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Frequency Control of Large-Scale Interconnected Power Systems via Battery Integration: A Comparison Between the Hybrid Battery Model and WECC Model

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***Abstract*—The increasing penetration of renewable energy sources in power grids highlights the role of battery energy storage systems (BESSs) in enhancing the stability and reliability of electricity. A key challenge with the renewables', specially the BESSs, integration into the power system is the lack of proper dynamic model for stability analysis. Moreover, a proper control design for the power system is a complicated issue due to its complexity and inter-connectivity. Thus, the application of decentralized control to improve the stability of a large-scale power system is inevitable, especially in distributed energy sources (DERs). This paper presents an optimal distributed hybrid control design for the interconnected systems to suppress the effects of small disturbances in the power system employing utility-scale batteries based on existing battery models. The results show that i) the smart scheduling of the batteries' output reduces the inter-area oscillations and improves the stability of the power systems; ii) the hybrid model of the battery is more user-friendly compared to the Western electricity coordinating council (WECC) model in power system analysis.**

***Index Terms*—Battery energy storage system, inter-are oscillations, optimization, decentralized control, and hybrid control.**

I. Introduction

Sparsely interconnected power systems experience inter-area oscillations. The inter-area oscillations, with frequency of 0.1-2.0 hz, occur as generators in one area oscillate against the rest of the power system. These oscillations typically happen due to weak connections or high-power transmission between the areas [1] and can damage the stability of the power system. Hence, small-signal stability is one of the most challenging issues for current and future power grids, especially in renewables. There are several ways to damp or suppress these oscillations including the use of power system stabilizers (PSSs), improving the generators' exciters [2], [3], and improving transmission lines in the power systems [4]. The American Physical Society (APS) has proposed a long-term plan to the US Department of Energy (DOE) with a particular focus on renewables integration to the power system and the importance of BESSs to stabilize the future power grid [5].

Considering the promising position of batteries in the future power grid, properly managed battery integration can be considered an effective solution for inter-area oscillations in the power grid in both distribution and transmission levels. Batteries can absorb/inject both active and reactive power. This characteristic of the batteries provides the unique opportunity for power system to manage the battery's output power to improve the power grid stability.

The complexity of the power system is a significant challenge to design and implement a proper centralized control. Decentralized control methods have been widely used in power systems as more practical control strategies compared to centralized control methods in large-scale systems. In a decentralized control design, no information exchange among different areas is necessary to establish a controller for a subsystem. Also, any inputs to the subsystem other than local inputs are considered as perturbations [6]. This makes the control design and implementation easier in large power systems. In complex systems, where databases are developed around the plants with distributed data sources, a need for fast control action in response to local inputs and perturbations dictates the use of decentralized control structures. The main advantages of the decentralized observer and control design include higher computational efficiency of systems, higher reliability of estimators due to the distribution of resources, and scalability of controllers and observers designed for large systems [7].

However, in the decentralized control system, the multi-ownership and competition between the various actors (control units) are serious challenges. Moreover, renewables integration into the power system changes the architecture of the power grid to a more complicated and more interconnected. The control design for a system with strong inter-connectivity is a complex issue. In this subject, Siljak [8] proposed a suboptimal decentralized control approach for large-scale interconnected systems such as power system. In this approach the optimal control is designed for each subsystem considering the inter-connectivity of the subsystems. This approach allows the control units to take the advantage of the shared information and be robust to the other subsystems' behavior.

In this paper, we focus on large-scale battery integration

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into the power system to damp the frequency deviation due to its fast response. The control design for the power system in the presence of the BESSs depends on the dynamic model of the battery along with the power system dynamics. Two dynamic models, a hybrid battery model and the WECC model, are considered in this paper to simulate the large-scale battery behaviors in power systems. The WECC model is developed and introduced by the Western electricity coordinating council as a generic model for renewables including battery energy storage systems [9] - [11]. The hybrid model, is developed based on the dynamics of the battery and its inverter's electric circuit model [12]- [13]. Each model has its own advantages and disadvantages which is beyond the scope of this paper.

