

A Review of Modeling and Applications of Energy Storage Systems in Power Grids

Fabian Calero, *Member, IEEE*, Claudio A. Cañizares, *Fellow, IEEE*, Kankar Bhattacharya, *Fellow, IEEE*, Chioma Anierobi, *Member, IEEE*, Ivan Calero, *Member, IEEE*, Matheus F. de Souza, *Student Member, IEEE*, Mostafa Farrokhhabadi, *Member, IEEE*, Noela S. Guzman, *Student Member, IEEE*, William Mendieta, *Student Member, IEEE*, Dario Peralta, *Student Member, IEEE*, Bharat Solanki, *Member, IEEE*, Nitin Padmanabhan, *Member, IEEE*, and Walter Violante

Abstract—As the penetration of variable renewable generation increases in power systems, issues such as grid stiffness, larger frequency deviations, and grid stability are becoming more relevant, particularly in view of 100% renewable energy networks, which is the future of smart grids. In this context, Energy Storage Systems (ESSs) are proving to be indispensable for facilitating the integration of Renewable Energy Sources (RES), and thus are being widely deployed in both microgrids and bulk power systems, and thus will be the hallmark of the clean electrical grids of the future. Hence, this paper reviews several energy storage technologies that are rapidly evolving to address the RES integration challenge, particularly Compress Air Energy Storage (CAES), flywheels, batteries, and thermal energy storage systems, and their modeling and applications in power grids. An overview of these energy storage systems is provided, focusing on new models and applications in microgrids and distribution and transmission grids for grid operation, markets, stability, and control.

Index Terms—Active distribution networks, battery energy storage, compress air energy storage, electricity markets, flywheel energy storage, microgrids, power system operation, power system stability and control, transmission systems, thermal energy storage.

NOMENCLATURE

AA	Affine Arithmetic
ACE	Area Control Error
ADN	Active Distribution Network
AGC	Automatic Generation Control
ATR	Alternate Technologies for Regulation

BESS	Battery Energy Storage System
CAES	Compress Air Energy Storage
CAISO	California ISO
CHP	Combined Heat and Power
DA	Day Ahead
DAE	Differential and Algebraic Equation
DER	Distributed Energy Resources
DoD	Depth of Discharge
DR	Demand Response
EA	Energy Arbitrage
EMS	Energy Management System
EMT	Electro-Magnetic Transient
EnC	Energy Cost
ESS	Energy Storage System
EV	Electric vehicle
EWB	Electric Water Heaters
FESS	Flywheel Energy Storage System
GA	Genetic Algorithm
GAD	Global Adjustment
GAC	Genetic Algorithm Cost
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GT	Gas Turbine
HOEP	Hourly Ontario Energy Price
HP	High pressure
HVAC	Heat, Ventilation and Air Conditioner
IBG	Inverter Based Generators
ICT	Information and Communication Technology
ID	Idling Reserve
IGBT	Insulated-gate Bipolar Transistors
IGV	Inlet Guide Vanes
IESO	Independent Electricity System Operator
ISO	Independent System Operator
IM	Induction Machine
IRR	Internal Rate of Return
KLFN	Kasabonika Lake First Nation
LMP	Locational Marginal Price
LP	Low pressure
MARR	Minimum Acceptable Rate of Return
MCS	Monte Carlo Simulations
MG	Microgrid
NARX	Nonlinear Autoregressive Exogenous NNs
NN	Neural Network
NYSO	New York ISO

The work presented here was mostly supported by the NSERC Energy Storage Technology (NEST) Network, Canada.

F. Calero, C. A. Cañizares, K. Bhattacharya, I. Calero, M. de Souza, N. Guzman, and D. Peralta are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, N2L 3G1, Canada (e-mail: fcalero@uwaterloo.ca, ccanizar@uwaterloo.ca, kankar@uwaterloo.ca, icalero@uwaterloo.ca, d2peralta@uwaterloo.ca, m6ferreirazambonidesouza@uwaterloo.ca, nguzman@uwaterloo.ca).

C. Anierobi is with CPCS Canada (e-mail: chiomaanierobi@gmail.com).

M. Farrokhhabadi is with with Bluwave-ai Inc., Ottawa, Canada (e-mail: mostafa.farrokhhabadi@bluwave-ai.com).

W. Mendieta is with the School of Electrical and Electronic Engineering, University College Dublin, Ireland (e-mail: william.mendieta@ucdconnect.ie).

B. Solanki is with Siemens Canada, Mississauga, ON, Canada (e-mail: bharat.solanki@siemens.com).

N. Padmanabhan is with NS Consulting, Kitchener, ON, Canada (e-mail: n2padman@uwaterloo.ca).

W. Violante is with Terna, Italy (e-mail: walter.violante@gmail.com).

OD	Oscillation Damping
PCC	Point of Common Coupling
PFC	Primary Frequency Control
PFR	Primary Frequency Regulation
PH	Pump Hydro
PID	Proportional, Integral and Derivative
PMSM	Permanent Magnet Synchronous Machine
PSS	Power System Stabilizer
PV	Photovoltaic
RES	Renewable Energy Sources
RO	Robust Optimization
RT	Real Time
RTO	Regional Transmission Organization
SC	Supercapacitor
SFC	Secondary Frequency Control
SFR	Secondary Frequency Regulation
SHE	Sensitivity Heat Storage
SMES	Superconducting Magnetic Energy Storage
SoC	State of Charge
SR	Spinning Reserve
TCL	Thermostatically Controllable Loads
TG	Traditional Generator
TESS	Thermal Energy Storage System
VSC	Voltage Source Converter
WECC	Western Electricity Coordinating Council

I. INTRODUCTION

Generation resources have evolved during the last few decades to address the issues of environmental pollution and Greenhouse Gas (GHG) emissions. This has led to the development and penetration of a wide mix of Renewable Energy Sources (RES) as well as Distributed Energy Resources (DERs), in particular, Inverted Based Generators (IBGs) such as Photovoltaic (PV), wind, small natural-gas-fueled generators, as well as controllable loads, Electric Vehicles (EVs) and Energy Storage Systems (ESSs). These are modifying the traditional power system structure to create smart grids that contain decentralized medium- and low-voltage networks based on DERs, namely, Active Distribution Networks (ADNs) and Microgrids (MGs) [1]–[3]. This new grid paradigm is illustrated in Figure 1, where Information and Communication Technologies (ICTs) play a significant role, transforming power grids into cyber-physical systems.

The stochastic nature of RES, with their dependence on weather conditions that results in intermittent operation, requiring adequate generation-load balancing and reserve capacity, are some of the fundamental issues to be considered in the planning and operation of these new grids for stability and reliability [4], [5]. In traditional schemes, system solutions such as load shifting through demand management controls and interconnection with external grids have been used to address these problems [6]. However, as penetration of RES increases, the use of ESSs has been shown to be one of the most promising approaches to counteract these problems and facilitating full integration of RES into the grids, as part of DER deployment [7]. In fact, ESS paired with both small- and large-scale RES facilities has become a common practice

in recent years, as prices of storage continue to decrease [8]. This configuration has several advantages, including decoupled time dependence of RES and the system demand needs, which is particularly relevant for PV generation that is available at a specific time window during the day, thus increasing reliability. It may also turn RES facilities into dispatchable generators, thus helping grid operators to reduce the uncertainty in their resources forecasting. The economic performance of coupled RES and ESS facilities is subject to market conditions and access to incentives and tax credits [9]. Thus, ESSs are currently being developed and deployed in small-, medium-, and large-scale applications to improve the technical and economic performance of smart grids, since they not only have the capability of exchanging power with the grid, but also can provide grid services, such as voltage and frequency regulation, which can contribute to improved system stability [10], in particular in the case of MGs operating in island mode [11].

MGs have been and are being used extensively for electrification of remote communities, which operate mostly as stand-alone systems. Dropping prices of PV and wind systems, has led to their increased deployments in MGs, which has increased the concerns about security of supply, power quality and resilience. Integration of ESSs are a promising solution to these problems [12], [13]. Therefore, understanding ESSs and their impact on interactions with the grid is becoming essential for MG/grid operators and planners, requiring appropriate modelling and control approaches [14]. This article, therefore, focuses on providing a comprehensive review of novel and distinct ESS models, controls, and operation of specific ESS technologies for applications in microgrids and distribution and transmission systems, rather than focusing on generic ESS models and controls for particular grid applications like in, for example, [14]. Thus, it provides a complete overview of the state-of-the-art ESS technologies being used and studied, with their models and controls depending on the application considered, which include Compressed Air, Battery, Flywheel, and Thermal ESSs for frequency regulation, grid stability, voltage regulation, and ancillary services in various types of grids and in a market context. Thus, in Section II the main features of relevant and evolving ESS technologies, in particular, Battery Energy Storage Systems (BESS), Flywheel Energy Storage Systems (FESS), Compressed Air Energy Storage Systems (CAES), and Thermal Energy Storage Systems (TESS) are first discussed. In Section III, the latest on ESS modelling of BESS, FESS, CAES and TESS are presented, focusing on grid dynamic models and controls, as well as market integration models of ESS. Some of the main applications of these ESS technologies for transmission systems, ADNs and MGs are reviewed in Section IV. Finally, the main conclusions on the state-of-the-art of ESS modeling, control, and applications are presented in Section V, together with a discussion of possible future advancements in these areas.

II. OVERVIEW OF ENERGY STORAGE TECHNOLOGIES

Storing energy from the power grid usually involves an energy conversion stage that transforms the electricity into

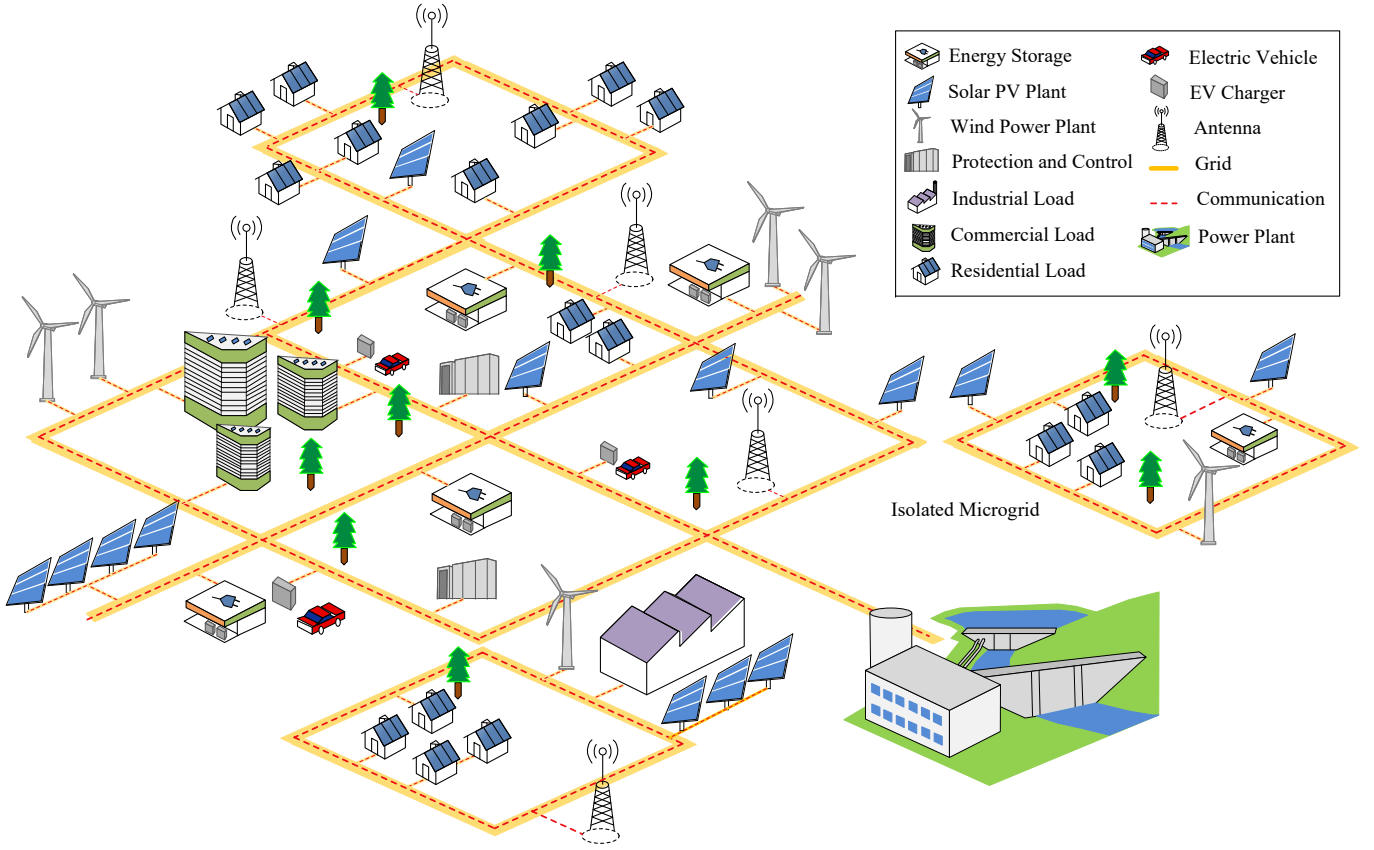


Fig. 1. Renewable-based smart grids of the future.

another form of energy that can be efficiently stored. Most ESSs for power grid applications classify the technologies based on the type of energy stored [15]–[19], as follows:

- Mechanical: Pumped Hydro (PH), CAES and FESS.
- Electrochemical: BESS, including all battery technologies such as lead-acid, lithium-ion (most common), NaS, Ni-Cd, and flow batteries.
- Electrical: Super Capacitors (SC) and Superconducting Magnetic Energy Storage (SMES).
- Thermal: TESS, including Sensitive Heat Storage (SHE) and Ground Source Heat Pump (GSHP) technologies.

In Table I, the main characteristics of the most relevant ESS technologies are summarised. The present paper focuses on the various ESS technologies, their modeling, control and application, that are commercially available and are being widely developed, studied, and deployed in MGs, ADNs and transmission grids, namely, BESS, FESS, CAES and TESS. Thus, the main characteristics of these ESS technologies are presented next.

A. Battery Energy Storage Systems (BESS)

BESS convert electrical energy into chemical energy, which is stored in lead-acid, Ni-Cd, or lithium-ion battery cells, with the latter being the most utilized in BESS due to their technical performance and relatively low cost, which has dropped considerably in recent years [25]. The scheme of a typical BESS is depicted in Fig. 2, wherein the power conditioning system

comprises a bi-directional buck-boost dc-to-dc converter that connects a battery pack to the dc side of a Voltage Source Converter (VSC). The battery pack contains cells organized in series and parallel to achieve the desired voltage and power rating, respectively. The dc-to-dc converter raises the battery pack voltage to a level appropriate to connect to the VSC's dc side, and controls the battery pack charging/discharging. The self-commutating VSC based on Insulated-gate Bipolar Transistors (IGBTs) can be controlled to allow four-quadrant operation, i.e., active and reactive power exchanged in both directions with the grid, while the dc-to-dc converter can be controlled to regulate the voltage on the dc side of the VSC. A low-pass RL filter connects the terminals of the VSC and the Point of Common Coupling (PCC) with the grid.

