

Frequency Regulation Model of Bulk Power Systems with Energy Storage

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Abstract—This paper presents a Frequency Regulation (FR) model of a large interconnected power system including Energy Storage Systems (ESSs) such as Battery Energy Storage Systems (BESSs) and Flywheel Energy Storage Systems (FESSs), considering all relevant stages in the frequency control process. Communication delays are considered in the transmission of the signals in the FR control loop and ESSs, and their State of Charge (SoC) management model is considered. The system, ESSs and SoC components are modelled in detail from a FR perspective. The model is validated using real system and ESSs data, based on a practical transient stability model of the North American Eastern Interconnection (NAEI), and the results show that the proposed model accurately represents the FR process of a large interconnected power network including ESS, and can be used for long-term FR studies. The impact of communication delays and SoC management of ESS facilities in the Area Control Error (ACE) is also studied and discussed, as well as the computational efficiency of the proposed FR model.

Index Terms—Area Control Error, batteries, communication delays, energy storage, flywheels, frequency regulation, frequency response.

NOMENCLATURE

Indices

0	Initial value.
ESS	ESS: FESS or BESS.
t	Time.

Parameters

a, b, c, d	Parameters used in the identification of ESS's SoC bands.
AV_{ESS}	Status availability of the ESS.
B	BA bias [MW/0.1Hz].
β_{EI}	Eastern Interconnection frequency response [MW/0.1Hz].
β_{IESO}	Ontario power system frequency response [MW/0.1Hz].
$C(z)$	ESS charging transfer function.
c_f	Stage II gain.

CD	Communication delay [s].
CD_{TG}	Communication delay for TGs [s].
CF	Correction Factor block.
CF_1^D, CF_2^D	Correction factor discharging input multipliers.
CF_{eq}, CF_1^C, CF_2^C	Correction factor charging input multipliers.
CF_{out}^C	CF block charging output.
CF_{out}^D	CF block discharging output.
$D(z)$	ESS discharging transfer function.
E_{ESS}	ESS energy capacity [MWh].
E_q	Equality condition parameter.
$F(z)$	Transfer function that allows closer fit between the model results and measured data for frequency.
f_s	Scheduled frequency [Hz].
F_{sr}	Falling slew rate[MW].
IME	Interchange metering error [MW].
In^C	CF block charging input.
In^D	CF block discharging input.
IP	Inadvertent payback [MW].
K	Power-to-energy value [hr/s].
k_i	Integral controller gain.
k_p	Proportional controller gain.
ks_{dw}, kr_{dw}	Parameters representing SoC values for k_{dw} flip-flop.
ks_{up}, kr_{up}	Parameters representing SoC values for k_{up} flip-flop.
$\bar{L}_{off}$	Upper limit of the ESS's lower SoC band.
$\underline{L}_{on}$	Lower limit of the ESS's lower SoC band.
NI_s	Scheduled net interchanges [MW].
ω_0	Pre-warping frequency.
P_D	Load of the system [MW].
P_{GT}	Generation total dispatch [MW].
P_{cESS}	ESS power capacity [MW].
RC	FR capacity limit [MW].
R_{sr}	Rising slew rate[MW].
$TG(z)$	Transfer function representing the action of TGs contracted for FR.
$\underline{U}_{off}$	Lower limit of the ESS's upper SoC band..
$\underline{U}_{on}$	Upper limit of the ESS's upper SoC band.

Variables

ACE	Area Control Error [MW].
$ACE_{filtered}$	ACE filtered signal [MW].

This work was supported by the NSERC Energy Storage Technology (NEST) Network. The energy storage data was kindly provided by NRStor Inc. under the auspices of an experimental research program facilitated by Ontario's Independent Electricity System Operator (IESO).

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BP_{ESS}	ESS fixed base point [MW].
BPm_{ESS}	ESS moving base-point [MW].
$F(IP)$	Function of inadvertent payback [MW].
f_a	Actual frequency [Hz].
k_{up}, k_{dw}	Outputs of the set-reset flip-flops.
$\overline{M}_{ESS}$	Maximum available capacity of the ESS [MW].
$\underline{M}_{ESS}$	Minimum available capacity of the ESS [MW].
NI_a	Actual net interchanges [MW].
P_{ESS}	Power output of the ESS [MW].
P_{TGr}	Output power of TG contracted for FR [MW].
R_{dw}	Reset state of the k_{dw} flip-flop.
R_{up}	Reset state of the k_{up} flip-flop.
S_{dw}	Set state of the k_{dw} flip-flop.
S_{up}	Set state of the k_{up} flip-flop.
SOc_{ESS}	ESS SoC [%].
SP_{ESS}	ESS SP signal [MW].
SR	Scheduled FR signal [MW].
SR_{ESS}	ESS regulation signal [MW].

I. INTRODUCTION

HIGH levels of penetration of Renewable Energy Sources (RESs) are increasing the operational challenges in power grids. Most of the challenges are linked to the uncertainty associated with RES, which leads to increased generation/load mismatches that particularly impact Frequency Regulation (FR) and stability. Energy Storage Systems (ESSs) can help to maintain grid stability and reliability [1], [2], providing energy arbitrage, and ancillary services such as FR, among others, while being competitive and economically viable [3], [4].

In recent years, there has been a significant interest in ESSs because of their decreasing costs [5]. Policies around the world are being modified, and new services are being created to facilitate participation of ESSs in the electricity markets [1], [6], [7]. In some instances, Independent System Operators (ISOs) are implementing grid-scale ESS projects to gain experience and evaluate the benefits and performance of different ESS technologies. For instance, the Alternate Technologies for Regulation (ATR) program by the Independent Electricity System Operator (IESO) of Ontario, which includes a Battery Energy Storage System (BESS) and a Flywheel Energy Storage System (FESS) for FR, was implemented to provide learning opportunities for all stakeholders [7].

The fast power response characteristic of ESSs, such as FESS and BESS, make them particularly suitable to provide fast FR services [4]. A coordination algorithm to dispatch regulation services between slow and fast resources is presented in [8], where the model of an FESS with State of Charge (SoC) band control is mentioned, based on a manufacturer provided model; however, only a block diagram is presented and not all the parts of the model are discussed. In [9], an auxiliary frequency modulation control strategy, which considers Area Control Error (ACE) and the SoC of ESS is presented; however, the ACE and SoC signals are assumed as

inputs without modeling them, which does not allow analyzing their close-loop effect on the FR process. Studies focusing on ESSs for the provision of FR, examine their contribution in helping conventional generators [10] and RES [11] to meet FR requirements, or provide FR themselves (e.g. [12], [13]). However, appropriate ESS models for frequency stability studies are lacking, which hampers the impact analysis studies of ESSs for FR from the ISO's perspective.

The authors in [14] and [15] present SoC evolution equations for FESS and BESS from an operational perspective, and in [16], a BESS model including the battery bank model and the dc-to-dc converter model is presented and tested on a benchmark transmission system. However, all these models are quite detailed and thus not necessary for long-term FR studies of bulk power systems. On the other hand, ESS models for frequency control are presented in [17]–[19]; however, these only consider primary frequency control provision and not secondary regulation.

The model of a two-area system with ESSs used for FR is presented in [20] from the system viewpoint; however, communication delays and SoC models of the ESS facilities are not considered, which may lead to unrealistic effects on the ACE. The studies in [21] and [22] include communication delays in the FR process, but ESSs are not included, and while [23] and [24] consider the SoC model of ESS, these works do not consider communication delays.

Based on the presented literature review, most of the current works that provides models suitable for FR analysis are focused on the control of the SoC or the regulation signal; however, a complete closed-loop and validated model considering all the main stages in the FR control process from the ISO perspective, including ESSs and communication delays, is needed for long-term FR studies. In this context, determining the actual and potential benefits of ESSs for FR in an interconnected power system requires a model that represents the overall frequency dynamics of the system and its limitations. Thus, the current paper contributes to the ongoing efforts of modelling a bulk power system including ESS technologies for FR as follows:

- Develop a FR model of a large interconnected power grid operating under normal conditions, estimating the system model parameters, and validating it with real system information.
- Develop empirically-based SoC models for FESS and BESS considering the charging and discharging process characteristics, validating them using data from actual facilities.
- Analyze the impact of communication delays on the ACE and SoC management of ESS facilities on the provision of FR services.
- Provide a validated FR model of a bulk interconnected power system under normal operating conditions to run longer-horizon FR simulations (i.e., days to months) in short periods of time (i.e., seconds to a few hours).

The rest of the paper is organized as follows: Section II provides a practical overview of frequency control and regulation in power systems, and reviews the ESS technologies used for such services. Section III presents the proposed system and

ESS FR models, and Section IV validates the models using real data from the Ontario Power System (OPS), two ESS facilities, and a model of the North American Eastern Interconnection (NAEI). Studies of the impact of communication delays and the SoC management model of ESS facilities as well as computational efficiency of the proposed FR model are presented in Section V. Finally, Section VI highlights the main conclusions and contributions of this paper.

II. BACKGROUND REVIEW

A. Overview of Frequency Control in Power Systems

Frequency is a system-wide characteristic of power grids and should be maintained within specified limits to ensure the stable and reliable operation of the system. Therefore, appropriate frequency control is essential to maintain the normal operation of the grid. FR services are required in order to compensate for forecast errors, non-linear behaviour of demand between dispatches, and generation/load resources that do not follow dispatch instructions. These uncertainties may exceed the contracted capacity of FR resources, which is automatically compensated by the grid inter-ties, thereby deviating the interchanges from their scheduled values [25].