In this study, a three-area loop-shape power system is considered as a large-scale interconnected system. Each area is equipped to a large-scale battery with controllable output power. The decentralized control approach for large-scale interconnected systems [8] is used to control the dis/charge profiles of the batteries to stabilize and improve system's performance in presence of the disturbances. We consider both battery models to design distributed controllers based on decentralized optimal control approach for the interconnected case study power system. The aim of this paper is to compare and analyze the control design and system performance in both cases.

In the first case, the hybrid model of the battery will be considered and augmented into the power system dynamics. Considering different charging/discharging dynamic models for the large-scale battery and the necessity of switching between charging/discharging modes, the power system dynamic model creates a hybrid system [13]. The hybrid nature of the battery operation and complexity of the power system require a new hybrid optimal approach for the control design. In this paper, we design a decentralized optimal control with switching policy to schedule active and reactive output power of the distributed batteries and switch among batteries operating modes to suppress the frequency deviations. In the second case, the dynamics of the battery with the WECC model is integrated with the power system and the optimal decentralized controller is designed. The advantage of this paper is that the batteries in each area will (dis)charge based on their local information and the operating conditions of the other batteries to suppress the frequency deviation without compromising the stability of the power system.

The rest of the paper is organized as follows. Section II describes the problem statement. In Section III, the optimal decentralized control design for interconnected systems is explained. Section IV presents the hybrid and WECC battery models integration into the power grid and control; Section V discusses conclusions and final remarks.

II. Problem Statement and System Description

Load deviations are one of the most challenging issues in power system planning and stability analysis in both distribution and transmission levels, which can be intensified in the presence of renewables and existing tariffs [13]. Load deviations as small disturbances lead to frequency deviations in power systems which can cause notable stress to generators' rotors. Distributed battery integration to power systems is a promising solution to reduce the load and subsequently frequency deviations. The integrated batteries are capable of smoothing the load profile by absorbing the surplus power or injecting the deficit power. Several studies show the effectiveness of battery integration on reducing the frequency deviation by controlling the battery's output power and its power factor [14]- [15]. This paper aims to use distributed batteries to implement a decentralized optimal control strategy with a hybrid switching approach to charge or discharge each battery independently (based on their local information) and damp the frequency deviations in the power system without compromising the voltage stability of the system.

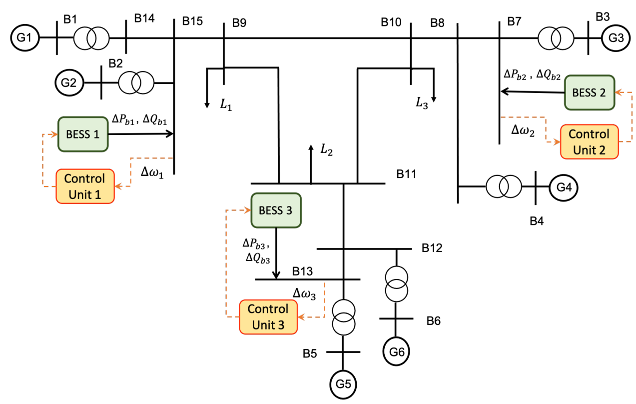

Fig. 1. Three area power system case study model

For this purpose, we consider a three-area six-machine power system as our case study. This model is adapted from [15] and represents a large-scale interconnected power system. Each generator is modeled by seven states and the three areas are connected together through transmission lines to supply load demands. A large-scale battery is connected to each area as shown in Fig. 1. Each battery's control unit has direct access to local information including generators frequency deviation data. Moreover, the batteries have access to other generators' information through the power grid interconnections (admittance matrix, Y_{bus}). The state space representation of the interconnected power system is

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

where, $x \in R^n$, $u \in R^p$, and $y \in R^m$ are states, inputs, and outputs of the system, respectively.

In this study, we consider a recently introduced battery model [13] which is known as hybrid model of the battery.

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The firing angles of the batteries' inverters are considered as control input signals. The control inputs schedule the active and reactive power of the batteries to reduce the frequency deviations. We aim to design optimal hybrid control on the new model and compare the results to the WECC model to evaluate the hybrid battery model effectiveness in frequency regulation.

III. Decentralized Optimal Control for Interconnected Systems

In interconnected systems, the optimality of the system is a complicated context in the presence of some essential uncertainties among the subsystems, which cannot be described in either deterministic or stochastic terms. Unlike standard optimization schemes where robustness is a part of the solution, robustness in complex systems is a part of the problem and it has to be considered in the design process.