BESS are characterized by very fast response and are capable of providing regulation services such as frequency and voltage regulation, low-frequency oscillation damping, improving the system transient stability, and other ancillary services. BESS have large energy density (40-7000 kJ/kg), which facilitate their deployment in relatively small spaces as compared to other ESS technologies such as PH, and have high efficiencies in the order of 75% to 97%, depending on the battery chemistry [15]. However, the large number of operating cycles and deep discharging affects the performance of the battery cells and the overall lifetime of BESS, which are issues that must be taken into consideration when providing grid services. Flow-battery based BESS partially solve these problems

TABLE I
CHARACTERISTICS OF ESS TECHNOLOGIES [20]–[24]

Technology	Power Density [kW/m ³]	Energy Density [kWh/m ³]	Power Rating [MW]	Energy Capacity [MWh]	Capital Cost [\$ /kW]	Lifetime [years]	Cycling Times [10 ³ cycles]	Round-trip Efficiency [%]	Response Time	Maturity
PH	0.01-0.12	0.5-0.133	100-5,000	500-8,000	500-2,000	30-60	10-30	70-85	mins	Mature
CAES	0.04-10	0.4-20	5-300	≤1,000	400-1,800	20-40	8-12	42-54	sec-min	Developed
FESS	40-20,000	0.25-424	0.01-0.25	0.025-5	100-350	15-20	20-100	90-95	msec	Commercial
SEMS	300-4,000	0.2-13.8	0.1-10	0.015	200-300	20+	>100	95	msec	Commercial
SC	15-4,500	1-35	0-0.3	0.0005	100-300	10-12	10-1,000	85-98	msec	Developing
TESS	-	80-500	0.01-300	-	200-300	5-40	-	30-80	slow	Developing
Li-ion	56-800	94-500	0-0.1	0.004-10	1,200-4,000	5-15	0.2-2	85-90	msec	Commercial
Lead-acid	10-400	25-90	0-20	0.001-40	300-600	5-15	0.2-2	85-90	msec	Mature
NiCd	38-141	15-150	0-40	6.75	500-1,500	10-20	1.5-3	60-90	msec	Commercial
VRB	2.5-33.4	10-33	0.03-3	2	600-1,500	5-10	>16	85	msec	Commercial
ZnBr	3-8.5	5.2-70	0.05-2	4	700-2,500	5-10	2-3.5	75	msec	Demonstration

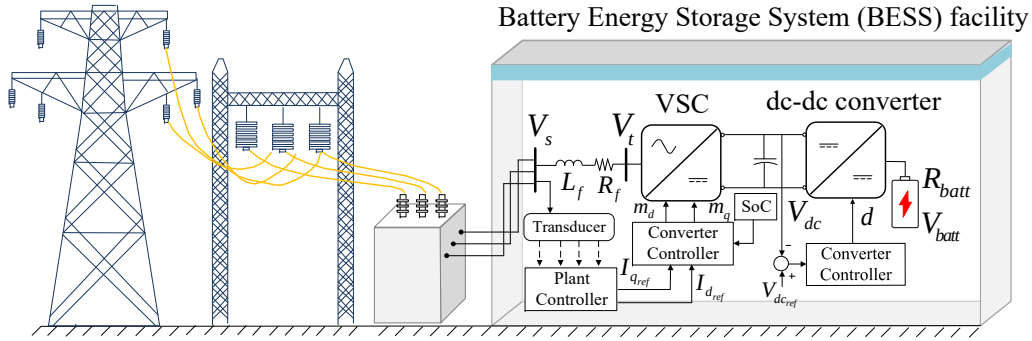


Fig. 2. Typical topology and control blocks of a BESS.

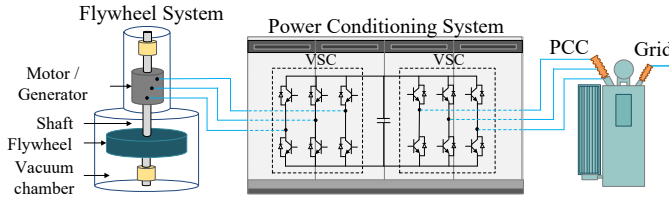


Fig. 3. Flywheel components.

by separating the battery's electrolytes in tanks, which are then combined to produce the chemical reaction in a flow reactor. This configuration facilitates replacing the electrolytes when their quality has been affected by either profound discharging or excessive cycling; however, their efficiency is reduced by the operation of the additional equipment involved, such as shunt currents in the electrolytes and pumps to move them.

B. Flywheel Energy Storage System (FESS)

A flywheel stores energy in the form of inertia of a heavy rotating disk that spins at very high speeds, typically more than 10,000 rpm. A chamber encapsulates the rotor that is suspended by magnetic bearings, allowing its rotation without any physical contact between the static and moving parts. The chamber is a vacuum space to reduce losses arising due to air friction. The flywheel's rotor is connected to an electrical machine, which can be a Permanent Magnet Synchronous Machine (PMSM) or an Induction Machine (IM); the former

is preferred for applications requiring high rotational speeds, while the latter is better for high power applications. The FESS power conditioning system can be based on dc-to-ac or ac-to-ac converters, or a combination of these; however, the most common topology comprises two back-to-back VSCs connecting the PCC and the machine, as illustrated in Fig. 3 [21], [26], [27]. The back-to-back configuration allows active power flow in both directions to charge and discharge the flywheel, while also decoupling the flywheel's ac frequency from the grid's [26]. The energy storage capacity depends on both, the speed and the combined inertia of the flywheel's rotor J_{FW} and machines rotor J_M , given by:

$$E = \frac{1}{2}(J_{FW} + J_M)\omega_r^2 \quad (1)$$

where J_{FW} and J_M are constants; thus, the FESS charging/discharging energy can be controlled by regulating the rotor speed ω_r .

FESSs have very fast response times (in ms), and high specific power (400 to 1,500 W/kg) [15]; thus, along with BESS, they are ideal candidates to provide grid services such as frequency regulation. However, FESS are superior in terms of cycling (>150,000 cycles) and Depth of Discharge (DoD) capability, which are two well-known issues that affect BESS performance. Their round trip efficiency is in the range of 75% to 95% and have a typical life of 15 to 20 years [15]. Some existing flywheel facilities include the 2 MW Minto facility in Ontario, Canada [28], and the Beacon's 20 MW Stephentown

and 20 MW Hazel facilities in New York and Pennsylvania in the US, respectively [29].

C. Compressed Air Energy Storage (CAES) System

In CAES, energy is stored as pressurized air in natural reservoirs such as an underground salt cavern or above-ground tank, with the latter being suitable only for small-scale applications. In the charging mode, a compressor physically coupled with a synchronous motor that draws power from the grid, pressurizes the air, which is carried through pipes to the cavern. The heat produced in the compression process is removed by heat exchangers and can be stored for later use during expansion, thus improving the system efficiency. In discharging mode, the air at high pressure is extracted from the cavern and expanded in a turbine which is attached to the rotor of a synchronous generator that injects the power back to the grid.

In diabatic CAES, the air is preheated in a recuperator before the expansion using the remnant heat of the gasses at the exhaust of the turbine, and then combined with natural gas and burned in a combustion chamber to increase the temperature further [31], [32]. On the other hand, an adiabatic CAES does not burn gas, and rather preheats the air using the compression heat stored. CAES can have a single synchronous machine interfacing with the grid, which operates as motor or as generator, or two independent machines; the latter allows simultaneous operation in charging and discharging mode, and provides more flexibility in the design and size of the system. Through the synchronous generator, CAES can provide voltage and frequency regulation, but unlike other ESSs, they add inertia to the power grid. A typical CAES system is depicted in Fig. 4.

Along with PH, CAES are the only ESSs which are currently economically viable for bulk applications, with lifetimes longer than 40 years, and efficiencies greater than equivalent gas turbines or combined cycle units, i.e., in the range of 30% to 70%, depending on the type of CAES (diabatic or adiabatic) [33], [34]. They can provide black start, with start-up times of 10-12 min and also have fast ramping capability, i.e., 25%/min. Currently, there are two large diabatic CAES projects operating world wide, the 290 MW Huntorf facility in Germany [31] and the 110 MW McIntosh facility in Alabama, USA [32]. There are also small-scale pilot plants such as the adiabatic facility in Goderich, Ontario, Canada [35].

D. Thermal Energy Storage Systems (TESS)

TESS store heat in a reservoir which can be a tank [36], hot bricks [37] or an underground borehole [38], while the medium to transfer this heat can be liquid or gas. A generic TESS configuration is depicted in Fig. 5. In discharging mode (heating mode), the thermal load is supplied by the heat obtained from a thermal storage device through a heat exchanger, while in charging mode (cooling mode) the heat is removed from the thermal load and transferred to the storage device through the heat exchanger. A pump is used to circulate the heat in both directions so that the TESS can be charged/discharged directly from/to the thermal load, whose heat depends on the

application, such as supplying a building's heat needs during cold winter days, or air conditioning (A/C) during summer days. Hence, an electrical interface is usually associated with the thermal load, allowing the TESS to discharge when the price of electricity is high or grid RES power is not available, or to charge when the price is low or grid RES power is in excess.

TESS have becoming popular for supplying the Heat, Ventilation and Air Conditioning (HVAC) and Water Heating (WH) needs of households, especially in locations with cold weather, and the GSHP systems. In these systems, heat extracted from the house is pumped to the ground and hence cool down the house during warm summer days, while the stored heat is pumped back to the house during winter, to provide space heating [38], [39]. Typically, one or multiple boreholes can be drilled into the ground in an external loop, which uses a pump to circulate the water mixed with anti-freezing through a high-density polyethylene pipe, which acts as a heat exchanger between the fluid and the borehole surroundings, as depicted in Fig. 6. An evaporator transfers the heat from a refrigerant in an inner loop to the borehole loop. The refrigerant, whose circulation is through a compressor that further increases its temperature, carries the heat, extracted in a condenser, from the warm air moving through the ductwork in the house. A reversible valve in the inner loop allows charging the GSHP system by changing the direction of circulation of the refrigerant, thus also switching the tasks of the condenser and evaporator. By controlling the compressor, the heat transfer can be regulated, thus allowing the system to also provide short-term grid services such as frequency regulation [38], or participate in Demand Response (DR) through aggregators [39]. Note that in this system, the electrical and thermal paths are physically decoupled.

III. ENERGY STORAGE SYSTEM MODELS

In this section, the state-of-art on ESS modeling is discussed, focusing on the technologies described in Section-II and covering different modeling domains such as single models and aggregated dynamic models, and operation models at the wholesale electricity market level as well as at the ADN and microgrid level.

A. Dynamic Models

1) *BESS*: Depending on the application, the dynamic model of BESS can have different levels of complexity. For example, in Electro-Magnetic Transient (EMT) studies, MGs or unbalanced ADNs, a three-phase model of a VSC coupled with a dc-to-dc converter provides an accurate representation, as illustrated in Fig. 7. A further approximation may involve replacing the dc-to-dc converter by a constant voltage source, and/or averaging the terminal voltage of the VSC, thus replacing the switches by controlled voltage sources. The former preserves the high-frequency response of VSC in the BESS, while the latter removes all high-frequency responses, resulting in a less-computationally demanding model [40].

For large power systems studies, averaged BESS models are more common, to be consistent with other system component models available, which often neglect high frequency

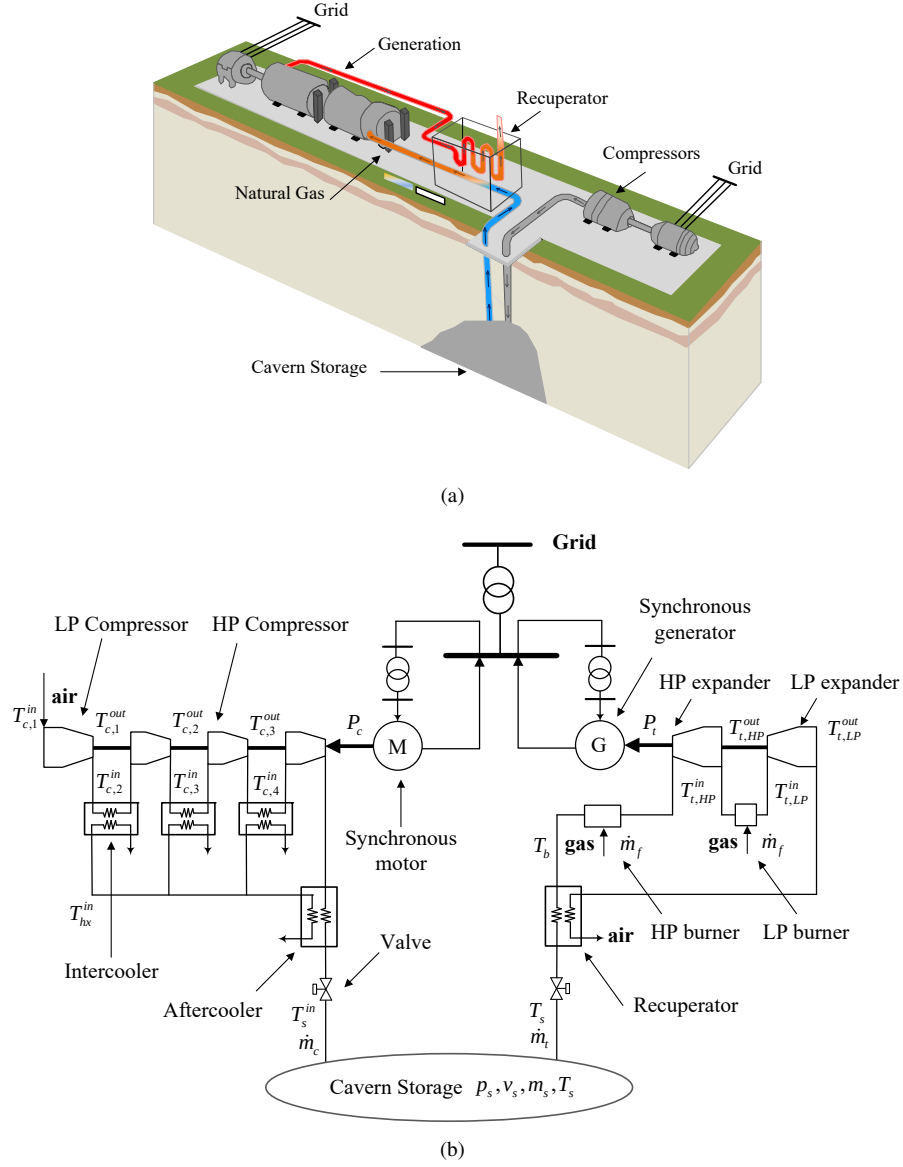


Fig. 4. Diabatic CAES (a) physical system layout and (b) dynamic model for power system analysis [30].

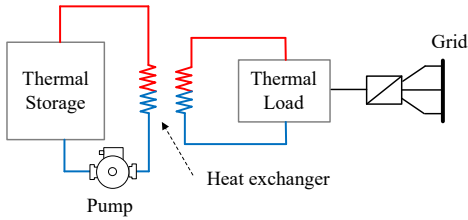


Fig. 5. Generic TESS.

[41]:

$$\dot{V}_{in} = -\frac{1}{C_2 R_{bat}} V_{in} - \frac{1}{C_2} I_L + \frac{1}{C_2 R_{bat}} V_{bat} \quad (2)$$

$$\dot{V}_{dc} = \frac{1-d}{C_1} I_L - \frac{1}{C_1} I_{dc} \quad (3)$$

$$\dot{I}_L = \frac{1}{L} V_{in} - \frac{1-d}{L} V_{dc} \quad (4)$$

$$I_{dc} = \left(\frac{3V_{sd}}{2M_c V_{dc}} \right) I_{sd} \quad (5)$$

$$V_{td} = \frac{1}{2} m_d V_{dc} \quad (6)$$

$$V_{tq} = \frac{1}{2} m_q V_{dc} \quad (7)$$

$$P_s = \frac{3}{2} I_d V_{sd} N_c \quad (8)$$

$$Q_s = -\frac{3}{2} I_q V_{sd} N_c \quad (9)$$

$$L_f \dot{I}_{sd} = V_{td} - V_{sd} - R_f I_{ds} + \omega_o L_f I_{qs} \quad (10)$$

$$L_f \dot{I}_{sq} = V_{tq} - V_{sq} - R_f I_{qs} - \omega_o L_f I_{ds} \quad (11)$$

transients. In this context, the BESS can be modeled assuming balanced operation by a set of Differential Algebraic Equations (DAEs), based on the system presented in Fig. 7, as follows

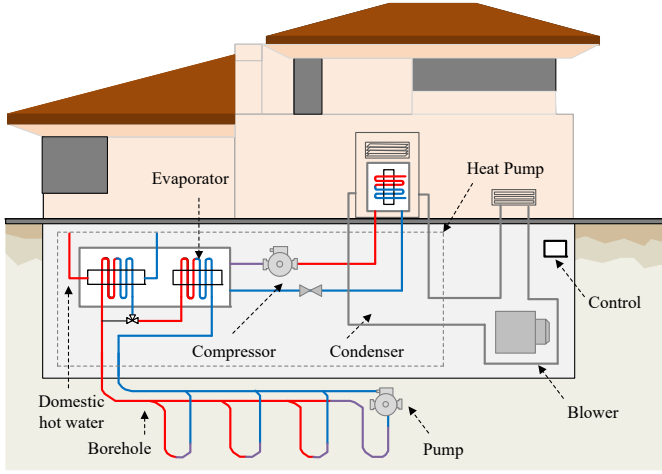


Fig. 6. GSHP system.

where (2)-(4) model the dc-to-dc converter with V_{in} , V_{dc} , and I_L representing the battery pack terminal voltage, dc-link voltage, and inductor L current, respectively; (5) is the link between the VSC and dc-to-dc converter, considering M_c dc-to-dc converters in parallel to achieve the VSC rated power; (6) and (7) are d- and q-axis components of the VSC's terminal voltage V_t , with modulation indices m_d and m_q ; (8) and (9) define the active P_s and reactive Q_s power injected by the BESS at the PCC, for a given voltage V_s and current I_s , comprising N_c VSCs in parallel to achieve the BESS rated power; (10) and (11) denotes the ac filter equations in the d- and q-axes in terms of L_f and R_f . This model assumes that the battery pack is modeled as a fixed voltage source V_{bat} with a resistor in series R_{bat} , but a more complex model can be considered as well, which can include the State-of-Charge (SoC) effect on V_{bat} as follows [40]:

$$V_{bat} = V_{bat_o} - K \frac{1}{SoC} + A^{-B(1-SoC)D} \quad (12)$$

where D is the battery capacity in Ah, K the polarization voltage in V, A and B are parameters that can be tuned to fit a specific battery model. Note that more complex representations of the battery pack may be used (e.g. [42]); however, these will increase computational burden, especially when other grid components are also modeled. On the other hand, the voltage source in series with a resistor depicted in Fig. 7 balances accuracy and complexity, to allow capturing relevant battery issues for most grid studies and applications, such as aging or degradation, which can be readily modeled through reduced values of V_{bat} and increased values of R_{bat} [43].