Primary frequency control is critical for maintaining the reliability of the interconnection after a disturbance, by restoring the generation-load balance, and it is implemented through governor control and automatically assisted by the response of frequency dependent loads [25]. Primary control stabilizes the system frequency at a different value from the scheduled one, with the turbine-governor closed loop control being the main component [26]. Thus, there is a need to correct the generation-demand mismatch created by steady-state frequency deviations, which is provided by the dispatched generators in the control area and units that could be started up in short time periods. This action, known as secondary control, has the objective to bring the frequency error back to zero to restore the primary control capability of the system, modifying the power reference of the generators that participate in this control, which is referred as Automatic Generation Control (AGC), and maintaining the ACE within an acceptable range by controlling multiple generators. The ACE extracts contributions of a control area to the interconnection frequency deviation, monitoring and keeping it within limits [25], [26].

B. Overview of Frequency Control in Ontario

In order to maintain the reliability of the power system, the IESO procures ancillary services, FR being one of them. This service seeks to match the generation and load, including losses, to reduce the deviations in the system frequency. Seven generation facilities (hydro and gas) plus two ATR units are contracted by the IESO to provide FR. A minimum requirement of ± 100 MW of AGC with a ramp rate of 50 MW/min must be scheduled every hour [27].

Historically, FR service has been provided by traditional facilities with AGC, which change their output in response to the regulation signals. In 2012, the IESO included the participation of alternative technologies, such as aggregate loads, FESS, and BESS to evaluate their ability to provide FR as compared to

the existing facilities [28]. The IESO procured 6 MW for FR from two ESS facilities in 2012, which provide FR services exclusively, thus receiving a regulation signal to reduce the system generation-load mismatch in seconds. The reason for including these ATR units was the need for increasing the FR capacity [28], which are being complemented by another 50 MW ESS capacity under the 2014 Grid Energy Storage Procurement plan [7].

In 2015, the IESO scheduled a minimum of ± 100 MW every hour for FR services, a need which was anticipated to increase due to the increasing penetration of intermittent generation, and only compensated for 53% of the forecast errors; this is expected to further decrease to 40% by 2020, resulting in increased dependency on the power from tie-lines [29]. In 2016, the IESO determined a need for additional FR capacity and one of the ways to reach this target is through the 2017 Request for Proposals (RFP) for incremental regulation capacity, which sought to increase the FR capacity while being open to different technologies. However, the IESO no longer has contracts with the two facilities. A procurement to acquire FR capacity is being considered by the IESO [30].

C. Overview of Energy Storage Systems

ESSs draw energy from the power system, convert it to another form of energy, and release it back to the system when needed. ESSs suitable for FR are those with fast response characteristic, since they can accurately follow the FR signal. Since, BESSs are able to modify their output in less than one second, it makes them a good fit for FR provision, with efficiencies depending on the type (flow or solid state), in the order of 75% to 95%; they also have long lifetimes and low energy density [4]. Another type of ESS apt for FR provision is FESS, which is capable of responding in milliseconds to minutes, have long life cycles, insensitivity to deep discharges, and high round-trip efficiency (90-95%) [4].

III. PROPOSED FREQUENCY REGULATION MODEL

To determine a baseline FR model of a real large interconnected power system and estimate the model parameters for a physical system, for which operational information is available, power system analysis tools, such as Dynamic Security Assessment Tools (DSATools™) used by the IESO [31], can be used, as these provide accurate results by properly modelling the system components. Large number of events in one contingency definition (i.e., load changes and FR signal sent to Traditional Generators (TGs) and ESS facilities) with one second between events limits the simulation time; for example, using DSATools™ to model and simulate load changes in the entire NAEI and the FR signal sent to a group of generators in one area, limits the maximum simulation time to 102 seconds for the OPS under study, since the maximum number of switching events to represent load and generation changes allowed by this tool is reached then. To make up for this limitation, multiple normal operating conditions were considered and simulated to develop the System model in Stage VII, so that the proposed FR model is appropriate for calculations such as the Control Performance Standard

1 (CPS1), which covers 12-month periods, or the Balancing Authority ACE Limit (BAAL), which requires calculations based on 30 consecutive clock minutes [32]. Therefore, the proposed FR model, developed from an ISO perspective, and depicted in Fig. 1, can be used for accurate long-term studies, i.e., hours, days, weeks or even months, representing the main stages in the FR control process under normal operating conditions, communication delays in the signal transfer, and SoC management of the ESS facilities, which ensures a realistic close-loop response.

The model presented here was developed with the help of the IESO, based on their recommendations and observations of the various signals provided, and through a trial and error approach, using real data. This was implemented in Simulink® [33], with the parameters within each block being determined using the Parameter Estimator application available in this software, since no parameter values were available. In this estimation process, the objective function is the sum of squared errors, the optimization solution is based on the gradient descent method and an interior-point algorithm, and the real data is selected as the measured signal in each case. The real data corresponds to all the 28 signals presented in Fig. 1, re-sampled to one second resolution.

A. Bulk Power System

The model in Fig. 1 is based on IESO's approach to FR, with seven stages that capture the most relevant aspects of the frequency control process of a large interconnected power system. It includes communication delays in the signals sent from/to the control center to/from the facilities contracted for regulation, which can significantly impact the FR process depending on the magnitude of the delay; for example, for the IESO, based on the available data, the average value of the one-way communication delay is about 4 s. However, this is not the case for all the facilities; the medium used to transmit the signals and the physical distance from the sending to the receiving point of the signal proportionally affect the delay. Based on the available data, an extra communication delay CD is included in the aggregated model of TG contracted for regulation. The aftereffect of communication delays is an ACE signal that deviates from zero, and in the worst case scenario, the delayed FR signal could worsen the ACE. For example, it could happen that at time t , the system requires a positive regulation action from the FR assets; however, due to CD , the regulation coming from the facilities could be negative, as a result of calculations based on the state of the system at a time $t - CD$, thus increasing the ACE. Therefore, delays play an important role in the FR control process and hence should be modeled. It should be noted that the delays do not exist in the signals that are calculated, processed, and saved at the control center.

1) *ACE Calculation*: This is the first stage of the frequency control process. The inputs of this block are the actual power in the interconnection NI_a , and actual frequency f_a , which are the outputs of the system block; the scheduled power in the interconnection NI_s and scheduled frequency f_s change over time and are set by the ISO based on the system's needs;

the inadvertent payback IP also changes over time and is set by the ISO; and the interchange metering error IME , which in this case is in manual mode set to -35 MW by the IESO. The block has two outputs: the ACE signal and the SR_{ESS} signal, calculated as follows:

$$ACE = (NI_a - NI_s) - 10B(f_a - f_s) - IME - IP - F(IP) \quad (1)$$

$$SR_{ESS} = (NI_a - NI_s) - 10B(f_a - f_s) - IME - F(IP) \quad (2)$$

where the Balancing Authority (BA) bias B is equal to -248.2 MW/0.1Hz for the IESO.

The IP is the pay back of the inadvertent interchange accumulations, which is an input for the proposed model, and can be calculated by a method agreed upon by all regions in the interconnection [34]. One method is the energy "in-kind" payback, which can be bilateral or unilateral for the control areas involved, and considers that if inadvertent interchanges took place during peak hours, they should be paid back only during peak hours; similarly, inadvertent interchanges at non-peak hours should only be paid back during non-peak hours. Thus, each control area should submit the monthly accumulated inadvertent interchange for peak and non-peak hours.

The $F(IP)$ function in (1) and (2) is introduced to represent the differences between the measured data and the model results, and is associated with the IP signal. This can be captured by a Neural Network (NN) with three signals as inputs: IP_t , IP_{t-10} , and $IP_t - IP_{t-10}$, and consists of 1 input layer with 3 neurons, 2 hidden layers with 48 and 1 neurons, respectively, and a 1-neuron output layer, with a tangent sigmoid as the activation function. The NN inputs are normalized between -1 and 1 before entering the training process, and the output is converted back to its real scale. One year data was used to obtain the NN model: 80% for training, 10% for testing, and 10% for validation.

2) *ACE Filtering*: This corresponds to Stage II in the FR process and is presented in Fig. 2. The input of this block is the ACE signal from Stage I, and includes a gain c_f and a first order Butterworth filter with a pre-warping frequency ω_0 . The purpose of this filter is to get rid of fast signal changes, since TGs are not able to react to them.

3) *AGC*: It corresponds to Stage III in the FR control process, and is depicted on Fig. 3. The input of this block is the filtered ACE signal from Stage II, and includes an initial negative gain, because the compensation provided by FR should be in the opposite direction to reduce the error. This signal goes into a discrete PI controller with parameters k_p and k_i , and clamping as anti-windup method. The output of the PI block goes through a rate limiter to ensure the generation changes are within limits defined by the ISO (± 50 MW/min for the IESO), and feeds a saturation block to avoid exceeding the contracted regulation capacity $\pm RC$. The output of this block is the scheduled FR signal SR , sent to the TGs contracted for regulation.

