

Control and Placement of Battery Energy Storage Systems for Power System Oscillation Damping

**A Dissertation Presented for the
Doctor of Philosophy
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To my parents

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ABSTRACT

Power system low-frequency oscillation, with frequency at 0.2-2.5Hz, is a common phenomenon arising between groups of generators, which is also called “electromechanical oscillation”. Current oscillation damping control measures are mainly based on power system stabilizers (PSS) and conventional FACTs (Flexible AC Transmission Systems). With the development of power electronics technologies, more and more battery energy storage systems (BESSs) have been integrated into power systems, which provide a new option for oscillation damping. In this dissertation, a systematical research work regarding optimal placement and control of BESS units for oscillation damping is presented.

In the first part, the BESS model is established based on the power output characteristics of its power converter interface considering the converter power limit, State of Charge (SOC) limit, and the converter time constant. A BESS based control method is then proposed to improve the damping ratio of a target electromechanical mode to a desired level by charging or discharging the BESSs based on local bus measurements. The relationship between the desired damping improvement and the BESS controller parameters is derived analytically for a single-machine-infinite-bus system and a multi-machine system respectively. This BESS-based approach is then tested on a four-generator power system. The factors of the power converter limit, converter time constant, PSSs and battery SOC are studied. Simulation results validate the effectiveness of the proposed analytical control formula.

In the second part, an optimal placement problem on the BESS locations and controller parameters is formulated for oscillation damping improvement. First, the objective function and constraints are introduced to establish a black-box mixed-integer optimization problem by interfacing the time-domain simulation with a Mixed-Integer Particle Swarm Optimization (Mixed-PSO) algorithm. Then, the proposed optimization procedure is tested on the New England 39-bus system and a Nordic test system. The local optimality of the results is also verified via time-domain simulations. Finally, the applicability of the proposed method is investigated regarding seasonal load changes, the minimum number of BESS units to be placed, improvement of the Mixed-PSO efficiency and performance comparison of different controllers. Results demonstrate the effectiveness of the proposed placement approach.

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CHAPTER ONE

INTRODUCTION

1.1 Background

1.1.1 Power System Oscillation

Power system (low frequency) oscillation, whose frequency typically ranges from 0.2 to 2.5Hz, often occurs in interconnected power grids, and is one of the major concerns in power system operations [1]. It can be excited by several reasons such as line faults, switching of lines or a sudden change of generator output and usually happens in large interconnected power grids. The root cause of this phenomenon can be ascribed to various reasons, such as: insufficient system damping, forced oscillation [2], external periodic load perturbation [3], parametric resonance [4] and modal interaction [5], etc.

It usually arises between groups of generators and is also named as “*electromechanical* oscillation” by some researchers. The following generator rotor angle (relative angle between generators at bus-35 and bus-77) curve in Fig. 1.1 shows a typical oscillation event after a temporary fault happens at bus-79 and lasts for 0.1 sec in the WECC (Western Electricity Coordinating Council) system [6]. The single-line-diagram of the WECC system is shown in Fig. 1.2.

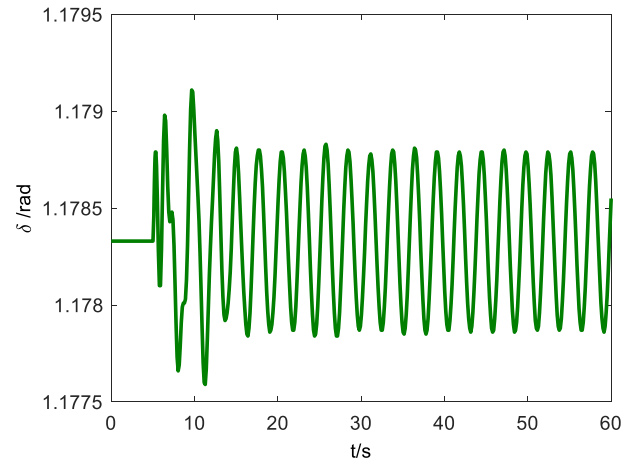


Figure 1.1. The relative rotor angle δ_{35-77}

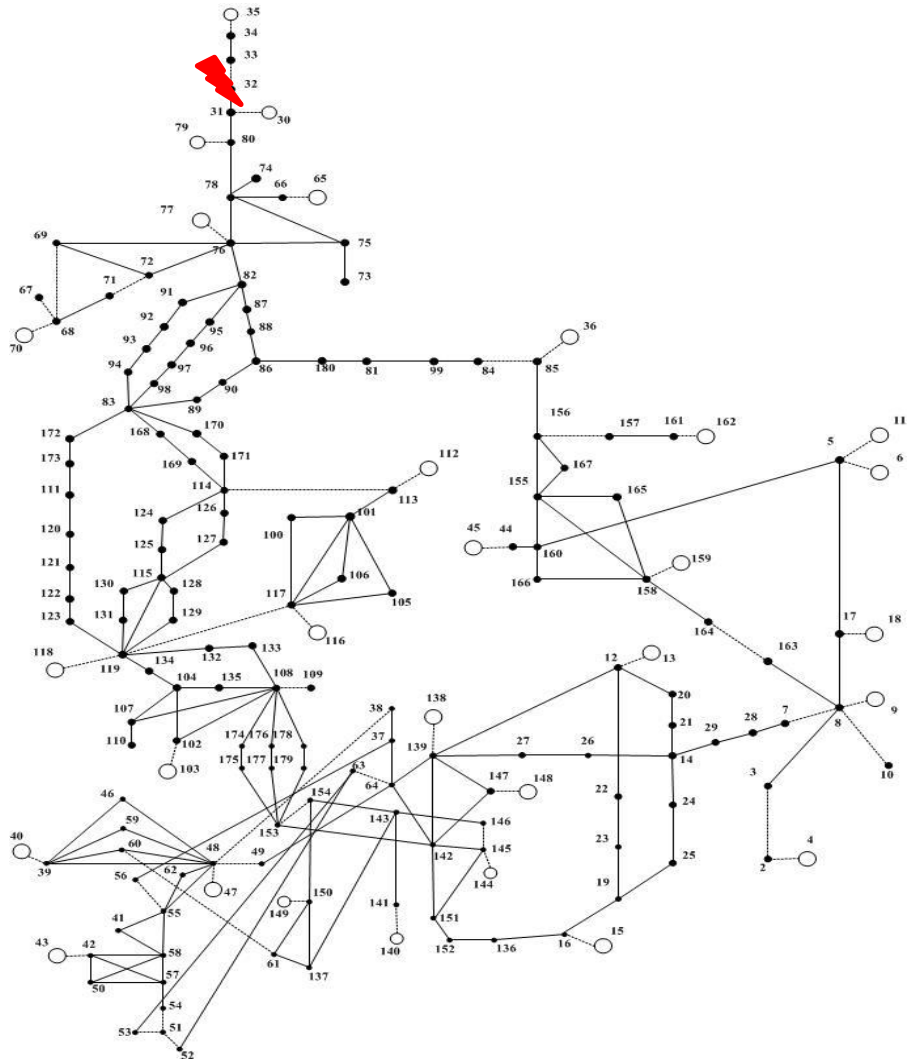


Figure 1.2. The WECC 179-bus system diagram

The power system oscillation phenomenon can be harmful because:

1) It narrows the system security margin.

For example, it can make the original large power system slowly evolve into system disintegration status.

2) It has negative impacts on load side

For example, long-duration frequency instability may reduce the yield rate of wafer-fabrication factories

3) It Reduce power transmission capabilities of the existing interconnection lines (“interties”).

1.1.2 Modal Analysis

In classic linear control theory, an n^{th} -order system (or a system with n different state variables) can have n eigenvalues. Among those eigenvalues, there can be either real eigenvalues or complex eigen-pairs. Each complex eigen-pair (denote λ_i and its conjugate) is called one “mode”. The procedure or algorithm to find such eigen-pairs is named as “Modal Analysis”.

For each mode, several important concepts are:

The damping ratio ξ (usually represented in percentage format) is a measure about how fast the signal (waveform) of this mode can decay;

Natural oscillation frequency ω_n (rad/s) is the angular frequency when $\xi = 0$ (i.e. zero-damping);

Oscillation frequency ω_d (rad/s) is the angular frequency when $\xi \neq 0$ (also called “damped frequency”);

The mode shape is a right eigenvector m_i (note: a complex vector)

The above concepts can be summarized as follows

$$\begin{aligned} \dot{x} = Ax \in \mathbf{R}^n &\Rightarrow \text{eig}(A) = \Lambda = \mathbf{diag}\{\lambda_i\}_{i=1 \sim n}, \\ \text{If complex pair : } \lambda_i, \bar{\lambda}_i &= -\xi\omega_n \pm j\omega_n\sqrt{1-\xi^2} = \sigma \pm j\omega_d \end{aligned} \quad (1.1)$$

The definitions of modal matrices M and N , the modal vectors m_i and n_i , and the final modal-decomposition expression of the state variable $x(t)$ are expressed as follows:

$$\begin{aligned} M^{-1}AM &= \Lambda, M = [m_1, m_2, \dots, m_n], N^T = M^{-1} \\ Am_i &= \lambda_i m_i, n_i^T A = \lambda_i n_i^T, x(t) = \sum_{i=1}^N e^{\lambda_i t} m_i n_i^T x(0) \end{aligned} \quad (1.2)$$

Low frequency oscillation typically happens during small disturbances; under which, the power system can be linearized around certain operating points (called “equilibrium points”).

The modal vectors have clear and useful physical meanings, e.g. the right eigenvector m_i can give information about which groups of generators (called “dominant groups”) contribute to the oscillation for that certain mode. Due to this reason, a right eigenvector is also named as *observability vector* in some literature.

The modal analysis theory introduced here will be utilized and expanded in chapters 2 and 3 to design our oscillation damping control strategy by BESS units and the associated optimal placement algorithm.

1.2 Motivation of the Research

1.2.1 Selective Damping Control by BESS

Typically, oscillations regarding inter-area modes are more concerned than local modes in system operations, which have high priorities to be damped. If not damped well, they can be extremely harmful to power system stability.

With the fast development of energy storage and power electronics technologies, many utility-scale BESSs (Battery Energy Storage Systems) have been deployed in power systems and have participated in the power markets as shown in Fig. 1.3. As an active source, the BESS can be used for balancing the power systems to provide various ancillary services.



Figure 1.3. Utility-scale BESS and renewable sources integrated in power systems

In normal conditions of a power system, a BESS is operated in the normal state, i.e. either charging or discharging in a scheduled mode. However, due to

their considerable initial investment, its function can be further exploited not only as a system balancing unit, but also to provide extra damping for system oscillations. Although large damping ratio typically lead to fast damping response, due to the realistic actuator output and battery power/energy cost limits, it is will be more beneficial to BESS owners and system operators by designing the BESS-based damping controller for a target mode to precisely achieve a pre-defined damping ratio goal (e.g. 5%).

Thus, a method is proposed in this dissertation, which can damp a target mode to a desired damping ratio and, meanwhile, will not worsen damping ratios of other oscillation modes.

1.2.2 Optimal Placement of BESS for Oscillation Damping

In real systems, multiple BESSs can exist, especially in a large power grid. Besides the controller design for a single BESS device, another challenging issue is the placement of multiple BESSs, i.e. how to determine their locations of installation. This is a practical issue for power system planners, which layouts the foundation for the BESS control and operation in the next step.

Thus, an optimal BESS placement scheme is proposed, which can help damp a target inter-area mode with a desired damping ratio improvement without weakening other oscillation modes.

In the following section, we go through the literature on two aspects: 1) oscillation damping control by energy storage devices (especially by BESS) in power systems, and 2) motivations and formulations of different optimal placement problems of energy storage devices, especially for BESS.

1.3 State of the Art

1.3.1 Oscillation Damping

Conventionally, this problem can be partially solved by fine-tuning the parameters of power system stabilizers (PSSs) of the involved generators. However, for an interconnected bulk power system, the offline tuning of PSS parameters of different generators by a coordinated scheme may involve the regulatory entities from different regions that require high-standard cooperation and information sharing. Furthermore, many researchers proposed to use a centralized control scheme for online tuning the parameters of PSSs. However, this approach will introduce the problems of the time delay and communication cost among different interconnected areas. An alternative option for oscillation damping is to use local FACTS devices such as SVC, TCSC, and STATCOM to provide extra damping support for the power system [7]–[9]. Basically, those are passive elements/sources alleviating oscillations mainly by controlling reactive power or changing the line admittance.

Regarding using energy storage for oscillation damping, some research activities have been reported in recent literatures [10] – [16]. In [10], robust damping controllers are designed for multiple Superconducting Magnetic Energy Storage devices in a multi-machine system by solving a constrained Min-Max optimization problem. Paper [11] proposes a Particle Swarm Optimization (PSO) based oscillation damping controller optimized by heuristic dynamic programming and tested it on a two-area system with only one energy storage device. In [12], the analysis and design of a BESS controller for a two-machine system are discussed and tested, but the analysis for the general multi-machine system is not comprehensively covered. Designing the damping controller based on certain damping-torque relationships and indices is also a focused topic [13]. Those indices can be regarded as a generalization of the damping-torque coefficients in a single-machine-infinite-bus (SMIB) system and can be combined with classic residual methods [14] in designing the PSS. Regarding robust control for damping oscillation by BESS, there are two mainstreams: linear and nonlinear robust control. In [15], the LMI (Linear Matrix Inequality) method is adopted, which requires the solving of a matrix-optimization problem. In [16], the Port-Hamiltonian formulation and the related controller design method are applied on BESS to improve the transient stability of the power grid.

In this dissertation , we investigate this problem from an alternative viewpoint, i.e. symbolically solving the equations regarding eigenvalues based on

the linearized system model, and then applying the analytical results on the design of the BESS-based damping controllers.

1.3.2 Energy Storage Placement

Regarding the placement issue, most researchers investigate from the energy management viewpoint focusing on the economic benefit like minimum operating costs. For instance, in [17], the optimal siting and sizing of multiple BESSs for daily energy management of the distribution network has been studied. In [18], research was conducted for optimal scheduling and sizing of BESSs in a microgrid by the VRB (Vanadium Redox Battery) systems.

Though most efforts of the previous studies about energy storage placement have been in the economic or steady-state aspects in distribution level, fewer investigate this problem from the stability enhancement perspective for transmission power grids. In [19], a preliminary application of GA (Genetic Algorithm) is tested on the IEEE 14-bus system to determine the best installation locations of energy storage devices for power system voltage stability. However, the control parameters of the SMES are predefined and not optimized simultaneously with the locations. In [20], the control parameters are optimized by Tabu-Search while locations are fixed. The optimal BESS placement for system oscillation damping improvement has not been studied well.

Therefore, in this dissertation, we investigate the optimal BESS placement for power system oscillation damping by co-optimizing the locations and control

parameters of multiple BESS units. The Mixed-integer Particle Swarm Optimization (“Mixed-PSO” in short) method is implemented as the solver of this optimization problem.

1.4 Chapter Organization

This remainder of this dissertation is organized as follows:

In Chapter 2, the linearized state-space model for a power system with multiple BESS units is derived and the eigenvalues are solved. The solution is then used to design the controller to improve the damping ratio of a target mode to an expected value. A BESS power output model suitable for power system oscillation studies is also established based on the analysis of BESS power converters. The proposed method is tested on a SMIB system and a four-machine two-area system, respectively.

Chapter 3 formulates the optimization problem with its objective and constraints. Then, the implementation details of the simulation-based-optimization approach based on the Mixed-PSO is explained. Case studies on the New England 39-bus system and the Nordic test system are also presented, respectively.

Then, an algorithm evaluation is performed from two aspects: computational scalability regarding the number of BESS units, and the solution quality in terms of the location optimality by comparison with the results from exhaustive search. An approach to improve the searching efficiency of the

proposed Mixed-PSO placement algorithm based on the modal observability analysis is also investigated.

By the established simulation-based optimization framework, an economic analysis on the investment cost of BESS units in power systems is done. Based on the proposed cost evaluation model, the minimum number of BESS units to be placed can be determined.

To tackle the challenges of seasonal load change, a multi-scenario optimization scheme is implemented in our simulation-based optimization framework by introducing extra constraints. Case studies are then performed on two power systems. The differences between the new placement results and the old results from the original single-loading-level case are also discussed.

Finally, the performance of our proposed controller is compared with a classic PI (proportional-integral) controller. The merits of our controller are demonstrated by a case study on the New England 39-bus system.

Chapter 4 summarizes the whole work of this dissertation and some future research directions are also discussed in the end.

CHAPTER TWO

SELECTIVE DAMPING CONTROL BY BESS

This chapter is mainly based on the author's following publication: Y. Zhu, C. Liu, B. Wang, K. Sun, "Damping Control for a Target Oscillation Mode Using Battery Energy Storage," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 4, pp. 833-845, July 2018.

2.1 BESS Model for Oscillating Damping Studies

2.1.1 Power Conditioning System

Typically, a BESS includes a storage part (i.e. the battery cells) and a converter interface called PCS (Power Conditioning System) as shown in Fig. 2.1. The PCS is essentially the set of power converters used for keeping the pre-specified voltage and power output. For the BESS, PCS is typically composed of a DC/DC converter mainly used for battery charging/discharging control and a DC/AC converter (typically a voltage sourced converter) used for the AC-grid integration with the desired voltage and power output.

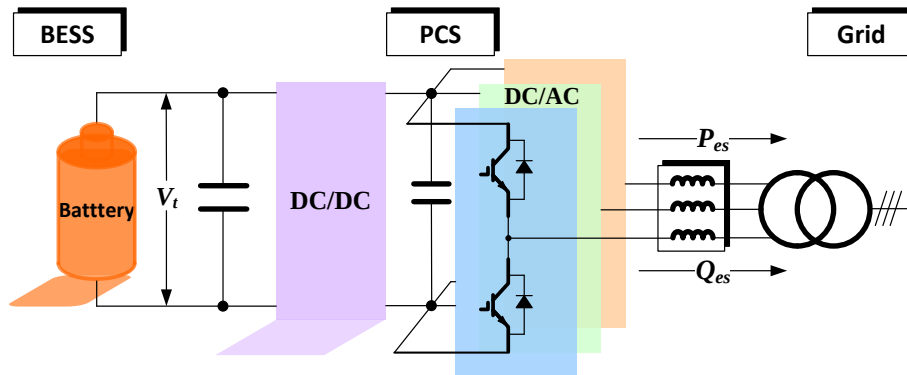


Figure 2.1. A typical topology of utility-scale BESS

A battery cell can be represented by an equivalent voltage source nonlinearly depending on its SOC (State-Of-Charge), which is equal to the remaining energy divided by its energy capacity (E_{total}) as shown in (2.1), where t_0 and t_1 are respectively the starting and ending time point for a period of discharging (when $P_{es}>0$) or charging (when $P_{es}<0$). The equivalent circuit model considering SOC is shown in Fig. 2.2.

$$SOC = 1 - \frac{\Delta E}{E_{total}}, \quad \Delta E = \int_{t_0}^t P_{es}(t) dt \quad (2.1)$$

Most grid-related control strategies are implemented in the DC/AC part, and the cell voltage is maintained by the DC/DC part or its own battery manage system (BMS) to a specific level. Therefore, in this dissertation, the BESS will be modeled as its PCS part focusing on the DC/AC part but simultaneously considering the nonlinearity of the cell via its SOC. In practice, the battery cell will be protected from deep charging or discharging for life-span considerations. The allowable SOC range is set between SOC_{min} and SOC_{max} in this dissertation. The SOC range is assumed to be 20% to 80% in this dissertation.

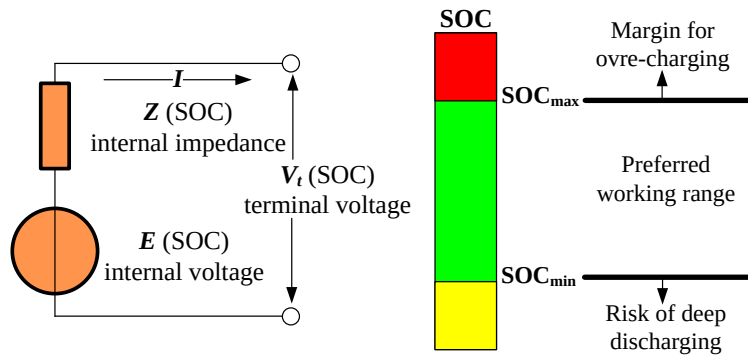


Figure 2.2. A typical topology of utility-scale BESS

For system oscillation studies, the PCS of the ES can be approximated by a first order transfer function shown in Fig. 2.3 [20] – [22]. The reason is that: in a typical P-Q decoupled control scheme in Fig. 2.3 and 2.4, the active and reactive powers can be independently regulated to their reference values. Meanwhile, the response of power electronic device (e.g. switching on or off) is typically much faster than the electromechanical dynamics of synchronous generators. The effectiveness and accuracy of this model for oscillation damping studies have been validated by experiment and analyses in [21] [22].