Let us consider the interconnected power system in (1) consist of N subsystems (areas). In our case study, the power system has three areas as three subsystems ($N = 3$). Each subsystem i, $i \in N$, has the following dynamics

$$\begin{cases} \dot{x}_i = A_i x_i + B_i u_i + \sum_{j=1}^{N} A_{ij} x_j \\ y_i = C_i x_i \end{cases} \qquad i \in N \tag{2}$$

The system can be rewritten in compact form of

$$\dot{x} = A_D x + B_D u + A_c x \tag{3}$$

where,

$$A_D = diag(A_{D1}, A_{D2}, ..., A_{DN}) \tag{4}$$

The matrix A_D is a block diagonal matrix representing the state matrices of the subsystems and A_C defines the interconnection matrix between the subsystems [8].

The dynamics of the decoupled part of the system in (3) can be written as

$$\dot{x} = A_D x + B_D u \tag{5}$$

where, (A_D, B_D) is controllable with subsystems as

$$\dot{x}_i = A_i x_i + B_i u_i \qquad i \in N \tag{6}$$

To design optimal controller for (5), we define a total cost function as $J_D = \sum_{i=1}^{N} J_i$, , where, J_i is an individual cost function for subsystem i as

$$J_i(x_{i0}, u_i) = \int_0^{\infty} (x_i^T Q_i x_i + u_i^T R_i u_i) d\tau \tag{7}$$

with the state and input weighting matrices as

$$Q_D = diag(Q_1, Q_2, ..., Q_N) \tag{8}$$

$$R_D = diag(R_1, R_2, ..., R_N) \tag{9}$$

where Q_D is symmetric nonnegative definite, and R_D is a symmetric positive definite matrix.

The optimal control law for system in (5) is $u_D^* = -K_D x$, where, K_D= diag $(K_1, K_2, \ldots, K_N)$ and P_D = diag $(P_1, P_2, \ldots, P_N)$ is the solution of the Riccati equation

$$A_D^T P_D + P_D A_D - P_D B_D R_D^{-1} B_D^T P_D + Q_D = 0 \tag{10}$$

The closed loop system and optimal cost will be

$$\dot{x} = (A_D - B_D K_D) x \tag{11}$$

$$J_D^* = x_0^T P_D x_0 \tag{12}$$

It is clear that the obtained results are optimal for a closed loop system in form of (11); however, for an interconnected system of (1), the closed loop system will be in form of (13) and the obtained solution is not optimal. In other words, the u_D^* is locally optimal due to the interconnectivity of the system. The decentralized optimal control is suboptimal and stable for the system (1) under certain conditions [8].

$$\dot{x} = (A_D - B_D K_D + A_C) x \tag{13}$$

Remark: ***Suboptimality and Stability***

Considering the interconnectivity of the system and the closed loop system (13), the interconnections of the system, matrix A_C, plays the perturbation role in the system. Hence, the obtained control law, u_D^*, is suboptimal for the systems (1) and (3) if and only if $\hat{A}$ is stable.

$$\hat{A} = A_D - B_D K_D + A_C \tag{14}$$

The matrix $\hat{A}$ is stable if the pair of$((A_D + A_C), Q_D^{1/2})$ is detectable.

To calculate the cost function for (1), a suboptimality index is defined to measure the cost of the robustness of the control to the existing structural perturbations. Considering system (14), the performance index is defined as

$$J_D^* = x_0^T H x_0 \tag{15}$$

$$H = \int_0^{\infty} exp(\hat{A}^T t).G_D.exp(\hat{A} t) d\tau \tag{16}$$

$$G_D = Q_D + P_D B_D R_D^{-1} B_D^T P_D \tag{17}$$

Theorem:

A control law u_D^* is suboptimal with (largest) degree of suboptimality for the system if and only if the matrix H is finite.

$$\mu^* = \lambda_M{}^{-1} (H P_D{}^{-1}) \tag{18}$$

Matrix H is finite when the $\hat{A}$ is stable and it can be calculated as the unique solution of the Lyapunov matrix equation

$$\hat{A}^T H + H \hat{A} + G_D = 0 \tag{19}$$

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Note: The objective of this paper is to integrate batteries into the power grid and schedule their output power to suppress the frequency deviations. For this purpose, we develop two models for the battery and integrate them separately. Then, based on the developed system model, for each case, a decentralized optimal control for the interconnected systems will be designed and applied to the case study.