4) *Aggregated TG*: It corresponds to Stage IV in the frequency control process, and is illustrated in Fig. 4. Since the real signal available is the aggregated response of all the TGs to the SR signal, an aggregated model of these TGs is

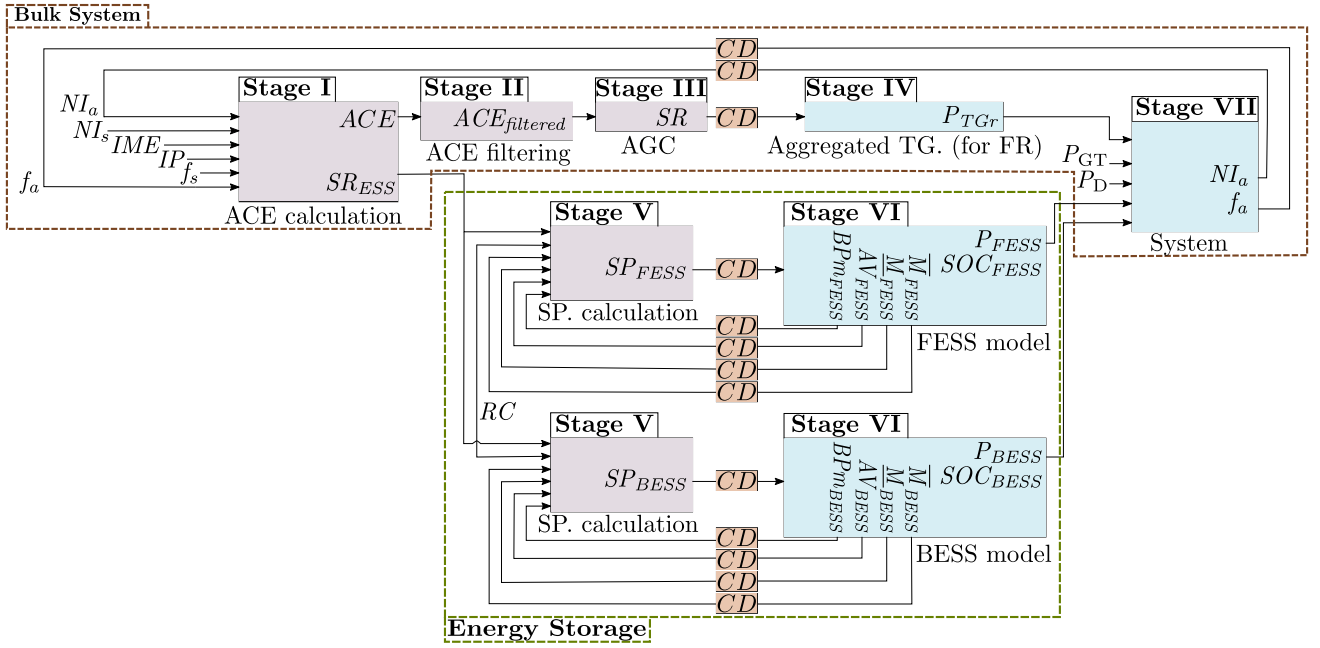


Fig. 1: Frequency response model of a large interconnected power system with FESS and BESS. The stages in fuchsia correspond to calculations carried out at the control center, whereas the ones in light blue represent actual and relevant system components.

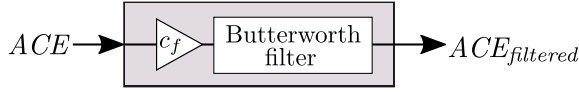


Fig. 2: Stage II ACE filtering block.

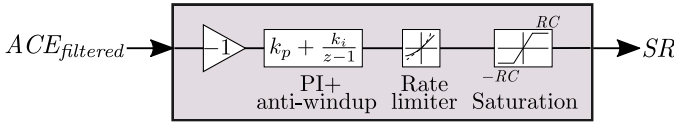


Fig. 3: Stage III AGC.

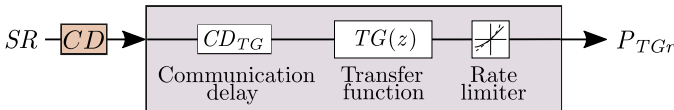


Fig. 4: Stage IV Aggregated model of TG contracted for FR.

needed; the input of this block is the SR signal from Stage III plus the communication delay CD associated with the FR signal, as previously discussed. The delay in the signals is proportional to the physical distance from the control center to the facilities, which are typically located at different parts of the system. An extra communication delay CD_{TG} is included in this model (30 s for the IESO) to represent the slower network used for signal transmission and measurements of the power response of the TGs to the FR signal. The third order transfer function $TG(z)$ represents the action of the TGs contracted for regulation, and can be readily estimated from actual measurements. The rate limiter, similar to that in Stage III, ensures the output of this model matches the real data by avoiding unrealistic power changes in the output of the TG group.

5) *System Model*: It represents the primary frequency response of the elements in the system and the power in the

tie-lines, and corresponds to Stage VII in the FR control process. It has five inputs: the load of the system P_D ; the generation total dispatch P_{GT} ; and the outputs of the facilities contracted for regulation P_{TGr} , P_{FESS} , and P_{BESS} . This block calculates the actual frequency f_a and power in the interconnection NI_a at time t , as follows:

$$f_{at} = f_{a0} + [-\Delta P_{Dt} + \Delta P_{GTt} + \Delta P_{TGr t} + \Delta P_{FESS t} + \Delta P_{BESS t}] \left[\frac{-1}{\beta_{EI}} \frac{1}{z-1} - F(z) \right] \quad (3)$$

$$NI_{at} = NI_{a0} + [-\Delta P_{Dt} + \Delta P_{GTt} + \Delta P_{TGr t} + \Delta P_{FESS t} + \Delta P_{BESS t}] \left[\frac{\beta_{EI} - \beta_{IESO}}{\beta_{EI}} \frac{1}{z-1} \right] \quad (4)$$

which include an OPS frequency response of 248.2 MW/0.1Hz, and an NAEI frequency response β_{EI} calculated from [35], using available data and a detailed transient stability model. In (3), the function $F(z)$ allows obtaining a closer fit between the model results and the measured data.

B. Energy Storage

1) *Set-point Calculation*: This is Stage V in the FR control process, and includes the calculation of the Set-Point (SP) signals SP_{FESS} and SP_{BESS} sent from the control center to the FESS and BESS facilities, respectively. The calculation of both SP signals is as follows, with the inputs changing for each facility:

$$SP_{ESS} = \begin{cases} \frac{1}{2}(\overline{M}_{ESS} - \underline{M}_{ESS}) \frac{\min(SR_{ESS}, RC)}{RC} + BPm_{ESS} & \forall AV_{ESS} = 1, RC \neq 0, SR_{ESS} \geq 0 \\ \frac{1}{2}(\overline{M}_{ESS} - \underline{M}_{ESS}) \frac{\max(SR_{ESS}, -RC)}{RC} + BPm_{ESS} & \forall AV_{ESS} = 1, RC \neq 0, SR_{ESS} < 0 \end{cases} \quad (5)$$

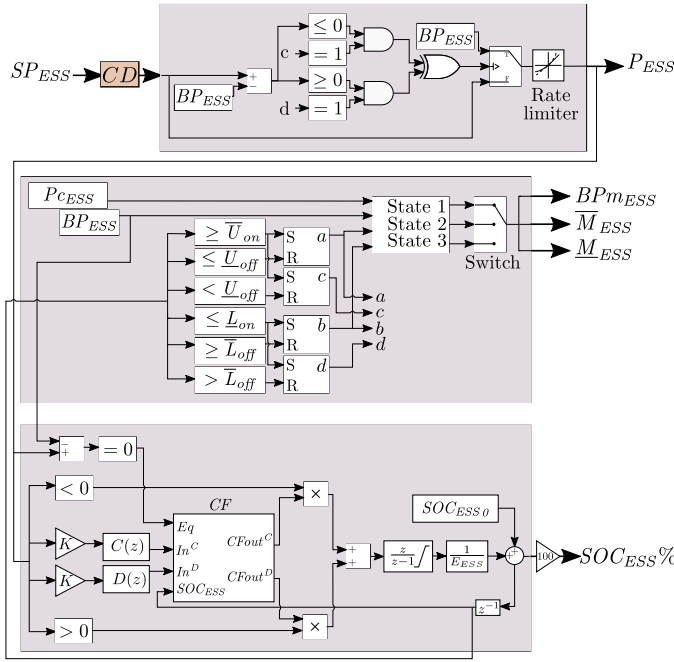
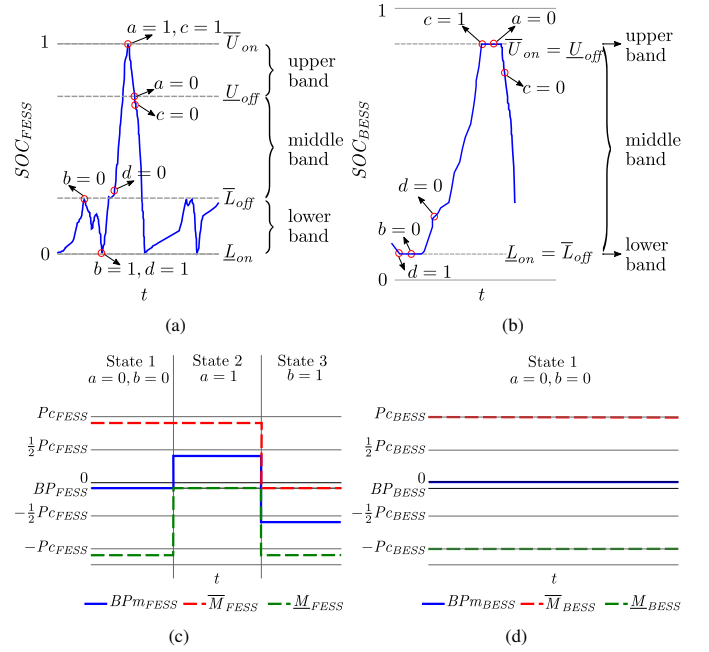


Fig. 5: Stage VI base ESS model including SoC management.

where AV_{ESS} is the status availability of the facility, $\underline{M}_{ESS}$ and $\overline{M}_{ESS}$ are the minimum and maximum available capacity of the facility, respectively, and BPm_{ESS} is the moving base-point, which is modelled as the fixed base point of the facility BP_{ESS} moving between $\underline{M}_{ESS}$ and $\overline{M}_{ESS}$, and containing SoC information. Since these signals come from the ESS facilities, communication delays are considered before they arrive at the control center, as shown in Fig. 1. In addition, the FR capacity limit RC , and the SR_{ESS} signal are required in this calculation. The SP_{ESS} signal is in essence a scaled version of the SR_{ESS} signal that takes into account the SoC of the ESS facility reflected through the $\overline{M}_{ESS}$, $\underline{M}_{ESS}$, and BPm_{ESS} signals.