In actual BESS facilities, multiple VSC, multiple dc-to-dc converters per VSC, and battery cell arrays may be needed depending on the facility's size [44]. Modelling each of these components individually may be computationally cumbersome for grid studies; therefore, a common practice consists of representing only one VSC and one dc-to-dc converter per VSC, when this converter is modeled, assuming a simple aggregation of active and reactive power injected to the grid, as depicted in Fig. 7.

2) CAES: The dynamics associated with the mechanical and thermal sub-systems are relevant in frequency regulation and frequency stability studies, and thus these need to be modeled. Conversely, transient stability or EMT studies are not focused on slow dynamics, and hence is more important to model the electric machines (generator/motor) and their controls in some detail. However, it has been demonstrated that some fast-acting mechanical power controls may have a significant impact on a CAES system performance during fast transient events [45]. Therefore, the CAES model discussed in this section assumes [30]:

- A steady-flow process within the compressor and turbine, ideal gas behaviour, and neglect kinetic and potential energy during compression and expansion.
- A diabatic CAES system, i.e., gas is burned to preheat the air before expansion.
- A very small proportion of gas to air in the expander.
- Constant efficiencies in all elements.
- Independent generation and expansion drivetrains.

In Fig. 4(b), the mechanical power $P_{t,k}$ produced in a stage of expansion $k = \{LP, HP\}$ of a multi-stage turbine, and consumed power $P_{c,j}$ in a stage of compression $j = \{1, 2, 3, 4\}$ of a multi-stage compressor of diabatic CAES, can be calculated based on the isentropic expansion/compression of the air, as follows [30]:

$$P_{t,k} = \eta_{t,k}^m \eta_{t,k}^i c_p T_{t,k}^{in} \left(1 - \pi_{t,k}^{1/\gamma-1}\right) \dot{m}_t \quad (13)$$

$$P_{c,j} = \frac{c_p T_{c,j}^{in}}{\eta_{c,j}^m \eta_{c,j}^i} \left(\pi_{c,j}^{1-1/\gamma} - 1\right) \dot{m}_c \quad (14)$$

where $\dot{m}_t$ and $\dot{m}_c$ are the turbine and compressor air flows, respectively; $\eta_{t,k}^m$ and $\eta_{c,j}^m$, and $\eta_{t,k}^i$ and $\eta_{c,j}^i$ are the mechanical and isentropic efficiencies of the turbine and compressor, respectively; $T_{t,k}^{in}$ and $T_{c,j}^{in}$ are the air temperatures at the inlet of the turbine and compressor, respectively; c_p is the specific heat gain of air; and $\pi_{t,k}$ and $\pi_{c,j}$ are the turbine and compressor pressure ratios, respectively, which are functions of air flow, rotor speed and inlet conditions, i.e., temperature and pressure. The thermal dynamics of the recuperator shown in Fig. 8(a) can be modeled as a first order system, as follows [30]:

$$\dot{v}_r = \frac{1}{\tau_R} [\epsilon_r (T_{t,LP}^{out} - T_s) - v_r] \quad (15)$$

$$T_{b,HP} = T_s + v_r \quad (16)$$

where ϵ_r and τ_R are the effectiveness and time constant of the recuperator; v_r is the dynamic temperature rise in the recuperator; T_s is the cavern temperature; $T_{t,LP}^{out}$ is the exhaust temperature of the LP turbine stage; and $T_{b,HP}$ is the input temperature to the HP burner. The relation between the burner temperature and turbine input temperature can be expressed as follows:

$$T_{t,k}^{in} = T_{b,k} + (T_{to,k}^{in} - T_{bo,k}) \frac{\dot{m}_f}{\dot{m}_t} \quad (17)$$

where $(T_{to,k}^{in} - T_{bo,k})$ is the design burner rise temperature, and $\dot{m}_f$ is the fuel flow into the burner. The thermal dynamics of

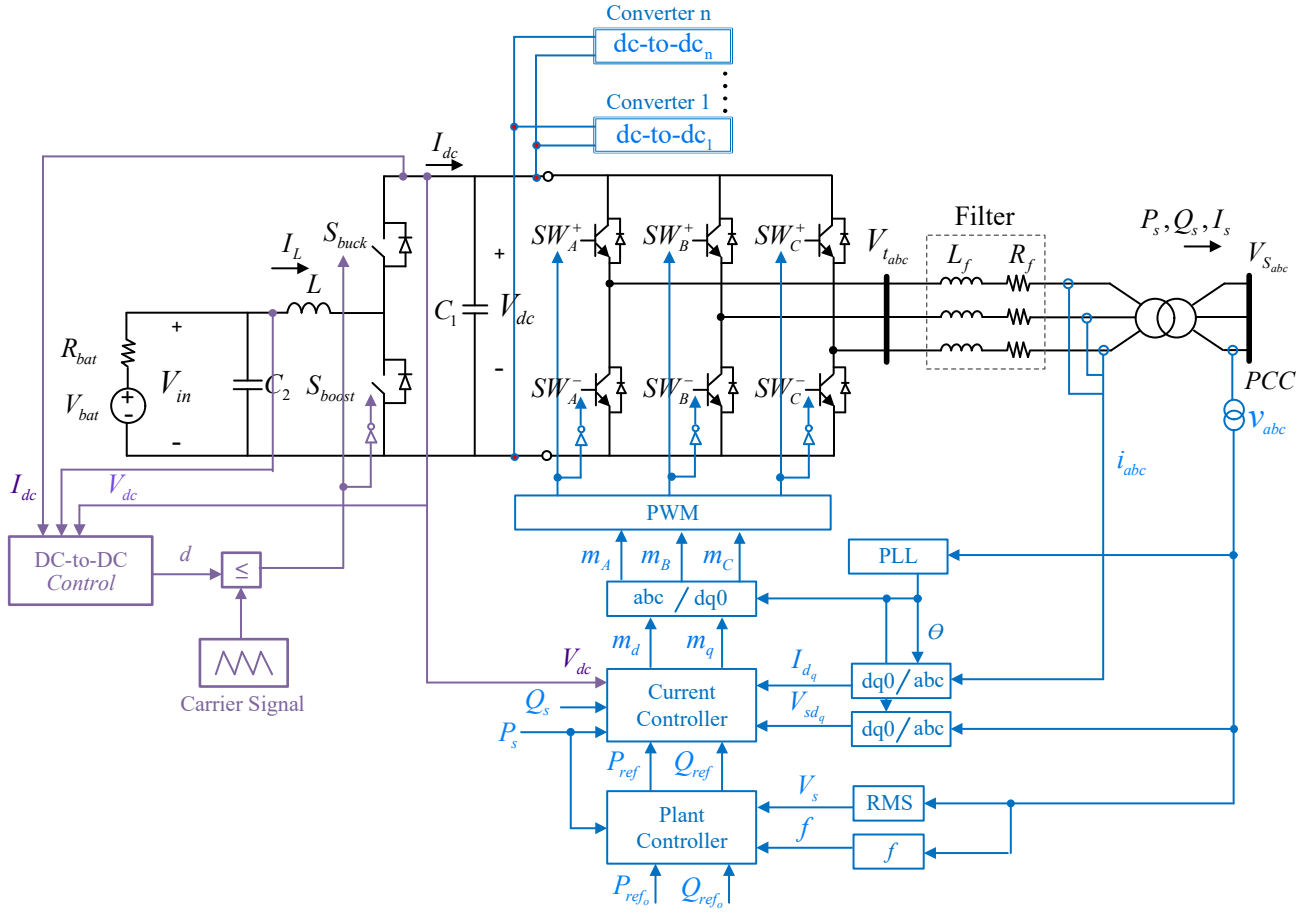


Fig. 7. Detailed 3-phase BESS model with its generalized controls, for dynamic analysis.

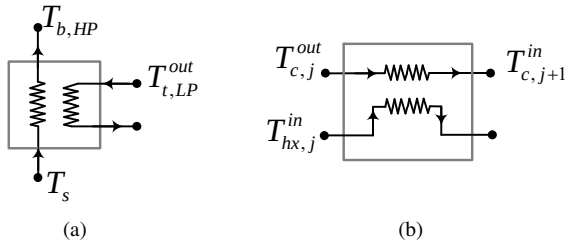


Fig. 8. CAES component level thermal dynamic models for (a) recuperator and (b) intercooler.

the intercoolers at each compression stage, shown in Fig. 8(b), can be modeled as a first order system, as follows:

$$\dot{v}_{hx,j} = \frac{1}{\tau_{hx}} [\epsilon_j (T_{c,j}^{out} - T_{hx,j}^{in}) - v_{hx,j}] \quad (18)$$

$$T_{c,j+1}^{in} = T_{c,j}^{out} - v_{hx,j} \quad (19)$$

where $\dot{v}_{hx,j}$ and τ_{hx} are the intercooler temperature drop and time constant, respectively. Finally, the turbine and compressor output temperatures at each stage, $T_{t,k}^{out}$ and $T_{c,j}^{out}$ respectively,

can be calculated as follows:

$$T_{t,k}^{out} = T_{t,k}^{in} \left[1 - \left(1 - \pi_{t,j}^{1/\gamma-1} \right) \eta_{t,k}^i \right] \quad (20)$$

$$T_{c,j}^{out} = T_{c,j}^{in} \left[1 + \left(\pi_{c,j}^{1-1/\gamma} - 1 \right) \frac{1}{\eta_{c,j}^i} \right] \quad (21)$$

To complete the model, synchronous machines that couple the turbine and compressor to the grid and their controls must be represented. These models are well defined in the literature, as for example in [46] and [47].

3) *FESS*: A detailed FESS model based on an IM and a back-to-back configuration is presented in Fig. 9. The same model assumptions discussed for the BESS' power conditioning systems apply for the FESS, i.e., detailed 3-phase physical-based or balanced average models of the FESS can be considered depending on the application, with average models being more common for large power system dynamic studies. The model of the VSCs is similar to that discussed for the BESS in Section III-A1, while typical transient IM models are readily available e.g., ([46], [47]). The VSC₁ connected to the terminals of the IM can be controlled to regulate the active power exchanged with the flywheel, and thus the charging and discharging of the FESS. The electromechanical coupling between the flywheel and the IM can be calculated as follows

[46]:

$$\dot{\omega}_r = \frac{1}{J_{IM} + J_M} (\mathcal{T}_e - F\omega_r) \quad (22)$$

where $\mathcal{T}_e$ is the IM electromagnetic torque; ω_r is the rotor speed and F is a friction coefficient. The electromagnetic torque depends on the IM stator currents, and thus on VSC₁'s I_d and I_q currents, which are regulated by the current controller. Note that the sign of $\mathcal{T}_e$ depends on the direction of the active power flow to the flywheel, i.e., it is positive if the flywheel is charging, and negative if it is discharging. Similarly, from (1), the useful energy stored in a FESS can be determined as follows:

$$E = \frac{J_{FW} + J_M}{2} (\omega_r^2 - \omega_{r\min}^2) \quad (23)$$

where $\omega_{r\min}$ is the minimum rotational speed of the flywheel.

4) *TESS*: The heat storage model depends on the physical characteristics of the storage reservoir. For example, a simple model is that of a tank storing a fluid such as water, whose temperature can be calculated as follows [36]:

$$m_s c_w \dot{T}_s = \dot{Q}_s^{in} - \dot{Q}_s^{out} - \dot{Q}_s^L \quad (24)$$

where m_s is the mass of water in the tank; T_s is the water temperature in the tank; c_w is specific heat capacity of water; $\dot{Q}_s^{in}$ and $\dot{Q}_s^{out}$ are the heat rates for water entering and leaving the tank, respectively; and $\dot{Q}_s^L$ represents the rate of heat loss. Note that $\dot{Q}_s^{in}$ and $\dot{Q}_s^{out}$ depends on the thermal loops of the TESS. This model assumes that the water density and temperature are uniform in the tank, with no phase changes in the water and neglecting pressure dynamics [48]. Due to these assumptions, the application of this model results in fast computation times, and it is thus extensively used in operation and planning studies, or when multiple TESS need to be modeled. However, the model is not accurate enough to reflect effects such as thermal stratification inside the TES, and it thus tends to overestimate heating losses [49].

In the specific case of the GSHP system illustrated in Fig. 6, $\dot{Q}_s^{in}$ when the GSHP operates in cooling mode, i.e., replacing an A/C in the household, can be obtained by following the thermal loops and observing the heat transfers and energy conversion processes. For example, the cooling power $\dot{Q}_c$, can be calculated as a function of the wet-bulb house temperature T_{wb} , the mass flow rate in the borehole loop $\dot{m}_w$, and the water temperature at the inlet of the heat pump, i.e., borehole temperature T_s , as follows [38]:

$$\frac{\dot{Q}_c}{\dot{Q}_{c,ref}} = \mathcal{A} + \mathcal{B} \left(\frac{T_s}{T_{ref}} \right) + \mathcal{C} \left(\frac{T_{ref}}{T_{wb}} \right) \left(\frac{\dot{m}_w}{\dot{m}_{w,ref}} \right) \quad (25)$$

where $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ are model parameters that can be obtained from actual systems; T_{ref} is a reference temperature (283 °K); $\dot{m}_{w,ref}$ is the reference mass flow rate; and $\dot{Q}_{c,ref}$ is the rated cooling capacity of the heat pump. Thus, the compressor power P_c can be computed as follows [38]:

$$P_c = \frac{\dot{Q}_c}{ERR} \quad (26)$$

$$\frac{ERR}{ERR_{ref}} = \mathcal{D} + \mathcal{E} \left(\frac{T_s}{T_{ref}} \right) + \mathcal{F} \left(\frac{T_{ref}}{T_{wb}} \right) \left(\frac{\dot{m}_w}{\dot{m}_{w,ref}} \right) \quad (27)$$

where ERR and ERR_{ref} are the actual and rated efficiency ratios of the heat pump, respectively, and $\mathcal{D}$, $\mathcal{E}$ and $\mathcal{F}$ are model parameters that can be obtained from actual deployed systems. The heat power rejected to the ground $\dot{Q}_s^{in}$ and the heat pump outlet water temperature T_w^{out} can be calculated as follows:

$$\dot{Q}_s^{in} = \dot{Q}_c + P_c \quad (28)$$

$$T_w^{out} = \frac{\dot{Q}_s^{in}}{c_p \dot{m}_w} + T_s \quad (29)$$

To model the GSHP in heating mode, the parameter ERR is replaced by the coefficient of performance $COP = \dot{Q}_c/P_c$; T_{wb} is replaced by the dry-bulb indoor temperature; and (28) and (29) are reformulated as follows:

$$\dot{Q}_s^{out} = \dot{Q}_c - P_c \quad (30)$$

$$T_w^{out} = \frac{\dot{Q}_s^{in}}{c_p \dot{m}_w} - T_s \quad (31)$$

where $\dot{Q}_s^{out}$ is the heat extracted from the borehole. Note that this model assumes that the COP is constant. For shorter term studies, such as using the TESS for frequency control, a more complex model than (24) should be used to describe the borehole, like the one, for example, in [38], which is able to accurately reproduce the dynamic behavior of the ground heat exchange under transient operating conditions (ON/OFF operations) for cooling and heating modes.

B. Control Strategies

1) *BESS*: In most grid connected BESS, the VSC can be controlled to regulate the active and reactive power injections, while the dc-to-dc converter regulates the dc-link voltage. An alternative to this approach involves regulating the dc-link voltage and Q injections along with the VSC and the active power by means of the dc-to-dc converter. In either case, a decoupled dq current controller facilitates independent control of P and Q services.

A two-level hierarchical control strategy for BESS is presented in Fig. 10 [50]. In the first level, known as plant controller, the set points of the BESS active and reactive power injections are calculated and split into N_c modules in the second level, each comprising a VSC, its current controller, and M_c dc-to-dc converter per VSC. The active power plant controller allows the BESS to provide Oscillation Damping (OD), primary and secondary frequency regulation, operate in constant P mode following an external reference signal, P_{refo} , or a combination of these. Similarly, the reactive power plant controller allows voltage regulation, constant power factor operation, or constant Q control following an external reference signal Q_{refo} . To choose between different operating modes, two flags are used. The dc-to-dc converter controls the S_{boost} and S_{buck} switches in Fig. 7, while keeping the current through the dc converter inductor L within limits, thus also limiting the battery bank charge and discharge.