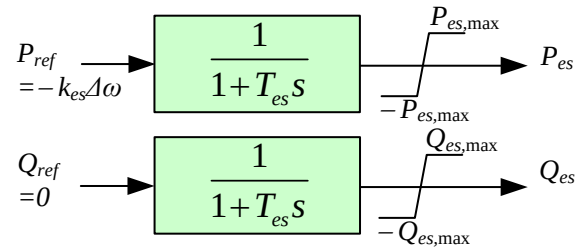


Figure 2.3. P-Q decoupled control scheme: outer-loop

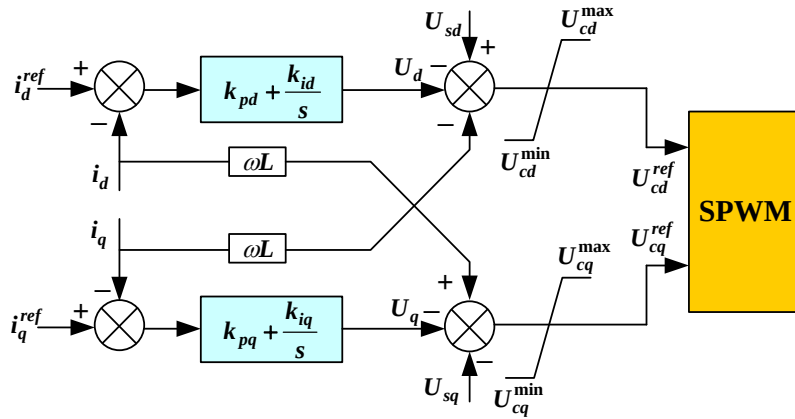


Figure 2.4. P-Q decoupled control scheme: inner-loop

The proposed damping controller mainly adjusts the active power output (positive when the battery discharges) by using a frequency deviation signal ($\Delta\omega$) while maintaining the PCS reactive power output to zero as shown in Fig. 2.3. In Fig. 2.3, the terminal bus frequency deviation ($\Delta\omega$) is used as the input signal for P_{ref} . Because for an AC system, the active power and frequency signal are typically more correlated. Thus, the speed of a generator or its terminal bus frequency is used as the input signal for P_{ref} .

In the above diagram, k_{es} (>0) is the controller gain for each BESS, which is directly associated with the objective function for optimization in the next section. T_{es} is the time constant of the BESS power converter and is set to be 0.02s in simulations. Generally, it is much smaller than the inertia time constants of large generators [22]. In addition, the energy capacity E_{total} of utility-scale BESS can range from about 2 to 300 MWh [23]. For our research, it is set to 10MWh in this dissertation. Finally, the power output model of the BESS is:

$$P_{es} = \begin{cases} \frac{P_{ref}}{1+T_{es}s}, & \text{SOC} < \text{SOC}_{\max} \text{ and } P_{ref} < 0 \\ \frac{P_{ref}}{1+T_{es}s}, & \text{SOC} > \text{SOC}_{\min} \text{ and } P_{ref} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (2.2)$$

$$P_{es} \in [-P_{es,\max}, P_{es,\max}], \quad P_{ref} = -k_{es}\Delta\omega \quad (2.3)$$

2.1.2 Effects of the Converter Time Constant

The effect of T_{es} is slightly reducing the desired damping ratio of the target mode, which will be verified in later sections. T_{es} usually ranges from 0.01s to 0.05s, depending on different specifications of the BESS. Thus, in the following section of small signal analysis, T_{es} will be set temporarily to zero during the mathematic derivation, while given as 0.05s in simulations. Since T_{es} is much smaller than the inertia time constant of a generator [22], [24], in the following analysis, the actual power output of the BESS is approximated by the power output reference, i.e.:

$$P_{es} = \frac{P_{ref}}{1 + T_{es}s} \Rightarrow P_{ref} - P_{es} = T_{es} \frac{dP_{es}}{dt} \approx 0 \Rightarrow P_{es} \approx P_{ref} = -k_{es}(\omega - 1) \quad (2.4)$$

2.2 BESS based Damping Control

2.2.1 Basic Ideas

The basic idea of the proposed damping control is a two-step procedure:

- 1) deriving the analytic relationship between the gain k_{es} in BESS damping controller and the damping ratio ξ for a target oscillation mode
- 2) implementing that gain in the outer-loop controller of the BESS placed nearby the generator's terminal bus.

In the following part, the SMIB system will be investigated first to derive the damping control algorithm. Then, the algorithm will be extended to multi-machine systems having a BESS placed near each generator.

2.2.2 BESS in the SMIB System

- Small Signal State Space Model

In Fig. 2.5, x_1 is the sum of the generator transient reactance x'_d and the transformer reactance x_T , and x is the transmission line reactance.

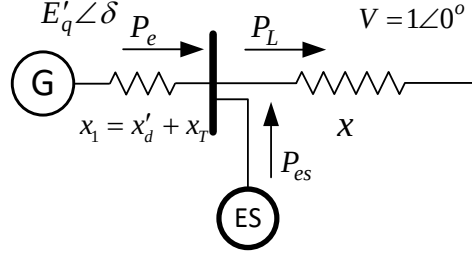


Figure 2.5. The SMIB system in Case-I

The system differential algebraic equations (DAEs) are:

$$\begin{aligned}
 \frac{d\delta}{dt} &= \Omega_0(\omega - 1) \\
 \frac{d\omega}{dt} &= \frac{1}{M}(P_m - P_e - D(\omega - 1)) \\
 P_{es} &\approx -k_{es}(\omega - 1) \\
 P_{es} + P_e &= P_L \approx \frac{E'_q V}{x} \sin \delta
 \end{aligned} \tag{2.5}$$

where, $\Omega_0 = 377$ rad/s for 60Hz system; ω is the generator angular frequency and δ is the rotor angle; E'_q is the transient q -axis voltage of the generator. P_m and P_e are the mechanic power and electric power respectively. P_{es} is the active power output of energy storage. M ($=2H$) is the generator inertia time constant. The last equation holds approximately in the SMIB system, in which the generator connected to the infinite bus by a long transmission line, i.e. $x'_d + x_T \ll x$.

Then, linearize (2.5) around the equilibrium. (Note: quantities with subscript “0” represent the steady-state value, which can be solved from the power flow solution):

$$\begin{aligned}
\frac{d\Delta\delta}{dt} &= \Omega_0 \Delta\omega \\
\frac{d\Delta\omega}{dt} &= \frac{1}{M} (\Delta P_m - \Delta P_e - D\Delta\omega) \\
\Delta P_{es} &= -k_{es} \Delta\omega \\
\Delta P_{es} + \Delta P_e &= \Delta P_L \approx \frac{E'_{q0} V}{X} \cos \delta_0 \Delta\delta
\end{aligned} \tag{2.6}$$

Linearize ΔP_e w.r.t. two state variables $\Delta\delta$ and $\Delta\omega$:

$$\Delta P_e = K_1 \Delta\delta + K_2 \Delta\omega \tag{2.7}$$

where K_1 and K_2 are constant coefficients to be determined. Substitute them into the swing equation (2.6) leads to:

$$\frac{d\Delta\omega}{dt} = \frac{1}{M} (\Delta P_m - K_1 \Delta\delta - K_2 \Delta\omega - D\Delta\omega) \tag{2.8}$$

Apply Laplace transformation to the swing equation and assume the mechanical power input of generator does not change, i.e. $\Delta P_m = 0$ [24]:

$$\begin{aligned}
s\Delta\delta(s) &= \Omega_0 \Delta\omega(s) \\
s\Delta\omega(s) &= \frac{1}{M} (-K_1 \Delta\delta - K_2 \Delta\omega - D\Delta\omega)
\end{aligned} \tag{2.9}$$

Then, the characteristic equation is:

$$s^2 + \Omega_0 \frac{(D + K_2)}{M} s + \Omega_0 \frac{K_1}{M} = 0 \tag{2.10}$$

Compare it with the standard characteristic equation of a second-order system,

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \quad (2.11)$$

It gives:

$$\omega_n = \sqrt{\frac{\Omega_0 K_1}{M}}, \quad \xi = \frac{D + K_2}{2M\omega_n} \quad (2.12)$$

Then, consider $M = 2H$ in the above expression, we have:

$$\xi = \frac{D + K_2}{4H\omega_n} \quad (2.13)$$

In practice, D needs to be estimated from real system data [25]. For simulation studies, it can be treated as zero if generation and load are modeled in detail [24], [26]. Consider $D = 0$ here, then:

$$K_2 = 4H\omega_n\xi = 8\pi f_n H\xi \quad (2.14)$$

Therefore, the damping ratio ξ is related to K_2 , i.e. the partial derivative of P_e to ω .

From the last equation in (2.6), it can lead to:

$$\Delta P_e \approx \frac{E'_{q0} V}{X} \cos \delta_0 \Delta \delta - \Delta P_{es} \approx \frac{E'_{q0} V}{X} \cos \delta_0 \Delta \delta + k_{es} \Delta \omega \quad (2.15)$$

Thus, by (2.14) and (3.15) the relationship between ξ and k_{es} is:

$$k_{es} = K_2 = 8\pi f_n H\xi \quad (2.16)$$

- BESS at General Locations

Now consider a more general case. Here, $x_1 = x'_d + x_T + x_{line-1}$, $x_2 = x_{line-2}$,

where $x_{line-1} + x_{line-2} = x$ (i.e. the total reactance of the previous transmission line).

The single-line-diagram is shown in Fig. 2.6.

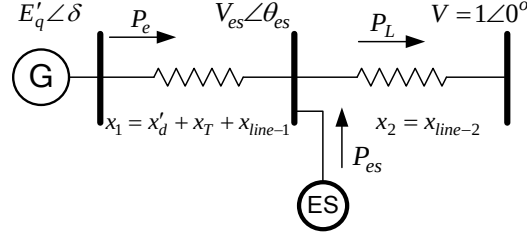


Figure 2.6. The SMIB system with BESS in Case-II

The following (2.17) and (2.18) can be derived based on the power balance equation.

$$P_e = \frac{E'_q V_{es} \sin(\delta - \theta)}{x_1} = \frac{V_{es} V}{x_2} \sin \theta - P_{es} \quad (2.17)$$

$$[E'_q V_{es} \cos(\delta - \theta) - V_{es}^2] x_2 = x_1 [V_{es}^2 - V_{es} V \cos \theta] \quad (2.18)$$

By linearizing (2.17) and (2.18), the following expression is finally obtained after some manipulation:

$$\Delta P_e = K_7 \Delta \delta + K_8 \Delta P_{es} = K_7 \Delta \delta - K_8 k_{es} \Delta \omega \quad (2.19)$$

The coefficient K_8 can be named as the “location effect constant” and its expression is given in (2.20).

$$K_8 = \frac{-E'_q x_2 (E'_q x_2 + V x_1 \cos \delta_0 - 2V_{es0} (x_1 + x_2) \cos(\delta_0 - \theta_0))}{E_q'^2 x_2^2 + V^2 x_1^2 - 2E'_q V_{es0} x_2^2 \cos(\delta_0 - \theta_0) + 2E'_q V x_2 x_1 \cos \delta_0 - 2V_{es0} V (x_1 + x_2) x_1 \cos \theta_0} \quad (2.20)$$

Then, to check the correctness of this formula for Case-I, letting $x_1 = 0$ and K_8 becomes -1 as shown in (2.21) and (2.22).

$$K_8 = \frac{-E'_q x_2^2 (E'_q - 2V_{es0} \cos(\delta_0 - \theta_0))}{E_q'^2 x_2^2 - 2E'_q V_{es0} x_2^2 \cos(\delta_0 - \theta_0)} = -\frac{E_q'^2 x_2^2 - 2E'_q V_{es0} x_2^2 \cos(\delta_0 - \theta_0)}{E_q'^2 x_2^2 - 2E'_q V_{es0} x_2^2 \cos(\delta_0 - \theta_0)} = -1 \quad (2.21)$$

$$\Delta P_e = K_7 \Delta \delta - \Delta P_{es} = K_7 \Delta \delta + k_{es} \Delta \omega \quad (2.22)$$

It can be noticed that in (2.22), the coefficient of $\Delta \omega$ is exactly the same as that in Case-I when neglecting x_1 . Finally, k_{es} is given by:

$$\xi = \frac{K_2}{4H\omega_n} = \frac{-K_8 k_{es}}{4H\omega_n} \Rightarrow k_{es} = \frac{8\pi f_n H \xi}{-K_8} \quad (2.23)$$

To investigate the impact of the BESS installing location, denote $k = x_1/(x_1+x_2)$. δ is the rotor angle of the generator, typically within $[-\pi/2, \pi/2]$ [24]; E'_q , is the generator transient q -axis voltage with a typical range $[0.5, 2.5]$. Fig. 2.7 depicts how $-K_8$ changes w.r.t. k for different combinations of δ and E'_q . $-K_8$ achieves its maximum value 1.0 at $x_1=0$. When the specified damping ratio ξ is given, the larger $-K_8$ leads to smaller k_{es} .

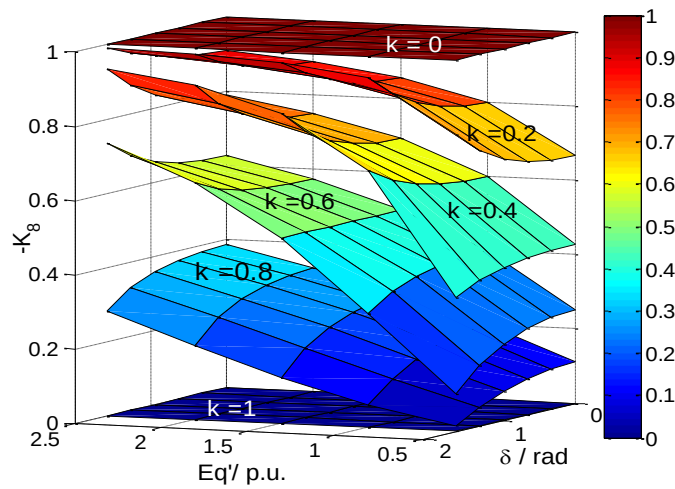


Figure 2.7. $-K_8$ versus different pairs of δ and E'_q under different line ratio k

Since k_{es} represents the BESS energy injection/absorption per unit time, a smaller k_{es} means a smaller BESS discharge/charge depth. This will be more attractive for utility companies and system planners, i.e. the BESS can be used as an ancillary service for oscillation damping with lower energy cost.

2.2.3 BESS in the Multi-Machine System

- Small Signal State Space Model

In an n -generator system, similar to the SMIB case, the BESS device can be installed at the terminal buses or nearby buses of generators. As shown in Fig. 2.8, P_{ei} , P_{esi} , P_{gi} are the electromagnetic power, the BESS output power and active power output of the i -th generator respectively.

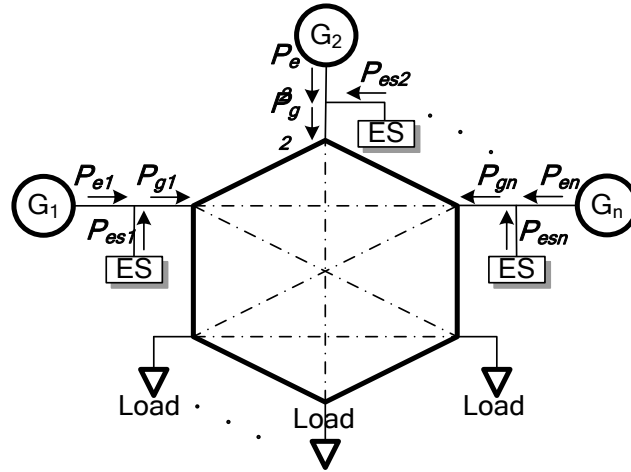


Figure 2.8. Multi-machine system with BESS integration

Apply the reduced network technique [26] by keeping only the generator buses, the system model is:

$$\begin{cases} \frac{d\delta}{dt} = \Omega(\omega - 1) \\ \frac{d\omega}{dt} = \mathbf{M}^{-1}(\mathbf{P}_m - \mathbf{P}_e - \mathbf{D}(\omega - 1)) \\ \mathbf{P}_e = \mathbf{P}_g - \mathbf{P}_{es} \end{cases} \quad (2.24)$$

Where

$$\begin{aligned} \mathbf{M}^{-1} &= \mathbf{diag}[M_i^{-1}]_{n \times n}, \quad \Omega = \mathbf{diag}[\Omega_0]_{n \times n} \\ \delta &= [\delta_i]_{n \times 1} : rad, \quad \omega = [\omega_i]_{n \times 1} : p.u. \\ \mathbf{P}_e &= [P_{ei}]_{n \times 1}, \quad \mathbf{P}_m = [P_{mi}]_{n \times 1}, \quad \mathbf{P}_{es} = [P_{esi}]_{n \times 1}, \quad \mathbf{P}_g = [P_{gi}]_{n \times 1} \\ \mathbf{D} &= \mathbf{diag}(D_1, D_2, \dots, D_n) \end{aligned}$$

D_i is the damping constant for the i -th generator. P_{gi} can be approximately expressed by [26]:

$$P_{gi} = E_i^2 G_{ii} + E_i \sum_{j=1, j \neq i}^n E_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \quad (2.25)$$

where, G_{ij} and B_{ij} are the real and imaginary part of the Y_{ij} in the reduced nodal admittance matrix [24] [27]. Power outputs of BESSs in a compact form are:

$$P_{esi} = -k_{esi} \Delta \omega_i \Rightarrow \mathbf{P}_{es} = -\mathbf{K}_{es} \Delta \omega \quad (2.26)$$

Where, $\mathbf{K}_{es} = \mathbf{diag}[k_{esi}]_{n \times n}$, ($k_{esi} \geq 0$)

Then, linearize the above equations around the equilibrium point:

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \end{bmatrix} = \begin{bmatrix} \mathbf{O} & \mathbf{\Omega} \\ -\mathbf{M}^{-1} \mathbf{J}_p(\delta\delta) & -\mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es}) \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \end{bmatrix} \quad (2.27)$$

Here, the Jacobian matrix $\mathbf{J}_p$ is:

$$\mathbf{J}_p(\boldsymbol{\delta}) = \frac{\partial(P_{e1}, P_{e2}, \dots, P_{en})}{\partial(\delta_1, \delta_2, \dots, \delta_n)} \bigg|_{\delta_i = \delta_{i0}} = \begin{pmatrix} \frac{\partial P_{e1}}{\partial \delta_1} & \dots & \frac{\partial P_{e1}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_{en}}{\partial \delta_1} & \dots & \frac{\partial P_{en}}{\partial \delta_n} \end{pmatrix} \bigg|_{\delta_i = \delta_{i0}} \quad (2.28)$$

- Analytic Eigenvalue Solutions

Step-1: Determinant simplification

From above section, the $2n$ -by- $2n$ system matrix $\mathbf{A}$ is:

$$\mathbf{A} = \begin{pmatrix} \mathbf{O} & \mathbf{\Omega} \\ -\mathbf{M}^{-1}\mathbf{J}_p & -\mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es}) \end{pmatrix} \quad (2.29)$$

the eigenvalues λ are the roots of the determinant equation:

$$\det(\lambda \mathbf{I} - \mathbf{A}) = \det \begin{pmatrix} \lambda \mathbf{I} & -\mathbf{\Omega} \\ \mathbf{M}^{-1}\mathbf{J}_p & \lambda \mathbf{I} + \mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es}) \end{pmatrix} \quad (2.30)$$

where, $\mathbf{I}$ is the identity matrix of n -by- n .

Then the following block matrix lemma will be utilized to get the analytic solution. Its proof can be found in [28]:

Lemma: For matrix $\mathbf{M} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix}$, if $\mathbf{CD} = \mathbf{DC}$, then

$$\det \mathbf{M} = \det(\mathbf{AD} - \mathbf{BC})$$

To apply this lemma to (2.31), it requires:

$$\begin{aligned} \mathbf{M}^{-1}\mathbf{J}_p(\lambda \mathbf{I} + \mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es})) &= (\lambda \mathbf{I} + \mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es}))\mathbf{M}^{-1}\mathbf{J}_p \\ \Rightarrow \mathbf{M}^{-1}\mathbf{J}_p\mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es}) &= \mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es})\mathbf{M}^{-1}\mathbf{J}_p \end{aligned} \quad (2.31)$$

Denoting $\mathbf{S} = \mathbf{M}^{-1}(\mathbf{D} + \mathbf{K}_{es})$, it is easy to see that $\mathbf{S}$ is a diagonal. If $\mathbf{S}$ is equal-diagonal, i.e. $\mathbf{S} = \text{diag}[S]_{n \times n}$:

$$\frac{(D_1 + k_{es,1})}{M_1} = \frac{(D_2 + k_{es,2})}{M_2} = \dots = \frac{(D_n + k_{es,n})}{M_n} = S \quad (2.32)$$

Then, it is easy to verify that (2.31) can hold.

Thus finally, (2.33) is obtained:

$$\det(\lambda \mathbf{I} - \mathbf{A}) = \det((\lambda^2 + \lambda S) \mathbf{I} + \Omega_0 \mathbf{M}^{-1} \mathbf{J}_p) \quad (2.33)$$

For matrix product $\mathbf{M}^{-1} \mathbf{J}_p$, by eigenvalue or singular value decomposition [25], it can be transformed to:

$$\mathbf{M}^{-1} \mathbf{J}_p = \mathbf{T}^{-1} \mathbf{\Lambda} \mathbf{T}, \quad \mathbf{\Lambda} = \begin{pmatrix} \mu_1 & & \\ & \ddots & \\ & & \mu_n \end{pmatrix} \quad (2.34)$$

where, μ_i is the eigenvalue of $\mathbf{M}^{-1} \mathbf{J}_p$. The real matrix $\mathbf{J}_p$ is semi-definite and nearly symmetric [14]. $\mathbf{M}^{-1}$ is diagonal. By matrix theory, each μ_i is a real non-negative number and the above diagonalization process can be guaranteed [28].