2) *ESS Model*: This is Stage VI in the frequency control process and includes the ESS models of the BESS and FESS facilities, as well as their SoC management model. Considering that similar operational data was available for the BESS and FESS facilities, similar ESS models were developed for both facilities, with different parameters and some specific features for each facility.

Fig. 5 illustrates the base ESS model, representing both FESS and BESS, since similar input and output signals are used for both facilities at the control center. However, differences in these facilities are captured in the model by their different parameters in the Rate limiter, different transfer functions $C(z)$ and $D(z)$, differences in the CF block, and different values of $\overline{U}_{on}$, $\underline{U}_{off}$, $\underline{L}_{on}$, $\overline{L}_{off}$ for each ESS facility, which define the bands in SoC management. This model has two main parts: The first part, which is the output of the ESS facility in megawatts, depends on the sign of the regulation required from the facility ($SP_{ESS} - BP_{ESS}$), and the SoC parameters c and d . As shown in Fig. 5, the output signal could be equal to BP_{ESS} or to the delayed SP signal coming from Stage V, and primarily considers the charging or discharging efficiencies of the ESS. The output signal goes through a ramp

Fig. 6: Relation of parameters a , b , c , and d in (a) and (b), and $\overline{M}_{ESS}$, $\underline{M}_{ESS}$, and BP_{ESS} in (c) and (d) to the SoC management of the ESS model.

rate block with rising slew rate Rsr , and falling slew rate Fsr . The charging and discharging efficiencies of the ESS facilities are internally accounted for in their response to the set-point signal.

The second part of the model is the SoC management of the facility, and it is divided in two sections. In the first section, BPm_{ESS} , $\overline{M}_{ESS}$, and $\underline{M}_{ESS}$, and the four SoC parameters a , b , c , and d are calculated. Furthermore, three sections of the SoC are considered: a lower band from $\underline{L}_{on}$ to $\overline{L}_{off}$, a middle band from $\overline{L}_{off}$ to $\underline{U}_{off}$, and an upper band from $\underline{U}_{off}$ to $\overline{U}_{on}$. As illustrated in Fig. 6a and Fig. 6b and in the second block of Fig. 5, the parameters a , b , c , and d are defined to identify the SoC operational band in which SOC_{ESS} is in, which defines the values of P_{ESS} , BPm_{ESS} , $\overline{M}_{ESS}$, and $\underline{M}_{ESS}$. As illustrated in Fig. 5, the parameters c and d are part of the P_{ESS} calculation while a and b are part of the BPm_{ESS} , $\overline{M}_{ESS}$, and $\underline{M}_{ESS}$ calculations. After the SoC parameters are calculated and considering the power capacity and base-point of the facility designated for regulation, i.e., the P_{CESS} , and BP_{ESS} signals, respectively, three cases are formulated. State 1 considers the SoC in the middle band of Fig. 6a and Fig. 6b, where $a = 0$ and $b = 0$; the second state considers $a = 1$, and the third state considers $b = 1$. Observe that the difference between a and c is not very relevant for the proposed FESS model, since SOC_{FESS} would rarely be at $\underline{U}_{off}$ for more than one time step. However, for the BESS model, the difference between a and c can be significant, since its upper band is defined as $\overline{U}_{on} = \underline{U}_{off}$, with the facility remaining at this point, where $a = 0$ and $c = 1$, with an output BP_{BESS} until it is able to follow SP_{BESS} again. Likewise, b and d are similar for the proposed FESS model when the SOC_{FESS} reaches $\overline{L}_{off}$, whereas for the BESS model, the differences can be significant.

The signals BPm_{ESS} , $\overline{M}_{ESS}$, and $\underline{M}_{ESS}$, illustrated in

Fig. 6c and Fig. 6d, are calculated as follows:

$$Bpm_{ESS} = \begin{cases} BP_{ESS} & \forall a = 0, b = 0 \\ BP_{ESS} + \frac{1}{2}P_{CESS} & \forall a = 1 \\ BP_{ESS} - \frac{1}{2}P_{CESS} & \forall b = 1 \end{cases} \quad (6)$$

$$\overline{M}_{ESS} = \begin{cases} BP_{ESS} + P_{CESS} & \forall a = 0, b = 0 \\ BP_{ESS} + P_{CESS} & \forall a = 1 \\ BP_{ESS} & \forall b = 1 \end{cases} \quad (7)$$

$$\underline{M}_{ESS} = \begin{cases} BP_{ESS} - P_{CESS} & \forall a = 0, b = 0 \\ BP_{ESS} & \forall a = 1 \\ BP_{ESS} - P_{CESS} & \forall b = 1 \end{cases} \quad (8)$$

In general, for the proposed base ESS model shown in Fig. 5, if the output of the ESS causes the SoC to reach $\underline{L}_{on}$ ($b = 1$) or $\overline{U}_{on}$ ($a = 1$), the facility starts charging or discharging, respectively, irrespective of the system's needs, which are represented in the SR_{ESS} signal. This behavior continues until the SoC reaches values greater than or equal to $\overline{L}_{off}$ ($b = 0$) or lower than or equal to $\underline{U}_{off}$ ($a = 0$), during the charging/discharging operations, correspondingly. The rationale of dividing the range on which the SoC signal changes in three bands is to bring the SoC from a value where it can only act in one direction to a value that allows room for moving in both directions.

For the FESS, when the SoC reaches $\overline{U}_{on}$ or $\underline{L}_{on}$, the values of $\overline{M}_{FESS}$, $\underline{M}_{FESS}$, and Bpm_{FESS} change as per (6)-(8), and if the SR_{ESS} signal indicates that the FESS should keep respectively charging or discharging, two things can take place until reaching $\underline{U}_{off}$ or $\overline{L}_{off}$, depending on the value of the SR_{ESS} signal. Thus, if $SOC_{FESS} = \overline{U}_{on}$ and $SR_{ESS} > -RC$, then the SP_{FESS} signal orders discharging as if the SR_{ESS} were shifted above the zero axis; otherwise, $SP_{FESS} = Bpm_{FESS}$. On the other hand, if $SOC_{FESS} = \underline{L}_{on}$ and $SR_{ESS} < RC$, then the SP_{FESS} signal orders charging as if the SR_{ESS} were shifted below the zero axis; otherwise, $SP_{FESS} = Bpm_{FESS}$. Since the FESS ignores the needs of the system in the aforementioned cases, this could negatively impact the ACE by increasing its value. An idling SoC, which would keep the facility from acting against the system's needs, could be implemented with a different SP calculation; however, additional simulations are required to determine the impact of a different SP calculation on the ACE.

For the BESS, the upper band defined as $\overline{U}_{on} = \underline{U}_{off}$ and a lower band defined as $\underline{L}_{on} = \overline{L}_{off}$ limit the 3 possible ESS states in Fig. 5 to only State 1. Thus, after the SOC_{BESS} signal reaches $\overline{U}_{on}$ or $\underline{L}_{on}$ values, $\overline{M}_{BESS}$, $\underline{M}_{BESS}$, and Bpm_{BESS} change as per (6)-(8), forcing the SP_{BESS} signal sent to the BESS to take into account the needs of system represented in the SR_{ESS} signal when possible. For the cases where the SoC is at $\overline{U}_{on}$ or $\underline{L}_{on}$ and the SR_{ESS} requires the BESS to keep charging or discharging respectively, P_{BESS} goes to zero, since following the SP_{BESS} is not possible.