Another BESS model widely used in the industry, which was developed by the the Western Electricity Coordinating Council (WECC), based on a generic renewable generator

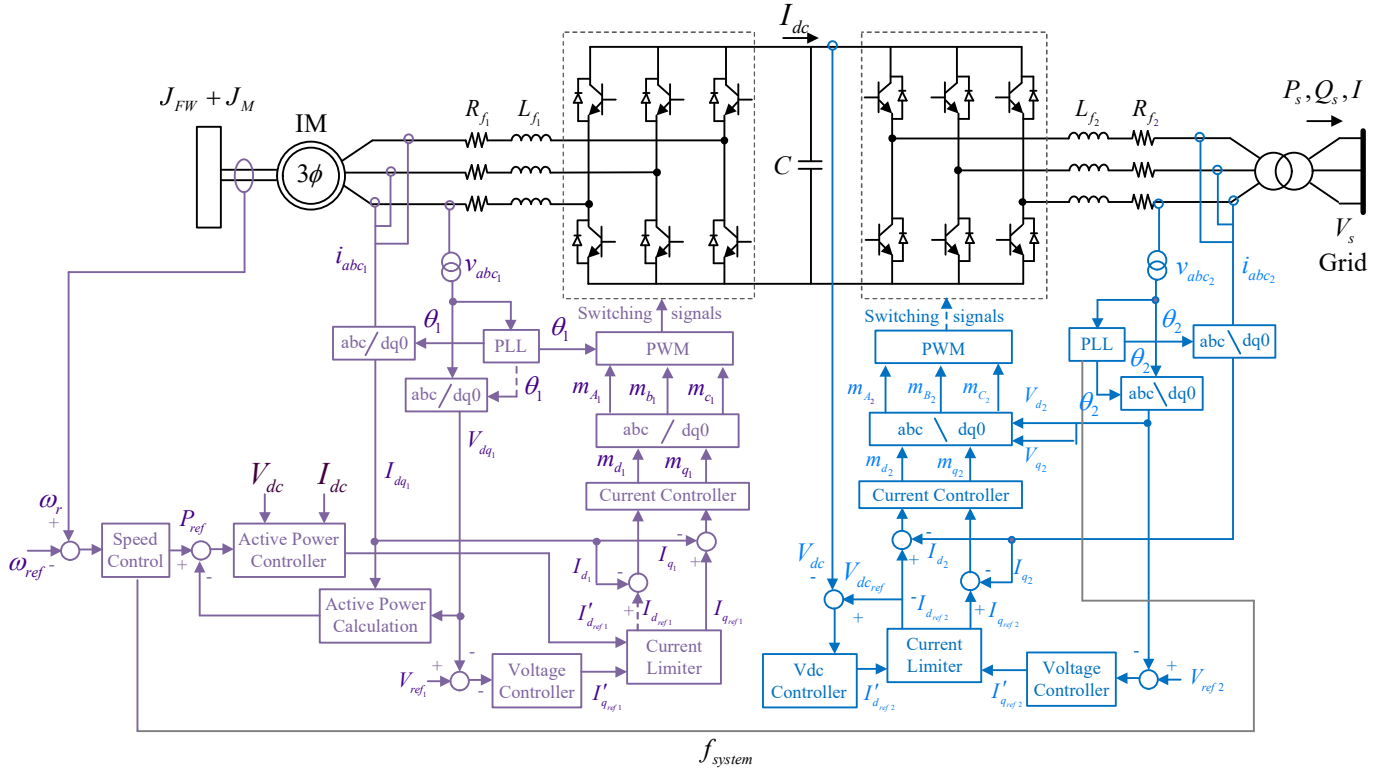


Fig. 9. Detailed FESS model based on an IM and a back-to-back converter configuration, with its generalized controls for dynamic analysis.

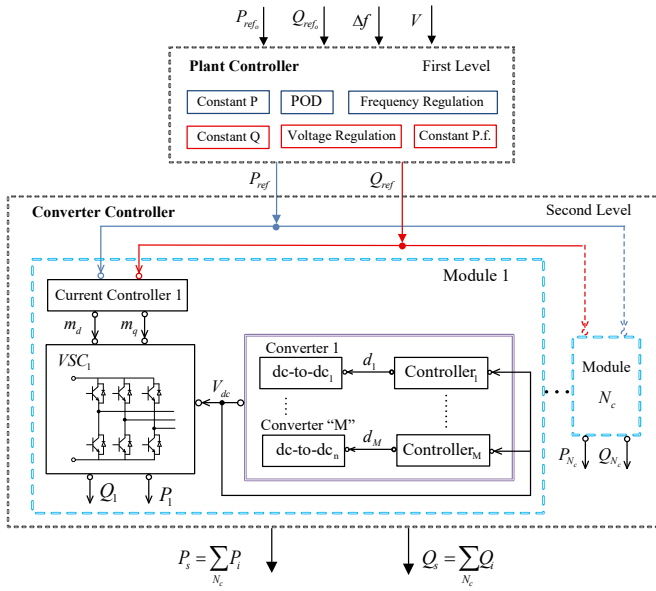


Fig. 10. Two-level hierarchical control of BESS [50].

model, is the so-called WECC BESS model [51]. It comprises three modules: energy converter model (REGC_A), electrical control model (REEC_C), and plant controller (REPC_A). The current control for the VSC is modeled in the REPC_A, which allows the BESS to provide frequency regulation, constant PQ control, constant power factor control, and voltage regulation with droop. Also, a current control limiter is incorporated in REPC_A, which prevents the BESS from operating overloaded

by limiting the current that can be drawn from the VSC, whereas an SoC logic control limits the current if the battery is completely charged or discharged. In [52], modules REGC_A, REEC_C, and REPC_A are updated with more accurate modules REGC_C, REEC_D, and REPC_C, respectively.

2) CAES: A general scheme of the control system for a diabatic CAES in presented in Fig. 11, based on [45]. The active power control in the turbine is achieved by varying the air flow, using a valve whose cross-sectional area is represented by λ , i.e., when $\lambda=1$ the valve is fully open, and when $\lambda=0$ the valve is fully closed. The temperature in the burners is regulated by adjusting the amount of fuel injected into the fuel flow system y , aiming to keep the expansion temperature constant and thus increase the system efficiency.

The Inlet Guide Vanes (IGVs) of the first compression stage can be used to regulate the air flow through the compressor, and thus its mechanical power. Additional control systems are necessary to prevent compressor surge and regulate the output pressure by limiting the air flow. As in other storage technologies, an SoC limit control can be used to track the SoC, which in CAES is directly related to the cavern pressure. Finally, when considering two independent machines, a coordinated droop-based control would allow CAES to provide frequency regulation, reactive power with its two synchronous machines (motor and generator) connected at the same bus, while distributing the active and reactive power between the machines as a function of their loading.

3) FESS: The grid-side VSC can be controlled to regulate the PCC voltage and the dc-side voltage by independently controlling the reactive and active power injected, which can

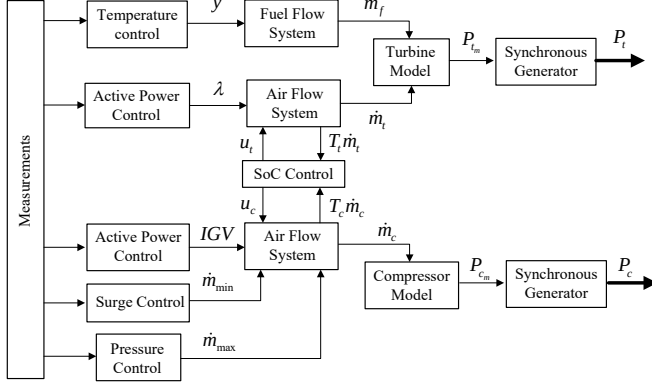


Fig. 11. CAES control system architecture [30].

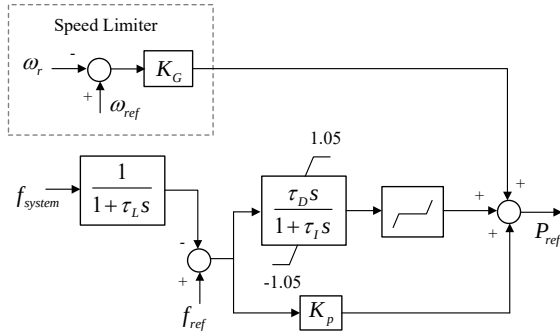


Fig. 12. FESS speed control [53].

be achieved with a decoupled dq current controller, as in BESS, and depicted in Fig. 9. On the other hand, the flywheel side converter can be controlled to regulate the active power exchanged with the flywheel, as well as the IM terminal voltage. The speed control for the IM side converter control limits the maximum and minimum rotational speed of the flywheel, thus its SoC, and allows the provision of frequency regulation by a PID controller [39], which uses the measured system frequency f_{sys} as input, as illustrated in Fig. 12. The output of this controller is the power reference P_{ref} in Fig. 9, which is then compared to a calculated active power, based on I_{dc} and V_{dc} , and the error passed through a PI regulator that yields the $I_{d_{ref1}}$ fed to the current controller. On the other hand, the measured IM terminal voltage can be used in a PI-based voltage controller, which yields $I_{q_{ref1}}$. In the grid side converter, the measured dc link is compared to a reference value and the error is passed through a PI controller (V_{dc} controller), which yields $I_{d_{ref2}}$, while the terminal voltage at the PCC is regulated by another PI (voltage controller) that controls I_{q2} .

Another common control strategy for the IM side converter VSC₁ is the flux-oriented control, in which the d-q reference frame is locked to the rotor-flux, i.e., $\psi_{r_q} = 0$, thus allowing independent rotor flux and torque control, by controlling I_{d1}

and I_{q1} respectively, given as follows [54], [55]:

$$I_{q_{ref1}} = \frac{\mathcal{T}_{ref} L_r}{M \psi_{ref}} \quad (32)$$

$$\psi_{ref} = \frac{P_e L_r}{M I_{q_{max1}}} \quad (33)$$

$$I_{d_{ref1}} = h(\psi_{ref} - \psi_{rd}) \quad (34)$$

where the reference current $I_{q_{ref1}}$ is a function of the desired torque flux ψ_{ref} ; $\mathcal{T}_{ref}$ is the electromagnetic torque; M is the mutual inductance; L_r is the rotor inductance; P_e is the electrical power; and the reference current $I_{d_{ref1}}$ is obtained as output of a controller represented by the function h , which has the rotor flux error ψ_{rd} as input. These reference currents are then passed through current controllers, which ultimately define the modulating signals to control the switches of the IM-side VSC.

4) TESS: The control strategies for TESS involve regulating the heat injections to the thermal storage element to achieve a desired objective. For example, the power exchanged with the electrical grid by a GSHP can be controlled to provide frequency regulation by switching its compressor on/off, while satisfying the thermal needs of the house [38].

In a MG, on the other hand, where multiple independent heat sources may be available such as solar collectors, boilers, or heat as sub product of other processes (e.g., the remnant heat from thermal generators), an Energy Management System (EMS) can be developed to coordinate the operation of all these energy resources. For example, for the MG depicted in Fig. 13 the discrete-time version of (24), which models the storage tank, can be expressed as follows [36]:

$$m_s c_w \left(\frac{T_{s,t} - T_{s,t-1}}{3600 \Delta t_t} \right) = \dot{Q}_{s,t}^{in} - \dot{Q}_{s,t}^{out} - \dot{Q}_t^L \quad (35)$$

$$\dot{Q}_{s,t}^{in} = \sum_{g \in G} \dot{Q}_{g,t}^u + \sum_{j \in J} \dot{Q}_{j,t}^B \quad (36)$$

where t is a time step index; T_s is the water temperature; m_s mass of the water in TSS; c_w water specific heat; Δt_t is the time interval between t and $t + 1$; $\dot{Q}_{s,t}^{in}$ and $\dot{Q}_{s,t}^{out}$ are the thermal power injected and extracted from the tank at period t , respectively; $\dot{Q}_{g,t}^u$ is the usable heat power produced in the generator g ; $\dot{Q}_{j,t}^B$ is thermal power from boiler j ; and $\dot{Q}_t^L$ is the thermal losses of the TESS. This model can be readily integrated in an EMS to keep track of the thermal storage element, also defining temperature limits for its safe operation, i.e., $T_s^{\min} \leq T_{s,t} \leq T_s^{\max}$. Note that $\dot{Q}_{s,t}^{in}$ in (36) can be modified to include the heat from other sources, such as solar collectors, while $\dot{Q}_{s,t}^{out}$ depends on the objective sought by the EMS, such as to control the import/export from the main grid, minimize losses, maximize the use of renewables, minimize fuel costs, among others [37]. Furthermore, an EMS such as the one depicted in Fig. 13 could improve the efficiency of the MG energy supply, considering that remnant heat from Combined Heat and Power (CHP) units, TESSs, or boilers can be used to supply the heating/cooling needs, thus replacing A/C or grid-connected HPs when it is economical to do so.

If a GSHP supplies a part of the thermal demand of a building in a MG, the heat power injected, $\dot{Q}_{HP}$, if it operates

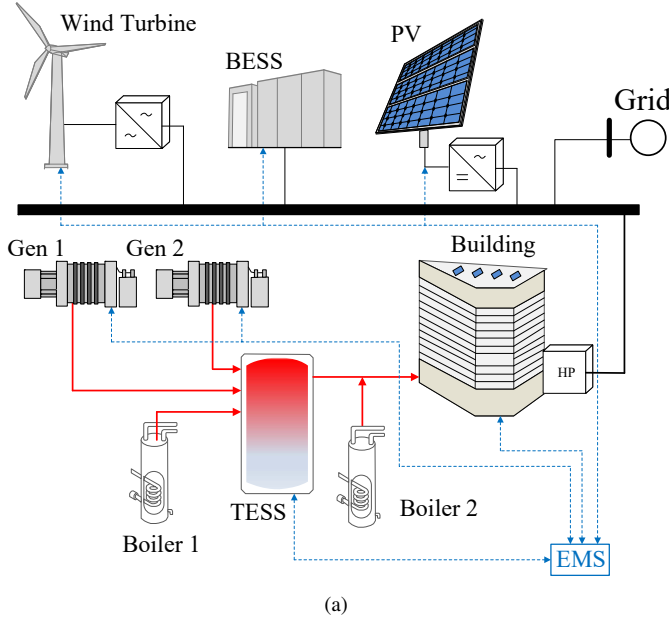


Fig. 13. A typical microgrid configuration with (a) hot water based TESS and (b) its corresponding EMS [36].

in heating mode, can be modeled based on its COP , and (24) and (30), given as follows [39]:

$$\dot{Q}_{HP} = c_w \dot{m}_w (T_{w,t}^{in} - T_{w,t}^{out}) + P_{c,t} COP \quad (37)$$

where $T_{w,t}^{in}$ and $T_{w,t}^{out}$ are the inlet and outlet water temperatures in the borehole terminals at period t , respectively, $\dot{m}_w$ mass of water, and $P_{c,t}$ is the power consumed by the heat pump. The first term in (37) represents the heat obtained from the borehole whereas the second is the heat added by the compressor.

C. Aggregated Models

Existing computing capabilities can handle large and complex models and simulations with relative ease, which was not possible in the past; however, detailed modeling of distribution systems connected to transmission systems is still computationally challenging. On the other hand, the trend in ESS, particularly BESS and TESS, indicates that many new deployments will be at the distribution level, rather than large

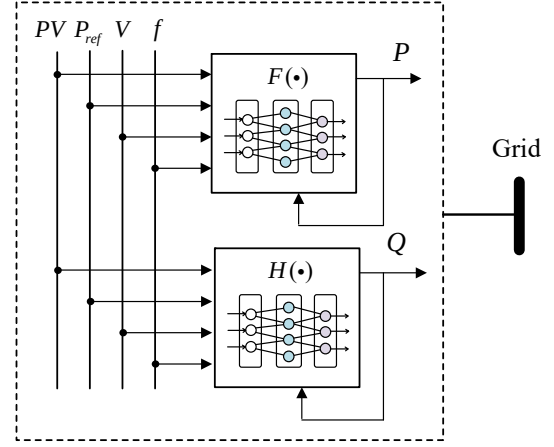


Fig. 14. Black-box aggregated model of BESS [56].

utility-scale ESS at the transmission level. Hence, aggregation of ESSs is an important topic to consider when modeling and simulating power systems. Aggregation of DERs typically involves developing gray-box or black-box models, which can either represent a portion of the power grid, or the aggregated response at the aggregating point of a group of DERs. However, black-box models are more advantageous than gray-box models in that the former do not require knowledge of the grid topology or its components, and are capable of representing highly nonlinear behaviour; nevertheless, these are data-intensive models that require a training stage. For example, in Fig. 14, a Neural Network (NN) based black-box model to aggregate the BESSs in ADNs is depicted. This model, which comprises a NN for the aggregated BESS P injections at the boundary bus between the ADN and the transmission system, and another for Q , assumes that the BESSs are controlled to provide upstream grid services such as frequency regulation, local voltage regulation and Oscillation Damping (OD). This model aggregates the active and reactive BESS power injections P and Q , respectively, using two Nonlinear Autoregressive Exogenous (NARX) NNs. These NNs can be trained with simulation or measurement data of V , f and PV at the boundary bus, with the latter being proportional to the solar irradiance, thus allowing capturing the effects of distributed PV generation on the BESS response; plus the external control signals P_{ref} that directly modifies the BESS set points. The topology of the black-box model, i.e., number of neurons per hidden layer, is obtained as the solution of an optimization procedure that seeks to minimize the validation error of the model with respect to measurements obtained for some contingencies using a Genetic Algorithm (GA) [56].