Step-2: Analytic solution of each eigenvalue

Apply the *Laplace* Theorem [28] for the determinant of product matrices on

(2.33):

$$\begin{aligned} \det(\lambda \mathbf{I} - \mathbf{A}) &= \det(\mathbf{T}^{-1}) \det((\lambda^2 + \lambda S) \mathbf{I} + \Omega_0 \mathbf{\Lambda}) \det(\mathbf{T}) \\ &= \det(\mathbf{T}^{-1}) \det(\mathbf{T}) \det((\lambda^2 + \lambda S) \mathbf{I} + \Omega_0 \mathbf{\Lambda}) \\ &= \det(\underbrace{(\lambda^2 + \lambda S) \mathbf{I} + \Omega_0 \mathbf{\Lambda}}_{\text{diagonal}}) = \prod_i^n (\lambda^2 + \lambda S + \Omega_0 \mu_i) \end{aligned} \quad (2.35)$$

Thus, eigenvalues of the original system are the roots for each of the above n quadratic equations, i.e.:

$$\lambda = \frac{-S \pm \sqrt{S^2 - 4\Omega_0\mu_i}}{2} \quad (2.36)$$

Furthermore:

If $S^2 - 4\Omega_0\mu_i \geq 0, \lambda \in R$

If $S^2 - 4\Omega_0\mu_i < 0 \Rightarrow$ complex roots ($\mu_i > 0$):

$$\lambda_i = \frac{-S \pm j\sqrt{4\Omega_0\mu_i - S^2}}{2} \Leftrightarrow \sigma_i \pm j\omega_{di} = -\xi_i\omega_{ni} \pm j\sqrt{1-\xi_i^2}\omega_{ni} \Rightarrow$$

$$\begin{cases} \xi_i = S/(2\sqrt{\Omega_0\mu_i}), S = 2\xi_i\sqrt{\Omega_0\mu_i} = 2\xi_i\omega_{ni} \\ \omega_{di} = \sqrt{4\Omega_0\mu_i - S^2}/2 \end{cases} \quad (2.37)$$

Step-3: Calculate k_{esi}

To make (2.32) hold, suppose the k th mode is our target mode (this can be easily identified by its natural oscillation frequency ω_{nk}). Then by (2.37), and substitute $S=2\xi_k\omega_{nk}$ into (2.32):

$$\frac{D_i + k_{esi}}{M_i} = 2\xi_k\omega_{nk} \Rightarrow k_{esi} = 4H_i\xi_k\omega_{nk} - D_i, (i=1,\dots,n) \quad (2.38)$$

Especially, when $D_i = 0 \Rightarrow k_{esi} = 4H_i\xi_k\omega_{nk}$.

2.3 Case Studies

2.3.1 SMIB System

To test the proposed method for the general location case, the system parameter for the SMIB system are: $x_1 = x'_d + x_{T1} = 0.05 + 0.10 = 0.15$, $x_2 = 0.35$, $k = x_1 / (x_1 + x_2) = 0.3$, i.e. about 1/3 of the electric distance between generator and infinity bus. Note that here x_1 is not much smaller than x_2 . Mechanical input power $P_m = 1.0$ p.u., $D = 0$ and the nominal frequency $f_0 = 60$ Hz. $K_8 = 0.71898$ by (2.20).

Two groups of tests on the SMIB system with different generator inertia parameters ($H=5$ s and $H=10$ s) are performed with the BESS device targeting at 5% damping ratio. A three-phase fault is applied at 1 sec and cleared at 1.1 sec. *Prony* analysis is used to estimate the actual damping ratio from generator angle and speed waveforms. The results can closely match the expected damping ratio as shown in Table 2.1. Note that a damping ratio of 5% is usually enough for power system operations; here the test runs from 5% to 40% just to test the derived formula by simulations.

Table 2.1. Control performance of BESS in SMIB Case-II

<i>Expected damping ratio</i>	<i>Actual damping ratio from Prony analysis ($H=5$s) and k_{es} value</i>		<i>Actual damping ratio from Prony analysis ($H=10$s) and k_{es} value</i>	
5%	5.009%	11.518	5.015%	20.036
10%	10.03%	23.036	10.072%	46.072
20%	20.16%	46.072	20.310%	92.144
30%	30.37%	69.108	30.134%	138.22
40%	40.21%	92.144	40.17%	184.29

Then, Fig. 2.9 illustrates the 20% damping ratio case to compare with the original system without BESS.

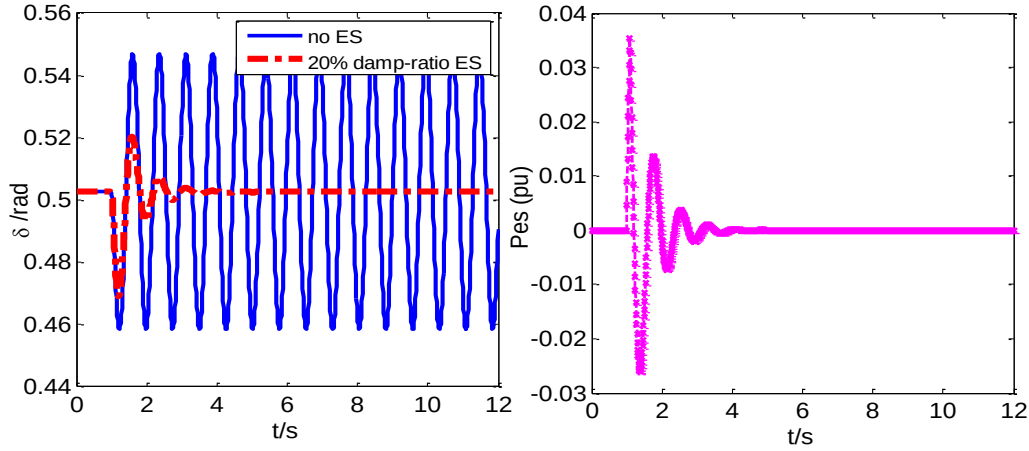


Figure 2.9. Simulation plots for SMIB with 20% damping ratio control

If the impact of T_{es} , i.e. the converter time constant, is considered, generally it will slightly reduce the expected damping ratio. In real power converters, T_{es} can be up to 50ms. Consider the worst case here i.e. $T_{es} = 50\text{ms}$. The result is listed in Table 2.2 for the case with $H = 5\text{s}$:

Table 2.2. Effect of the converter time constants T_{es}

<i>Expected damping ratio</i>	<i>Actual damping ratio from Prony analysis ($T_{es}=50\text{ms}$) and k_{es}</i>		<i>Actual damping ratio from Prony analysis ($T_{es}=0$) and k_{es}</i>	
5%	4.565%	11.518	5.009%	11.518
10%	9.299%	23.036	10.03%	23.036
20%	19.26%	46.072	20.16%	46.072
30%	30.03%	69.108	30.37%	69.108
40%	40.16%	92.144	40.21%	92.144

From Table 2.2, the maximum reduction of damping ratio is only 20.16%
 $-19.26\% = 0.009$ for 20% case, so the negative impact of T_{es} is not severe for the

proposed control method. A comparison on the active power outputs of the BESS for $\xi = 20\%$ is shown in Fig.2.10.

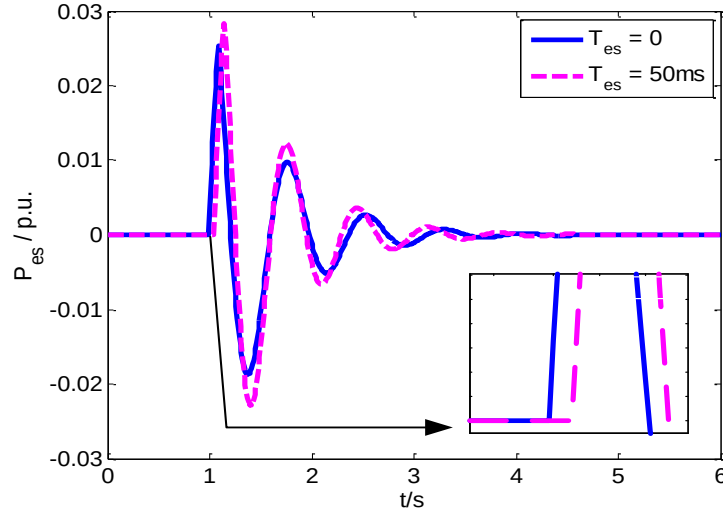


Figure 2.10. Comparison of BESS active power response considering T_{es}

2.3.2 Two-Area System

In this section, the Kundur's two-area system model [24] is used to investigate the performance of the proposed method on a multi-machine power system. The single line diagram is shown in Fig.2.11. The battery storage device is modeled by the DIgSILENT Simulation Language (DSL) [29].

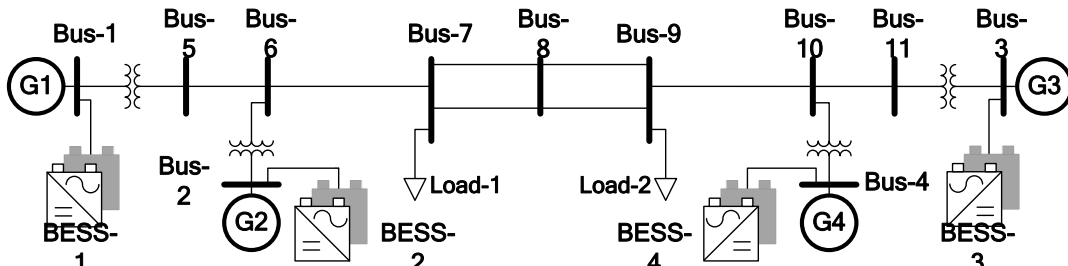


Figure 2.11. Single line diagram of the Kundur two area system

The simulation model is built in DIgSILENT/PowerFactory as shown in Fig.2.12.

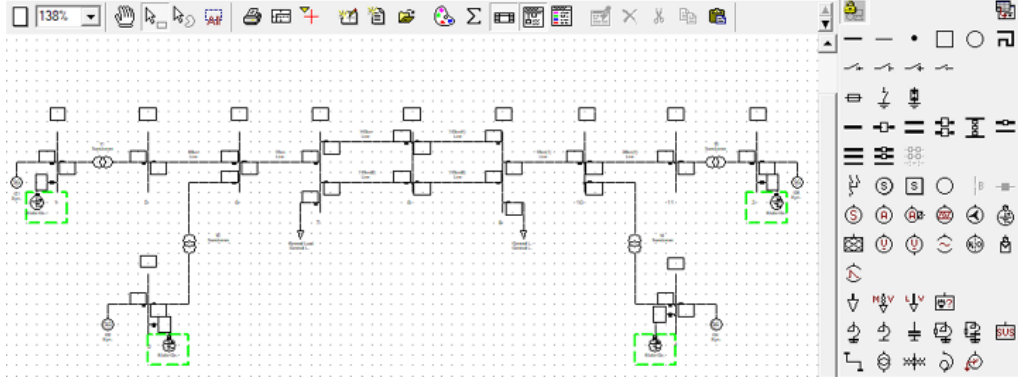


Figure 2.12. Simulation model in DIgSILENT/PowerFactory

By modal analysis, the system has three oscillation modes: 1) 0.548Hz with a damping ratio of 4.38%, is an inter-area mode between Area-1 (G1, G2) and Area-2 (G3, G4); 2) 1.002Hz with a damping ratio of 4.86% and 3) 1.036Hz with a damping ratio of 4.92%. The last two are local modes. The 0.548Hz mode has the weakest damping, so its damping ratio needs to be improved. In simulation, a temporary three-phase ground fault is added at bus-8 at 2 sec and cleared after 0.02 sec. The objective damping ratio is set to 5%. By formula (2.38), the k_{esi} ($i=1 \sim 4$) is:

$$k_{esi} = 4H_i \xi_1^* \sqrt{\Omega_0 \mu_1} - D_i \approx 4H_i \omega_{n1} \Delta \xi_1, \quad \Delta \xi_1 = (\xi_1^* - \xi_1) \quad (2.39)$$

where, $\xi_1^* = 5\%$ and ξ_1 is 4.38%, $\omega_{n1} = 2\pi f_{n1}$ is the natural oscillation frequency for mode-1, i.e. the target mode.

- Adding BESS in the Original System

Four BESS units are placed in the above four-area system. Then the damping ratios of all the three modes have been calculated. Control effects on those three interarea modes are shown in Table 2.3. It can be observed that the damping ratios of all the three modes have been improved. The improvement for the target mode is the most significant and reaches the 5% goal.

Table 2.3. Control effect of BESS on each mode

<i>Oscillation Modes</i>	<i>Without BESS</i>		<i>With BESS</i>	
	<i>Damping ratio</i>	<i>Freq.(Hz)</i>	<i>Damping ratio</i>	<i>Freq.(Hz)</i>
0.548Hz	4.38%	0.54865	5.04%	0.54857
1.002Hz	4.86%	1.00218	5.00%	1.00205
1.036HZ	4.92%	1.03642	5.06%	1.03628

In Table 2.4, the performance of the proposed method is tested for expected damping ratios changing from 5% to 10%. Each result is close to the expectation.

Table 2.4. Control performance test for target mode with BESS

<i>Expected damping ratio</i>	<i>Actual Damping ratio of target mode</i>	<i>Actual Frequency of target mode (Hz)</i>
5%	5.04%	0.549
6%	5.99%	0.548
7%	6.93%	0.548
8%	7.89%	0.548
9%	8.84%	0.548
10%	9.79%	0.547

- Impact of the Converter Power Limit

Either for the sake of protecting the power switch device due to their thermal limits or other technical reasons, a realistic power converter will have a power limit,

which may have impact on the control effect of the proposed method. On the other hand, utility-scale power converter output levels have been improved in recent years allowing the maximum power limit to reach 5MW for single utility scale power converter [23] [30]. If considering aggregating configuration of multi-converters like energy storage systems in a wind farm or a substation-level battery park, the overall power output level can be as large as 100MW [23].

To investigate the power limit impact on the proposed control, similar tests are done with results listed in Table 2.5.

Table 2.5. Control performance test considering BESS power limit

<i>Expected damping ratio</i>	<i>Actual Damping ratio of target mode</i>	<i>Actual Frequency of target mode (Hz)</i>
5%	4.99%	0.548
6%	5.92%	0.548
7%	6.92%	0.547
8%	7.84%	0.547
9%	8.79%	0.547
10%	9.71%	0.546

To visually inspect the nonlinear effect of converter power limit, the following case study is presented with a 10% damping ratio requirement for the target mode. Typically, that means more and faster energy injection/absorption from the BESS than 5% damping ratio requirement. The power limit is set to 3MW for each BESS.

The BESS power output result is shown in Fig. 2.13 (in the plot, y-axis is $-P_{es}$). From the plots, it shows that each BESS is in charging state nearly all the time during this disturbance. The relative generator rotor angles are shown in Fig. 2.14.

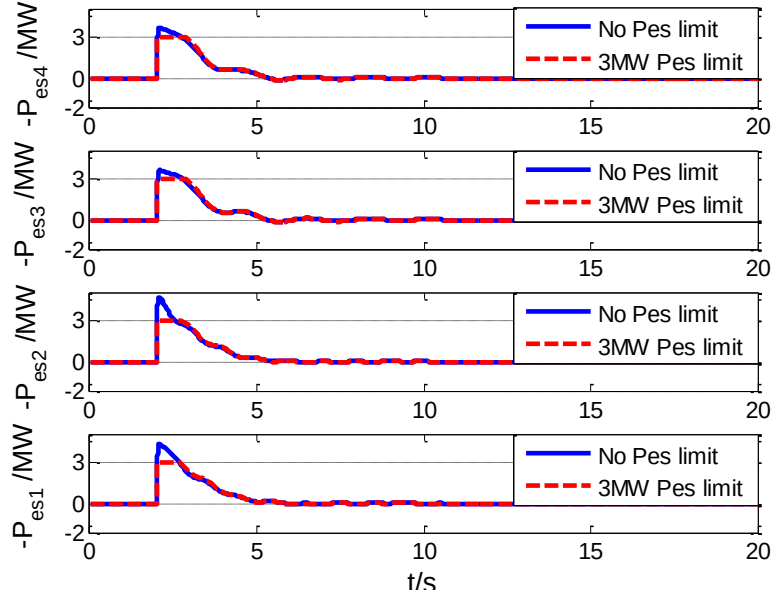


Figure 2.13. BESS active power responses for $\xi = 10\%$ in Kundur system

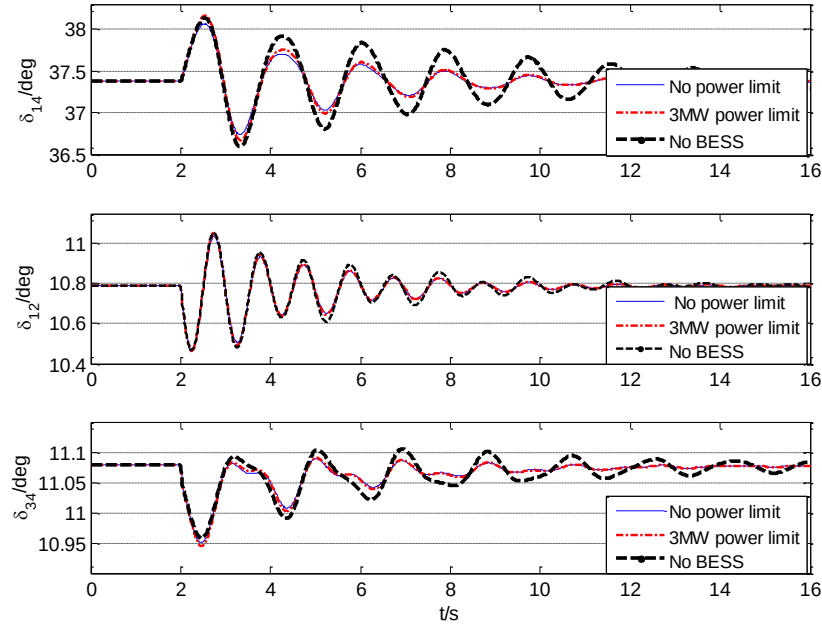


Figure 2.14. Relative generator rotor angles for $\xi^* = 10\%$ in Kundur system

Gen-1 and Gen-4 belong to different areas. Thus, δ_{14} mainly reflects the target mode at 0.548Hz; the other two modes (1.002Hz and 1.036Hz) are mainly caused by oscillations between local generators inside each area, as shown by δ_{12} and δ_{34} respectively. Damping improvement for δ_{14} is the most significant. The damping ratios for other two relative angles are also improved. This phenomenon verifies the control effect and is in consistence with the previous modal analysis result.

- Impact of the Converter Time Constant

Like the previous study in SMIB case, the converter time constant T_{es} is set to 50ms. To better demonstrate the impact of T_{es} , no converter power limit is assumed here. Results are shown in Table 2.6.

Table 2.6. Control performance test considering time constant T_{es}

<i>Expected damping ratio</i>	$T_{es} = 50ms$		$T_{es} = 0ms$	
	<i>Damping ratio</i>	<i>Freq.(Hz)</i>	<i>Damping ratio</i>	<i>Freq.(Hz)</i>
5%	5.029%	0.549	5.04%	0.549
6%	5.951%	0.550	5.99%	0.548
7%	6.888%	0.551	6.93%	0.548
8%	7.819%	0.551	7.89%	0.548
9%	8.753%	0.552	8.84%	0.548
10%	9.688%	0.553	9.79%	0.547

In Table 2.6, as expected, the effect of T_{es} is to slightly lower down the damping ratio, and its largest error is only $9.79\% - 9.688\% \approx 0.001$. This magnitude of error is acceptable in practical power system operations. This result

again validates the assumption that, in the proposed method, the converter time constant can be ignored during the analytic formula derivation with small errors introduced. In Table 2.7, effect on each mode is listed. It shows that the target mode can meet the 5% damping ratio goal with other modes slightly improved.

Table 2.7. Effect of the converter time constant T_{es} on each mode

Oscillation Modes	Before control		After control ($T_{es}=50ms$)	
	Damping ratio	Freq.(Hz)	Damping ratio	Freq.(Hz)
0.548Hz	4.38%	0.54865	5.029%	0.549
1.002Hz	4.86%	1.00218	4.997%	1.002
1.036HZ	4.92%	1.03642	5.053%	1.037

The BESS power responses are shown in Fig. 2.15.

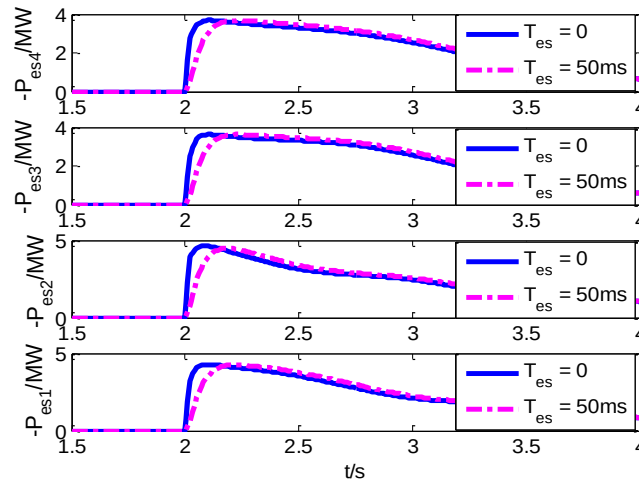


Figure 2.15. Zoom-in plot of BESS active power responses when $T_{es} = 50ms$

- Error Analysis

The Absolute Percentage Error (APE) of the damping ratio ($|\Delta e| = |\xi - \xi^*| / |\xi^*|$) for the above three cases are compared in Fig. 2.16, from which there are following

observations: 1) the APE for each case is below 5% which can satisfy practical engineering needs 2) the power converter time constant T_{es} has slightly more influence on the accuracy of the proposed method than other factors, because in the second subplot of Fig. 2.16, the APE for the three cases are respectively 1.20%, 1.65% and 1.85%, where the APE of case-c considering T_{es} is the largest 3) the APE will slightly increase with the increase of the desired damping ratio. This can be explained because the proposed BESS controller is essentially a linear type. For most systems, a 5% to 10% damping ratio will be sufficient and reasonable for small-signal stability.