The second section of the SoC management model is the SoC calculation itself, with the ESS output power P_{ESS} , and the base-point signal BP_{ESS} as inputs, as illustrated in the last block of Fig. 5. The constant K is the power-to-energy

value subject to the sampling-time resolution, which in this case is $K = -1/3600$ hr/s. Thus, $P_{ESS}K$ is the preliminary charge/discharge energy per sampling-time, which is equivalent to a simplified Coulomb counting SoC method [36]. Additionally, the model assumes two second order transfer functions $C(z)$ and $D(z)$ to account for the different charging and discharging characteristics of the ESS facilities, respectively, such as variations in their charging and discharging efficiencies, as confirmed by the SoC response to the SP_{ESS} signals sent from the control center. The outputs of these blocks In^C and In^D , correspondingly, are inputs of the correction factor CF block in Fig. 5, which compensates for different charge/discharge energy rates observed in the data provided after $\overline{U}_{on}$ and $\underline{L}_{on}$ are reached, as the charging/discharging slows or speeds up after reaching these limits. The CF block has a charging ($CFout^C$) and discharging ($CFout^D$) output, which for the FESS can be defined as follows:

$$CFout^C = \begin{cases} In^C & \forall k_{up} = 0, k_{dw} = 0 \\ In^C CF_{eq} & \forall Eq = 1, (k_{up} = 1 \vee k_{dw} = 1) \\ In^C CF_1^C & \forall Eq = 0, k_{up} = 1 \\ In^C CF_2^C & \forall Eq = 0, k_{up} = 0, k_{dw} = 1 \end{cases} \quad (9)$$

$$CFout^D = \begin{cases} In^D & \forall k_{up} = 0, k_{dw} = 0 \\ In^D CF_1^D & \forall k_{dw} = 1 \\ In^D CF_2^D & \forall k_{up} = 1, k_{dw} = 0 \end{cases} \quad (10)$$

where CF_{eq} , CF_1^C , CF_2^C are estimated parameters that multiply In^C , according to the conditions shown in (9). The input Eq takes the value of 1 when the P_{FESS} is equal to Bpm_{FESS} . Furthermore, CF_1^D and CF_2^D are estimated parameters, which multiply In^D , according to the conditions in (10). The variables k_{up} and k_{dw} are the outputs of set-reset flip-flops defined as follows:

$$k_{up_t} = S_{up_t} + k_{up_{t-1}}(\neg R_{up_t}) \quad (11)$$

$$k_{dw_t} = S_{dw_t} + k_{dw_{t-1}}(\neg R_{dw_t}) \quad (12)$$

where

$$S_{up_t} = 1 \vee SOC_{ESS} \geq ks_{up} \quad (13)$$

$$R_{up_t} = 1 \vee SOC_{ESS} \leq kr_{up} \quad (14)$$

$$S_{dw_t} = 1 \vee SOC_{ESS} \leq ks_{dw} \quad (15)$$

$$R_{dw_t} = 1 \vee SOC_{ESS} \geq kr_{dw} \quad (16)$$

and ks_{up} and kr_{up} are estimated parameters that represent the values of the SoC that cause the set S_{up_t} and reset R_{up_t} signals of the flip-flop k_{up_t} to become 1. Likewise, ks_{dw} and kr_{dw} are estimated parameters associated with the SoC values that activates the set (S_{dw_t}) and reset (R_{dw_t}) signals of the flip-flop k_{dw_t} , correspondingly.

For the case of BESS, the CF block can be defined as follows:

$$CFout^C = \begin{cases} In^C & \forall k_{up} = 0, k_{dw} = 0 \\ In^C \left[\frac{1}{1 + SOC_{BESS}} \right] CF_1^C & \forall k_{up} = 1 \\ In^C [1 + SOC_{BESS}] CF_2^C & \forall k_{up} = 0, k_{dw} = 1 \end{cases} \quad (17)$$

$CF_{out}^D =$

$$\begin{cases} In^D & \forall k_{up} = 0, k_{dw} = 0 \\ In^D [1 + SOC_{BESS}] CF_1^D & \forall k_{dw} = 1 \\ In^D \left[\frac{1}{1 + SOC_{BESS}} \right] CF_2^D & \forall k_{up} = 1, k_{dw} = 0 \end{cases} \quad (18)$$

where CF_1^C , CF_2^C , and CF_1^D , CF_2^D are estimated parameters that multiply a function of the SoC, and the inputs In^C and In^D , respectively. The variables k_{up} and k_{dw} in (17) and (18) are the same as in (11) and (12).

The transfer functions $C(z)$ and $D(z)$ both have a parallel comparison block (binary variables) to operate in either mode, which are related to the value of P_{ESS} ; these binary variables are multiplied by CF_{out}^C and CF_{out}^D , as shown in Fig. 5. Finally, the estimated corrected energy for the sampling interval is integrated and divided by the ESS energy capacity E_{ESS} and added to the initial SoC value to obtain the estimated SoC output at time t . This value is later multiplied by 100% to obtain $SOC_{ESS}\%$ at time t . The SoC empirical model proposed in this paper is derived by analyzing operational data for an actual FESS and a BESS used for FR by the IESO. Note that the SoC model does not consider degradation or cell failure which will impact the output; further data would be required to model such effects.

Currently, the base-point signal BP_{ESS} for the IESO is zero or a value close to zero, set in each ESS facility. However, the control center may replace the BP_{ESS} with the dispatch from the energy market for facilities that are able to simultaneously participate in both markets. In such a situation, the regulation required from the ESS facilities would be in addition to the base-point signal ($SP_{ESS} - BP_{ESS}$), as currently is the case for TGs.

IV. VALIDATION OF PROPOSED FREQUENCY REGULATION MODEL ON ONTARIO POWER SYSTEM

All the stages in the proposed FR model shown in Fig. 1 were validated using information provided by the IESO, which included a DSATools™ model of the NAEI, OPS data, and data from a 2 MW/0.5 MWh FESS, and a 4 MW/2.76 MWh BESS used for FR by the IESO. All the parameter values of the proposed model presented in Table I were determined using the Parameter Estimator tool in Simulink® for the large interconnected OPS with ESS. In 2020, this system had a peak demand of 24.4 GW [39], and a typical FR scheduled capacity of ± 100 MW [28].

Parameter estimation was carried out sequentially for each stage of Fig. 1, except for Stage VI, for which three steps were used. The first step considers the first block in Fig. 5 with SP_{ESS} and P_{ESS} as input and output, respectively. The second step considers the first section of the SoC management model with $P_{c_{ESS}}$, BP_{ESS} , and $SOC_{ESS}/100$ as inputs, and $BP_{m_{ESS}}$, $\bar{M}_{ESS}$, and $\underline{M}_{ESS}$ as the outputs to be fitted. The third step considers the second section of the SoC management model with the signals P_{ESS} and BP_{ESS} as inputs and $SOC_{ESS}\%$ as the output to be fitted. For Stages I to V, and Stage VII, and the three blocks considered in Stage VI, the Parameter Estimation tool used is fed with the real input signals to fit the output of each stage or block to the

TABLE I: Model Parameters.

Stage II: ACE filtering			
Parameter	Value	Parameter	Value
c_f	0.974	ω_0 [rad/s]	0.097
Stage III: AGC			
Parameter	Value	Parameter	Value
k_i	0.022	k_p	0.42
Stage IV: Aggregated model of TG contracted for FR			
Parameter	Value		
$TG(z)$	$\frac{3.45z^2+1.58}{3.78z^3+1.47z^2}$		
Stage VI: ESS models			
FESS Model		BESS Model	
Parameter	Value	Parameter	Value
R_{sr} [MW]	0.6	R_{sr} [MW]	1.28
F_{sr} [MW]	-0.6	F_{sr} [MW]	-1.28
$\overline{U}_{on}$	1	$\overline{U}_{on}$	0.885
$\overline{U}_{off}$	0.75	$\overline{U}_{off}$	0.885
$\overline{L}_{off}$	0.25	$\overline{L}_{off}$	0.125
$\overline{L}_{on}$	0	$\overline{L}_{on}$	0.125
K	-1/3600	K	-1/3600
$C(z)$	$\frac{4.23z^2+1.06z+2.8}{z^2+0.57z+0.42}$	$C(z)$	$\frac{0.16z^2+4.11z+7.52}{z^2+0.93z+0.54}$
$D(z)$	$\frac{5.57z^2+6.72z+3.02}{z^2+0.72z+0.81}$	$D(z)$	$\frac{2.88z^2+3.78z+4.57}{z^2+0.48z+0.55}$
CF_1^C	1.22	CF_1^C	0.014
CF_2^C	0.99	CF_2^C	0.50
CF_1^D	1.19	CF_1^D	0.51
CF_2^D	1.10	CF_2^D	0.64
CF_{eq}	0.35	CF_{eq}	—
ks_{up}	1	ks_{up}	0.885
kr_{up}	0.55	kr_{up}	0.884
ks_{dw}	0	ks_{dw}	0.125
kr_{dw}	0.60	kr_{dw}	0.144
Stage VII: System model			
Parameter	Value		
$F(z)$	$\frac{0.51z^5-1.97z^4+2.31z^3+2.93z^2-1.18z-2.73}{z^5-0.45z^4-0.77z^3-0.23z^2+0.6z-0.12}e^{-5}$		

real output signals. All the parameters to be estimated are considered as variables in this process, and each is assigned a smallest and largest allowable value which depends on the variable and its position in the model. Since a trial-and-error approach was used to determine the proposed model, several orders for all the transfer functions involved were tested, with those presented in Table I providing the least error in the fitting process.