D. ESS for Frequency Regulation in Large Power Systems

Power systems require a continuous balance between generation and load to safely operate without any mismatch causing the system frequency to deviate from its nominal value and affecting some frequency-sensitive loads such as motors. The generation-load unbalance is especially damaging for thermal units such as steam units, whose mechanical components can

suffer excessive cumulative stress when their turbines operate at frequencies different from the nominal, requiring special protection equipment that may trip these units, and this result in system stability problems. The control actions performed by generating units to adjust their output power in response to frequency deviations is called frequency regulation.

After a disturbance, most generating units automatically adjust their output power through a local proportional controller that receives a speed deviation feedback, known as Primary Frequency Control (PFC), whose objective is to stabilize the system frequency at a value different from the nominal, with all units contributing in proportion to their governor droop rates. Some generators, which operate in Automatic Generation Control (AGC), receive signals from the Independent System Operator (ISO) to further adjust their power references to bring the system frequency back to its nominal value, which is referred to as Secondary Frequency Control (SFC). In large interconnected power systems, generation-load mismatches could also affect the scheduled power flows through the tie lines. Thus, a special control signal synthesized from the deviations in tie line flow and frequency, known as Area Control Error (ACE) is determined by the ISO and fed to the units on AGC, aiming to keep the ACE within acceptable limits.

In Ontario, Canada, the Independent Electricity System Operator (IESO) has contracts with hydro and gas units, and ESSs to provide regulation services, for a minimum of ± 100 MW at a ramp rate of ± 50 MW/min every hour [57]. In 2012, ESS participation was procured under the IESO's Alternate Technologies for Regulation (ATR) initiative, which contracted a total of 6 MW of storage in two projects: BESS and FESS. Later, in 2014, a competitive energy storage procurement framework expanded this capacity by another 50 MW, including CAES. Most of these storage units receive regulation signals by the IESO, which they must follow.

A model to study the frequency regulation, considering the participation of fast ESS units such as BESS and FESS, is depicted in Fig.15 [58]. Such a model allows performing long term frequency studies and helps in tuning the ACE calculation and filtering without the need of modeling the entire electrical grid. The model is divided into seven stages. Stage I corresponds to the ACE block which compares the actual and scheduled power in the interconnection NI_a and NI_s , respectively, and the actual and scheduled system frequency f_a and f_s , respectively, to calculate the ACE signal sent to the Traditional Generators (TGs) contracted for regulation and a signal SR_{ESS} sent to the ESSs, based on the bias factor B . The complementary signals IME and IP representing metering errors and inadvertent payback, respectively, adjust the ACE. Stage II filters out fast ACE changes before being sent to the TGs, and Stage III models the AGC, which is a PI controller with anti-windup, a rate limiter (e.g., ± 50 MW/min in Ontario), and a saturation block to limit the regulation capacity (e.g., ± 100 MW in Ontario). Stage IV models the aggregated TG response, Stage V calculates the ESS set-points based on the SR_{ESS} signal, and Stage VI models the ESS. Finally, Stage VII corresponds to a model of the primary frequency response of the system, which considers

the load of the system, generation total dispatch, and outputs of the TGs and ESSs contracted for frequency regulation. One major challenge faced by large interconnected systems, such as the Ontario system, is the communication delays between the IESO and the regulating facilities, represented by the blocks CD in the figure. These delays can significantly impact the performance of the system frequency regulation, particularly worsening the ACE signal if they are not properly accounted for.

A further improvement of the model in Fig. 15 consists of replacing Stage II and Stage III by a filter, to split the ACE signal into a fast component ($SREG_D$), which is sent to fast-response units such as BESS or FESS, and slower component ($SREG_A$), sent to slower assets such as TGs or CAES. Also, Stage V can be modified to take advantage of the fast $SREG_D$ signal when defining the operating point of the ESSs [59].

E. Behind-the-meter CAES

For small-scale CAES owned by customers and connected behind-their meter, the system operation model proposed in [60] minimizes the electricity cost and CAES operation cost of the customer. The optimization problem considers a given small-scale CAES facility to determine its optimal charging/discharging decisions and energy purchase/consumption schedules of the customer. In the model, the base case cost of the customer considers an energy cost and demand charges, i.e., the Global Adjustment (GAD) in Ontario. Particularly, the CAES is arranged to shave the demand during the top 5 Ontario peak load hours, referred to as 5 coincident peak (or 5 cp) hours, and also to reduce the energy drawn from the grid. The CAES power/energy rating is considered feasible if the total cost of the customer with CAES is lower than its total cost without CAES, given by:

$$TC^{NoCAES} = EC^{NoCAES} + GAD^{NoCAES} \quad (38)$$

where EC^{NoCAES} is the cost of energy consumed by the customer over 1 year at the corresponding energy price. The component GAD^{NoCAES} considers the customer's contribution to the 5 cp hours. On the other hand, the total annual electricity bill savings obtained by deploying the CAES facility is determined using the optimization model to minimize the total annual cost of the customer, given by:

$$TC^{CAES} = EC^{CAES} + GAD^{CAES} + SVOMC + SFOMC \quad (39)$$

where the Variable Operation and Maintenance (O&M) Cost ($VOMC$) during charging/discharging operation of the CAES facility is represented by $SVOMC$, and the Annual Fixed O&M Cost ($FOMC$) per year is given by $SFOMC$. According to [60], an appropriate general starting point for the $FOMC$ is between 1% and 1.5% of the capital cost.

F. Ground Source Heat Pump

A thermal load aggregation approach to minimize an aggregator's energy procurement cost is proposed in [39], [61]. This model considers the GSHP characteristics to optimize

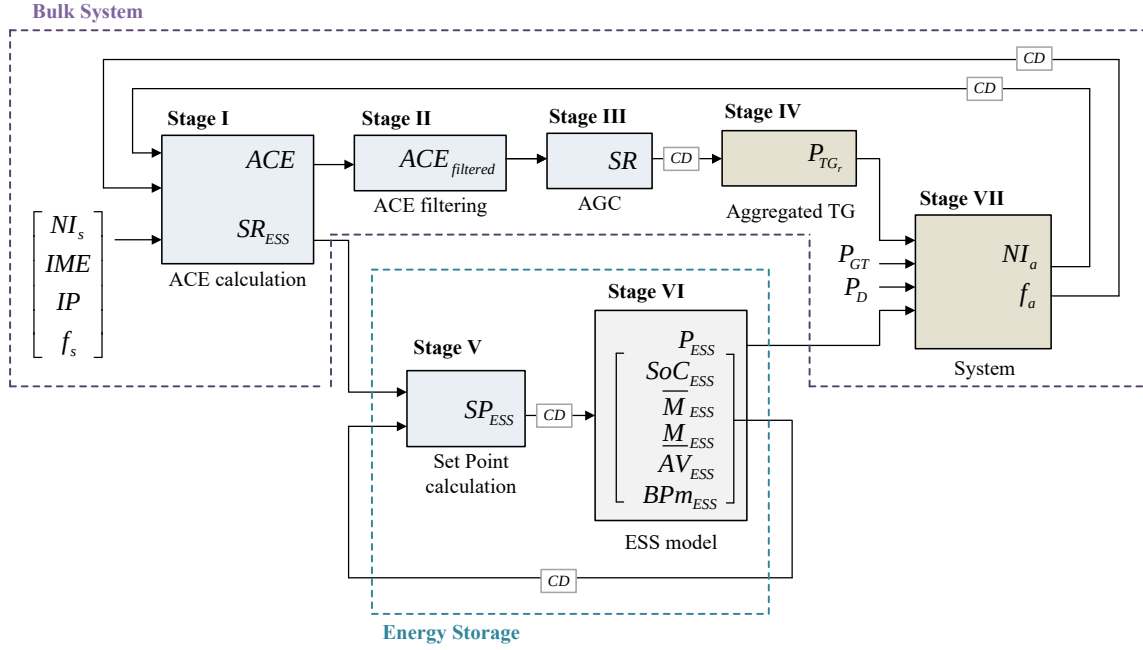


Fig. 15. Frequency response model of large interconnected power systems with ESS [58].

the electricity usage by end-users while considering household thermal comfort. The model aggregates the information of the uncontrolled loads in the house, the house thermal and heating system characteristics, and the current and forecasted ambient temperatures, which are used to optimally schedule the heating load of each house in order to minimize its total electricity cost. Two stages for the purchase of energy are considered, i.e., Day-Ahead (DA) and Real-Time (RT) markets.

In the first DA stage, the aggregator participates considering a forecasted market price for the next day λ_t^{DA} , while minimizing the following total electricity cost to determine the thermal load of the house that satisfies a required in-house temperature comfort range:

$$J_1 = \sum_t^T \lambda_t^{DA} P_t^{DA} \quad (40)$$

Accordingly, hourly demand bids are submitted to the wholesale electricity market to serve the scheduled load for 24 hours of the next day. In the RT stage, the aggregator's objective is to minimize the penalty payable for any deviations in RT load dispatch from the day-ahead dispatch, at the real-time market price, defined by:

$$J_2 = \sum_t^T \lambda_t^{RT} |P_t^{DA*} - P_t^{RT}| \quad (41)$$

Both market models contemplate constraints related to the total load that the aggregator will procure at a specific hour, thermal power consumption, in-house temperature levels for an end-user's comfort range, cycling constraints, power consumption of the GSHP, and in-house and external wall temperatures.

G. Integration of ESS in Electricity Markets

Market participation models for ESS must consider their special operational characteristics that differentiate them from other market participants loads and generators, such as, the ability to charge/discharge, fast ramp rates, cycling limitations, and their energy and power dependency. These aspects need to be properly reflected in the cost structure of the ESSs and hence in their bids/offers; consequently, operational models for each specific ESS technology are needed. Likewise, the market structure should be adapted to allow participation of ESSs in the wholesale energy market, capacity market, and ancillary service market in a fair and competitive manner, with the latter being particularly relevant for fast-response ESSs, such as BESSs and FESSs. For example, in the USA, the New York ISO (NYISO), PJM, California ISO (CAISO) and ISO New England have already implemented some market design changes to allow ESS participation to comply with FERC Order 841 [62]. Depending on the ESS capacity compared to the overall system, its participation strategy may change, operating as a price-taker if small, or as a price-maker if large.

In North America, motivated by the FERC Orders 841 and 755 [63], [64], some ISOs and Regional Transmission Organizations (RTOs) have implemented a mechanism that remunerates market participants that provide frequency regulation services, based on their performance and considering [65]: the capacity that they can offer at a given period; the "mileage", defined as the sum of the absolute value of the regulation signal they have to follow over a given period; and a performance factor, which measures how close the facility follows the regulation signal. This mechanism aims to promote the participation of fast regulation assets, such as ESSs, which are characterized for having large ramping rates and very fast response. To further incentivise ESSs participation, some

markets have split the regulation signal into fast and slow, with the former receiving a higher compensation for being followed.

In the existing market frameworks that allow ESSs, particularly BESS, to participate, the bids/offers do not explicitly represent degradation, discharge rates or SoC; however, BESS operational costs including degradation costs based on their depth of discharge and discharge rate should be taken into account [62]. In such markets, BESS can participate in electricity markets as loads or generators, being able to submit bids to charge and offers to discharge, while reflecting their marginal operating costs. BESS may also participate in reserve markets by providing its capacity in the form of a discharge offer. In such market model, the operation cost of a BESS is comprised of the following components:

- A degradation cost based on Depth of Discharge (DoD) and discharge rate. A relevant aspect in this cost is considering into the DoD the impact of SoC starting and ending levels. To model this, the ISO-monitored energy level should be considered, where the SoC and lower/upper storage limits of the ESS are available to the ISO, to ensure that the facility's schedules in the day-ahead and real-time markets are feasible within their operating limits.
- High charging and discharging currents expressed by the discharge rate of a battery, as these contribute to BESS degradation.

Therefore, the BESS operational cost that can be integrated into a market model is based on the DoD and discharge rate of the facility. A second component of the cost is related to the spinning reserve capability in the spinning reserve market. The opportunity cost of not participating in energy-only markets can be attributed to the spinning reserve cost of BESS, which could be determined as the difference in revenue earning from the participation in an energy-only market, and in a co-optimized energy and spinning reserve market.

A framework and mathematical model for BESS participation in a Locational Marginal Price (LMP) based, co-optimized energy and spinning reserve market are presented in [62]. The objective is to maximize the social welfare, which includes the gross surplus of customers and BESS during charging, the total cost of generators including the generator start-up cost and shut-down cost, the cost of spinning reserve provisions from generators, and the cost of BESS for energy provisions during discharging, accounting for degradation based on DoD and discharge rate, and spinning reserve provision from the BESS during discharging.

A price-taker ESS facility participating in a day-ahead market providing energy, spinning and idling reserves, i.e., $Y := \{E, SR, ID\}$, is able to operate in different modes $X := \{C, D, SRC, SRD, ID\}$, i.e., charging C or discharging D in the energy market, charging and discharging in the spinning reserve market SRC and SRD , respectively, and operating in idling mode ID . In this context, the owner seeks

to maximize its profit $\mathcal{F}$ as follows [66]:

$$\max_{P_t^X} \mathcal{F} = \sum_t^\tau \left(\sum_{X \in \mathcal{M} \setminus C} \phi_t^Y P_t^X - \phi_t^E P_t^C - OC_t \right) \quad (42)$$

where ϕ_t^Y is the hourly price of the market Y ; P_t^X is the ESS power for mode X ; and OC_t is the operational cost of the ESS, which includes variable operational and maintenance costs, and other costs specific to certain ESS technologies (e.g., fuel costs for CAES [66], or degradation costs for BESS [62]). This is subject to the following operational constraints:

$$P_t^C \leq \bar{P}^C x_t^C \quad (43)$$

$$\underline{P}_X^C x_t^C \leq P_t^C - P_t^{SRC} \quad (44)$$

$$P_t^D + P_t^{SRD} \leq \bar{P}^D x_t^D \quad (45)$$

$$\underline{P}_X^D x_t^D \leq P_t^D \quad (46)$$

$$0 \leq P^{ID} \leq QSC [1 - (x_t^C + x_t^D)] \quad (47)$$

$$x_t^C + x_t^D \leq 1 \quad (48)$$

where x_t^C and x_t^D are binary variables at time t , which are equal to 1 when the ESS charges or discharges, respectively; QSC is the quick start capacity of the ESS; and the parameters with bars above and below represent the ESS's maximum and minimum power P capacities in its different operating model X , respectively. Note that (48) prevents the ESS facility from simultaneously charging and discharging, and thus could be eliminated if, for instance, an ESS such as the CAES with such capability is considered. Furthermore, ESS are limited by their SOC, which requires adding dynamic constraints to the model as follows [66]:

$$SOC_{t+1} = SOC_t + P_t^C \eta^C - P_t^D / \eta^D \quad (49)$$

$$\underline{SOC} \leq SOC_t \leq \overline{SOC} \quad (50)$$

where η^C and η^D are the charging and discharging efficiency of the ESS, respectively. Even though (49) works relatively well for most ESSs, some technologies require more complex nonlinear relations that describe the conversion of electricity into another energy form to be stored. For example, the SoC for CAES can be expressed as a function of the mass flow rates as follows:

$$SOC_{t+1} = SOC_t + \frac{3,600 P_t^C AFR^C(SOC_t)}{\bar{CA}} - \frac{3,600 P_t^D AFR^D(P_t^D)}{\bar{CA}} \quad (51)$$

where AFR_t^C and AFR_t^D are the charging and discharging air flow rates, which are functions of SOC_t and P_t^D , respectively, and $\bar{CA}$ is the cavern's air mass when it is fully charged.

To account for uncertainties, prices ϕ_t^Y in the different markets Y can be expressed based on a forecasted center value $\phi_{o,t}^Y$ and a price deviation $\Delta\phi_t^Y$, as follows [66]:

$$\phi_t^Y = \phi_{o,t}^Y (1 + \Delta\phi_t^Y) \quad (52)$$

$$\Delta\phi_t^Y = \Delta\phi_t^{Y+} - \Delta\phi_t^{Y-} \quad (53)$$

where $\Delta\phi_t^{Y+}$ and $\Delta\phi_t^{Y-}$ are upward and downward price deviations. By substituting (52) and (53) in (42), the objective

function becomes a function of the price deviations $\Delta\phi_t^Y$, assuming the forecasted values $\phi_{0,t}^Y$ are known. Thus, a Robust Optimization (RO) approach, which seeks to maximize the profit and minimize the price deviation, can be used to solve the problem, with the following additional constraints:

$$0 \leq \Delta\phi_t^{Y+}; \Delta\phi_t^{Y-} \leq \overline{\Delta\phi} \quad (54)$$

$$\sum_t \frac{\Delta\phi_t^{Y+} + \Delta\phi_t^{Y-}}{\overline{\Delta\phi}} - \Gamma \leq 0 \quad (55)$$

where $\overline{\Delta\phi}$ is the maximum price mismatch, and Γ , known as the budget of uncertainty, limits the number of times the prices deviates from the forecast value, thus allowing to adjust the conservatism level of the price uncertainty.