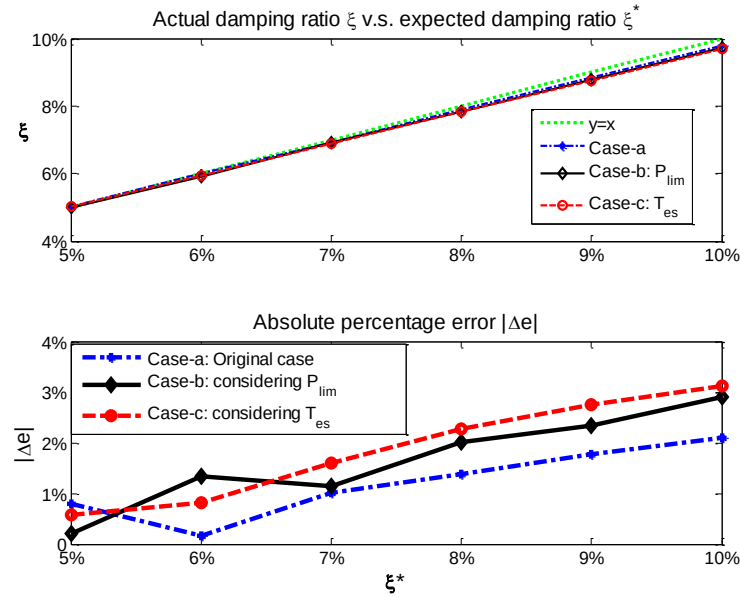


Figure 2.16. Performance comparison and error analysis

- Case Study on a Power System with PSSs

In a real power system, there could be multiple existing PSSs for oscillation damping control. To investigate the damping improvement by the proposed BESS controller on such a system, each generator in the two-area system is equipped

with a PSS. All PSSs are designed to make the damping ratio of the target mode reach 4.99% without BESS. Suppose that a higher damping ratio is expected by adding the proposed controller. Then, the new damping ratio goal is set from 6% to 10%, respectively, to design the controller based on (3.38).

The test results are in Table 2.8. The APE of the damping ratio is depicted in Fig. 2.17, which are all less than 2%. Note that here ξ_1 in (3.38) becomes 4.99%, so the calculated value of k_{es} is smaller than its values in previous case studies without a PSS. Since the k_{es} can be interpreted as the power output coefficient of the BESS converter during the disturbance, a smaller k_{es} means a smaller converter capacity required for the BESS. Since the converter capacity takes a major portion of the overall cost of a BESS, the investment on the BESS for damping control in a power system that already has PSSs can be decreased.

Table 2.8. Test results on a power system having PSS

<i>Expected damping ratio</i>	<i>Actual Damping ratio of target mode</i>	<i>Actual Frequency of target mode (Hz)</i>
6%	5.97%	0.543
7%	6.93%	0.542
8%	7.90%	0.542
9%	8.86%	0.542
10%	9.82%	0.542

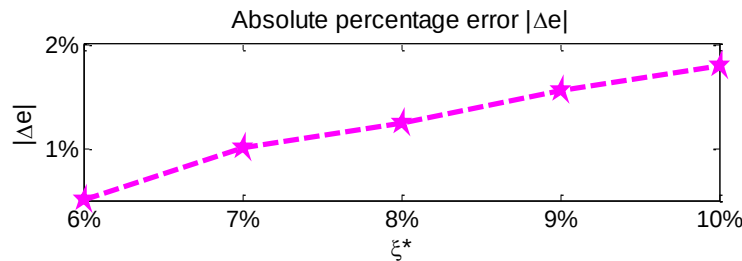


Figure 2.17. Error analysis for BESS damping control considering PSS

- Impact on the Battery SOC

Consider the worst case in subsection-b, i.e. with 3MW converter power limit for each BESS and 10% damping ratio requirement for the target mode. In Fig. 2.13, it is observed that the battery is mainly charged during the disturbance. The energy charged is nothing but the area under the power (absorption) curve during disturbance as shown in Fig. 2.18 of the zoom-in plot for $-P_{es4}$.

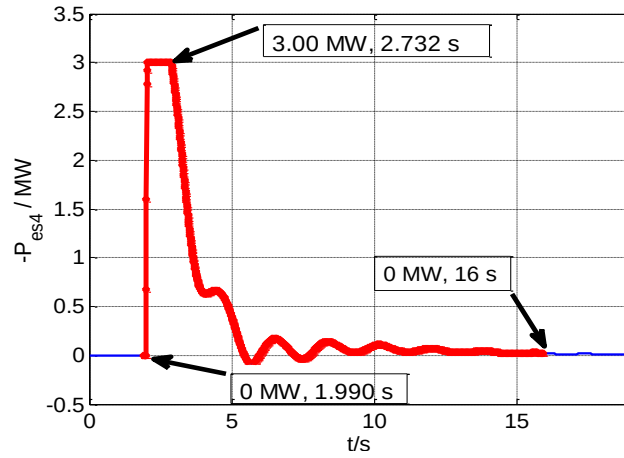


Figure 2.18. Zoom-in plot of BESS-4 active power response

For example, for BESS-4, the energy absorbed is:

$$E_{es4} = \int_{t_0=1.99}^{t=16.0} P_{es4}(t) dt = 5.6483 \text{ MJ} \Leftrightarrow 0.0016 \text{ MWh}$$

To evaluate the impact on SOC, assume a small energy capacity for BESS-4 (SOCs of other three BESS units can be calculated similarly) as 0.5MWh (in utility scale BESS, this value can be much larger [23]). Then the depth of charge = $0.0016/0.5 = 0.0032$.

Assume the range of SOC is limited to [0.2, 0.8], then, the new maximum and minimum theoretical SOC values at the end of this oscillation process are respectively:

$SOC_{new_max} = 0.8 + 0.0032 = 0.8032$, and the relatively change is only:
 $0.0032/0.8 = 0.4\%$;

$SOC_{new_min} = 0.2 + 0.0032 = 0.2032$, and the relatively change is only:
 $0.0032/0.2 = 1.6\%$.

Thus, in both cases the impact on SOC is small, implying that using a BESS for oscillation damping may not weaken its available capacity for other functions like load following/balancing because the energy provided/absorbed by oscillation is much smaller than the total BESS capacity during disturbance. Moreover, a small portion of energy means potentially a low cost in using BESS for damping oscillation. Due to this fact, the BESS is very promising as a new kind of ancillary service in providing auxiliary damping when needed.

2.4 Conclusion

In this chapter, we proposed a novel damping control method based on the usage of BESS. Analytic eigenvalue solutions were derived on both the SMIB and multi-machine systems. Controller based on those solutions was verified successfully by simulation. The results demonstrated a promising performance in damping target oscillation mode with quantifiable improvement of damping ratio.

Thus, to alleviate system oscillations by providing extra damping support based on the proposed method is validated.

The candidate locations are limited to generator buses as in this chapter. When this limitation is relaxed, i.e. any non-generator buses can be also considered, then an optimization framework is needed which will be discussed in the following chapters.

CHAPTER THREE OPTIMIZATION OF BESS LOCATIONS AND PARAMETERS

This chapter is mainly based on the author's following publication: Y. Zhu, C. Liu, K. Sun, D. Shi, Z. Wang, "Optimization of Battery Energy Storage to Improve Power System Oscillation Damping," IEEE Trans. Sustainable Energy, in press, doi: 10.1109/TSTE.2018.2858262.

3.1 Single Scenario Optimization

3.1.1 Problem Formulation

Recap the BESS model in Chapter 2 here:

$$P_{es} = \begin{cases} \frac{P_{ref}}{1+T_{es}s}, & \text{SOC} < \text{SOC}_{\max} \text{ and } P_{ref} < 0 \\ \frac{P_{ref}}{1+T_{es}s}, & \text{SOC} > \text{SOC}_{\min} \text{ and } P_{ref} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (2.2)$$

$$P_{es} \in [-P_{es,\max}, P_{es,\max}], \quad P_{ref} = -k_{es}\Delta\omega \quad (2.3)$$

The overall formulation of the optimization problem in this chapter is given by:

$$\min_{z_i, k_{esi}} Obj = \sum_{i=1}^N z_i k_{esi} \quad (3.1)$$

$$\text{s.t.} \quad \sum_{i=1}^N z_i = N_{es} \quad z_i \in \{0, 1\} \quad (3.2)$$

$$\zeta_k \geq \zeta_k^* \quad (3.3)$$

$$\Delta\zeta_i \geq 0 \quad i = 1, 2, \dots, n \quad (3.4)$$

$$k_{es,\min} \leq k_{esi} \leq k_{es,\max} \quad i = 1, 2, \dots, N_{es} \quad (3.5)$$

- Objective Function

The interpretation for the objective function is: for an acceptable frequency deviation during power system oscillation, k_{es} directly tells the theoretically maximum power of DC/AC converter used for damping improvement. Therefore, the objective here is to minimize the sum of k_{es} values of all the BESSs:

$$Obj = \sum_{i=1}^N z_i k_{esi} \quad (3.6)$$

where, z_i is a binary variable equal to 1 if and only if a BESS is placed at the i -th bus.

- Constraints

The explanations for the constraints considered here:

1) The total number of BESS is given, i.e.

$$\sum_{i=1}^N z_i = N_{es}, \quad z_i \in \{0,1\} \quad (3.7)$$

2) The damping ratio ξ_k for a target mode should not be less than a threshold (typically 5% in practice):

$$\xi_k \geq \xi_k^* = 5\% \quad (3.8)$$

3) Damping ratios for other electromechanical modes are not worsened for an n-machine system:

$$\Delta \xi_i = \xi_i - \xi_{i0} \geq 0, \quad i = 1, 2, \dots, n \quad (3.9)$$

4) BESS controller gains are within a range:

$$k_{es,\min} \leq k_{esi} \leq k_{es,\max} \quad (3.10)$$

The values of $k_{es,\max}$ and $k_{es,\min}$ depend on the converter power limits. A natural choice can be some large (small) enough constant. However, an overlarge $k_{es,\max}$ may lead to conservative optimization results; moreover, the larger (smaller) the $k_{es,\max}$ ($k_{es,\min}$) is, the longer the algorithm running time can be, since it enlarges the potential search region. In this dissertation, the possible range of the k_{es} value is determined by the following empirical approach: the power rating for most existing utility-scale BESS projects ranges from about 5 to 100MW [23], i.e. $P_{es,\max} \in [0.05, 1.0]$ p.u. (refer to 100MVA base); also assume $|\Delta\omega| = 0.01$ p.u. Finally, by (2.3), it leads to: $k_{es} = |-P_{es}|/|\Delta\omega| \leq P_{es,\max}/|\Delta\omega| \in [0.05/0.01, 1.0/0.01] = [5, 100]$. In practice, the upper limit $k_{es,\max}$ can be further adjusted by trial-and-error method depending on the studied systems scale.

Obviously, this is a non-convex, non-smooth, nonlinear, mixed-integer optimization problem, because the mode damping ratio ξ_i has no explicit closed-form expression.

3.1.2 Simulation-based Optimization Scheme

- Mixed-PSO Algorithm

1) Encoding Scheme for Mixed-variables: due to the non-smooth, non-convex, black-box nature of the above optimization problem, the conventional gradient-based mathematical programming methods cannot be directly applied

here. Thus, metaheuristics methods can be considered. In this dissertation, each decision vector $\mathbf{X}_i \in \mathbf{Z}^N \times \mathbf{R}^N$ is composed of location variables and control gain variables, i.e. $\mathbf{X}_i = [\mathbf{locs}; \mathbf{k}_{es}]$. Thus, a mixed integer encoding PSO is proposed here to solve it. For integer variables, there can be two schemes for encoding, one is binary encoding, such as $\mathbf{locs} = [01000\dots111] \in \{0, 1\}^N$, each bit represents the decision of placing a BESS or not. The other is direct-integer-encoding, i.e. $\mathbf{locs} = [loc1, loc2, \dots, loc_{N_{es}}] \in \mathbf{Z}^{N_{es}}$ and $loc_i \in \{1, 2, \dots, N\}$. In a large power system, the number of total buses N could be very large, e.g. around hundreds level; while, N_{es} , the number of utility scale BESSs to be placed is typically smaller due to the considerable initial investment. Thus, the search space resulted by the integer-encoding scheme can be smaller than that of the binary encoding scheme, e.g. $O(N^{N_{es}}) < O(2^N)$ when $N \geq 25$ and $1 \leq N_{es} \leq 5$. Therefore, the direct-integer-encoding scheme will be adopted for $\mathbf{locs}$. For $\mathbf{k}_{es}$, the conventional real-number-encoding is used due to its continuous nature.

2) Updating Formula: in PSO, each solution vector is named as “particle” representing its current “position” in the searching space. To update the solution vector, the so called “velocity” vector is internally generated within the algorithm to update the “particle position” in each “generation” (i.e. iteration). The update uses a weighted sum of the previous velocity, the difference between the current position and the best individual position, the difference between the current

position and the best group position. For an n -particle swarm in D -dimension space, they are shown in the following equations:

$$V_{id}^{k+1} = \omega V_{id}^k + c_1 r_1 (P_{id}^k - X_{id}^k) + c_2 r_2 (P_{gd}^k - X_{id}^k) \quad (3.11)$$

$$X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1} \quad i = 1, 2, \dots, n; \quad d = 1, 2, \dots, D \quad (3.12)$$

where, ω is the “inertia” weight, i.e. the portion of the velocity component in the previous generation; V_{id}^{k+1} is the d -th component of the i -th speed vector in the $(k+1)$ -th generation; X_{id}^{k+1} is the d -th component of the i -th particle in the $(k+1)$ -th generation; X_{id}^k is the d -th component of the i -th particle in the k -th generation; P_{id}^k is the d -th component of the “individual best” position of the i -th particle so far in the k -th generation; P_{gd}^k is the d -th component of the “group best” particle position found until in the k -th generation; r_1, r_2 are random constants drawn uniformly from $[0,1]$; c_1, c_2 are non-negative numbers (“accelerating factors”) for speeding convergence.

3) Checking Validity of the Solution (Particle): the particle position and speed generated by the PSO should be within a valid range and satisfy certain explicit conditions due to the problem nature and engineering needs. For example, the elements of the location vector should be distinct during the optimization after updating. To check repeating integer variables, there are many algorithms; here an algorithm by iteratively replacing duplicates is adopted. Its core idea is to find the nearest neighbors for those duplicates: in each time, replacing the first found

duplicate by the nearest non-repeating integer. Its pseudocode is described as follows:

Algorithm 1: Duplicates replacing for the location vector	
1	Input: location vector $X = [X_1, X_2, \dots, X_{Nes}]$
2	create a set $S := \{1, 2, \dots, N\}$
3	$[val, idx] := \text{unique}(X)$
4	$S := S \setminus \{val\}$
5	create a set $O := \{1, 2, \dots, N_{es}\}$
6	$O := O \setminus O[idx]$
7	for $i := 1$ to $\text{length}(O)$
8	$k = \text{argmin}_k S[k] - X[O[i]] $
9	$X[O[i]] := S[k]$
10	$S := S \setminus S[k]$
11	end
12	Output: the updated location vector X without duplicates

- Co-Simulation Framework

A joint framework of power system dynamic simulation and PSO optimization is implemented by interfacing DigSILENT with MATLAB. DigSILENT is used as the simulation engine to provide “constraints” and “objective” values dynamically. This can be regarded as a nonlinear mapping from the power grid dynamic process to the parameter space (**locs** and **k_{es}**). Compared with the linearized methods (e.g. small signal analysis), one of the merits of this simulation-based optimization is that, the damping ratio can be calculated dynamically from the nonlinear time domain simulation (e.g. generator angles or speeds) other than the eigen-decomposition of the linearized model. Thus, the simulation-based method is in nature nonlinear and its results is closer to real system behaviors. By simulation, most nonlinear details can be considered, such as the hard limit of

exciter controller and the power limit of BESS converters, which are typically omitted in linearized methods.

DlgSILENT has a comprehensive power system components library and a flexible communication interface for other tools like MATLAB. MATLAB has its merits in stable numerical algorithm and plentiful data processing functions. The communication scheme used in DlgSILENT is coded in its DPL (DlgSILENT Programming Language) file which encapsulates all the necessary data structures such as the solution vector [*locs*; *kes*] (sent from MATLAB) and the energy storage objects vector. On MATLAB side, DlgSILENT will be called to execute simulation whenever the objective function or constraints needs to be updated.

Regarding the calculation of the modal damping ratio from the simulation curves, the **TLS-ESPRIT** (Total Least Square-Estimation of Signal Parameters through Rotational Invariant Technique) [31] method is chosen to implement in MATLAB. Its basic idea is to apply SVD (Singular Value Decomposition) twice: the first SVD is on the measurement matrix to extract the modal subspace $\mathbf{U}_s$; then the 2nd SVD decomposes $\mathbf{U}_s$ to get the optimal estimation for the so-called rotation matrix Ψ , whose eigenvalues contain all the modal information of the original signal. This algorithm is reported to be superior to conventional methods like *Prony* in terms of less sensitivity to noises [31]. Its math details can be found in [32] and Appendix-I.

The basic flowchart is shown in Fig. 3.1. Note that two internal interface variables: **ES_Locs** and **ES_kes** are pre-defined in the DPL file to modify the grid model dynamically.

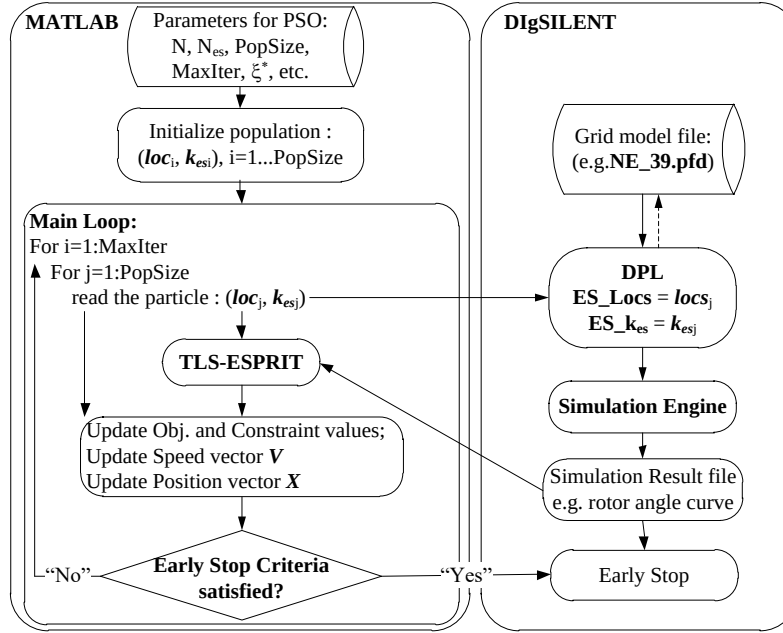


Figure 3.1. Flowchart of the simulation-based Mixed-PSO optimization scheme

3.1.3 Case Study: New England 39-Bus System

The optimal BESS placement algorithm is firstly tested on the New England 39-bus system (in short, “NE 39-bus”) and set $N_{es} = 3$. In DigSILENT default NE 39-bus model, all its inter-area oscillation modes have large enough damping (>5%). Thus, a modified system is adopted with a weak mode of 0.657Hz and 1.68% damping ratio, by increasing control gain parameters with the AVRs and governors of seven generators, which are listed in Appendix-II. The mode shape plot is in Fig. 3.2. The single-line diagram is shown in Fig. 3.3.

