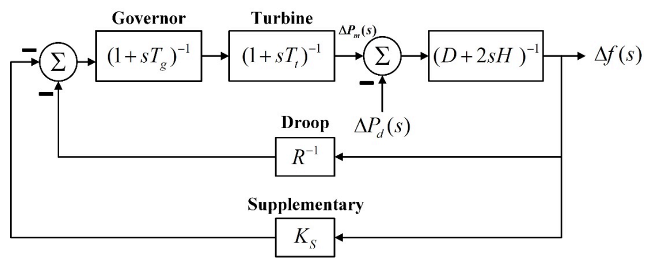
2. Modification in Inertia Constant and Damping Coefficient

In Figure 1, two typical configurations of power systems for load frequency control (LFC) are shown where transfer function of turbine considers a non-reheat turbine. In Figure 1(a), only droop control is considered while Figure 1(b) considers an extra supplementary control which is a part of automatic generation control (AGC), and provides an integral controller to diminish the frequency error. Moreover, for frequency control synthesis and analysis in the presence of a step load disturbance ($\Delta P_d(s)$), a low-order linearized model presented by power balance relation of Eq. (1) is used [1], [13], [35].

$$\Delta P_m(s) - \Delta P_d(s) = D\Delta f(s) + 2sH\Delta f(s) \tag{1}$$



(a)



(b)

Figure 1. Block diagram of a power system (a). with only droop control (b). with supplementary control

For the system containing a non-reheat turbine and a droop control mechanism as shown in Figure 1(a), the mathematical relation for the calculation of frequency deviation ($\Delta f(s)$) due to a load disturbance ($\Delta P_d(s)$) is provided in Eq. (2) as follows:

$$\Delta f(s) = -\frac{\Delta P_d}{2sH + D + \dfrac{1}{R(sT_t+1)(sT_g+1)}} \tag{2}$$

This relation considers a non-reheat turbine, however, the model is valid for other types of turbines as well, and only requires a modification in the turbine transfer function for reheated or hydro turbines. The transfer functions for the two types of turbines are:

$$T_{turbine}(s) = \begin{cases} \dfrac{cT_r s+1}{(T_t s+1)(T_r s+1)} & \text{for reheated turbine} \\ \dfrac{1-T_w s}{(0.5T_w s+1)} & \text{for hydro turbine} \end{cases} \tag{3}$$

Similarly, for the power system containing a supplementary integral control (i.e. $K_S(s) \triangleq K_S / s$), as shown in Figure 1(b), the frequency deviation ($\Delta f(s)$) is calculated according to Eq. (4):

$$\Delta f(s) = -\frac{\Delta P_d(s)}{2sH + D + (\dfrac{K_S}{s} + \dfrac{1}{R})\cdot\dfrac{1}{(sT_t+1)(sT_g+1)}} \tag{4}$$

The mathematical model represented by above equations, however, does not incorporate the role of virtual inertia and DR. In the following sub-sections, the role of DER and DR for frequency regulation services is explained, and it is shown that how they affect the system parameters.

2.1 VISMA and Inertia Constant (H)

As discussed in the previous section, the objective of VISMA is to imitate the dynamic characteristics of a real synchronous generator for enhanced grid stability using power electronics-based RES. The major components of a VISMA are BESS, a power electronics-based converter, and a control system as shown in Figure 2. The concept of VISMA establishes a basis to integrate a greater share of DERs in the modern power systems without compromising the system's performance. During normal operation, to maintain the capability of VISMA to absorb or inject power from/to the grid, state of charge of the BESS is kept at 60~70%. In this way, VISMA operates in two modes as follows:

1. virtual load mode: when surplus energy from the grid is stored to the VISMA's BESS
2. virtual generator mode: when the BESS provides power to the grid

In an electromechanical synchronous generator, the resistance of damping windings absorbs the energy which is represented by the damping term in its model. However, in the case of VISMA, energy storage device absorbs this power variation to balance the grid power. From the above discussion, it is clear that VISMA modifies the inertia constant of the power system (modified inertia constant will be represented by H'). The exact value of H' depends upon the several factors, and is beyond the scope of this work as this study primarily aims to show the impact of modified parameters. Generally, the state of charge and battery technology are two important parameters affecting the role VISMA. The choice of BESS technology for VISMA applications is dependent on the numerous factors including the load rating, environmental parameters, control delay, detection time, and average state of charge during regular operation [13], [36].