Another approach to incorporate uncertainty in the model is Affine Arithmetic (AA). In this case, the uncertain price is expressed as follows [66]:

$$\hat{\phi}_t^Y = \phi_{0,t}^Y(1 + \varepsilon_t^Y \overline{\Delta\phi}) \quad (56)$$

where $\phi_{0,t}^Y$ is the center value of the price, and $\varepsilon_t^Y \in [-1, 1]$ and $\overline{\Delta\phi}$ are the noise term and magnitude of the uncertain price component, respectively. This approach requires that all model variables are expressed in their affine forms, sharing the same noise variables. This problem can be solved by maximizing the center and radius of the objective function, which has to be also expressed in its affine form, separately or simultaneously, if binary and inter-temporal variables are considered in the model. A price-maker model for ESSs participating in electricity markets is discussed in [62].

IV. ESS APPLICATIONS AND CASE STUDIES

In this section, the most common ESS applications for transmission and distribution grids, and MGs are illustrated through simulations based on the ESS models, controls, and EMSs, discussed in the previous section, and focusing on results obtained for test benchmark systems.

A. Frequency Regulation

Fast-response ESSs such as BESS or FESS can significantly improve the system frequency regulation, either by following the regulation signals from the ISO in a centralized approach, or acting independently based on local decentralized controls. Furthermore, given the distributed characteristics of the ESS assets, regulation services based on properly coordinated local measurements can help address the issue of communication delays associated with a centralized approach.

1) *WSCC 9-bus Test System*: The effectiveness of a grid-scale and distributed BESS connected to a transmission systems to provide frequency regulation was studied on the WSCC 9-bus test system depicted in Fig. 16 [56], [67]. Topology A corresponds to a bulk 45 MW BESS connected at Bus 5, and Topology B represents groups of three 1.5 MW BESSs connected at each load bus, with the latter corresponding to around 2.4% of the system installed capacity and 4% of the total system load [41]. In both topologies, the BESSs were configured to provide PFC and SFC based on local

frequency measurements, while the three generators in the system provide PFC only. Fig. 18 shows the system frequency fluctuations for 20 MW generation outage in Topology A. In this case, the following four BESS models were compared:

- **Complete**: Considers the VSC, dc-to-dc converter, battery bank and their controls.
- **Simplified**: Neglects the dc-to-dc converter and battery bank, models the VSC dc-link as a constant source.
- **WECC**: A widely used BESS model in academia and industry.
- **Degraded**: Similar to the Complete model but the batteries are assumed to be degraded, i.e., lower internal voltage and larger internal resistance are used.

Note that the BESS rapidly restores the frequency back to its nominal after the disturbance when providing SFC, while the frequency stabilizes at a different value with PFC only, which depends on the droop gain used in the frequency controller. Observe that when batteries are degraded, the frequency regulation performance is significantly affected because the BESS control system limits its active power injections. When the WECC model was used, the system frequency experienced a larger initial deviation.

Fast acting ESSs, such as BESSs, can be used to damp low frequency system oscillations by injecting active power in phase with the target undamped system frequency component; i.e., $-\Delta f_{osc}$, due to oscillating generators. Thus, an ADN is connected to Bus 5 of the WSCC 9-bus benchmark system through a step-up transformer, in Topology B in Fig. 16. In the ADN, a high penetration of PV generation is assumed, with ESS capacity spread across the distribution system, i.e., small units at households and larger units all aggregated at the MV level, corresponding to an equivalent 1.5 MVA PV and 1.5 MVA / 2 MWh BESS at each of the 14 buses of the ADN, as depicted in Fig. 16; simplified models for the loads and PV generation are used. A short circuit is applied at Bus 8 at $t = 3s$, and then removed after 50 ms, while all BESSs are operating in OD mode, for both the full ADN model and its aggregated model, while all the generator Power System Stabilizer (PSS)s are disabled. In this case, it is shown in Fig. 19 that proper control of distributed BESSs can help to damp the low frequency oscillations at the transmission level even in this small-scale BESS scenario, and that the aggregated model based on neural networks for P and Q injections of the ADN, i.e., NN-P and NN-Q, respectively, are able to properly represent the aggregated BESS response.

2) *CAES*: In order to assess the benefits of ESSs adding physical inertia, a CAES system providing frequency regulation in the test system depicted in Fig. 17, in which 30% of its demand is supplied by a wind farm, was studied in [30]. The performance of the CAES system was compared to an equivalent Gas Turbine (GT), with the former operating both in discharging mode, and in simultaneous charging/discharging modes. Observe in Fig. 20 that the CAES system is more effective than the GT in regulating the system frequency, reducing the number of excursions beyond the allowed limits and the frequency deviations. Note also that the simultaneous charging and discharging mode yields the best results, further

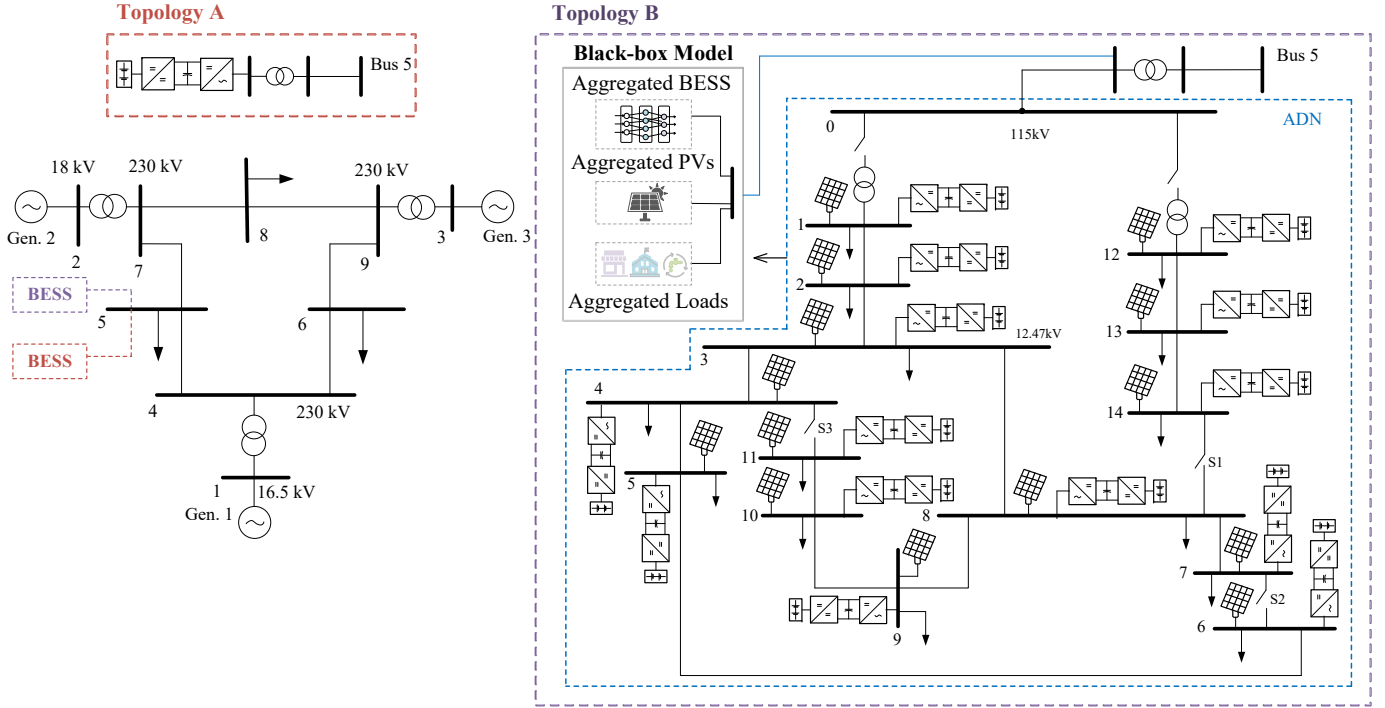


Fig. 16. Modified WSCC 9-bus test system for ESS grid studies.

reducing the frequency deviations, mainly due to the inertia added by the compressor.

3) *FESS*: Another effective ESS technology for frequency regulation is FESS. To demonstrate its frequency regulation capability, simulations were performed for a 10 MVA FESS connected to a test system comprising a 10 MVA wind farm and 30 MVA traditional generator supplying a 28.5 MW load, illustrated in Fig. 21 [53]. Fig. 22 presents a comparison of system frequency when it is regulated by the FESS, with a base case when regulation is provided only by the traditional generating unit. Given the large size of the wind farm, the system frequency deviations are significant in the base case; however, when the FESS regulates the frequency, the deviations are practically eliminated.

4) *ESSs in the Ontario Power System*: Each component of the model in Fig. 15 was validated in [58] using information provided by the IESO, which included a detailed dynamic model of the North American Eastern Interconnection, and one year of data from the Ontario Power System and an FESS and BESS currently providing frequency regulation in Ontario. Since the data from two ESS facilities are included, the actual implementation of the model in Fig. 15 includes two sets of ESS blocks Stage V and VI, one pair for a FESS and the other for a BESS. A statistical comparison between the actual data and simulation results for the FESS and BESS is summarized in Table II for 6 of the 21 signals presented in Fig. 15, for a one day period (July 14, 2018) with one second resolution. Note that both the mean and standard deviations for each signal of the model are very similar, which implies that the model is capable of accurately replicating the behaviour of actual components for the entire simulation period. Further detailed validation results for longer periods of time, up to one year,

TABLE II
VALIDATION OF FREQUENCY REGULATION MODEL FOR ONTARIO (FIG. 15).

Stage and Output	Actual Data		Model Results	
	Mean [MW]	σ [MW]	Mean [MW]	σ [MW]
I ACE	32.61	80.79	32.01	80.86
II $ACE_{filtered}$	19.85	79.6	19.96	81.64
III SR	-30.39	78.73	-35.88	80.68
IV P_{TGr}	-30.40	75.73	-29.05	75.36
V SP_{FESS}	-0.1277	0.5945	-0.129	0.5653
VI P_{FESS}	-0.118	0.585	-0.120	0.565

can be found in [58].

5) *Microgrids*: The Xeni Gwet'in First Nation community of Nemiah Valley in British Columbia, which is a battery-free PV-diesel off-grid network, was used as the test MG to investigate the feasibility of using Thermostatically Controllable Loads (TCLs) such as Electric Water Heaters (EWH), A/Cs and GSHPs to help regulate the frequency of the MG [38]. The MG comprises a commercial complex and a residential zone with 22 houses, whose demand is supplied by two 95 kW diesel gensets, operated one at the time, and a 30 kW genset that operates during weeknights and weekends. In addition, PV generation is available in some of the houses, as depicted in Fig. 23.

The MG frequency is defined based on the operating range of the 95 kW gensets, i.e., within 30% and 90% efficiency, which corresponds to frequency limits of $f_{max} = 61.37$ Hz and $f_{min} = 60.33$ Hz. Thus, a control logic that operates the EWH, A/C and GSHP, available in all houses (except three), changes their temperature set-points in proportion to the system frequency deviation, such that they are turned on

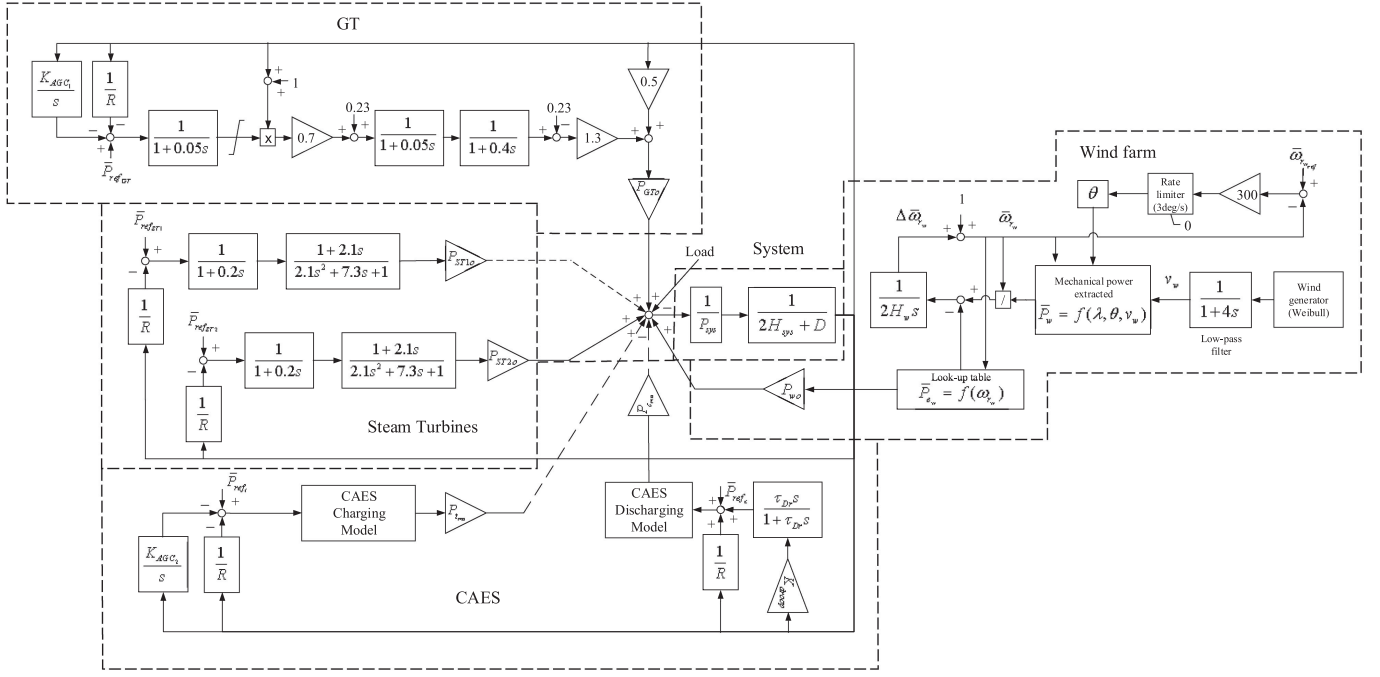


Fig. 17. System configuration for frequency regulation studies with CAES [30].

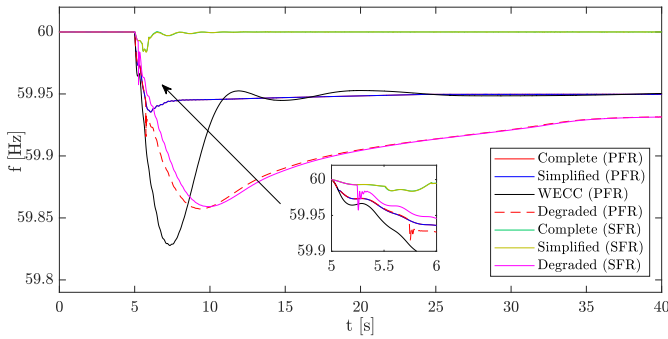


Fig. 18. System frequency for lumped BESS Topology A.

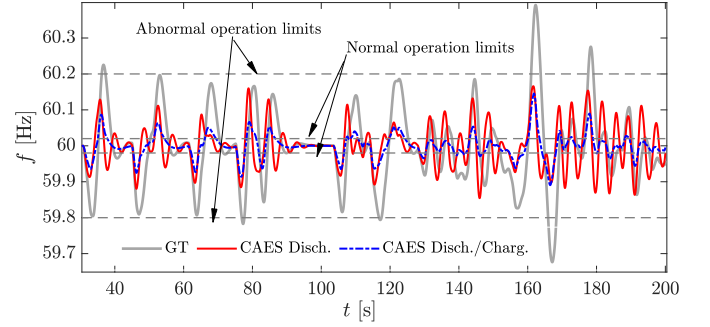


Fig. 20. Frequency regulation by CAES [30].

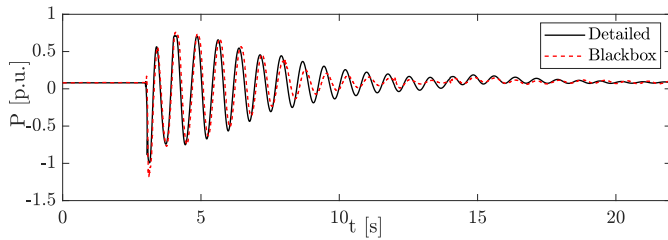


Fig. 19. Active power injections for Topology B.