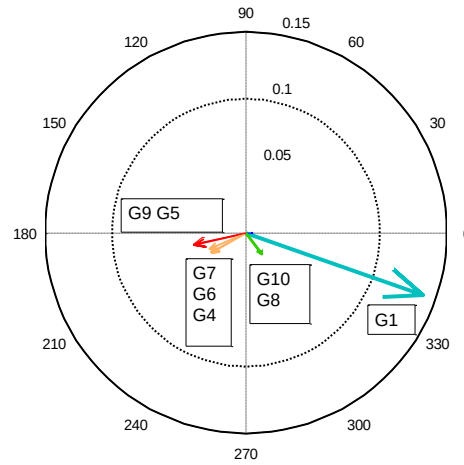


Figure 3.2. Mode shape plot of the NE 39-bus system

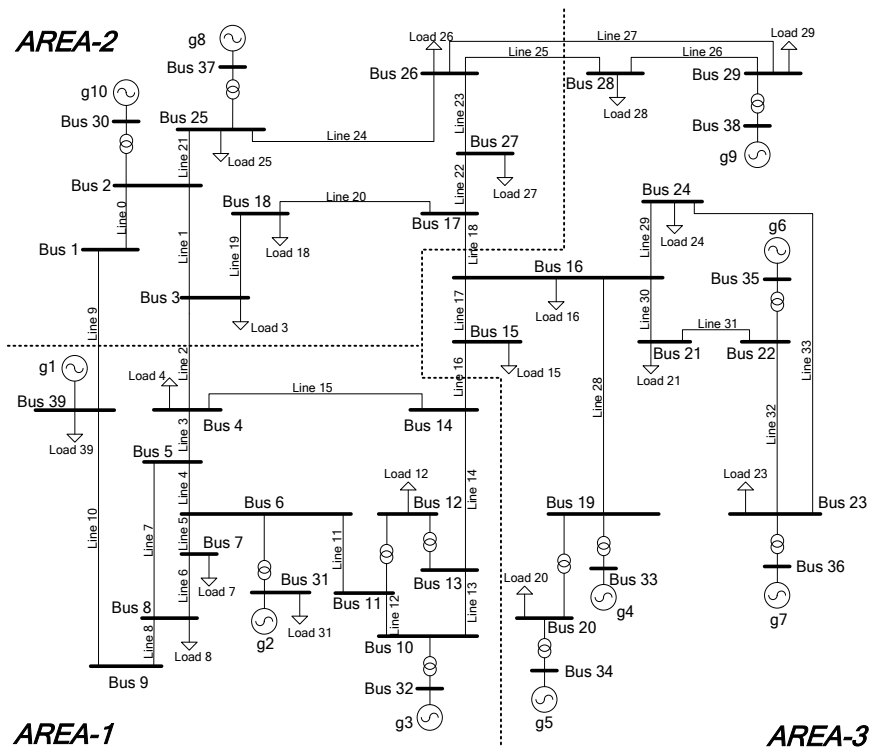


Figure 3.3. The single-line diagram of the NE 39-bus system

Here, the goal is to improve the damping ratio of the target mode to at least 5% with the minimum sum of k_{es} . This mode arises mainly due to the oscillation between generator groups {1, 10, 8} and {9, 5, 7, 6, 4} as reflected by the mode shape plot in Fig. 3.2.

In the time domain simulation, a three-phase temporary fault is applied at $t=0s$ and cleared after 0.1s on bus-16, which lies on the main system oscillation interface. Parameters for the Mixed-PSO is shown in Table 3.1 and 3.2. The meanings of each parameters can be refereed to section 3.1.2. The up-limit for k_{es} is set to 50 but not 100 (in p.u.), because by simple trial-and-error experiments, we found the case when $k_{es}=100$ is too large (“over-qualified”) for the NE 39-bus system. Because this may easily lead the PSO to the “early-mature” status, i.e. even some randomly selected locations with such k_{es} values could be a “local optimal point”, and make the PSO algorithm early stop the iteration process.

Table 3.1. PSO parameters

Parameter	Value
c_1	2
c_2	2
ω	0.9
PopSize	30
MaxIter	30
k_{es} range	[5, 50]

Table 3.2. Simulation parameters

Simulation length	20s
Step Size	0.01s
Output Size	0.01s

- Mixed-PSO Results

Fig. 3.4 shows the iteration curve of the Mixed-PSO algorithm.

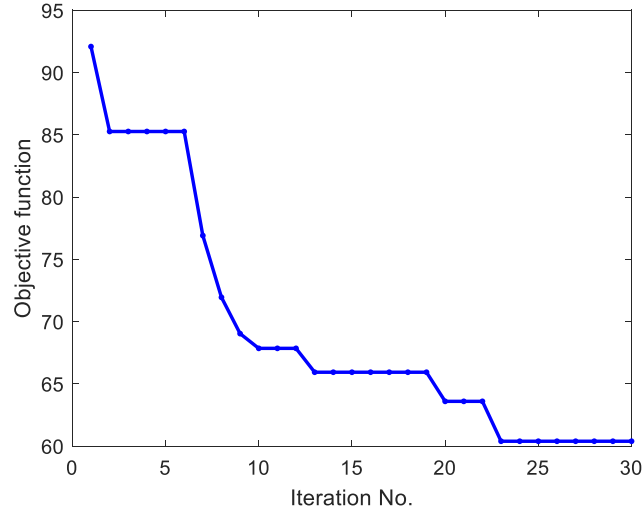


Figure 3.4. The solution iteration curve for the NE 39-bus system

The best location vector and controller gain vector are: **locs** = [35, 36, 38] and **k_{es}** = [29.5894, 8.2391, 22.5577] with damping ratio of the target mode at 5.005% and the objective value at 60.3862.

- Effects of Different Operating Conditions

To investigate the effects of different operation conditions on the placement result, the following four scenarios are designed to re-run the optimization procedure: “**LoadDown**” (Loads have their active power reduced by 2.5%); “**GenUp**” (Generators have their active power increased by 2.5%); “**GenLoadDown**” (Both generators and loads have their active power reduced by 2.5%); “**GenDownUp**” (Half of the generators had their active power increased by 2.5%; the other half reduced by 2.5%). Note that, in practice not all the scenarios

need to be run, because in some scenarios the damping ratio of the target mode even without energy storage is already larger than the damping ratio requirement, viz. 5%.

The considered scenarios and optimal solutions are listed in Table 3.3. As in [33], the Placement Similarity Index (**PSI**) is calculated for each case, i.e. the ratio of the locations same as those in the base case to all newly selected locations.

Table 3.3. Optimization result: different operating conditions

	<i>locs</i>	<i>Old $\xi_k\%$</i>	<i>New $\xi_k\%$</i>	<i>Obj.</i>	<i>PSI</i>
LoadDown	34, 36 , 35	1.571	5.020	69.609	0.67
GenUp	26, 38 , 36	3.060	5.004	50.935	0.67
GenLoadDown	30, 35 , 38	1.834	5.004	46.571	0.67
GenDownUp	38 , 35 , 36	2.923	5.002	60.674	1.00

It should be pointed out that, though the location results are relatively stable, the k_{es} values are typically not. Although k_{es} values vary with the operating condition, they are adjustable as BESS controller parameters. In the real life, placing BESSs usually has a higher priority than designing their controller parameters, which are relatively easier to adjust.

- Simulation Verification

To better demonstrate the performance of the optimal solution for the original scenario, the following experiments are designed and compared: 1) fixing the *locs* vector and randomly disturb each k_{esi} within a small percentage interval,

viz. within the range of [0.95,1.25]; 2) fixing the k_{es} vector and randomly change each loc_i in a one-by-one manner.

Then, the rotor angle curve of generator 1 (g1 in Fig. 3.3) is considered for plots, which has the highest observability for the target mode on the rotor angles.

Table 3.4. Simulation verification: fixed $locs$

	$locs$	k_{es}	Σk_{es}	$\xi_k\%$
Opt.	35, 36, 38	29.5894, 8.2391, 22.5577	60.3862	5.005
#1	35, 36, 38	28.9957, 8.0738, 22.1051	59.1746	4.985
#2	35, 36, 38	29.9136, 8.3294, 22.8048	61.0479	5.016

Table 3.5. Simulation verification: fixed k_{es}

	$locs$	k_{es}	Σk_{es}	$\xi_k\%$
Opt.	35, 36, 38	29.5894, 8.2391, 22.5577	60.3862	5.005
#1	13, 36, 38	29.5894, 8.2391, 22.5577	60.3862	4.681
#2	35, 27, 38	29.5894, 8.2391, 22.5577	60.3862	4.917
#3	35, 36, 25	29.5894, 8.2391, 22.5577	60.3862	4.727

The results are respectively shown in Table 3.4 and Table 3.5. Note that in both tables, “Opt.” means “optimal solution”.

The comparison plots on the rotor angle of generator-1 for the case with “fixed BESS locations” and the case with “Fixed k_{es} values” are respectively shown in Fig. 3.5 and Fig. 3.6, where the highly nonlinear system responses in the first second are ignored and “w/o” stands for “the case without BESS”. From those figures and tables, it is easily observed that the obtained solution can achieve local optimum with satisfactory performance.

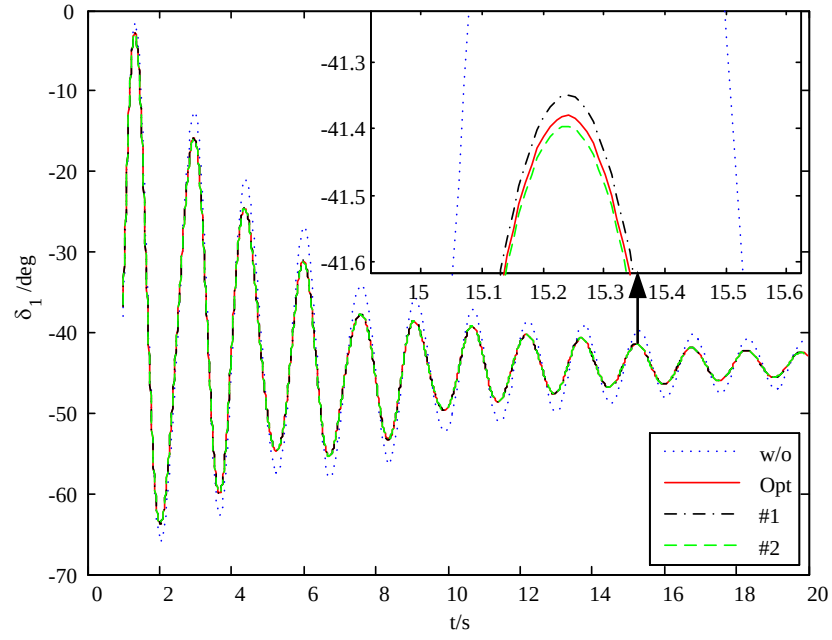


Figure 3.5. Comparison results on the rotor angle of generator-1: Fixed BESS locations

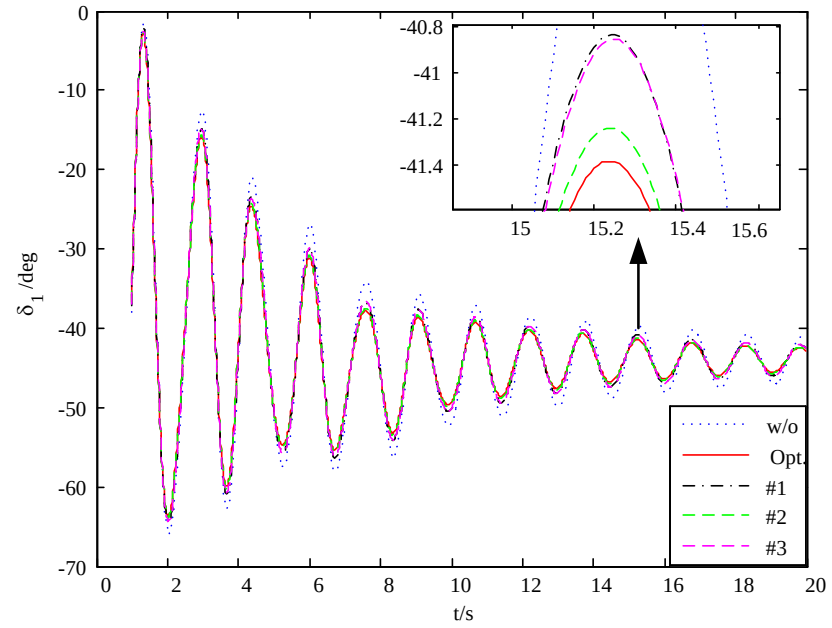


Figure 3.6. Comparison results on the rotor angle of generator-1: Fixed k_{es} values

- BESS Output and SOC Changes

The power outputs of the three BESS units are respectively depicted in Fig. 3.7 to Fig. 3.9.

Then, the change of the SOC for each BESS is calculated by first integrating the response over time and then dividing the result by the capacity of 10 MWh, i.e.:

- For the BESS unit at bus-35:

$$\begin{aligned}\Delta E &= 22.4055 \text{ MJ} = 0.0062 \text{ MWh}, \\ \Delta \text{SOC} &= -0.0062 \text{ MWh} / 10 \text{ MWh} = -0.062 \text{ \%};\end{aligned}$$

- For the BESS unit at bus-36:

$$\begin{aligned}\Delta E &= 6.2368 \text{ MJ} = -0.0017 \text{ MWh}, \\ \Delta \text{SOC} &= -0.0017 \text{ MWh} / 10 \text{ MWh} = -0.017 \text{ \%};\end{aligned}$$

- For the BESS unit at bus-38:

$$\begin{aligned}\Delta E &= 17.0892 \text{ MJ} = 0.0047 \text{ MWh}, \\ \Delta \text{SOC} &= -0.0047 \text{ MWh} / 10 \text{ MWh} = -0.047 \text{ \%}.\end{aligned}$$

As can be observed, compared with the total energy capacity of batteries, the final change of SOC at the end of the oscillation process is very small.

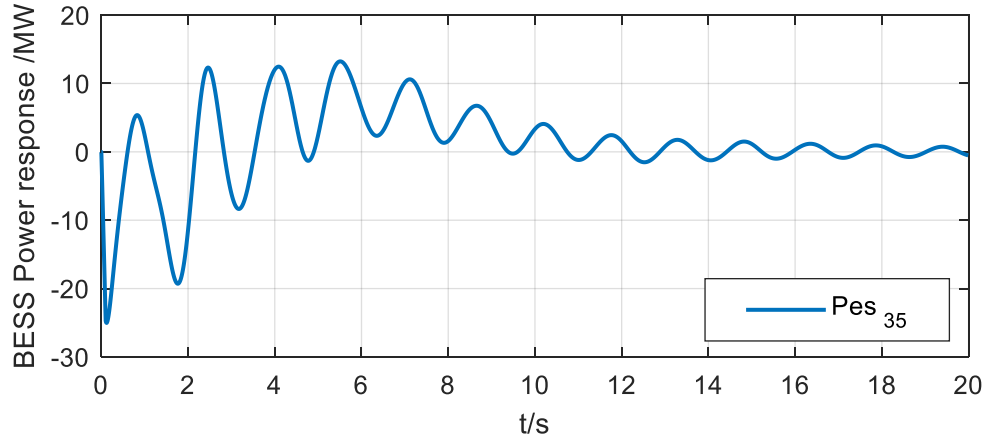


Figure 3.7. The BESS (at bus-35) power response in the NE 39-bus system

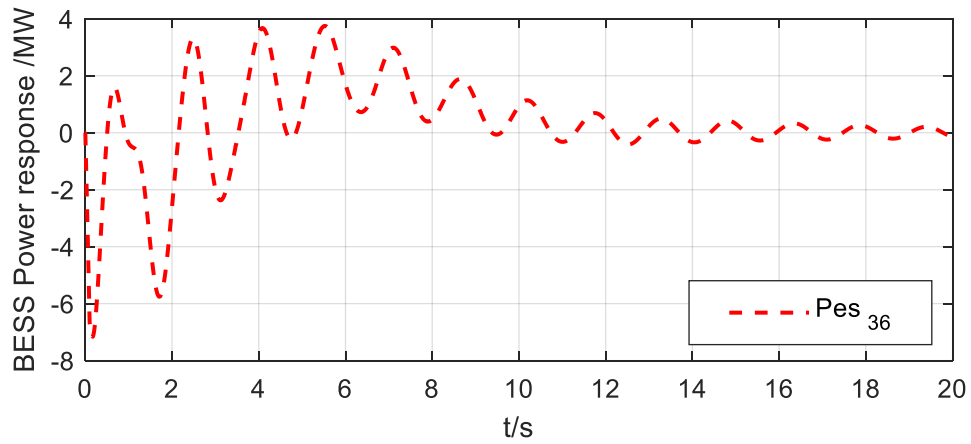


Figure 3.8. The BESS (at bus-36) power response in the NE 39-bus system

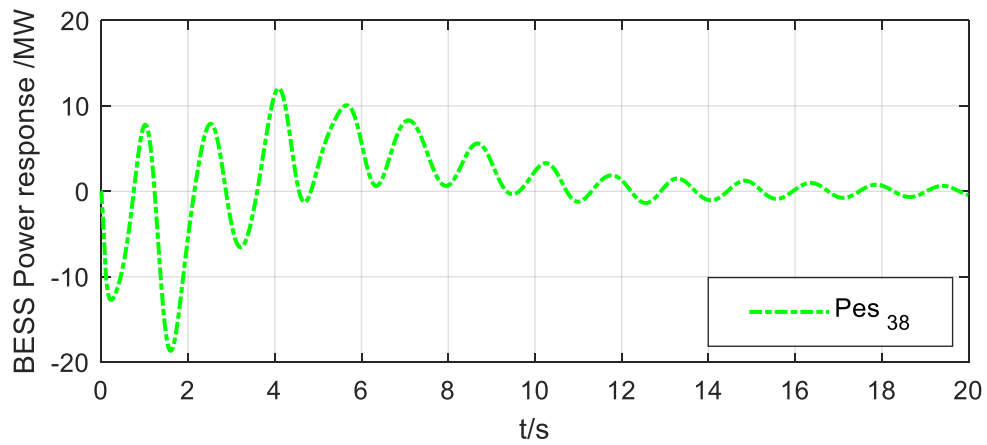


Figure 3.9. The BESS (at bus-38) power response in the NE 39-bus system

3.1.4 Case Study: Nordic Test System

The Nordic test system (50Hz), as the core part of the northern European power grid, is heavily loaded with large power transfers basically from its “**North**” to “**Central**” areas. The model has 74 buses and 20 generators. The system diagram is shown in Fig. 3.10 [34].

The four areas are briefly introduced as follows:

- “**North**”: with hydro generation and some load
- “**Central**”: with much load and thermal power generation
- “**Equiv**”: connected to the “**North**”, which is an equivalent of the external system
- “**South**”: with thermal generation and loosely connected to the system remaining part.

Originally, the system frequency is only controlled by the speed governors of the hydro generators in the “**North**” and “**Equiv**” areas. The thermal units of the “**Central**” and “**South**” areas do not participate in this control. g20 is an equivalent generator, with a large participation in the primary frequency control, thus chosen as the swing bus.

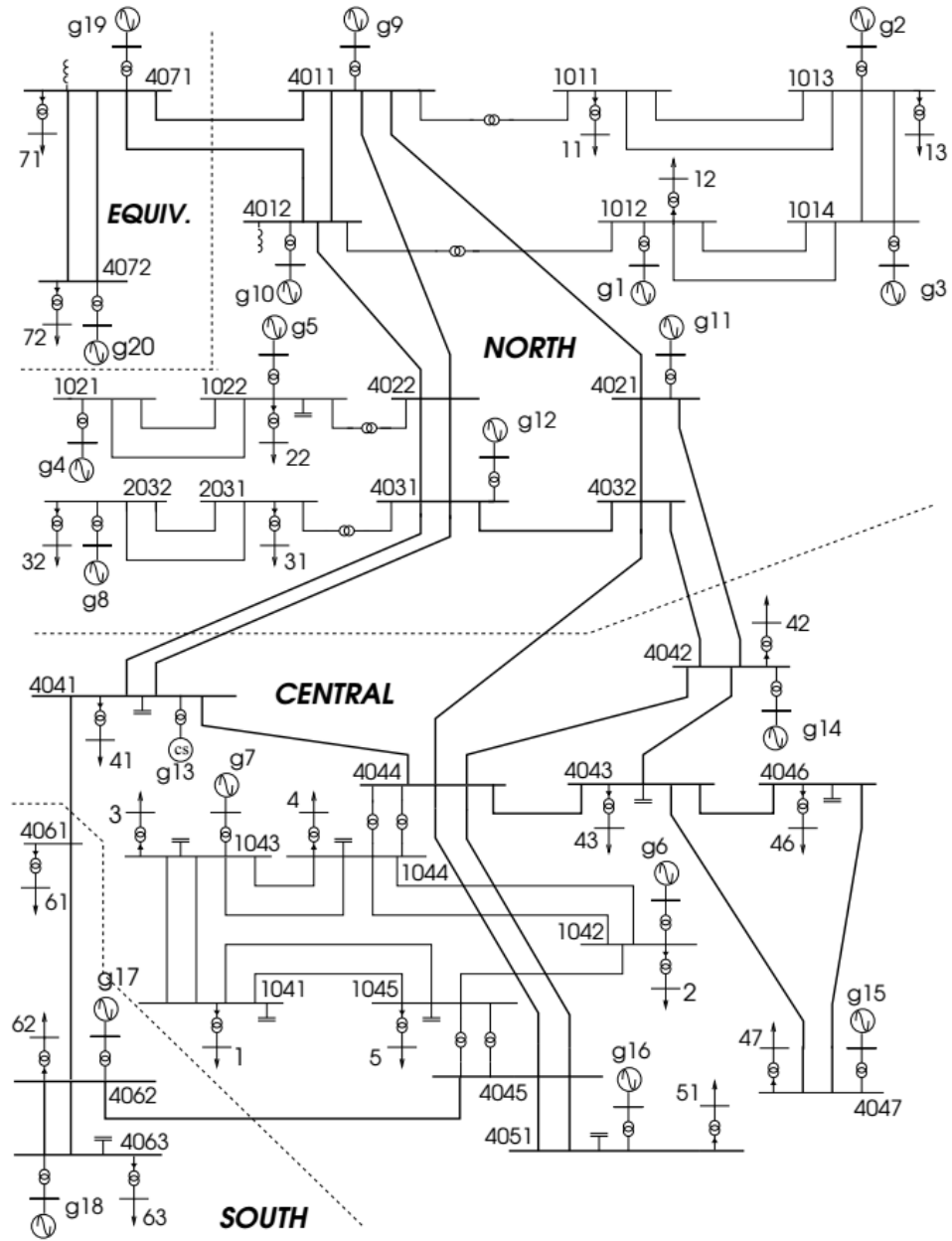


Figure 3.10. The Nordic test system diagram

The original DIgSILENT model has large enough damping for each mode. Thus, a modified system was obtained by increasing the controller gains with the AVRs of six generators as listed in Appendix-II. Then, an inter-area mode at 0.537Hz with 1.15% damping ratio was selected as the target mode.