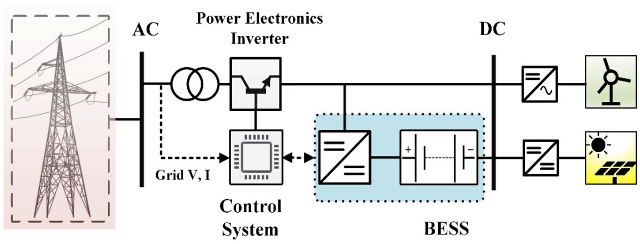


Figure 2. Block diagram of VISMA

2.2 DR and Load Damping Coefficient (D)

Frequency-dependent load-damping coefficient (D) is a constant that specifies the percentage of the change in the load over the percentage of the change in the system frequency [37]. Generally, based on operational experience, the value of D is empirically set for normal system operation, and effect of load changes on its value is neglected. This is due to the fact that effect of error in damping coefficient in an essentially stable system is bounded and the control system is robust enough to hide its impact. However, the calculation / estimation of D in modern power systems requires more attention as a large amount of frequency-sensitive loads such as motors take part in DR programs. In such systems, the impact of miscalculated damping coefficient can accelerate the frequency deviation after a power system is unstable due to disturbance. As suggested by [14], the difference between actual and supposed damping coefficient has the largest impact on frequency deviation at the same time when the largest frequency deviation occurs, and it can result in malfunction of the frequency protection devices.

If the changed or updated damping coefficient is represented by D', a term 'relative change in damping coefficient (σ) is defined by Eq. (5).

$$\sigma @ \frac{\text{absolute change in damping coefficient due to DR}}{\text{original damping coefficient}} = \frac{|D - D'|}{D} \tag{5}$$

The purpose of defining a new coefficient is to evaluate the frequency sensitivity with respect to change in damping coefficient. The unit-less sensitivity function is defined and determined by Eq. (6).

$$S_D = \frac{\dfrac{d\Delta f(s)}{\Delta f(s)}}{\dfrac{dD}{D}} = \frac{\partial \Delta f(s)}{\partial D} \cdot \frac{D}{\Delta f(s)} = \frac{\Delta f(s)}{\Delta P_d(s)} \cdot D \tag{6}$$

Combing Eq. (5) with Eq. (6), Eq. (7) is obtained which demonstrates the impact of relative change in damping coefficient over frequency sensitivity function. It is clear that when there is an actual change in damping coefficient (i.e., $D \neq D'$ and $\sigma \neq 0$), there is a need to update this in frequency control model to avoid malfunction of frequency relays and other devices. As shown in Figure 3, the significance of this phenomenon is highlighted further as the relative change in damping coefficient increases. This will be in the case when increased amount of frequency-sensitive loads (e.g. motors) are considered as responsive loads for frequency regulation process. The term D' will be used to represent the modified damping coefficient in the subsequent sections.

$$S_D = \frac{\Delta f(s)}{\Delta P_d(s)} \cdot \frac{D'}{1 - \sigma} \tag{7}$$

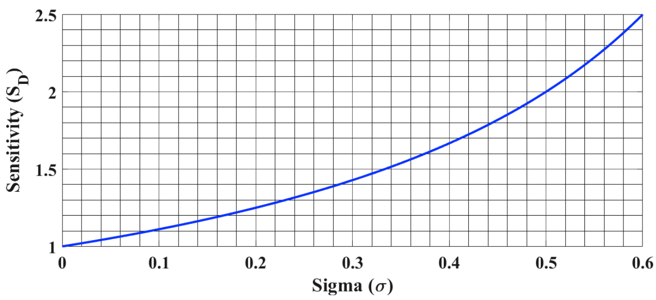


Figure 3. The plot of sensitivity function versus the relative change in load damping coefficient (σ)

3. Simulation Results

Table 1 shows the parameters of test system [19], [31]. The values H and D are changed in steps of 10% and 20% respectively above and below the nominal value as shown in Table 2. To observe the impact of modified system parameter on frequency response of the power system, a step load disturbance of 0.05 p.u. is applied in all the test cases, and the value of K_S is set as 0.1.