IV. Battery Integration into the Power System

The power system case study model in this study is a three-area ($N = 3$) loop-shaped interconnected power system consisting of six generators and three batteries. Power system network equations are used to integrate the batteries into the power system. For this scenario, we use hybrid battery modeling; the battery integration process is explained in detail in our previous work [13].

A. Case 1: Hybrid Battery Model

Each subsystem has 17 states ($n = 17$), one control input ($p = 1$) and eight outputs ($m = 8$). The states in each subsystem consists of 14 states for two generators (7 states for each generator) and three states to model the battery dynamics in the area. In the hybrid model, the battery is represented by two different dynamics for charging and discharging operation conditions creating a hybrid model for the battery [13]. It is shown that the dynamic of the battery differs due to the battery's internal resistances differences and the (dis)charge current directions. Batteries are considered the ancillary service provider to damp the inter-area oscillation by active/reactive power injection to the power system; therefore, the battery's inverter firing angle is considered as the control input in each area to schedule the battery active and reactive power to damp the frequency deviations. The details on the system model, state-space matrices, dynamics of the batteries are adapted from [16] and [17], and is modified to a three-area loop-shaped power system.

Hybrid Control Design

There are three batteries with hybrid model in the case study model; so, there will be eight $2^3 = 8$ charging and discharging possibilities for batteries operation. For all of these 8 modes of operation, a decentralized control is designed and applied to the case study model using the control approach in *Section III*. The poles of the case study system in the presence of the batteries are presented in Fig. 2. To make the results clearly and traceable, only two modes of operation with and without the designed controllers have been plotted. The results show that the uncontrolled battery integration into the power system can cause instability in the power system (depending on the (dis)charging statue and the bus they have been integrated to). The controlled operation of the battery stabilizes the system and relocates the system eigenvalues/poles to the further left. The frequency deviations of the first generator corresponding to the scenarios in Fig.2, are depicted in Fig. 3. The generator's frequency deviations have been improved significantly in controlled cases. In some scenarios, such as all batteries charging scenario frequency has been damped in a shorter time compared to the others. However, the cost of battery operation can be higher than the other scenarios. To minimize the batteries final operation cost, the hybrid switching strategy is proposed in the next section.

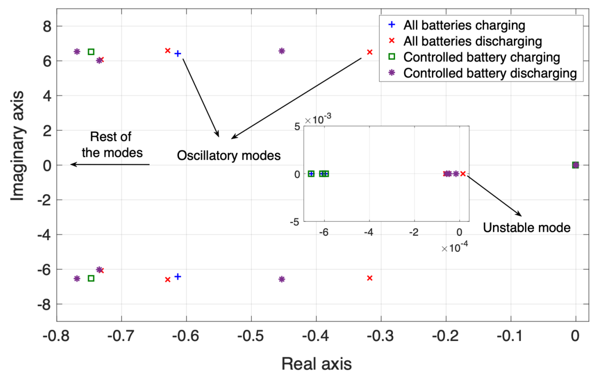

Fig. 2. Eigenvalues of the system in the presence of batteries

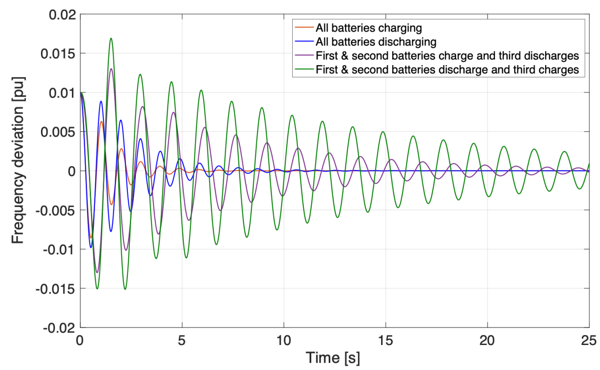

Fig. 3. Three area power system case study model

Hybrid Switching

Subsystem i^{th} of our case study has two state space models for charging and discharging scenarios. Thus, the control strategy should be able to frequently switch between charging and discharging operating conditions to optimize the battery's operation and reduce the frequency deviations of the system, simultaneously. The proposed control system schematic, for the battery in the area i is presented in Fig. 4.