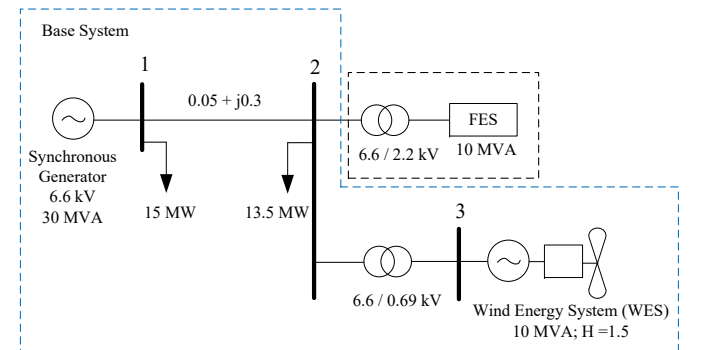


Fig. 21. Test system configuration [53].

if the MG frequency is too high, and turned off if the frequency is too low. This decentralized control architecture, which acts in addition to the genset's droop-based control, avoids the need of communication between the TCL and a MG's EMS, measuring the system frequency locally. The results of time domain simulations for 4 cases considered are presented in Table III [38]. Comparing the length of time the system frequency exceeds limits in Case 1 (no TLC control) with

the other cases, observe that TLC control can significantly improve the system frequency regulation, particularly when A/C (Case 3) and GSHP (Case 4) are used; the latter also presents the lowest fuel consumption and lowest frequency standard deviation σ .

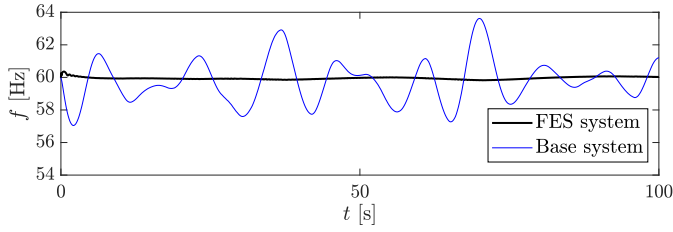


Fig. 22. Frequency regulation by FESS [53]

TABLE III
FREQUENCY REGULATION FOR NEMIAH VALLEY'S TEST MG.

		Cases			
		1	2	3	4
TCL		None	EWB	EWB & A/C	EWB & GSHP
Frequency	$f_{\max}$ [Hz]	61.98	61.57	61.62	61.57
	$f_{\min}$ [Hz]	59.83	60.20	60.33	60.35
	σ [Hz]	0.447	0.255	0.251	0.244
Power	$P_{\max}$ [kW]	72.77	60.61	59.45	58.79
	$P_{\min}$ [kW]	11.61	25.50	25.01	23.97
Energy	EWBs [kWh]	174.8	175.3	177.6	178.8
	A/Cs [kWh]	28.91	28.7	27.88	-
	GSHPs [kWh]	-	-	-	18.06
Fuel consumption [l]		207	205	205.2	203.6
Time f exceeds limits [%]		32.22	7.55	4.16	7.15

B. Peak Shaving

Peak shaving refers to the ability of large commercial and industrial customers to reduce their power consumption, particularly during peak hours when energy and demand charges are high. Some common ways in which customers can benefit from peak-shaving includes reducing their consumption, using local generation or installing behind-the-meter ESSs particularly for loads with limited flexibility.

In Ontario, as previously mentioned, electricity customers pay a monthly *GAD* charge, which covers the difference between the Hourly Ontario Energy Price (HOEP) and the regulated rates for some nuclear and hydroelectric generating stations, the cost of building and maintaining new electricity infrastructure, energy contracts, and delivering Ontario's conservation programs [57]. Large electricity customers, referred to as Class A, with an average peak demand above 5 MW, pay the *GAD* based on how much their peak demand use contributes to the top five provincial peaks during a base period (from May 1 to April 30). Hence, avoiding these five peak hours could significantly reduce their energy cost. In fact, nowadays, this is the main electricity cost for Class A customers, outweighing the energy prices by a large margin [68]. The use of a behind-the-meter CAES system to reduce the load demand and energy drawn from the grid by an actual Ontario Class A customer with a peak demand of 14.27 MW was investigated in [60].

The customer has an existing cavern that can be re-purposed for air storage, which reduces the capital cost. Thus, the optimal operation of the CAES system seeking to minimize the customer's total annual cost, i.e., Energy Cost *EnC*, *GAD* Cost *GADC*, and fixed and *VOMC*, was simulated assuming

TABLE IV
CUSTOMER'S ENERGY COSTS FOR DIFFERENT CAES SIZES.

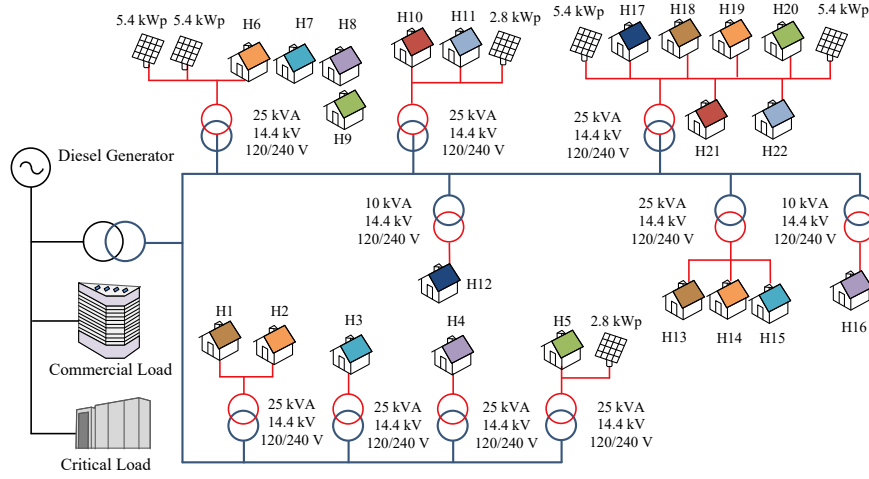
CAES MW/MWh	<i>GAC</i> (\$)	<i>EnG</i> (\$)	<i>OMC</i> (\$)	<i>TC</i> (\$)	Savings (\$)
0	6,671,682	1,053,483	0	7,730,165	0
2/4	5,662,064	989,084	108,274	6,669,424	970,743
4/8	4,652,446	920,447	160,104	5,732,999	1,997,166
6/12	3,642,828	859,172	211,061	4,713,062	3,017,103
8/16	2,633,210	809,065	0260,387	3,702,663	4,027,501
10/20	1,623,592	769,301	308,353	2,701,246	5,028,919

a fixed customer load and known HOEP and *GAD* values for that period. In Table IV, the energy savings for different CAES sizes, including no CAES, are summarized. Note that for CAES systems in the range of 2-10 MW, significant annual savings could be obtained; however, larger CAES sizes require larger initial investments. Hence, the Internal Rate of Return (IRR) of different CAES system sizes in Table IV, considering initial investments in the range of 1,500 \$/kW to 3,000 \$/kW, and assuming the energy cost savings as income, are presented in Fig. 24. Observe that, if a typical Minimum Acceptable Rate of Return (MARR) of 10% is considered, all investment options are reasonable, thus demonstrating that behind-the-meter storage, in particular CAES for the studied customer, would be an economically feasible solution to reduce energy costs.

C. Energy Arbitrage and Ancillary Services

Probably, the most common application for ESSs is energy arbitrage, which entails charging when the price of energy is low, and discharging when the price is high, thus achieving a revenue surplus operation from the price differential. This concept is not restricted to the energy market only, since ESSs could also profit from participating in ancillary services or reserves markets as previously discussed. A notable feature that differentiates ESSs from typical generators is their SoC dependency, which constraints the time intervals when these systems can charge/discharge, thus adding a layer of complexity to their operation. In this case, the model to self-schedule the operation of an ESS acting as price-taker must consider both the physical characteristics of the ESS as well as the main market uncertainties.

Energy arbitrage favors ESSs with large storage capacity. Currently, PH and CAES are the only two economically and technically feasible alternatives for bulk storage [16], [20], [69], with CAES being less restrictive in terms of its location, especially in North America, where abundant geological formations suitable to host underground caverns for air storage are available [70]. BESSs can also be used for arbitrage; however, they may need to provide additional grid services to become economically feasible [17]. For low-energy-density ESSs, such as FESS, arbitrage is less attractive, particularly due to its relatively large self discharge losses [21]. On the other hand, the fast-response, high ramp rates and capability to provide upward and downward response of most ESSs (e.g., CAES, BESS, and FESS) makes these technologies more suitable for ancillary services such as frequency regulation



57

Fig. 23. Nemiah Valley's test MG topology.

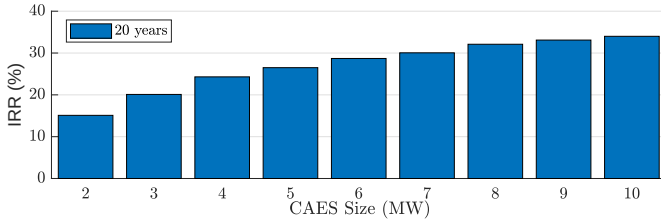


Fig. 24. IRR for different CAES sizes.

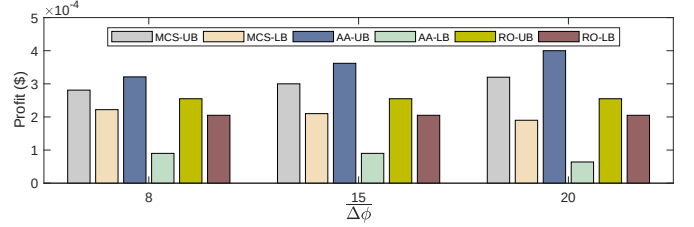


Fig. 25. Profits for a CAES price-taker facility for MCS, AA, and RO methodologies.

reserves. TESSs are mostly used to help optimally supply the local energy needs of buildings (residential, commercial, or industrial); therefore, their most common applications are load leveling and peak shaving, through demand response. Energy arbitrage are less common grid services for TESS; however, these systems may be also used for frequency regulation reserves, as shown in Section IV-A5 and discussed, for example in [23].

1) *CAES*: As an arbitrage and ancillary services applications, a 100 MW charging/60 MW discharging CAES participating in Ontario's energy, spinning reserve, and idle reserve markets was studied in [66]. This facility has a minimum discharging and charging rates of 30 MW and 25 MW respectively, a quick start capacity of 40 MW, and it seeks to maximize its profit for volatile prices. Accordingly, the CAES would discharge or offer its reserve capacity when prices in the respective markets are high, or charge when the prices are low. As highlighted in Section III-G, price uncertainties can be handled using RO, AA or Monte Carlo Simulations (MCS); thus, these three approaches were used to obtain the optimal CAES schedule that maximizes its daily profits. The RO simulations considered a risk-profit trade-off based on combinations of price variations $\Delta\phi \in [8\%, 15\%, 20\%]$ and uncertainty budget $\Gamma \in [0; 5; 10; 15; 20; 24]$, with larger Γ values yielding protection against more conservative results, and higher $\Delta\phi$ values providing more financial protection against large price mismatches, both resulting in lower profits. The AA approach, on the other hand, yields a single optimum

schedule interval based on the $\overline{\Delta\phi}$ value; thus, large $\overline{\Delta\phi}$ values produce large profit radius and center values, and hence larger profit intervals. MCS based on several random prices and uniform probability density functions (pdfs), with the prices varying within the same range $\Delta\phi$, was used for validation purposes.

The CAES's profit upper bounds (UB) and lower bounds (LB) obtained using RO, AA and MC for different values of $\Delta\phi$ are depicted in Fig. 25. Note that as $\Delta\phi$ increases, so do the intervals, which is reasonable, given the wider range of prices. In RO, the upper and lower bounds corresponds to $\Gamma = 0$ (deterministic case) and $\Gamma = 24$ (most conservative case), respectively, while the bounds in the AA case depend directly on $\Delta\phi$. Observe that AA yields the largest intervals for all $\Delta\phi$. Since MCS presents a much larger computational burden than AA or RO, the latter would be preferred to solve the optimal schedule of the plant in a daily basis.

2) *GSHP Aggregation*: The aggregation of residential demand for the participation on a DA and RT electricity markets was studied in [39], [61] for Ontario, using GSHP as an alternative to conventional HVAC systems. In the DA market, the aggregator forecasts the electricity market price and ambient temperature for the next day, and along with information of the uncontrolled loads of the aggregated houses, optimally schedules their individual thermal loads such that their total electricity cost is minimized, while satisfying the houses temperature comfort range. These schedules can be used by the aggregator to submit hourly energy bids to the

TABLE V
AGGREGATOR RESULTS WITH HVAC AND GSHP SYSTEMS

		Cost (\$)		Heating Energy (kWh)	
		HVAC	GSP	HVAC	GSP
Max Comfort		5,700	4,999	68,645	53,655
Min. Cost	DA	4,499	4,576	61,229	52,096
	RT	133	68	65,625	52,096
Total		5,078	4,645		

wholesale market for the next day. For the RT market, the temperature and uncontrolled loads forecasts are updated, and the thermal loads are dispatched in real time to minimize the aggregator's total penalty payable for deviations from the DA dispatch, at a market price that is not affected by the aggregator's decision.

In Table V, the results for the aggregation of 800 houses located in Ontario, on a cold Winter day, are presented for cases in which the aggregator maximizes the customers' comfort or minimizes the households' total electricity costs [39]. This study assumed that people leave their houses at 08:00 and return at 18:00; the house thermostat set-points are kept constant at 22°C during this period to maximize comfort, while these set-points are relaxed when minimizing cost. The study also compared the aggregation when heat is supplied by conventional HVAC units and GSHPs in the houses. Note that the aggregator's total costs and energy consumed based on GSHPs are lower than with HVAC, thus demonstrating that the former would be preferable for space heating.

D. Microgrid EMS

ESSs play a central role in enabling the operation of MGs in stand-alone mode, particularly when relying on intermittent renewable generation such as PV or wind. In fossil fuel based MGs, ESSs can help to decrease fuel consumption by allowing the existing generation to operate at their most efficient operating points, reducing the required installed generation capacity, including back-up generation. Furthermore, MGs can also benefit from TESS to more efficiently supply their thermal demand, including space and water heating.

1) *Kasabonika Lake First Nation (KLFN)*: This is an isolated community located in the Northern Ontario, Canada. Its MG comprises three 10 kW and one 30 kW wind turbines, three gensets of 1.5 MW, 1 MW and 0.6 MW, operated one at a time, and 12.4 MW roof-top PV generation, with a 250 kW PV plant planned at some point. The total peak demand is approximately 850 kW, which corresponds to residential and commercial loads, including a store (STR), school (SCL), police station (PLS), nursery station (NRS), and a water treatment plant (WTP), as depicted in Fig. 26 [37].

A study was carried out to determine the possible use of TESS to supply part of KLFN's estimated heating demand, which is approximately 30% of the total residential electrical demand. Hence, three cases were considered: (I) no TESS, (II) 50%, and (III) 100% of the heating demand being replaced by a brick-core TESS. The total operating cost, net peak demand, and gensets' on time for 6 days of operation of the KLFN MG are summarized in Table VI. The results demonstrate

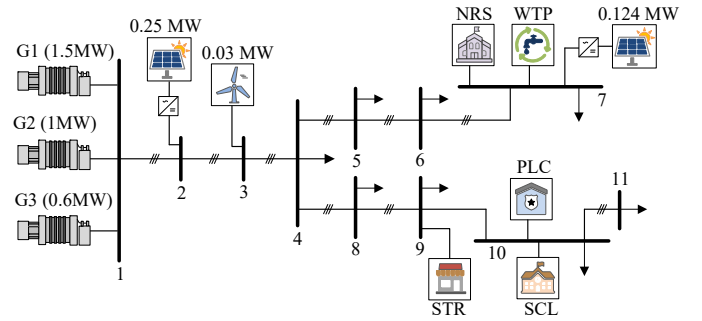


Fig. 26. KLFN Microgrid.

TABLE VI
KLFN MG DISPATCH FOR DIFFERENT TESS PENETRATION LEVELS.

250 kW PV	Case	Operating Cost of MG [\$]	Peak Demand [kW]	Total ON Time [t]		
				G1	G2	G3
No	I	45,724	771	-	97	47
	II	43,574	734	-	89	55
	III	40,220	790	-	73	71
Yes	I	42,632	771	-	90	54
	II	36,710	725	-	65	79
	III	32,898	772	-	49	95

that when TESS is available, operating the MG is cheaper, particularly when PV is available, with around 30% cost reduction for a 100% of TESS supplying the thermal demand. Also, generators operate at higher efficiencies, resulting in G3 being dispatched for longer periods, whereas the MG demand is not high enough for G1 to be dispatched.