Table 1. Parameters of test system

Parameter	Value	Unit
T_t	0.8	sec
T_g	0.3	sec
P_d	0.05	p.u.
R	2.4	Hz/p.u.
D	0.0083	p.u./Hz
H	1.5	p.u. sec
Deadband in governor control	±0.036	Hz
Generation rate constraint	±0.1	p.u.

Table 2. Description of test cases

Modification in H		Modification in D	
Case No	**Value of H**	**Case No**	**Value of D**
C1	1.20	C6	0.00498
C2	1.35	C7	0.00640
C3	1.50	C8	0.00830
C4	1.65	C9	0.00996
C5	1.80	C10	0.01162

3.1 *Effect of Modified H*

3.1.1 Power System with Droop Control

Figure 4 shows the effects of H' (changes in H with the steps of $\pm 10\%$) on the frequency of a power system having droop control only. The steady-state error in frequency response is due to absence of an integral controller in the loop, as shown in Figure 4. The important remarks concluded from this simulation study are:

1. The magnitude of frequency deviation depends on the value of H' as shown in Figure 4. For step disturbance of the same intensity, the maximum frequency deviation is dissimilar to the one calculated using fixed value of H (i.e., when $H' = H$).
2. This above mentioned remark raises concerns for practical considerations. For instance, the capacity of reserves (spinning as well as non-spinning) is determined on the basis of frequency deviation (along with other parameters). So, a difference between actual and calculated H can result in allocation of high or low capacity reserves which ultimately affects the economy or reliability of the system.
3. Moreover, due to effect of H', the actual frequency deviation may be different from the estimated values leading to maloperation (i.e., oversensitive or under sensitive operation) of protective relays.

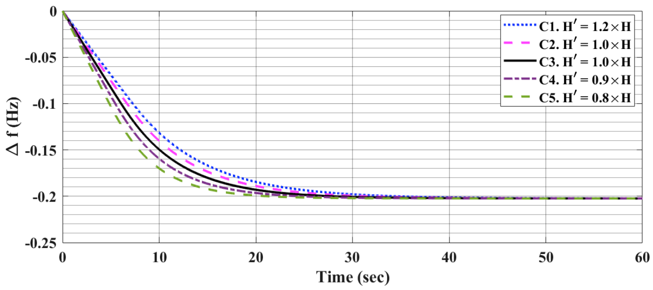


Figure 4. Frequency response of a power system having only droop control under step load disturbance for different values of inertia constant

3.1.2 Power System with Supplementary Control

Figure 5 shows the effects of changes in H on the frequency of a power system having a supplementary control in addition to the droop control. The observations for this simulation study are summarized as follows:

1. In contrast to the previous situation, the power system has an integral control which make the frequency deviation go to zero.
2. Similar to the previous simulation results, the magnitude of frequency deviation depends on the value of H'. Moreover, the discussion regarding allocation of reserves and operation of frequency relays is valid for this configuration as well.
3. It is notable that, for conventional LFC models, the value of inertia constant is considered a constant value which does not alter during an operational time-period. This study, however, requires to update the parameter depending upon integration level and operating characteristics of VISMA.