A. Test System Validation

The first step in the validation process of the proposed FR model is the validation of frequency response of the DSATools™ model against real data. The DSATools™ model is a reduced representation of the NAEI (all pink lines in Fig. 7), with a detailed representation of the OPS (shaded area), and a combination of detailed and equivalent aggregated models, depending on their impact and electrical distances of the rest. For the OPS, the f_a signal is measured at one of the Oakville buses, and thus a similar bus was selected in the DSATools™ system in the validation process. The DSATools™ model includes 7,840 ac buses, 2,071 generators, 3,082 loads, 12,272 lines, 2,858 adjustable transformers, 1,378 fixed shunts, 672 switchable shuts, 741 three winding

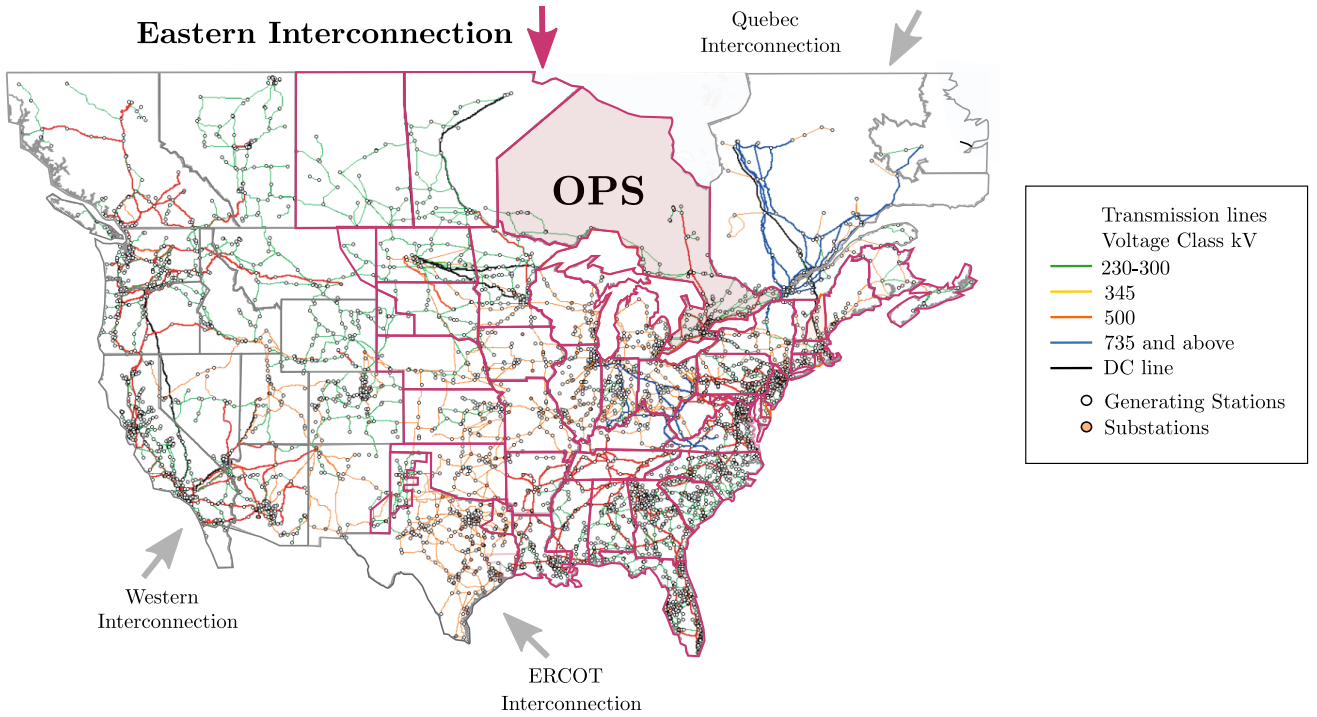


Fig. 7: DSATools™ model [37], [38].

transformers, 16 dc buses, 12 line commutated converters, and 10 dc lines.

For validation purposes, seven scenarios capturing the frequency response of the OPS were selected based on regulation signal changes. These cases correspond to various normal and typical operating conditions with different generators and loads involved, which is the main purpose and application of the proposed model, and thus it does not include major transmission system contingencies, i.e., abnormal operating conditions. The load changes for the NAEI were determined based on the measured frequency profile and load changes in the OPS; a frequency response value of $-2760 \text{ MW}/0.1 \text{ Hz}$ for the NAEI; and the initial powers of the load, generation, and the interconnection for each scenario. The difference between the total expected load change for the NAEI and the total change in the loads in the OPS was proportionally distributed to all the loads in the rest of the interconnection. Furthermore, three hydroelectric generators in the OPS, with enough capacity to follow the regulation signal, were selected for the provision of FR; the regulation signal was equally divided and sent to these generators. Because of the large number of changes per second (3,082 load changes plus 3 changes in the set-points of TGs providing FR), the maximum possible simulation time allowed by the DSATools™ software is 102 seconds for the system under study. Since the simulation period is less than two minutes and the dispatch changes every 5 minutes, it was assumed that the generator active powers were fixed for each scenario.

The Root-Mean Squared Error (RMSE) and Mean Absolute Error (MAE) of ACE for the seven cases on March 20, 2018 are presented in Table II, which can be considered acceptable. In addition, Case 1 and Case 4, which correspond to the

TABLE II: Validation of the frequency response of the DSATools™ model.

	RMSE [Hz]	MAE [Hz]		RMSE [Hz]	MAE [Hz]
Case 1	0.00101	0.00082	Case 5	0.00279	0.00225
Case 2	0.00103	0.00084	Case 6	0.00183	0.00139
Case 3	0.00186	0.00129	Case 7	0.00470	0.00359
Case 4	0.00592	0.00512			

best and worst validation results in Table II, are presented in Fig. 8. Thus, this validated DSATools™ model was used next to validate the system block of the proposed FR model. The difference between the measured data and DSATools™ model results could be due to the following reasons:

- The value of frequency response used to determine the power changes in the interconnection was assumed to be fixed for all the scenarios. However, with changes in loads, dispatched generators, and connected renewable generators, this value may change depending on the scenario.
- Since the load models are voltage dependent, and their parameters remain fixed during the simulation, while in the actual system these vary, the modelled load powers may not be the same as in the actual system.
- The dynamic file was modified to obtain a more realistic response from the system. However, these modifications may not be an exact representation of the day selected for simulations.

B. Frequency Regulation Model Validation

All the stages in the proposed FR model are validated in this subsection. The data made available by the IESO corresponds to all the signals associated with the proposed FR model (Fig. 1), which has two sections: the bulk system, which includes

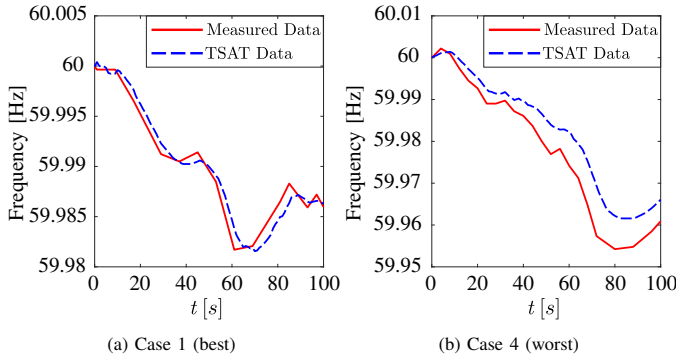


Fig. 8: Frequency response validation of the DSATools™ model.

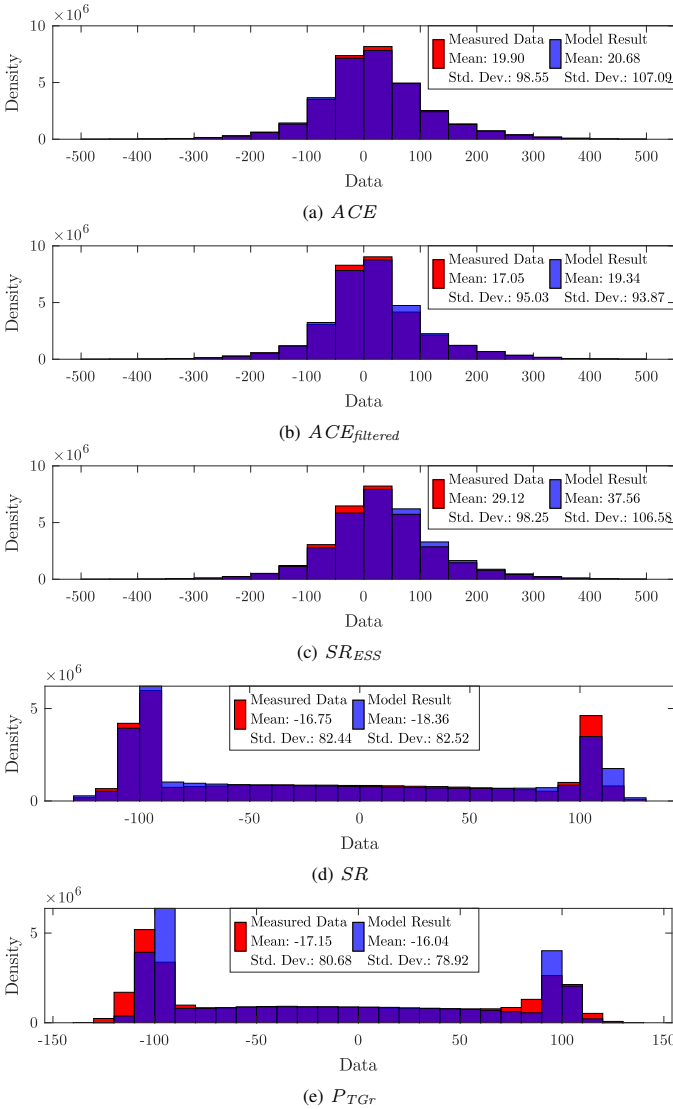


Fig. 9: Histograms of the measured data and model results for Stages I, II, III and IV.

Stages I to IV, and Stage VII, and the ESS section, which includes Stage V and VI. For the validation of Stage I to Stage IV, one year of data (April-2018 to March-2019) was used. Fig. 9 shows histograms comparing the measured data and the model results for the ACE , $ACE_{filtered}$, SR_{ESS} , SR , and P_{TGr} signals in MW.