Considering 1 for charging and 0 for discharging scenarios the charging/discharging possibilities are as follows

$j \in W = \{100, 110, 101, 111, 000, 001, 010, 011\}$

Each configuration provides a new state matrix and consequently a new cost function. For instance, for $j = 1$, the case the battery in the first area charges and batteries in the second and third areas discharge. The state matrix in (1) will be defined as A_1

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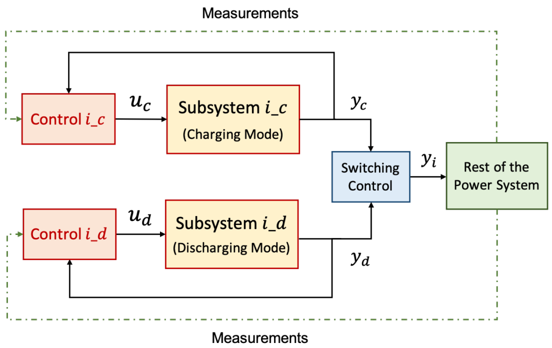

Fig. 4. Three area power system case study model

$$A_1 = \begin{bmatrix} A_{D-c1} & A_{C12} & A_{C13} \\ A_{C21} & A_{D-d2} & A_{C23} \\ A_{C31} & A_{C32} & A_{D-d3} \end{bmatrix} \tag{20}$$

where, referring to (2)-(4), $A_{(D_c i)}$ represents the A_D matrix of the subsystem i in charging mode, $A_{(D_d i)}$ is the A_D matrix of the subsystem i in discharging mode, A_{Cij} is the A_{Cij} matrix of the subsystem i corresponding to subsystem j. An optimum operation plan is designed to switch between the modes in each area/subsystem based on its local information and operating cost function. The decentralized sub-optimal control receives information from the rest of the power system and its previous states to update the control gains. To design a switching strategy to minimize the total cost function of the batteries' operation, we need to define an optimal cost function. The optimum cost function depends on the system's initial condition and the operating conditions. In this regard, an operating cost function for each scenario is defined, which will be updated at the beginning of each time interval. For example, we consider one of the battery operating scenarios as A_1 matrix (20). Similar to the state matrix, the weighting matrices associate with state matrix (20) will be defined as follows

$$Q_1 = diag(Q_{D-c1}, Q_{D-d2}, Q_{D-d3}) \tag{21}$$

$$R_1 = diag(R_{D-c1}, R_{D-d2}, R_{D-d3}) \tag{22}$$

Finally, to prevent frequent and unnecessary switching between modes of operations a normalized cost function is considered for above-mentioned switching scenarios. For example, in the first scenario, $j = 1$, with the system matrix A_1, the cost function will be

$$J_1 = \int_{t_{k-1}}^{t_k} (x^T Q_1 x + u_1^T R_1 u_1) d\tau \tag{23}$$

$$u_1 = [u_{c-1}, u_{d-2}, u_{d-3}]^T \tag{24}$$

$$K_1 = diag(K_{D-c1}, K_{D-d2}, K_{D-d3}) \tag{25}$$

$$G_1 = Q_1 + P_1 B_1 R_1^{-1} B_1^T P_1 \tag{26}$$

$$\hat{A}_1 = A_{1D} - B_1 K_1 + A_{1C} \tag{27}$$

$$J_1^+ = x_0^T H_1 x_0 \tag{28}$$

For each scenario, the performance index is calculated via (15)- (18). The worst operation index represents the minimum robustness of the system which is 0.034. The stability of hybrid systems includes several phenomena due to the interaction of continuous variable dynamics and discrete switching logics [18]. For instance, even when all the continuous variable subsystems are stable, the hybrid system may have divergent trajectories under certain discrete switching logic. On the other hand, a careful switching between unstable continuous variable subsystems can make the overall hybrid system exponentially stable; which suggests that the stability of hybrid systems depends on two factors: the continuous variable dynamics of each subsystem and the discrete switching logics properties. In this regard, the optimum switching time is a crucial factor to be considered in hybrid control strategy. Studies show that it is always possible to maintain stability of the system when all the subsystems are stable and switching time is slow enough, in the sense that switching time interval is sufficiently large [19]. Moreover, it is shown that if one of the subsystems has a smaller dwell time between switching, system still remains stable if the switching does not occur too frequently [**?**].