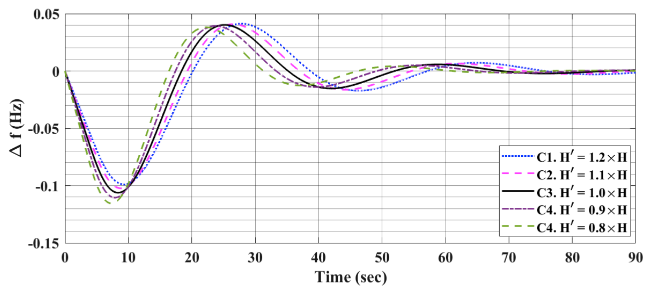


Figure 5. Frequency response of a power system having supplementary control under step load disturbance for different values of inertia constant

3.2 Effect of Modified D

3.2.1 Power System with Droop Control

As already explained, load manipulation due to DR causes modification in load damping coefficient. In this simulation study, the effects of D' on frequency response of the power system having only droop control are analyzed. The results are shown in Figure 6 where a zoomed-in view is also presented for a clear understanding. The summary of important observations is presented as follows:

1. A steady-state error in the frequency response is observed which is due to absence of any integral control in the control loop.
2. As shown in Figure 6, the magnitude of frequency deviation depends on the value of D'. The effects of D', however, are less noticeable as compared to that of H'.
3. It is once again noticed that an error in actual and supposed values of damping coefficient can lead to undesired frequency response, and economic and operational problems.

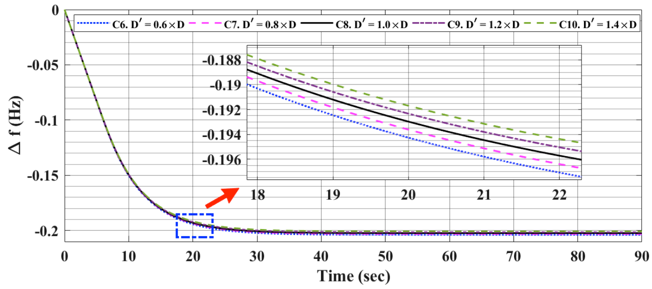


Figure 6. Frequency response of a power system having only droop control under step load disturbance for different values of damping coefficient

3.2.2 Power System with Supplementary Control

Figure 7 shows the effects of changes in D (which are proportional to nature and penetration level of controllable loads) on the frequency response of a power system having a supplementary control in addition to the droop control. The observations for this simulation study are similar to the already discussed cases. Compared to droop control of the previous case, the steady-state profile and general response is better in the presented case due to presence of an integral controller in the control loop.

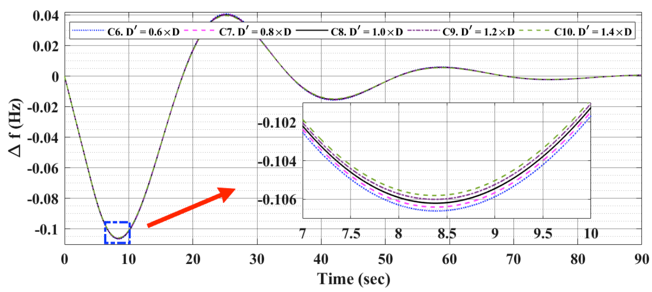


Figure 7. Frequency response of a power system having supplementary control under step load disturbance for different values of damping coefficient

4. Conclusion

The increased penetration of controllable loads through DR programs and virtual inertia provided by BESS with the help of power electronics-based power converters modifies the damping coefficient and inertia constant of a power system. These parameters are conventionally calculated via empirical methods or through experience, and are considered constant during operational time-periods. In this work, an analysis is presented to show the significance of accurate calculation of these parameters. Two typical configurations of the power systems are considered, and impacts of modifications in inertia constant and damping coefficient are simulated for both configurations. It is observed that:

- A difference between actual and presumed values of these parameters results in an undesired frequency response.
- The economy and reliability of the power system also depends on accurate determination of these parameters. An error in calculation of these critical parameters results in a deteriorated and uneconomic operation of the power system.

A motivating topic of future research is to establish the mathematical models for determination of these coefficients in the presence of VISMA and DR programs.

Acknowledgements

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