After the validation of the frequency response of the

TABLE III: Estimation errors for f_a and NI_a .

	Frequency		NI_a (523 – 731 MW)	
	RMSE [Hz]	MAE [Hz]	RMSE [MW]	MAE [MW]
Case 1	$2.7329e^{-04}$	$2.4423e^{-04}$	4.4963	4.0506
Case 2	$0.9063e^{-04}$	$0.8111e^{-04}$	5.1326	4.1198
Case 3	$1.8753e^{-04}$	$1.5642e^{-04}$	3.9204	3.2470
Case 4	$3.2162e^{-04}$	$2.5331e^{-04}$	15.953	14.161
Case 5	$1.9111e^{-04}$	$1.4437e^{-04}$	5.1016	3.8430
Case 6	$1.0038e^{-04}$	$0.7776e^{-04}$	4.0183	3.3039
Case 7	$0.3653e^{-04}$	$3.0986e^{-04}$	5.3813	4.1019

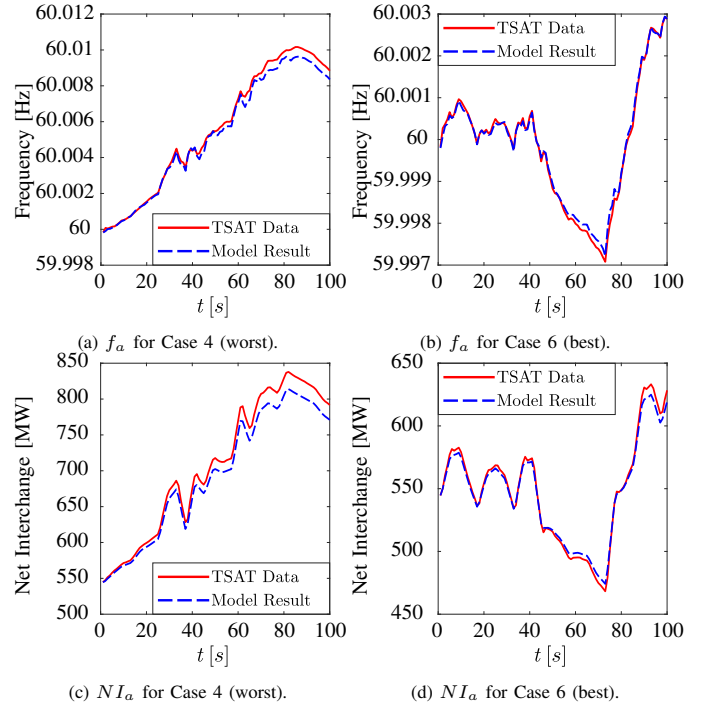


Fig. 10: Validation results of Stage VII.

DSATools™ model in the previous subsection, the Stage VII Simulink® model is validated against the DSATools™ model. Since the measured data of load changes in the neighboring interconnected areas is not available with the same resolution, and considering each BA is mainly responsible for compensating the load changes within its own area, load variations occurring only in the BA of interest are considered here. The same cases used for the validation of the DSATools™ model were used here, with the difference of no load changes considered in the other BAs within the NAEI. The RMSE and MAE of ACE for the seven cases are presented in Table III, with Cases 4 and 6 presented in Fig. 10, which correspond to the best and worst validation results for f_a and NI_a and are associated with the minimum and maximum NI_s values of 523 and 731 MW, respectively, for all seven cases. The results presented in Table III and Fig. 10 can be considered acceptable, thus concluding that the model in Stage VII properly captures the system's primary frequency response, as well as the power in the tie-lines.

The ESS section of the proposed FR model is validated next. Thus, both Stage V and Stage VI of the FR control process are validated for the FESS and BESS using one day of data for

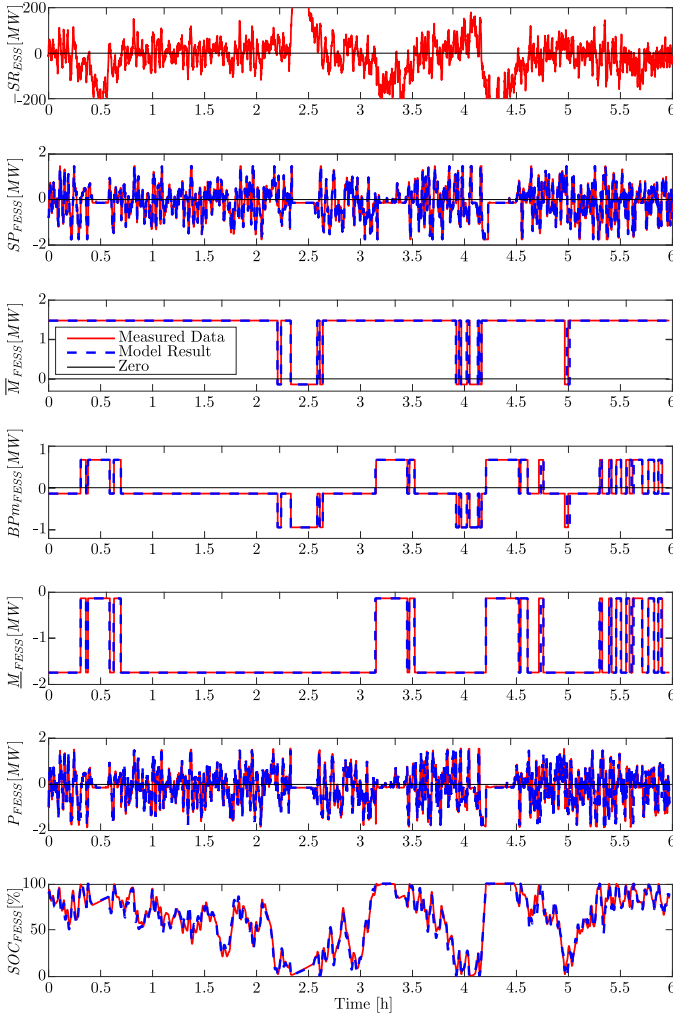


Fig. 11: FESS validation results for February 26, 2020.

TABLE IV: Estimation errors for FESS and BESS models for February 26, 2020.

		SP_{FESS} [MW]	M_{FESS} [MW]	BPm_{FESS} [MW]	M_{FESS} [MW]	P_{FESS} [MW]	SOC_{FESS} [%]
FESS	MAE	0.252	0.041	0.064	0.098	0.204	5.072
(± 2 MW)	RMSE	0.425	0.248	0.226	0.390	0.372	7.450
BESS	MAE	0.432	0.018	0.000	0.018	0.330	2.648
(± 4 MW)	RMSE	0.655	0.044	0.000	0.044	0.611	4.243

each facility. The target signals are SP_{FESS} from Stage V, and BPm_{FESS} , M_{FESS} , M_{FESS} , P_{FESS} and SOC_{FESS} from Stage VI. Simulation results comparing the measured data and the model results for the signals in these two stages are presented in Fig. 11 and Fig. 12 for FESS and BESS, respectively. In these figures, it can be observed that the signals from the proposed FR model closely follow the measurement data from the ESS facilities. For visualization purposes, only a time span of six hours is presented in these figures, while Table IV presents the MAE and RMSE of the FESS and BESS models for a period of one day, for all the signals in the SP calculation and ESS model blocks.

Some stages of the proposed model shown in Fig. 1 are specific to the FR control process of the IESO, which in general is similar to FR approaches used by other North American utilities to meet NERC requirements, while others

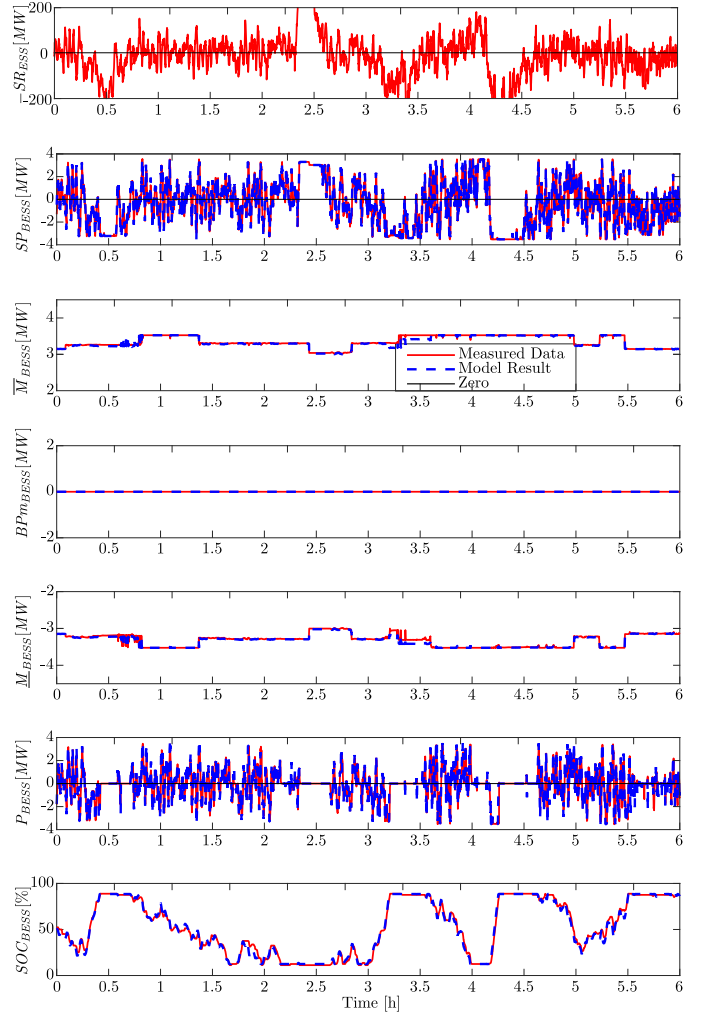


Fig. 12: BESS validation results for February 26, 2020.