B. Case 2: Western Electricity Coordinating Council (WECC) Battery Model

One of the key challenges with battery integration into the power system is the development of standard simulations models for power system studies such as stability analysis. In this subject, the Western Electricity Coordinating Council has developed a module-based model for the renewable sources. Each module in the model represents a specific aspect of the renewable energy system, and thus, each specific plant such as solar panels or battery can be represented by connecting together the right combination of these modules [20]. For instance, for battery dynamics model, the existing renewable energy generator/converter (REGC-A) model, without any modifications, is used to represent the power converter interface between the battery and the grid. Next, the existing renewable energy electrical control (REEC) model is augmented to the REGC-A to add a feature of charging and discharging operations to the battery model. The major draw backs in this model are i) the details of the dc dynamics is neglected; and ii) the model is basically consists of some PI controls that mimics the battery behavior in the power system.

As it is explained in hybrid battery model, the power system equation is needed to integrate the battery into the power system. For this purpose, the battery equation should be written is following format

$$\begin{cases} \Delta \dot{x}_b = [A_b]\Delta x_b + [B_b]\Delta v_b + [E_b]\Delta u_{cb} \\ \Delta I_b = [C_b]\Delta x_b + [D_b]\Delta v_b \end{cases} \quad (29)$$

The Δv_b represents the bus voltage that the battery is integrated into and E_b is the control input to schedule the battery's active and reactive power [13].

In WECC model battery and its control unit is represented by two modules, REGC-A and REEC-C. Considering the REGC-A and REEC-C modules, the battery dynamics equation is derived and linearized in the given structure of (29) and will be integrated into the power system model [13]. Similar to the hybrid battery model, the state matrix is decomposed to decoupled and interconnection parts. Then, the decentralized control for interconnected system is designed for the decoupled portion of the system such that by adding the interconnected part the whole system remains stable. In this model, the battery dynamics is represented by a 5×5 matrix with two inputs as follows:

$$A_b = \begin{bmatrix} -\frac{1}{T_g} & -\frac{1}{T g v_{tf0}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{pord}} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_g} & -\frac{1}{T_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{iq}} & -\frac{Q_0}{T_{iq} v_{tf0}^2} \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{rv}} \end{bmatrix} \quad (30)$$

$$B_b = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{V_{d0}}{T_{rv}} & \frac{V_{q0}}{T_{rv}} \end{bmatrix} \qquad E_b = \begin{bmatrix} 0 & 0 \\ \frac{1}{T_{pord}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{iq} v_{tf0}} \\ 0 & 0 \end{bmatrix} \quad (31)$$

Considering the WECC dynamics for the integrated batteries, each subsystem in the case study model has 19 states ($n = 19$) consisting of 14 states for two generators and five states for the battery. Also, each subsystem has two control inputs ($p = 2$), and eight outputs ($m = 8$) including dynamics of the battery. Using the discussed decentralized framework for the interconnected systems, a decentralized controller is designed and applied to the model.

V. Simulation Results

In this section, we run simulation studies on the interconnected loop shaped case study for both battery modeling approaches. In both cases, the corresponding designed controller is implemented into the case study model and the simulation runs for $10s$.

A. Case 1: Hybrid Battery Model

In this case, for the hybrid controller of the battery, we consider switching time as $(t_{k-1}, t_k) = 1.5s$ to guarantee the stability of the system. The hybrid controller selects the scenario with the minimum cost function as the operating mode for the given time interval. Then, the system's states are updated based on the selected scenario and the selected LQR control law for the next time slot. Consequently, the total cost function of the power system's battery operation as the summation of three selected cost functions (associated with each scenario) is minimized.

The hybrid control in each step picks the optimum case determining batteries charging/discharging modes. The control strategy switches between charging and discharging modes to optimize the total operation cost and reduce the frequency deviations of the system, simultaneously.

To illustrate the effectiveness of the hybrid control on frequency deviations of the generators one, three, and five (one generator from each area) are displayed in Fig. 5- Fig. 7, respectively.