The disturbance considered in simulation is a three-phase temporary fault on Line 4032-4044 at 1 sec and cleared at 1.1 sec. The disturbance is simulated for 50 seconds. This heavy loaded line lies on the critical oscillation interface.

- Mixed-PSO Results

Set the number of BESS units $N_{es} = 3$. Then, the obtained best location vector and controller gain vector are respectively: **locs** = [g19, g20, 4063] and **k_{es}** = [81.616, 88.435, 82.564]. The damping ratio of the target mode is increased to 5.007% and the objective value is 252.615. The PSO and simulation parameters are listed in Table 3.6 and 3.7.

Table 3.6. PSO parameters

Parameter	Value
c₁	2
c₂	2
ω	0.9
PopSize	30
MaxIter	35
k_{es} range	[5, 100]

Table 3.7. Simulation parameters

Simulation length	50s
Step Size	0.01s
Output Size	0.01s

- Effects of Different Operating Conditions

Three different scenarios with a weak target mode are tested as shown in Table 3.8. The meanings of the case names are similar to those previously used in the NE 39-bus case. Again, the results reflect the robustness of the optimized location solution to small changes.

Table 3.8. Optimization result: different operating conditions

	<i>locs.</i>	<i>Old $\xi_k\%$</i>	<i>New $\xi_k\%$</i>	<i>Obj.</i>	<i>PSI</i>
LoadDown	g19, 4063, g20	2.201	5.019	189.41	1.00
GenLoadDown	g20, 4063, g14	1.773	5.007	277.58	0.67
GenDownUp	4044, 4063, g20	1.170	5.031	300.00	0.67

- Simulation Verification

The settings and optimization results are shown in Table 3.9 and Table 3.10. Here the rotor angle of generator-18 is chosen to show the local optimality of the solution. Comparison plots (after 3 sec) are shown in Fig. 3.11 and Fig. 3.12.

Table 3.9. Simulation verification: fixed *locs*

	<i>locs.</i>	<i>k_{es}</i>	Σk_{es}	$\xi_k\%$
Opt.	g19, g20, 4063	81.616, 88.435, 82.564	252.615	5.007
1	g19, g20, 4063	80.849, 87.953, 82.180	250.982	4.985
2	g19, g20, 4063	83.640, 90.111, 84.209	257.960	5.086

Table 3.10. Simulation verification: fixed *k_{es}*

	<i>locs.</i>	<i>k_{es}</i>	Σk_{es}	$\xi_k\%$
Opt.	g19, g20, 4063	81.616, 88.435, 82.564	252.615	5.007
1	g9, g20, 4063	81.616, 88.435, 82.564	252.615	4.558
2	g19, 62, 4063	81.616, 88.435, 82.564	252.615	4.305
3	g19, g20, 4	81.616, 88.435, 82.564	252.615	4.368

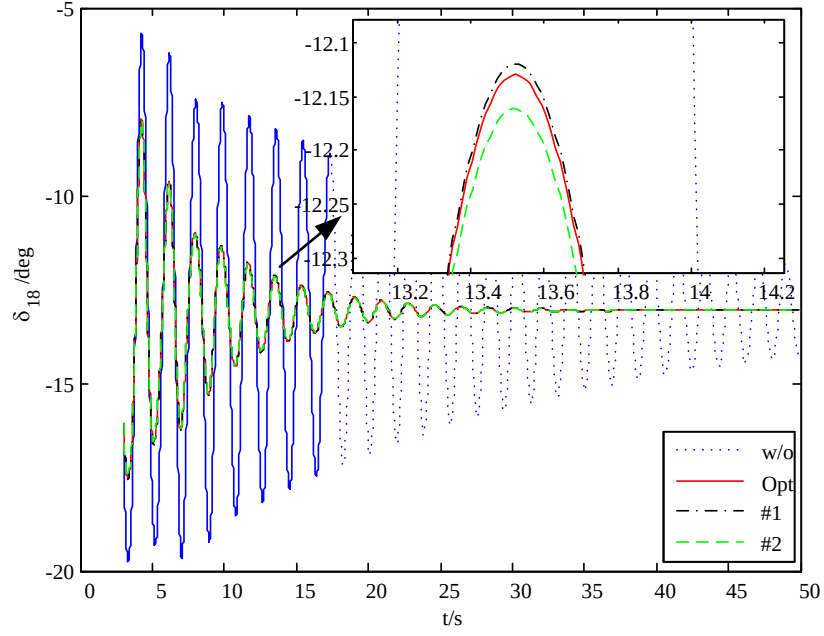


Figure 3.11. Comparison results on the rotor angle of generator-18: Fixed BESS locations

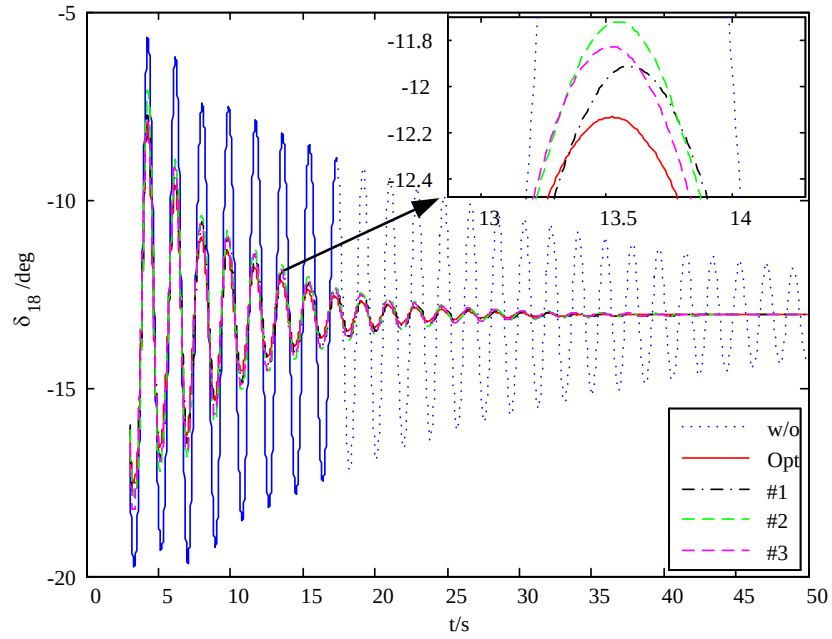


Figure 3.12. Comparison results on the rotor angle of generator-18: Fixed k_{es} values

- BESS Output and SOC Changes

The power response of the BESS unit at bus-g19 is shown in in Fig. 3.13. The power response of the BESS unit at bus-g20 is shown in Fig. 3.14. The power response of the BESS unit at bus-4063 is shown in Fig. 3.15.

The change of SOC for each BESS is calculated by integrating the corresponding power curve, i.e.:

- For the BESS unit at bus-g19:

$$\Delta E = 0.7535 \text{ MJ} = 0.00021 \text{ MWh},$$

$$\Delta \text{SOC} = -0.00021 \text{ MWh} / 10 \text{ MWh} = -0.0021\%;$$

- For the BESS unit at bus-g20:

$$\Delta E = 0.8151 \text{ MJ} = 0.00023 \text{ MWh},$$

$$\Delta \text{SOC} = -0.00023 \text{ MWh} / 10 \text{ MWh} = -0.0023\%;$$

- For the BESS unit at bus-4063:

$$\Delta E = 0.7637 \text{ MJ} = 0.00021 \text{ MWh},$$

$$\Delta \text{SOC} = -0.00021 \text{ MWh} / 10 \text{ MWh} = -0.0021\%.$$

Similar to the case study for NE 39-bus system, here the final SOC change is very small at the end of oscillation.

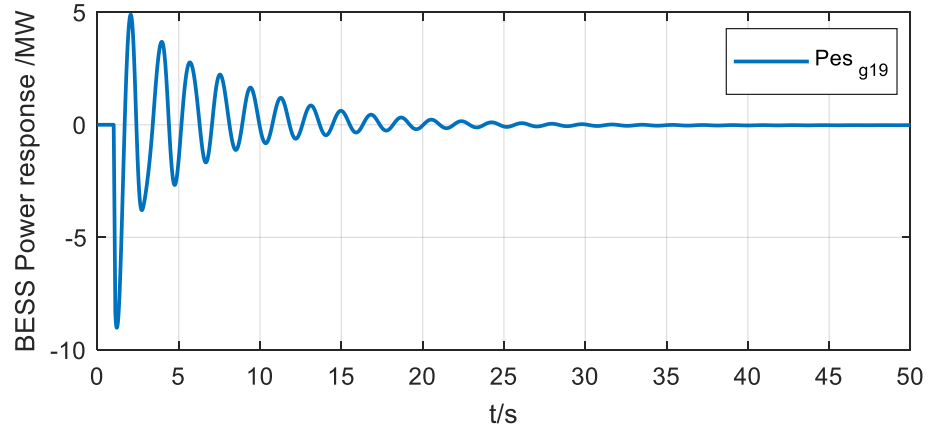


Figure 3.13. The BESS (at bus-g19) power response in the Nordic test system

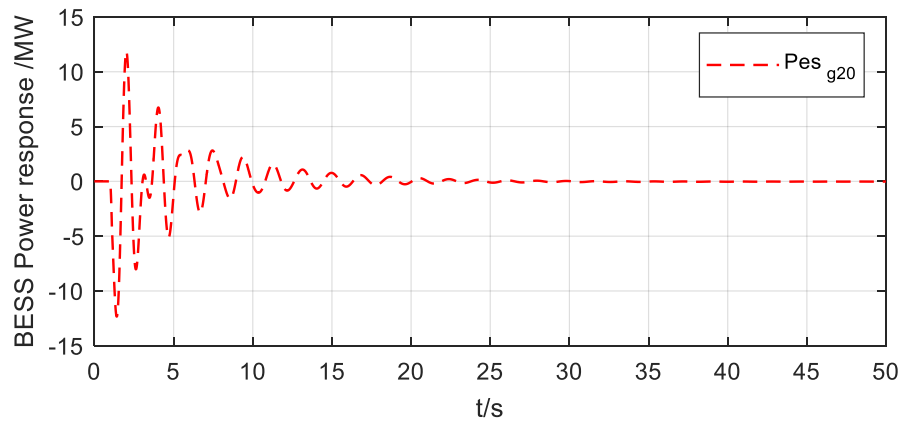


Figure 3.14. The BESS (at bus-g20) power response in the Nordic test system

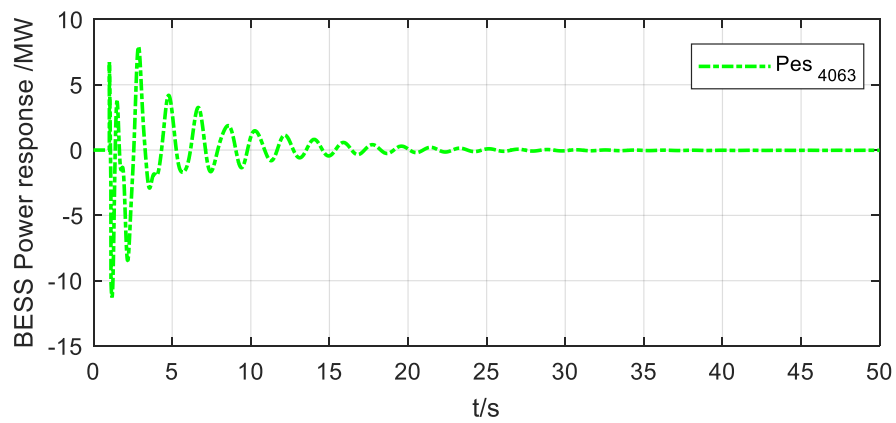


Figure 3.15. The BESS (at bus-4063) power response in the Nordic test system

3.1.5 Conclusion

In this chapter, the optimal placement and control parameter setting for BESS units in transmission grids are studied. The optimization problem is solved by the Mixed-Integer PSO method and tested on two power systems. The impact of operating conditions on the location robustness is also studied.

With the proposed simulation-based optimization framework, more detailed studies regarding the effect of BESS placement can be done for practical applications, e.g. considering more physical constraints of the BESS units (e.g. cell temperature effects) and analyzing the corresponding impacts on the placement results.

3.2 Algorithm Evaluation

In the previous chapters, the proposed Mixed-PSO optimal placement algorithm is tested on two transmission power systems, which demonstrate the effectiveness of its placement results. In this chapter, evaluations for our algorithm are presented in two aspects: 1) Algorithm scalability and 2) Solution quality. Techniques to speed up the algorithm searching efficiency is also discussed and tested in the last section.

3.2.1 Algorithm Scalability

- Complexity of PSO Algorithm

The basic PSO algorithm has the following computational time complexity:

$O(P \times I \times T)$; where:

- 1) O is the algorithm order symbol (the “Big O notation”);
- 2) P is the population size;
- 3) I is the maximum iteration number;
- 4) T is the function and constraints evaluation time of each “particle”. It is roughly equal to the single-run transient simulation time in our problem.

In practice, almost every heuristic algorithm has early termination mechanism, i.e. stopping iteration if no improvement in the recently two optimal objective values for certain iterations, e.g. 10 iterations.

- Case Study: IEEE 9-Bus System

First, investigate the algorithm on a small system, i.e. the IEEE 9-bus system [26]. The algorithm related parameter values are:

- 1) P : 24
- 2) I : 35
- 3) T : 0.42 (sec)

4) Early terminating the search if no improvement was made for the objective value in recent 10 iterations.

Then, the experiment results are shown in Fig. 3.16 and the average running time (sec) of each case is listed in Table 3.11.

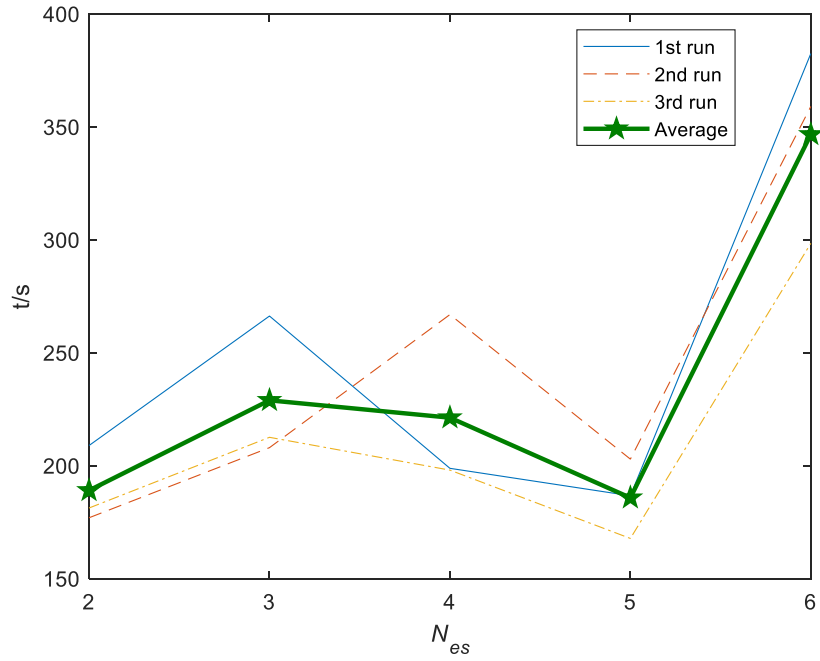


Figure 3.16. The average running time of the Mixed-PSO placement algorithm for the IEEE 9-bus system

Table 3.11. Scalability experiment: IEEE 9-bus system

N_{es}	<i>Average Running Time (sec)</i>
2	189.0
3	228.9
4	221.2
5	185.8
6	346.6

Obviously, in the above results, the growth of the time cost is not linear, which is in accordance with our expectation, since the early termination mechanism has been adopted here.

- Case Study: New England 39-Bus System

In the following experiment, the total number of placed BESSs (N_{es}) is increased from 3 to 8 and record the running times respectively.

For the NE 39-bus system, the algorithm related parameter values are:

- 1) P : 30
- 2) I : 35
- 3) T : 1.98 (sec)
- 4) Early terminating the search if no improvement was made for the objective value in recent 10 iterations.

Then, the experiment results are shown in Fig. 3.17 and the average running time (sec) of each case is listed in Table 3.12.

By the scalability test results for the above two systems, the following conclusions can be drawn:

1) The computational time is not linear due to early termination and the stochastic nature of PSO-type algorithm.

2) The power system scale (i.e. bus numbers) has a significantly influence on the computational burden.

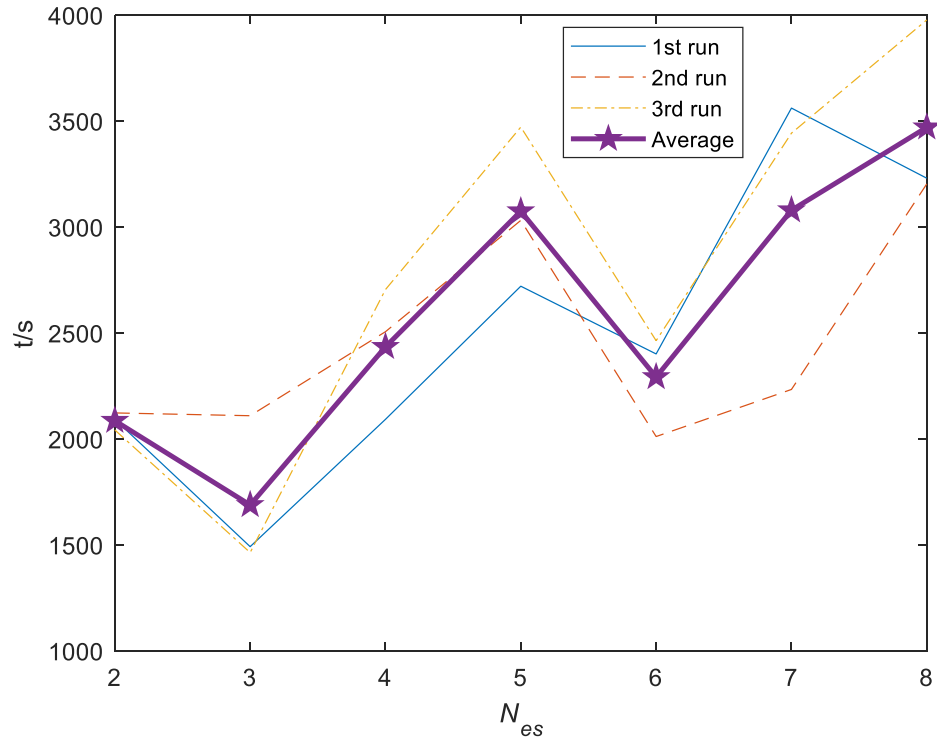


Figure 3.17. The average running time of the Mixed-PSO placement algorithm for the NE 39-bus system

Table 3.12. Scalability experiment: NE 39-bus system

N_{es}	<i>Average Running Time (sec)</i>
2	2087.6
3	1690.1
4	2436.2
5	3076.2
6	2293.7
7	3080.9
8	3471.9

It can be also observed that, the bus number mainly affects the time T . Empirically, the relationship between the one-time simulation T and the bus number is roughly linear [35] (assuming using the same order generator models, controller models, etc.). For example, the bus number ratio for the above two studied systems is $39/9 = 4.333$, which is approximately equal to their single-run time cost ratio, i.e., $T_1/T_2 = 1.98 \text{ sec} / 0.42 \text{ sec} = 4.714$.

3.2.2 Solution Quality

To evaluate the solution quality especially for the discrete variables, we did exhaustive searches on two transmission power grids, i.e. the IEEE 9-bus system and the NE 39-bus system. The system size here stands for the total bus number. Still consider $N_{es} = 3$ in the following studies.

- Case Study: IEEE 9-Bus System

For this system, there are 84 possible combinations for three locations.

By exhaustive search, the found optimal bus locations are shown in Table 3.13.

Table 3.13. Solution quality experiment: IEEE 9-bus system

	<i>Bus No.</i>	<i>Time Cost</i> (sec)
Optimal Locations by Exhaustive Search	2, 3, 7	71.43
Optimal Locations by our method	2, 3, 7	266.22

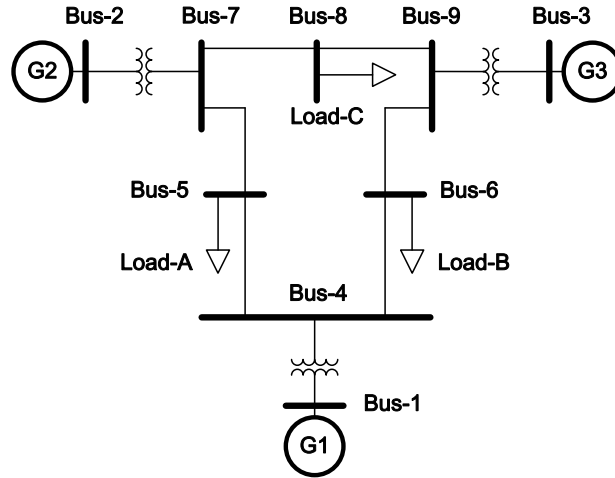


Figure 3.18. The single-line diagram of the IEEE 9-bus system

The system single-line diagram is shown in Fig. 3.18. It is observed that the found optimal locations are the same; the searching efficiency of our method is not better than exhaustive search in this small- system, because both the single-run simulation time cost (0.42 sec) and searching space (totally only 84 combinations) are relatively small.