can be partially modified for their use in other bulk power systems, and a few can be directly used in any system after estimating the appropriate parameters. Thus, for the ACE calculation block in Stage I, (1) could be readily used, while the NN that defines $F(IP)$ should be re-trained or eliminated in case there is no mismatch between the measured data and the model results. In addition, (2) could also be maintained or replaced by new calculations, depending on the FR signal the ISO wishes to send to the ESS facilities. The ACE filtering block (Stage II), and SP calculation block (Stage V) are specific to the IESO, and thus should be modified to fit other system's approaches. On the other hand, the AGC (Stage III), Aggregated model of TG contracted for FR (Stage IV), and System (Stage VII) blocks can be readily applied to other systems after estimating new parameters. Finally, the proposed FESS and BESS models (Stage VI) are generic, since these ESS facilities, whose real data was used to validate them from the FR perspective, are typical. Thus the proposed models can be readily adapted to represent similar ESSs in other systems.

V. SIMULATION STUDIES

The proposed FR model is used here to analyze the impact of communication delays and to demonstrate the effect of

TABLE V: Impact of communication delays for 100-day period.

Cases	RMSE [MW]	MAE [MW]
Current delay	87.55	56.91
Half of current delay	84.14	52.50
No delay	80.64	47.12

TABLE VI: Impact of SoC model for 100-day period.

Cases	RMSE [MW]	MAE [MW]
Current ESS for FR (SoC model)	87.55	56.91
30 MW ESS for FR (SoC model)	83.89	52.81
30 MW ESS for FR (no SoC model)	76.98	47.41
80 MW ESS for FR (SoC model)	80.37	49.34

the SoC model in the FR process. Also, the computational efficiency of the proposed FR model is discussed.

A. Communication Delays

In order to determine the impact of communication delays in the FR process, simulations with existing multiple delays, half of these delays, and no delays were considered. The impact is measured as a reduction in the ACE. Table V presents the RMSE and MAE with respect to the ideal ACE, i.e., 0 MW. As expected, the smaller the delay, the better is the ACE performance. Note that reducing the communication delays to half their current values has approximately the same effect on the ACE as increasing 30 MW of ESS capacity for FR with the current delay.

B. State of Charge Management

To demonstrate the effect of the SoC model in the FR control process, the ESS capacity used for FR was increased to 30 MW, comprising a ± 15 MW/30 MWh BESS and a ± 15 MW/3.75 MWh FESS. In the results presented in Table V, it can be observed that ignoring the SoC leads to unrealistic ACE reductions. Indeed, for the IESO case, considering ± 30 MW of fast FR without the SoC model yields a better ACE than increasing the ESS FR capacity to ± 80 MW (± 40 MW/80 MWh BESS, ± 40 MW/10 MWh FESS) with the SoC model, which could lead to under-procuring fast frequency response resources.

The case of half of existing delays and 30 MW of ESS for FR, including the SoC model, was considered to demonstrate how a combination of reduced communication delays and increased fast FR capacity can realistically reduce the ACE. This reduces the RMSE and MAE of ACE to 81.12 MW and 49.09 MW, respectively.

C. Computational Efficiency

One of the main advantages of the proposed FR model is that it allows long simulation times while still considering the main stages of the FR process under normal operating conditions, which is the main application of the model. In order to demonstrate the computational efficiency of the proposed FR model, a computer with a processor Intel(R) Core(TM) i9-9900K CPU @3.60 Hz, 32 GB RAM, 64-bit operating

TABLE VII: Computational efficiency of the proposed FR model.

DSATools™ Model	
Simulation Time	Comp. Time
102 s	268.80 s
Full FR Model in Simulink®	
Simulation Time	Comp. Time
102 s	1.09 s
86400 s (1 day)	30.55 s
604800 s (1 week)	200.01 s
2592000 s (1 month)	845.74 s
31536000 s (1 year)	10252.98 s

system, x64-based processor was used to run several cases with different simulation times.

Table VII presents the Simulation Time for each study and the corresponding average computation times for 5 simulation runs (Comp. Time), with a 1 s resolution for both the full FR model in Simulink® and the DSATools™ model, with the latter only allowing 102 s simulations due to the maximum number of switching events allowed, as previously explained. Note the speed up in the range of 2 to 3 orders of magnitude provided by the proposed model.

D. Stability Analysis

Given the complex nonlinear characteristics of the detailed FR model, eigenvalue analyses are used here to demonstrate the system stability for varying communication delays and ESS capacities, and hence evaluate the robustness of the system. To analyze the impact of increasing communication delays, a total ESS capacity of 30 MW which included a ± 15 MW/30 MWh BESS and a ± 15 MW/3.75 MWh FESS, were used, since these yielded reasonable FR performance for existing communication delays ($CD = 4$ s and $CD_{TG} = 30$ s). In this case, the system is marginally stable, presenting two poles on the real axis, both at (1, 0), associated with $F(z)$ in Stage VII. As communication delays are increased, the system performance deteriorates in terms of ACE, as expected, and finally becomes unstable for a 96 s increase in all the delays, i.e. for $CD = 100$ s and $CD_{TG} = 126$ s, as highlighted in Fig. 13. This shows that the stability of the system is quite robust for practical ranges of communication delays and only becomes unstable at significantly extreme values.

To analyze the impact of added ESS capacity on the stability of the proposed model, for the current communication delays, the capacities of the FESS and BESS facilities were increased simultaneously by the same values. As illustrated in Fig. 14, the system remains stable until the total capacity of the ESS reaches 86 MW, ± 43 MW/86 MWh BESS and a ± 43 MW/10.75 MWh FESS, when the system becomes unstable. This indicates that for the existing FR approach for ESS, the system is sensitive to ESS capacity increases, as also demonstrated in [40] where a new fast regulation approach for ESS is proposed that addresses this issue.

VI. CONCLUSIONS

This paper presented a validated model for long-term FR studies of a real interconnected power system including ESS

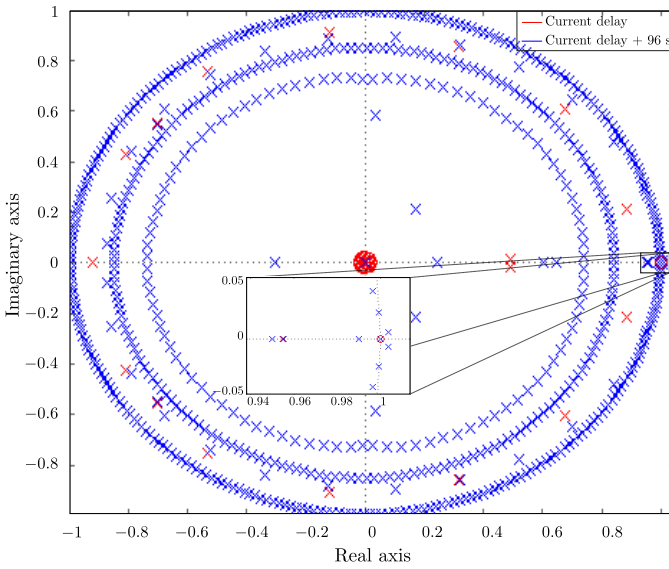


Fig. 13: Eigenvalues of the FR model with different communication delays.

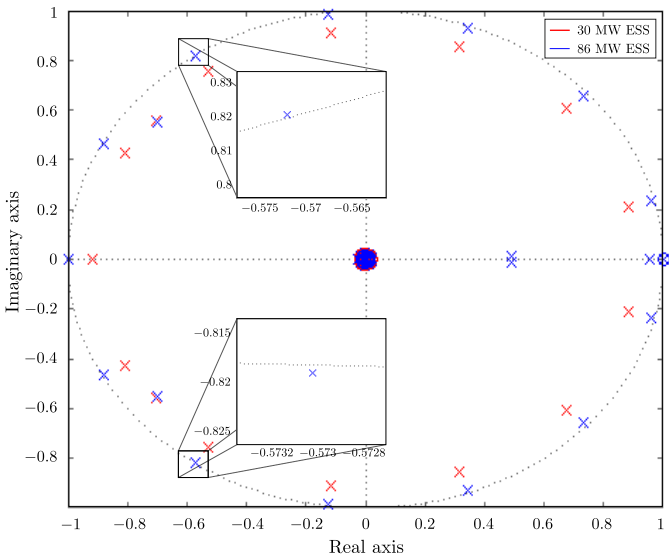


Fig. 14: Eigenvalues of the FR model with different ESS capacities.

facilities. The proposed estimated FR model was designed to closely represent the frequency behaviour of a large interconnected system, and the ESS model allowed an accurate representation of the SoC management and charging/discharging characteristics of FESS and BESS. Simulation results showed that reducing the communication delays can potentially reduce the ACE without requiring any increase in FR capacity, and that neglecting the SoC model of ESSs in the frequency control process yields unrealistic improvements in the ACE. Finally, it was shown that the stability of the existing FR system is robust with respect to communication delays, but sensitive to ESS capacities.

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