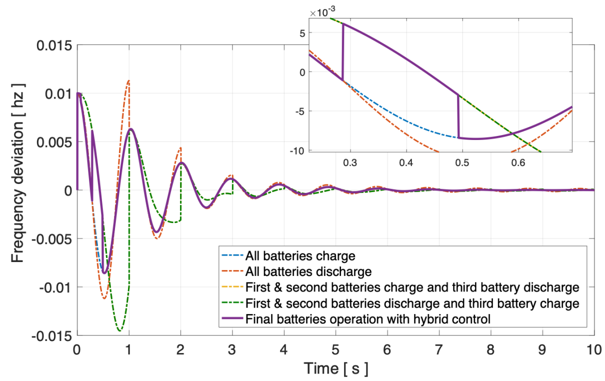

Fig. 5. Frequency deviations of the generator number one in the first area for different scenarios and hybrid control final decision

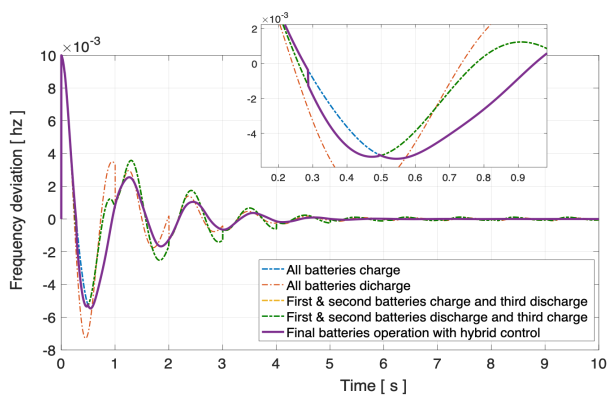

Fig. 6. Frequency deviations of the generator number three in the second area for different scenarios and hybrid control final decision

For the sake of simplicity, we only show the batteries operations for four scenarios out of total 8 cases. These scenarios are: all batteries are charging, all batteries are discharging, first and second batteries charging and third battery discharging, first and second batteries discharging and the third battery charging. In Fig. 5- Fig. 7, the dotted lines

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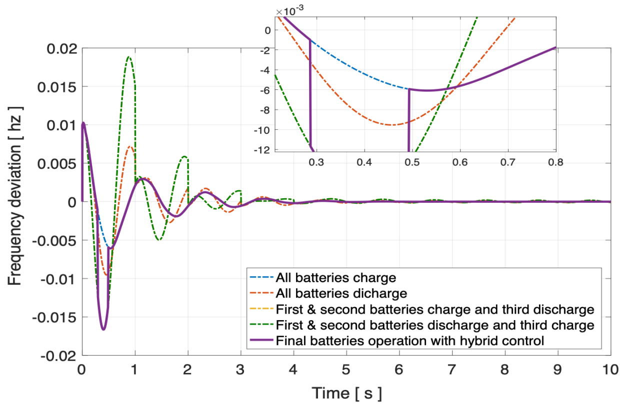

Fig. 7. Frequency deviations of the generator number five in the third area for different scenarios and hybrid control final decision

represent the generator's frequency deviations for these four scenarios. Generators frequency deviations under the optimal switching policy with the hybrid controller are shown with solid purple lines. At the end of each time interval, the initial conditions of all scenarios are updated based on the selected scenario.

B. Case 2: WECC Battery Model

The eigenvalues of the case study model with WECC model for battery dynamics are shown in Fig. 8. The buses that batteries are connected are same for both approaches. Similar to the hybrid model, the uncontrolled WECC model battery integration can cause instability in the power system. Note that the system eigenvalues/poles depend on the buses that batteries are integrated into. By changing the connection bus, the eigenvalues of the system will change. The frequency deviations of the generators one, three, and five (one from each area) are depicted in Fig. 9 - Fig. 11. Frequency deviations for the system with batteries modeled via hybrid model have been suppressed faster compared to the system with WECC model for batteries.