- Case Study: New England 39-Bus System

For the 39-bus system, there are 9139 possible combinations for three locations. By exhaustive search, the found optimal bus locations are shown in Table 3.14. It is observed that the found optimal locations by our method are the same as the results by the exhaustive search.

Table 3.14. Scalability experiment: NE 39-bus system

	<i>Bus No.</i>	<i>Time Cost</i> (sec)
Optimal Locations by Exhaustive Search	35, 36, 38	18410.7
Optimal Locations by our method	35, 36, 38	1465.6

Furthermore, the searching efficiency of our method is obviously better than exhaustive search in this middle-size system, because both the single-run simulation time cost (1.98 sec) and searching space (totally only 9192 combinations) are bigger than the previous 9-bus system case, so heuristic search is superior to the exhaustive method.

3.2.3 Searching Efficiency Improvement

- Observability Check

Since the computational complexity of a classic PSO algorithm is proportional to the population size P ; thus, to reduce the complexity, we can decrease the population size P , the maximum iteration number I or the time cost T for objective value evaluation, which roughly equals to the single-run simulation time.

However, reduce the above values bring the follows difficulties in both theory and practice:

- 1) For a fixed dimension of decision variables (x), the parameters P and I are in theory as large as better; thus, reducing them too small can incur a larger risk of being trapped in local optimal solutions earlier;
- 2) Reduce single simulation run time cost T means either using complicated parallel paradigm and expensive computing workstations or reducing the system model complexity, e.g. using classic model other than detailed model for generators. The drawback of the latter way is

that, by a too simple generator model, the credibility of such a simulation-based optimization algorithm will be compromised.

On the other hand, some observations by inspecting the optimization results in previous chapters are:

- The optimal locations may consist of both generator buses and non-generator buses;
- Most of the optimal locations are on or nearby the generator buses.

Thus, an alternative way to improve the searching efficiency is to shrink the potential searching space, e.g., find some rigorous way to excluding low quality combinations for discrete decision variables. For example, we can consider using only the generator buses plus m nearest buses based on the electric distance (i.e. the branch impedance) rankings as the candidate buses, instead of all the buses in the previous settings. In this study, $m = 1$ is adopted. Moreover, by doing this, the population size P in the PSO algorithm can be further decreased.

By using small-signal analysis, the normalized observability magnitudes of the target mode on generator speeds can provide a justification for the above improvement, as shown in Table 3.15:

Table 3.15. NE 39-bus system: the target mode observability magnitude on generator speeds

Gen No.	9	5	6	7	4
Bus No.	38	34	35	36	33
Magnitude	0.4109	0.4008	0.3681	0.3656	0.3508
Gen No.	3	2	8	10	1
Bus No.	32	31	37	30	39
Magnitude	0.2710	0.2514	0.2292	0.225	0.1962

As we can see, the previously found optimal locations [35, 36, 38] are in the top places of this table. However, it should be noted that, sequentially picking the top- N_{es} locations based on the observability results in the above table might not guarantee the optimality of the locations. The reason is: the modal analysis is based on the linearized system which ignores the higher-order nonlinearities of system models (generators, exciters, energy storages). Thus, linearized analysis can help narrow the searching space but an optimization produce is still needed.

For example, let N_{es} still be 3. Suppose that all $k_{es,i}$ have the same value, e.g. set all $k_{es,i} = 20.0$ for the NE 39-Bus system; then using the top-3 locations [38,34,35] for BESS placement, the damping ratio of the target mode is 5.169%; by the previously found location [35,36,38] in our simulation-based optimization method, also with all $k_{es,i} = 20$, the calculated damping ratio is 5.221%, which is higher. This example demonstrates the necessity of the optimization framework in searching for the best locations.

- Case Study

The main benefit of using generators and certain nearby buses to initialize the Mixed-PSO population is to provide a high-quality initial solution, especially for the discrete part (i.e. locations) of each particle. This characteristic can help to speed up the convergence of the searching process.

For the NE 39-bus system, still let $N_{es} = 3$ and run the improved PSO optimization program.

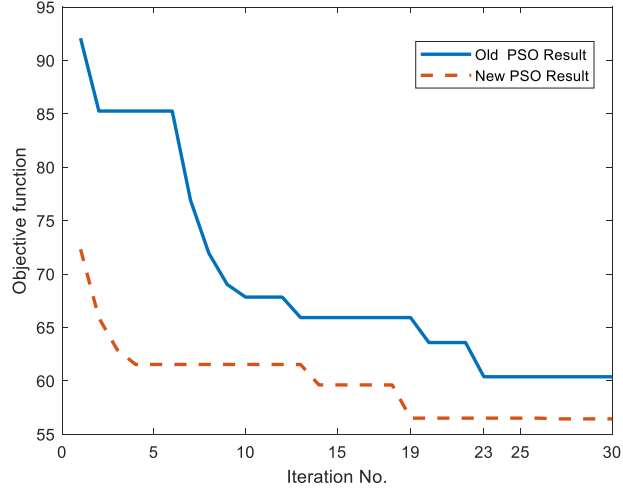


Figure 3.19. Iteration curves of the Old PSO vs. the Improved PSO

The comparison plots for the iteration curves are shown in Fig. 3.19. It is obvious that the improved PSO algorithm converges earlier (at the 19th iteration) than the old algorithm (at the 23rd iteration).

For the Nordic test system, a similar experiment is done. The numerical results for both systems are summarized in Table. 3.16, where, “Old result” stands for the baseline result in last section; “New result” is obtained by the improved PSO method in this section.

Table 3.16. Comparison of old PSO and improved PSO algorithms

NE 39-bus	locs	$\xi_k\%$	Obj.
Old result	35, 36, 38	5.005	60.3862
New result	33, 35, 38	5.000	56.4446
Nordic test	locs	$\xi_k\%$	Obj.
Old result	g19, g20, 4063	5.007	252.615
New result	g16, g20, 4063	5.009	265.923

Regarding the solution optimality, for the NE 39-bus system, this new scheme achieves a better (i.e. lower) objective value. For a larger system like the

Nordic test system, it yields a slightly larger objective value, though still close to the old result.

3.2.4 Conclusion

In this chapter, the computational scalability against the number of BESS units to be placed is investigated for the proposed Mixed-integer PSO algorithm. The computation burden increases with the increase of the BESS unit number and system bus number, though still less than the primitive exhaustive search algorithm,

In terms of the solution quality, the propose method can get the same results as those from the exhaustive search method in the studied two power grids here, while in our method, less amount time is consumed.

By reducing the candidate buses for originally the whole bus set to only generator buses and their nearby buses, the searching efficiency has been further improved.

It can be expected that, when the improved algorithm is applied to even larger power grids, an exactly or nearly optimal placement solution can be found within an acceptable amount of computational time with the above discussed improvement

3.3 Economic Analysis

Economic analysis is crucial and necessary for BESS placement projects in real power systems. Ideally, it is always expected that the overall investment cost

can be lower meanwhile the performance metrics can be higher; however, this typically requires some compromise in between the two aspects. In this chapter, a cost evaluation model is proposed and applied to the NE 39-bus system and Nordic test system to the minimum required number of BESS units.

3.3.1 Cost Breakdown of BESS

Generally, the overall investment cost of the placed BESS units will mainly depend on both the energy capacities of battery cells and the power capacities of the power electronic converters. Each cost component is explained as follows.

- Power Converter Cost

Typically, a BESS includes a storage part (i.e. the battery cells) and a converter interface called PCS (Power Conditioning System) as discussed in Chapter 2. The PCS cost typically take a major part in the investment. Regarding its cost, a usual way to estimate its cost is by pricing the unit power rating, e.g. \$/MW or \$/kW.

- Battery Cost

Similarly, the storage part can be priced by its unit energy, i.e. \$/MWh or \$/kWh [36]. It should be pointed out that, the price of different types of battery cells varies in a wide range, e.g. lead -acid battery is typically cheaper than Li-ion battery/Lithium battery. Some most cutting-edge technology such as Vanadium redox battery or NaS (Sodium–sulfur) battery that has even larger energy density (kW/kg or kW/cm³), can have much higher price per unit energy than the old types.

- Other Costs

In practice, placing BESS units will include other cost such as labor installation expense, tax and regulation fees, and other overhead cost. In this study, we assume those costs are already included in the above two cost components of one BESS unit.

3.3.2 Cost Evaluation Model

After the cost breakdown work is finished, the economical BESS number can be empirically determined by the following steps based on the previously proposed optimization framework in section 3.1:

- 1) Run the proposed optimization for a reasonable range of N_{es} based on engineering experience or *a priori* knowledge. For instance, in [10], N_{es} is equal to the number of interested inter-area modes needed for damping improvement. In this dissertation, we examine N_{es} from 1 to 6 for the two studied systems.
- 2) Estimate the investment cost based on the optimization results by using the following empirical cost-evaluation model:

$$\begin{aligned}
Cost_{Total} &\approx Cost_{Conv} + Cost_{Cell} \\
&= \sum_{j=1}^{N_{es}} (P_{es,j} S_{Base} Cost_1) + N_{es} E Cost_2 \\
&= \sum_{i=1}^N (z_i k_{esi} | \Delta \omega |_{\max} S_{Base} Cost_1) + N_{es} E Cost_2 \\
&= Obj | \Delta \omega |_{\max} S_{Base} Cost_1 + N_{es} E Cost_2 \quad (3.13)
\end{aligned}$$

The meanings of symbols in the above equation are:

$Cost_{Conv}$: cost corresponding to the power converter part;

$Cost_{Cell}$: cost corresponding to the battery cell part;

Obj : the objective value by the solution of the optimization problem formulation (3.1) - (3.5);

S_{Base} : the MVA base value used in this study, i.e. 100MVA;

$Cost_1$: unit cost for power converters in terms of the power capacity, \$421.43 /kW inferred from Tesla Powerwall [37];

$Cost_2$: unit cost for battery cells in terms of the energy capacity, \$218.52 /kWh inferred from Tesla Powerwall [37];

E : the maximum energy capacity of each BESS, 10MWh; here, a standard energy capacity is assumed for all the BESS units;

$|\Delta\omega|_{max}$: the maximum possible frequency deviation (p.u.) to be considered during the oscillation process. Larger $|\Delta\omega|_{max}$ can lead to a more conservative estimation result for the power capacity of BESS converters; while smaller $|\Delta\omega|_{max}$ may cause insufficient damping support. Since larger frequency deviation will be typically covered by Remedial Action Schemes (RAS) such as Under Frequency Load Shedding and generator tripping schemes [38], the BESS units are expected to help damp oscillations before RAS actions. Moreover, the low frequency oscillation is essentially a small-signal stability problem typically caused by small disturbances. Therefore, $|\Delta\omega|_{max} = 0.01$ p.u. (e.g. 0.6Hz for 60Hz system) is assumed by us in the BESS cost evaluation procedure here.

- Case Study: New England 39-Bus System

The evaluation results are listed in Table.3.17.

Table 3.17. NE 39-bus system: cost evaluation for different number of BESS units

<i>N_{es}</i>	<i>Obj</i>	<i>Constraint</i>	<i>Cost_{Conv}</i> (10⁶ \$)	<i>Cost_{Cell}</i> (10⁶ \$)	<i>Cost_{Total}</i> (10⁶ \$)
1	50.000	Unsatisfied	21.072	2.1852	23.257
2	59.722	Satisfied	25.169	4.3704	29.539
3	60.386	Satisfied	25.448	6.5556	32.004
4	59.766	Satisfied	25.187	8.7408	33.928
5	66.354	Satisfied	27.964	10.926	38.890
6	72.739	Satisfied	30.654	13.111	43.766

- Case Study: Nordic Test System

The evaluation results for the Nordic test system are shown in Table.3.18.

Table 3.18. Nordic test system: cost evaluation for different number of BESS units

<i>N_{es}</i>	<i>Obj</i>	<i>Constraint</i>	<i>Cost_{Conv}</i> (10⁶ \$)	<i>Cost_{Cell}</i> (10⁶ \$)	<i>Cost_{Total}</i> (10⁶ \$)
1	100.00	Unsatisfied	42.143	2.1852	44.328
2	200.00	Unsatisfied	84.286	4.3704	88.656
3	252.62	Satisfied	106.46	6.5556	113.02
4	301.65	Satisfied	127.12	8.7408	135.86
5	317.51	Satisfied	133.81	10.926	144.74
6	271.03	Satisfied	114.22	13.111	127.33

3.3.3 Conclusion

The minimum number of BESS units is determined by a cost analysis based on the proposed simulation-based optimization framework. From the results for the NE 39-bus system, two BESS units will be enough to provide the necessary

oscillation damping support. As for the Nordic test system, at least three BESS units are needed.

3.4 Multi-Scenario Optimization

In practice, the power system is essentially time-varying, not only depending on a single operating point. Thus, in realistic power planning procedure, the robustness of the placement results need to be considered against different types of scenario variations, e.g. when a large number of newly developed intermittent renewables (solar, wind, etc.) are integrated [39]; or when the seasonal (summer/winter) loading level changes. Then, the solution from the previous single-scenario-based optimization program might not be optimal or feasible any more. For such multi-scenario situations, typically the system operator will expect the placed BESS units to help confine any post-disturbance system trajectory within the security margin, i.e. the system states and control variables can still satisfy certain constraints. In our problem, those constraints are mainly the damping ratio requirement for the target mode. This consideration will change our original optimal placement problem to be the so-called *multi-scenario* formulation, which is one representative member of another big family of optimization problems: *robust optimization* [40]. In this chapter, we consider the seasonal load change case as an example of the multi-scenario optimization applied in our problem.

3.4.1 Seasonal Load Change

The seasonal load change is modeled by a series of different loading levels. In order to accommodate the previous optimization formulation (3.1) - (3.5) to multiple loading levels, the following modification is adopted:

$$\min_{z_i, k_{esi}} Obj = \sum_{i=1}^N z_i k_{esi} \quad (3.14)$$

$$\text{s.t. } \sum_{i=1}^N z_i = N_{es} \quad z_i \in \{0, 1\} \quad (3.15)$$

$$\zeta_k^l \geq \zeta_k^* \quad l \in \{0, 1, \dots, L\} \quad (3.16)$$

$$\Delta \zeta_i^l = \zeta_i^l - \zeta_{i0}^l \geq 0 \quad i = 1, 2, \dots, n \quad (3.17)$$

$$k_{es, \min} \leq k_{esi} \leq k_{es, \max} \quad i = 1, 2, \dots, N_{es} \quad (3.18)$$

Where, the meanings of the decision variables z_i and k_{esi} can be referred to section 3.1.1.

The main modification here is changing (3.3) and (3.4) to (3.16) and (3.17) respectively. As before, the BESS unit number N_{es} is fixed and L is the total number of different seasonal loading levels to be considered (here, suppose $L = 2$), ζ_k is the damping ratio of the target mode under the l -th loading level.

By such modified formulation, damping ratios of the target mode under all the loading conditions will be guaranteed to satisfy the requirement ζ_k^* , e.g. 5% in this work.

3.4.2 Case Study: New England 39-Bus System

Assume two seasonal loading levels: normal loading level and high loading level (+20%). The optimized placement result is:

$$\mathbf{locs} = [23, 38, 5],$$

$$\mathbf{k_{es}} = [24.9072, 38.8458, 5.0603],$$

The damping ratios of the target mode are [5.009%, 5.936%],

The objective function equals 68.8133.

Remember in chapter 4, the result for the base loading level case is:

$$\mathbf{locs} = [35, 36, 38],$$

$$\mathbf{k_{es}} = [29.5894, 8.2391, 22.5577],$$

the damping ratio of the target mode is 5.005%,

the objective function value is 60.3862.

The placement comparison plot is shown in Fig. 3.20. From the results, we can see, two of the three selected bus locations are almost the same as those found locations in the original single loading case. The only difference is that new location at bus-5 replacing the old location at bus-35 in the seasonal loading case here. An explanation is that, in bigger loading case, the increase load amount in the Area-1 is more than that in the other two areas, thus more energy storage support will be needed in the Area-1 when the power grid is subjected to transient disturbances.

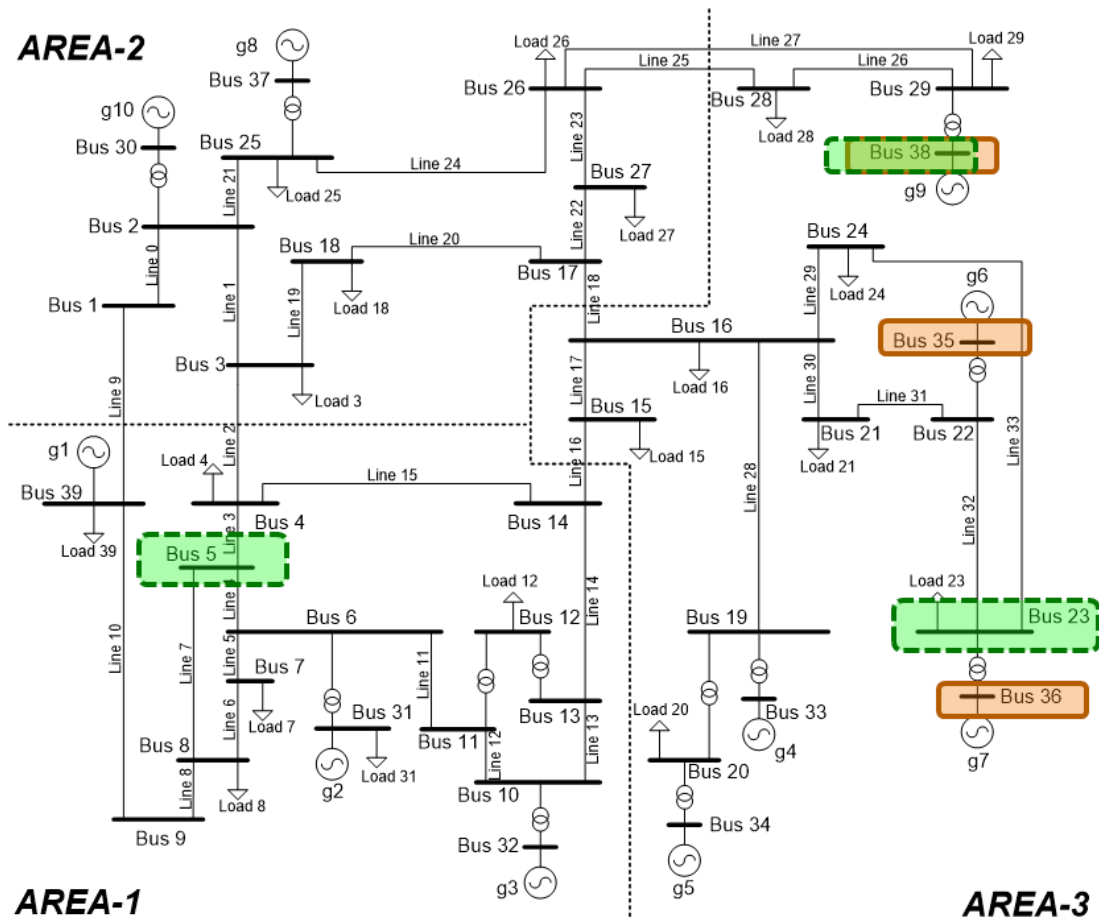


Figure 3.20. Placement comparison: Green dashed box: seasonal loading result; Brown solid box: (original) single loading result

3.4.3 Case Study: Nordic Test System

Assume two seasonal loading levels: normal loading level and high loading level (+10%). The optimized placement result is:

$$\mathbf{locs} = [g6, g20, g18],$$

$$\mathbf{k_{es}} = [95.2295, 97.6079, 92.3342],$$

The damping ratios of the target mode are [5.303%, 4.992%],

The objective function equals 285.1716.

Remember in section 3.1, the result for the base loading level case is:

$$\mathbf{locs} = [g19, g20, 4063],$$

$$\mathbf{k_{es}} = [81.616, 88.435, 82.564],$$

The damping ratio of the target mode is 5.007%,

The objective function value is 252.615.

The placement comparison plot is shown in Fig. 3.21. From the results, we can still observe that, two of the three selected bus locations are almost the same as those found locations in the original single loading case. The only difference is that the new location at generator bus g6 replacing the old location at generator bus-g19. An explanation is similar to that of the previous NE 39-bus case, i.e. in bigger loading case, the increase load amount in the **Central/South** area of this Nordic test system is more than in the **Equiv/North** area, so more energy storage support is needed in those areas when system oscillation happens.