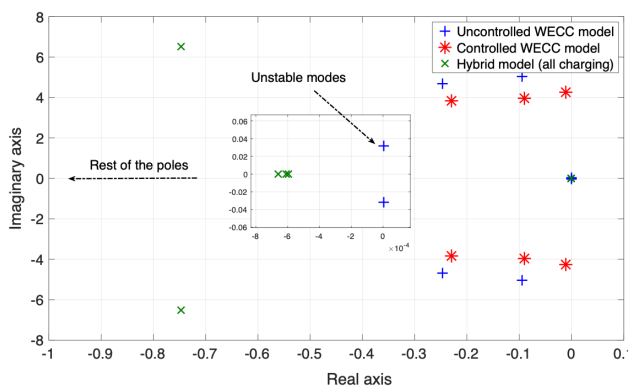

Fig. 8. The eigenvalues of the case study model with WECC model for battery dynamics

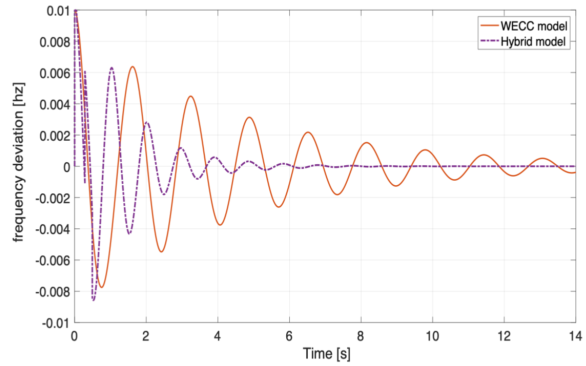

Fig. 9. First generator frequency deviation in the first area

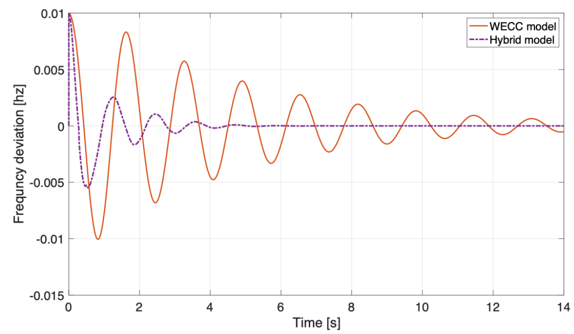

Fig. 10. Third generator frequency deviation in the second area

Although the WECC model has two control inputs, the control design is more challenging compare to the hybrid battery model. Since the WECC model has fifth order dynamics, it has strong inter-connectivity matrix which plays as a major perturbation in the system. The optimality index in the WECC model is 0.01 which is lower than the smallest optimality index in the hybrid model.

VI. CONCLUSION

In this paper, a decentralized LQR controller for an interconnected system is designed to damp the frequency oscillations via battery's output power. The batteries' active

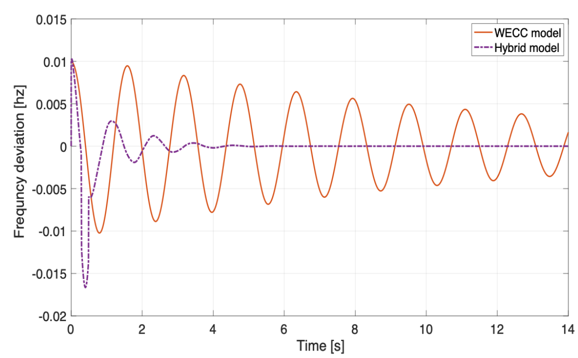

Fig. 11. Fifth generator frequency deviation in the third area

and reactive output power are regulated to control the frequency deviations in each area. In this study, we consider two different battery modeling approaches for the control design: a hybrid model and the WECC model. For each battery model we design the optimal decentralized controller and compare their performances on damping the frequency deviations. The optimal decentralized control strategy is designed considering based on the total operation cost function for battery modes to optimize the batteries output power and suppress the frequency deviations. In the former case where the battery dynamics is modeled with a hybrid model, all charging and discharging scenarios for the batteries operations are considered and for each scenario a decentralized optimal controller is designed. Then, a hybrid switching control is designed to select the best operating scenario for the batteries with minimum cost.

The results show a notable improvement in frequency deviations in the case study system for both hybrid and WECC models. The hybrid model has better frequency damping compared to the WECC model. In spite of WECC model's higher degree of freedom in control inputs, the control design for the hybrid model is more convenient due to the week inter-connectivity of the system under hybrid dynamics of the battery. For future work, a decentralized hybrid switching control will be designed for each area to study the impact of batteries independent operations with the centralized hybrid control. Also. system's stability under switching operation will be investigated to guarantee the stability of the power system.

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