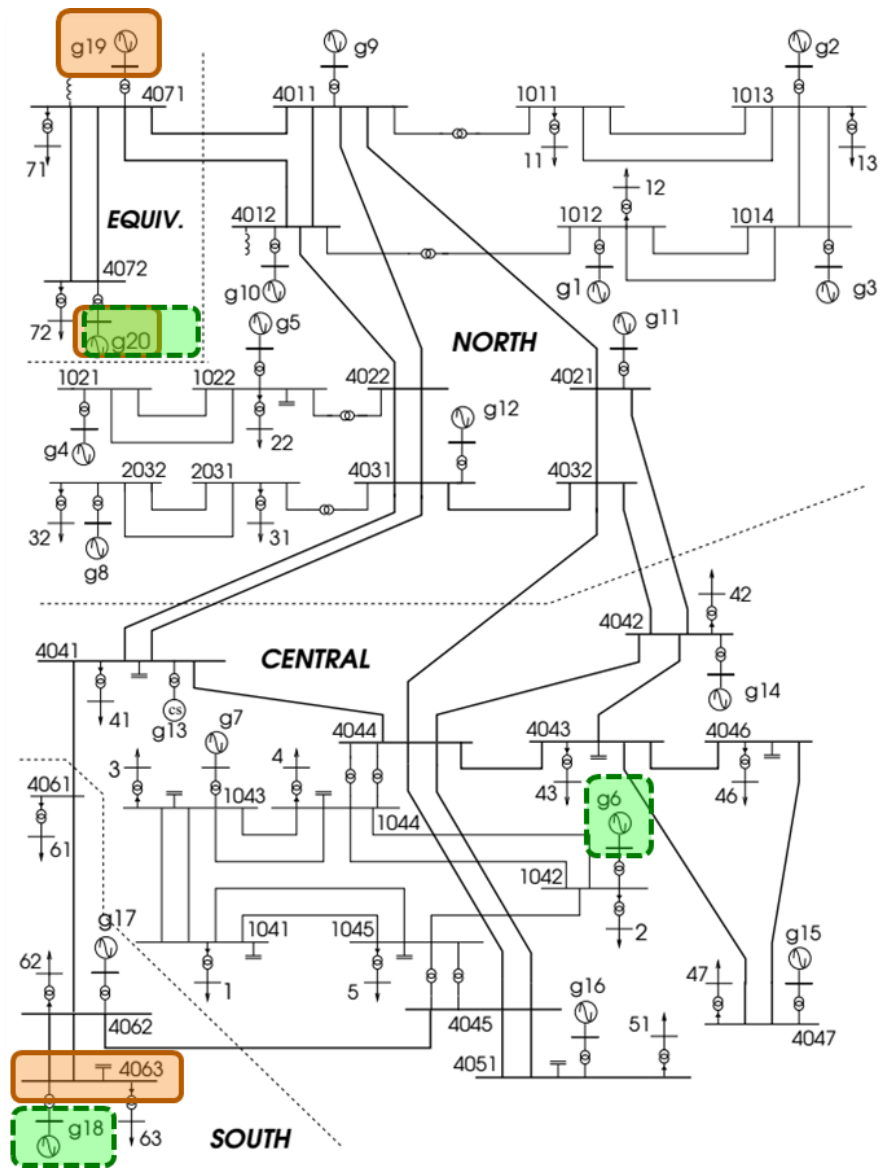


Figure 3.21. Placement comparison: Green dashed box: seasonal loading result; Brown solid box: original single loading result

3.4.4 Conclusion

After enhancement, the proposed optimization framework is successfully applied on seasonal load change cases. From the comparison results, it can be observed that, the two seasonal loading levels yield an objective value larger than that of the single (normal) loading level case. This phenomenon is in accordance with the robust optimization theory, where the objective value will typically become worse than an ordinary case, mainly due to two reasons: 1) the increased number of constraints adopted in the modified optimization formulation can narrow the feasibility region of the potential solution; 2) The non-convexity [41] of such simulation-based optimization becomes more severe than before after adding those robustness constraints when simultaneously considering multiple scenarios.

3.5 Controller Comparison

The proposed simulation-based optimization framework for BESS placement is model-dependent, i.e. different controller structures can bring different control performance. However, to fairly compare two different controller design methods can be sometimes impractical, because the specific design procedure of different controller serves for different control purpose, and depends on what plant models and input signals are adopted. Moreover, most controller design methodologies will inevitably involve human being's subjective experience.

Thus, to demonstrate the properness of our controller for the BESS model, we still conduct a preliminary case study in this chapter for the controller

performance comparison. We borrow the PI (Proportional-Integral) controller used in the energy storage device from reference [19].

3.5.1 PI Controller for BESS

The previous controller in our BESS model is essentially a P (Proportional) controller; here we examine the control performance of the classic PI controller in our problem. Its expression is the following equation:

$$K(s) = K_p + \frac{1}{T_i s} \quad (3.18)$$

In the above controller, we set K_p equal to the k_{es} value obtained in previous section 3.1 for the original NE 39-bus case. Then, set the following values for T_i as in Table 3.19, to compare the performance of this PI controller with our proposed controller, c.f. Eq. (2.3).

Table 3.19. Parameter settings of the integral time constant

T_i	0.01	0.1	1
$\xi_k\%$	3.826	4.055	5.151

Remember that the previous found optimal location vector and controller gain vector are: $\mathbf{locs} = [35, 36, 38]$ and $\mathbf{k}_{es} = [29.5894, 8.2391, 22.5577]$, and the damping ratio of the target mode is 5.005%. It can be observed that, with added

integrator part in the PI controller, its performance in terms of the damping ratio of the target mode becomes worse when the control parameter T_i is small.

The rotor angle responses of generator-1 under different BESS controller settings are shown in Fig. 3.22. Although larger value of T_i may bring certain improvement, the cost is the larger BESS power overshoot during transient response as shown in Fig.3.23, which leads to higher power capacity ratings of BESS converters and hence higher investment costs, which is undesired.

3.5.2 Conclusion

In this chapter, the original controller is compared with a PI controller to demonstrate its better performance.

From the result, it can be inferred that the PI controller does not perform as well as the proposed P controller, in terms of the damping ratio value when the integral constant cannot be large enough. Besides, the original controller eliminates the need of simultaneously tuning two parameters for each BESS unit, and thus reduce the design complexity of the whole system as well

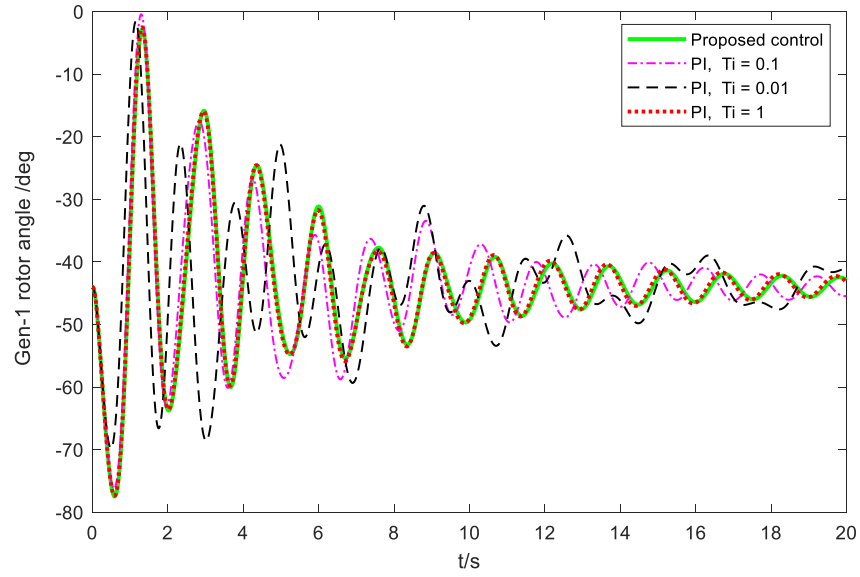


Figure 3.22. Comparison of generator-1 rotor angle responses under different BESS controller settings

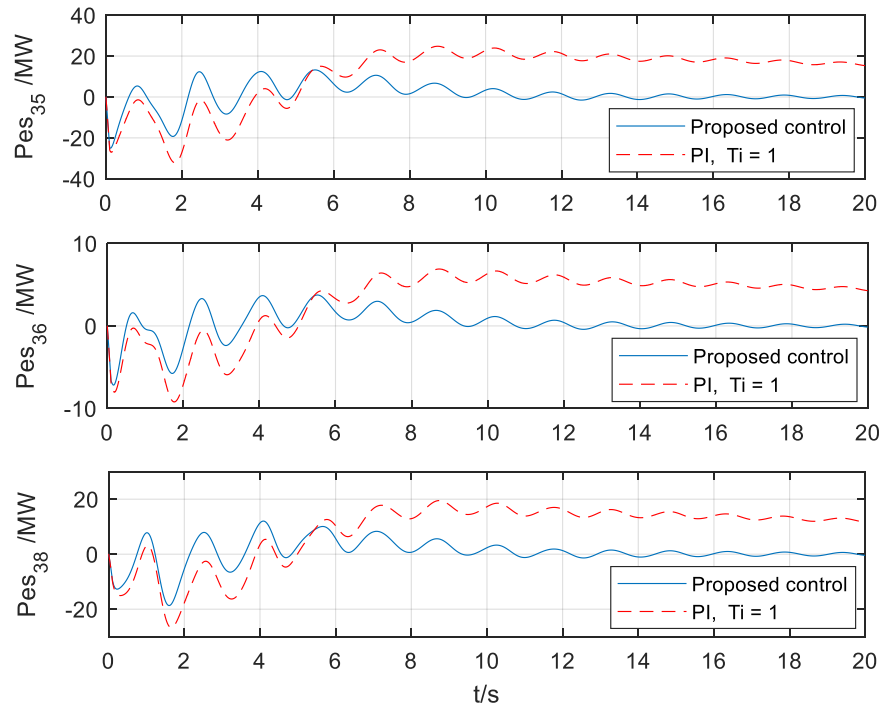


Figure 3.23. The power output comparison of the three BESS units in the NE 39-bus system by different controllers

CHAPTER FOUR

SUMMARY

In this dissertation, a novel BESS-based oscillation damping control approach was developed [41] [42]. Several findings are:

1. Quantifiable improvement of the damping ratio for a target mode can be achieved precisely by the proposed analytic-eigenvalue-solution based algorithm for a multi-machine system with BESSs.
2. The proposed control approach will not influence the damping ratios of the other oscillation modes and the energy variation of each BESS for oscillation damping control is small.
3. The optimization of BESS locations and control parameters can be effectively solved by the Mixed-Integer PSO algorithm. The optimized locations are robust against small changes of the operating condition.
4. The proposed optimization framework was successfully applied to seasonal load changes, which may lead to a larger objective value due to the increased number of the nonconvex constraints.

5. The minimum number of BESS units was found by a cost analysis based on the previously established optimization framework. Two and three are respectively the proper numbers of BESS units to be placed in the New England 39-bus system and the Nordic test system.

6. Using only generator terminal buses and several nearest neighbors as the candidate locations can speed up the Mixed-PSO algorithm in our problem.

7. The proposed BESS controller is compared with a classic PI controller. Results show that our proposed one outperforms the latter one in terms of the lower power overshoot in each BESS.

Future work may include consideration of more physical constraints of the BESS units and analysis of their impacts on the placement results, such as different time constants of controller, lifespan degradation effects, and cell temperature effects. Regarding the controller design, compensating the power response delay due to the converter time constant of the BESS converter for a higher control accuracy is another research direction

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APPENDIX

Appendix-I: ESPRIT Algorithm

The TLS-ESPRIT algorithm [31] [32] for spectral estimation is as follows:
an oscillation signal with multimodal components (suppose the modal number is q) can be expressed as:

$$x(n) = \sum_{i=1}^q a_i e^{-j\phi_i} e^{-(\sigma_i + j2\pi f_i)nT_s} + w(n) = \sum_{i=1}^q s_i z_i^n + w(n) \quad (\text{A.1})$$

where, $z_i = e^{-(\sigma_i + j2\pi f_i)T_s}$, $s_i = a_i e^{-j\phi_i}$.

Then, by introducing a so-called rotation operator Φ which contains all the modal information, and denoting, a sequence of the above signals with length m ($m > q$) can be expressed as:

$$\mathbf{x}(n) = \mathbf{A}\Phi^n \mathbf{s} + \mathbf{w}(n), \quad \Phi = \text{diag}[z_1, z_2, \dots, z_q] \quad (\text{A.2})$$

Where,

$$\mathbf{x}(n) = [x(n), x(n+1), \dots, x(n+m-1)]^T$$

$$\mathbf{w}(n) = [w(n), w(n+1), \dots, w(n+m-1)]^T$$

$$\mathbf{s} = [s_1, s_2, \dots, s_q]^T$$

$$\mathbf{A}(z_i) = [a(z_1), a(z_2), \dots, a(z_q)]$$

$$\mathbf{a}(z_i) = [1, z_i, \dots, z_i^{m-1}]^T$$

T_s is the sampling time.

The modal frequency and damping information are totally determined by Φ . Then split the matrix $\mathbf{A}$ as $\mathbf{A}_1$ and $\mathbf{A}_2$:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 \\ \text{last row} \end{bmatrix} = \begin{bmatrix} \text{first row} \\ \mathbf{A}_2 \end{bmatrix} \Rightarrow \mathbf{A}_2 = \mathbf{A}_1 \Phi \quad (\text{A.3})$$

It should be mentioned here that there are multiple implement versions of the original ESPRIT idea. The simplest one is using only the data matrix; other version involves calculating the covariance matrices or auto-correlation functions/matrices. In this dissertation, the former is adopted as the procedure listed in the following:

1) Construct data matrix:

$$\mathbf{X} = \begin{bmatrix} x(0) & x(1) & \dots & x(k-1) \\ x(1) & x(2) & \dots & x(k) \\ \vdots & & & \vdots \\ x(m-1) & x(m) & & x(N-1) \end{bmatrix} \quad (\text{A.4})$$

2) SVD for data matrix:

$$\mathbf{X} = \mathbf{U} \Sigma \mathbf{V}^H = \begin{bmatrix} \mathbf{U}_s & \mathbf{U}_n \end{bmatrix} \begin{bmatrix} \Sigma_s & \\ & \Sigma_n \end{bmatrix} \begin{bmatrix} \mathbf{V}_n^H \\ \mathbf{V}_s^H \end{bmatrix} \quad (\text{A.5})$$

The columns of $\mathbf{U}_s$ span the same subspace as the columns of the matrix

A. Thus, $\exists$ matrix $\mathbf{T}$, such that

$$\mathbf{A} = \mathbf{U}_s \mathbf{T}, \quad \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{U}_1 \mathbf{T} \\ \mathbf{U}_2 \mathbf{T} \end{bmatrix}, \quad \mathbf{U}_s = \begin{bmatrix} \mathbf{U}_1 \\ \text{last row} \end{bmatrix} = \begin{bmatrix} \text{first row} \\ \mathbf{U}_2 \end{bmatrix} \quad (\text{A.6})$$

Then by (A.3),

$$\mathbf{U}_2 \mathbf{T} = \mathbf{U}_1 \mathbf{T} \Phi \Rightarrow \mathbf{U}_2 = \mathbf{U}_1 \Psi, \quad \Psi = \mathbf{T} \Phi \mathbf{T}^{-1} \quad (\text{A.7})$$

The matrix Ψ has the same eigenvalues as the matrix Φ due to matrix similarity. To obtain Ψ , the convention least square solution using pseudoinverse can be given as:

$$\Psi = (\mathbf{U}_1^H \mathbf{U}_1)^{-1} \mathbf{U}_1^H \mathbf{U}_2 \quad (\text{A.8})$$

$\mathbf{U}_s$ may subject to certain measurement noise and disturbance error, thus the **Total Least Square (TLS)** method can be applied here, i.e., firstly obtain the SVD of the augmented matrix $[\mathbf{U}_1 \ \mathbf{U}_2]$ and partition its right singular vectors as:

$$[\mathbf{U}_1 \ \mathbf{U}_2] = \bar{\mathbf{U}} \bar{\Sigma} \bar{\mathbf{V}}^H, \quad \bar{\mathbf{V}} = \begin{bmatrix} \bar{\mathbf{V}}_{11} & \bar{\mathbf{V}}_{12} \\ \bar{\mathbf{V}}_{21} & \bar{\mathbf{V}}_{22} \end{bmatrix} \quad (\text{A.9})$$

Then the optimal estimation of Ψ under the TLS meaning is:

$$\Psi = -\bar{\mathbf{V}}_{12}^H \bar{\mathbf{V}}_{22}^{-1} \quad (\text{A.10})$$

After Ψ is estimated, its eigenvalues λ_q can be solved. Then the frequency, damping coefficient and damping ratio for the q -th mode can be calculated as:

$$\omega_q = \frac{\arg \lambda_q}{T_s}, \quad \sigma_q = -\frac{\ln |\lambda_q|}{T_s}, \quad \xi_q = \frac{\sigma_q}{\sqrt{\sigma_q^2 + \omega_q^2}} \quad (\text{A.11})$$

Appendix-II: Modified data of generator AVR and governor

In DIgSILENT, the modified parameters of AVR (the controller gain " K_a ") and governor (the controller gain " K ") for certain generators are listed in Table A.1 for the NE 39-bus system ("--" means no change); for the Nordic test system, the modified parameters of AVR (the controller gain " K_p " and " G ") are listed in Table A.2. The corresponding block diagrams of the above AVR and governor models are respectively shown in Fig. A.1 to Fig. A.3.

Table A.1. Modified parameters for the NE 39-bus system

Gen No.	K_a	K
4	80	50
5	80	50
6	80	50
7	80	50
8	80	50
9	60	50
10	80	--

Table A.2. Modified parameters for the Nordic test system

Gen No.	K_p	G
18	10	500
15	10	500
17	--	500
16	--	500
6	--	500
14	--	500

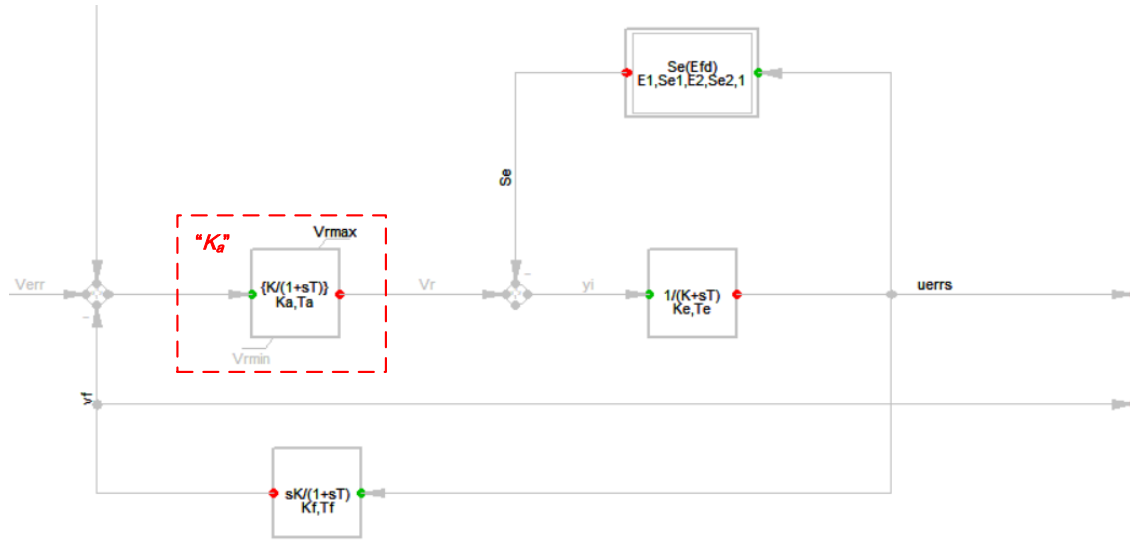


Figure A.1. The partial block diagram of the “IEEE1”-type AVR model for the NE 39-bus system in DigSILENT (for the parameter “ K_a ”)

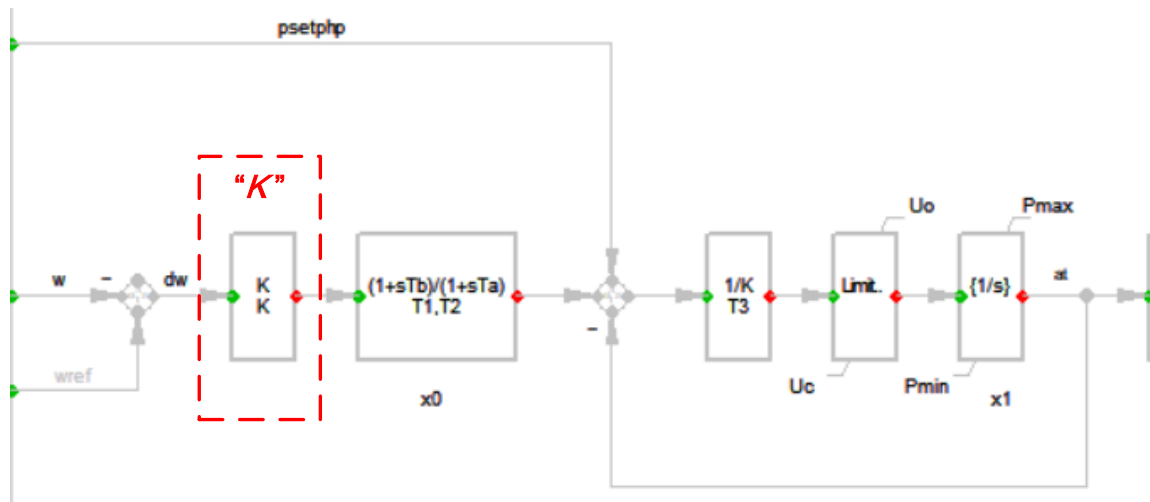
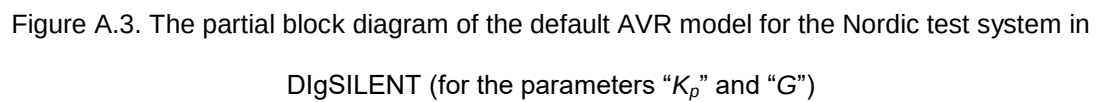


Figure A.2. The partial block diagram of the “IEEEG1”-type governor model for the NE 39-bus system in DigSILENT (for the parameter “ K ”)



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