2) *Innovative Process of Energy Conversion (PrInCE)*: This MG, depicted in Fig. 13, is a facility built at the Electric Power System Laboratory of the Politecnico di Bari, Italy [36]. It supplies the electricity and heat needs of a warehouse hosting offices and laboratories, and is characterized by a strong coupling between its thermal and electrical subsystems. The three-phase low-voltage network contains a 50-kW PV plant, a 60-kVA wind turbine emulator, a 70KVA BESS, a 120 kVA natural-gas fuelled reciprocating engine unit (CHP1), and a 30 kVA gas microturbine (CHP2) supplying two 150 kVA programmable loads. In addition, the heat demand of the building is supplied by a heat pump consuming power from the MG, and two boilers that heat up a water tank acting as TESS, which is also fed by the remnant heat from two generating units. Thus, an EMS that integrates the electrical and thermal subsystems was developed and simulated, seeking to minimize the MG's operational cost by coordinating all controllable assets to satisfy the electrical and thermal demands for two winter days, with Day 2 being colder than Day 1. The results showed that the EMS could significantly reduce the overall energy supply costs for both days, compared to a case when no coordination between thermal and electrical system is considered, as summarized in Table VII.

Since the EMS aims to minimize the energy cost, the temperature in the building mostly followed the lower band of the building's thermostat set-points, so that the HP is used less, and less heat is extracted from the TESS. The BESS mostly charges from the excess of renewable resources in the

TABLE VII
PRINCE MG DISPATCH SUMMARY FOR TWO WINTER DAYS

Daily Costs for the EMS						
Day	Opt. total cost [€]	Total elect. consump. [kWh]	Average elect. cost [€/kWh]	CHP units [€]	Boilers [€]	Net heat demand [kWh]
1	300.52	1,879.17	0.1588	298.39	2.13	2,225.44
2	348.41	1,824.51	0.1774	323.75	24.66	3,090.64
Daily Costs for the Electrical-Only EMS						
Day	Opt. elect. cost [€]	Total elect. consump. [kWh]	Average elect. cost [€/kWh]	Cost of heat supply [€]	Total cost [€]	Cost incr. [%]
1	424.58	281.21	1,770.43	0.1588	143.37	+41.3
2	496.46	297.35	1,650.60	0.1801	199.11	+42.5

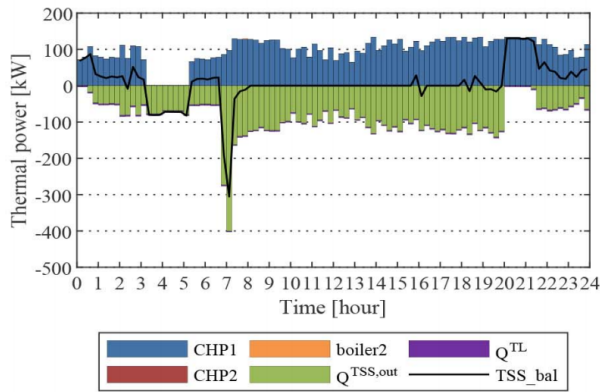


Fig. 27. PrInCE MG TESS power balance [36].

morning, and discharges when these yield limited power in the evening. On the other hand, the TESS discharges as the temperature difference between the ambient conditions and the building varies through the day, or the thermostat set points change. Fig. 27 illustrates the thermal power balance in the MG, with the blue bars representing the heat power provided by CHP 1, the green bars representing the discharging power of the TESS, and the black line is the TESS balance, with positive values representing the TESS charge and negative values corresponding to its discharge.

V. CONCLUSIONS

In this paper, novel models for dynamic electrical grid studies and market integration of BESS, FESS, CAES and TESS were discussed. The main features, topologies, power conditioning system, and control strategies of each ESS were described, and state-of-the-art models of ESS for dynamic operation, planning, and market integration studies were presented. Finally, ESS applications in actual grids or benchmarks were investigated focusing on BESS, CAES, FESS and TESS providing frequency and voltage regulation, oscillation damping, peak shaving, and energy arbitrage and ancillary services in power grids and microgrids, demonstrating the benefits of ESS for grid performance and economics.

Future research should explore how different ESS technologies can be coordinated to further improve the services

they can provide, either as stand-alone hybrid energy storage facilities (e.g., batteries with thermal storage) or distributed (e.g., home BESS and EVs) in an electrical grid, taking advantage of their specific characteristics. Furthermore, the need to study and apply ESS as grid forming generators to enable 100% RES bulk power systems, based on similar and proven MG applications, is rapidly evolving as a fundamental part of net-zero energy systems. All this will require extensive work towards the effective integration of different modelling domains, as well as new improved interfaces and control strategies. Furthermore, as more sensing data becomes available in bulk power grids and MGs, data-driven modelling based on artificial intelligence should be investigated as realistic alternatives to the exiting traditional modelling techniques for ESS, as demonstrated for BESS in this review.

REFERENCES

- [1] X. Liu, M. Shahidepour, Z. Li, X. Liu, Y. Cao, and Z. Bie, "Microgrids for enhancing the power grid resilience in extreme conditions," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 589–597, 2017.
- [2] R. H. Zubo and G. Mokryani, "Active distribution network operation: a market-based approach," *IEEE Syst. J.*, vol. 14, no. 1, pp. 1405–1416, 2019.
- [3] G. Chaspierre, G. Denis, P. Panciatici, and T. Van Cutsem, "A dynamic equivalent of active distribution network: Derivation, update, validation and use cases," *IEEE Open Access J. Power and Energy (OAJPE)*, no. 1, pp. 1–13, 2021.
- [4] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Control strategies for microgrids with distributed energy storage systems: An overview," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3652–3666, 2018.
- [5] E. Hossain, J. Hossain, and F. Un-Noor, "Utility grid: Present challenges and their potential solutions," *IEEE Access*, vol. 6, pp. 60294–60317, 2018.
- [6] R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala, and I. Gyuk, "Energy management and optimization methods for grid energy storage systems," *IEEE Access*, vol. 6, pp. 13 231–13 260, 2018.
- [7] S. O. Showers and A. K. Raji, "Benefits and challenges of energy storage technologies in high penetration renewable energy power systems," in *IEEE PES/IAS Power Africa*, Abuja, Nigeria, Dec. 2019, pp. 209–214.
- [8] "Large battery systems are often paired with renewable energy power plants," Tech. Rep., U.S. Energy Inf. Admin., Washington, DC, May 2020. [Online]. Available: <https://www.eia.gov/todayinenergy/detail.php?id=43775>
- [9] W. Gorman, C. C. Montañés, A. Mills, J. H. Kim, D. Millstein, and R. Wiser, "Are coupled renewable-battery power plants more valuable than independently sited installations?" *Energy Economics*, vol. 107, pp. 1–48, 2022.
- [10] U. Datta, A. Kalam, and J. Shi, "Battery energy storage system to stabilize transient voltage and frequency and enhance power export capability," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 1845–1857, 2018.
- [11] M. Farrokhhabadi, C. A. Cañizares, J. Simpson-Porco *et al.*, "Microgrid stability definitions, analysis, and examples," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 13–29, 2019.
- [12] X. Li, Z. Li, L. Guo, J. Zhu, Y. Wang, and C. Wang, "Enhanced dynamic stability control for low-inertia hybrid ac/dc microgrid with distributed energy storage systems," *IEEE Access*, pp. 91 234–91 242, 2019.
- [13] M. Farhadi and O. Mohammed, "Energy storage technologies for high-power applications," *IEEE Trans. Industry Applications*, vol. 52, no. 3, pp. 1953–1961, 2016.
- [14] I. Ortega and F. Milano, "Modeling, simulation, and comparison of control techniques for energy storage systems," *IEEE Trans. Power Syst.*, vol. 32, no. 3, pp. 2445–2454, 2017.
- [15] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy*, vol. 137, pp. 511–536, 2015.
- [16] V. A. Boicea, "Energy storage technologies: The past and the present," *Proc. IEEE*, vol. 102, no. 11, pp. 1777–1794, 2014.

- [17] "IESO Report: Energy Storage," Independent Electricity System Operator, Tech. Rep., March 2016. [Online]. Available: http://www.ieso.ca/-/media/files/ieso/document-library/energy-storage/ieso-energy-storage-report_march-2016.pdf
- [18] "Technology Roadmap - Energy Storage." International Energy Agency, Tech. Rep., March 2014. [Online]. Available: <https://iea.blob.core.windows.net/assets/80b629ee-597b-4f79-a236-3b9a36aedbe7/TechnologyRoadmapEnergyStorage.pdf>
- [19] A. A. Akhil *et al.*, "DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA." Sandia National Laboratories, Tech. Rep., July 2013. [Online]. Available: <https://www.energy.gov/sites/default/files/2013/08/f2/ElecStorageHndbk2013.pdf>
- [20] P. Nikolaidis and A. Poullikkas, "A comparative review of electrical energy storage systems for better sustainability," *J. Power Technol.*, vol. 97, no. 3, pp. 220–245, 2017.
- [21] M. E. Amiryar and K. R. Pullen, "A review of flywheel energy storage system technologies and their applications," *Applied Sciences*, vol. 7, no. 3, pp. 1–21, 2017.
- [22] S. Vazquez, S. M. Lukic, E. Galvan, L. G. Franquelo, and J. M. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3881–3895, 2010.
- [23] D. Enescu, G. Chicco, R. Porumb, and G. Seritan, "Thermal energy storage for grid applications: Current status and emerging trends," *Energies*, vol. 13, no. 2, pp. 1–21, 2020.
- [24] S. Koochi-Fayegh and M. A. Rosen, "A review of energy storage types, applications and recent developments," *J. Energy Storage*, vol. 27, pp. 1–23, 2020.
- [25] "Energy Storage Grand Challenge: Energy Storage Market Report," U.S. Department of Energy, Tech. Rep. NREL/TP-5400-78461 DOE/GO-102020-5497, Dec. 2020.
- [26] W. Kramer, S. Chakraborty, B. Kroposki, and H. Thomas, "Advanced power electronic interfaces for distributed energy systems part 1: systems and topologies," Tech. Rep. NREL/TP-581-42672, National Renewable Energy Lab.(NREL), Golden, CO, March 2008.
- [27] M. Ghanaatian and S. Lotfifard, "Control of flywheel energy storage systems in the presence of uncertainties," *IEEE Trans. Sustainable Energy*, vol. 10, no. 1, pp. 36–45, 2019.
- [28] "NRStor Project Spotlight: 2MW/500kWh Minto Flywheel Project," Brochure, NRStor, Toronto, Canada, 2022. [Online]. Available: <http://nrstor.com/wp-content/uploads/2019/06/flywheels.pdf>
- [29] "Operating Plants," Beacon Power, Tyngsboro, MA, 2022. [Online]. Available: <https://beaconpower.com/stephentown-new-york/>
- [30] I. Calero, C. A. Cañizares, and K. Bhattacharya, "Compressed air energy storage system modeling for power system studies," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3359–3371, 2019.
- [31] S. Succar and R. H. Williams, "Compressed air energy storage: theory, resources, and applications for wind power," Princeton Environmental Institute, Tech. Rep., 2008. [Online]. Available: https://acee.princeton.edu/wp-content/uploads/2016/10/SuccarWilliams_PEL_CAES_2008April8.pdf
- [32] "Huntorf air storage gas turbine power plant," Brown Boveri (BBC), Tech. Rep. D GK 90 202 E, 1979.
- [33] R. Carnegie, D. Gotham, D. Nderitu, and P. V. Preckel, "Utility scale energy storage systems, benefits, application, and technologies," State Utility Forecasting Group, Tech. Rep., June 2013.
- [34] R. B. Schainker and M. Nakhamkin, "Compressed-air energy storage (CAES): Overview, performance and cost data for 25MW to 220MW plants," *IEEE Trans. Power Apparatus and Syst.*, no. 4, pp. 790–795, 1985.
- [35] "Goderich A-CAES facility," Hydrostor, Tech. Rep., 2021. [Online]. Available: <https://www.hydrostor.ca/goderich-a-caes-facility/>
- [36] W. Violante, C. A. Canizares, M. A. Trovato, and G. Forte, "An energy management system for isolated microgrids with thermal energy resources," *IEEE Trans. Smart Grid*, vol. 11, no. 4, pp. 2880–2891, 2020.
- [37] P. S. Sauter, B. V. Solanki, C. A. Cañizares, K. Bhattacharya, and S. Hohmann, "Electric thermal storage system impact on northern communities' microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 852–863, 2019.
- [38] W. Mendieta and C. A. Cañizares, "Primary frequency control in isolated microgrids using thermostatically controllable loads," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 93–105, 2021.
- [39] D. Peralta, K. Bhattacharya, and C. Cañizares, "Ground source heat pump modeling and aggregation for services provision in electricity markets," in *IEEE PES General Meeting (PESGM)*, Montreal, QC, Aug. 2018, pp. 1–5.
- [40] M. Farrokhhabadi, S. König, C. A. Cañizares, K. Bhattacharya, and T. Leibfried, "Battery energy storage system models for microgrid stability analysis and dynamic simulation," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 2301–2312, 2017.
- [41] F. Calero, C. A. Cañizares, and K. Bhattacharya, "Dynamic modeling of battery energy storage and applications in transmission systems," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 589–598, August 2021.
- [42] M. Chen and G. A. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 504–511, 2006.
- [43] D. Bazargan, S. Filizadeh, and A. M. Gole, "Stability analysis of converter-connected battery energy storage systems in the grid," *IEEE Trans. Sustainable Energy*, vol. 5, no. 4, pp. 1204–1212, 2014.
- [44] "Wind energy R&D park and storage system for innovation in grid integration," The Wind Energy Institute of Canada (WEICAN), 2020. [Online]. Available: <https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/wind-energy-rd-park-and-storage-system-innovation-grid-integration/4979>
- [45] I. Calero, C. A. Cañizares, and K. Bhattacharya, "Implementation of transient stability model of compressed air energy storage systems," *IEEE Trans. Power Syst.*, vol. 35, no. 6, pp. 4734–4744, 2020.
- [46] P. Kundur, N. Balu, and M. Lauby, *Power system stability and control*. NY: McGraw-hill, 1994.
- [47] A. Gomez-Exposito, A. J. Conejo, and C. Canizares, *Electric energy systems: analysis and operation*. Boca Raton, FL, USA: CRC Press, 2016.
- [48] Y. Cengel and M. Boles, *Thermodynamics: An Engineering Approach*. 8th ed., NY: McGraw-hill, 2002.
- [49] T. Schütz, H. Harb, R. Streblow, and D. Müller, "Comparison of models for thermal energy storage units and heat pumps in mixed integer linear programming," in *28th Int. Conf. on ECOS*, Pau, France, Jul. 2015, pp. 1–12.
- [50] F. Calero, "Impact of Distributed Battery Energy Storage on Electric Power Transmission and Distribution Systems," Ph.D. dissertation, University of Waterloo, 2021.
- [51] "WECC battery storage dynamic modeling guideline," WECC, Modeling and Validation Work Group, Tech. Rep., 2016.
- [52] P. Pourbeik, "Proposal for new features for the renewable energy system generic models," WECC, Tech. Rep., 2019.
- [53] D. Peralta, C. Cañizares, and K. Bhattacharya, "Practical modeling of flywheel energy storage for primary frequency control in power grids," in *IEEE PES General Meeting (PESGM)*, Portland, OR, Aug. 2018, pp. 1–5.
- [54] G. O. Cimuca, C. Saudemont, B. Robyns, and M. M. Radulescu, "Control and performance evaluation of a flywheel energy-storage system associated to a variable-speed wind generator," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1074–1085, 2006.
- [55] G. Cimuca, S. Breban, M. M. Radulescu, C. Saudemont, and B. Robyns, "Design and control strategies of an induction-machine-based flywheel energy storage system associated to a variable-speed wind generator," *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 526–534, 2010.
- [56] F. Calero, C. A. Cañizares, and K. Bhattacharya, "Aggregated BESS dynamic models for active distribution network studies," *IEEE Trans. Smart Grid*, vol. 12, no. 3, pp. 2077–2088, 2021.
- [57] Ontario's Independent Electricity System Operator, 2021. [Online]. Available: <http://www.ieso.ca/>
- [58] N. S. Guzman, C. A. Canizares, K. Bhattacharya, and D. Sohm, "Frequency regulation model of bulk power systems with energy storage," *IEEE Trans. Power Syst.*, pp. 1–14, 2021.
- [59] N. S. Guzman, M. Arriaga, C. A. Canizares, J. W. Simpson-Porco, D. Sohm, and K. Bhattacharya, "Regulation signal design and fast frequency control with energy storage systems," *IEEE Trans. Power Syst.*, vol. 37, no. 1, pp. 224–236, 2021.
- [60] C. C. Anierobi, K. Bhattacharya, and C. A. Canizares, "Behind-the-meter compressed air energy storage feasibility and applications," *Electric Power Syst. Research*, vol. 189, pp. 1–7, 2020.
- [61] D. Peralta, K. Bhattacharya, and C. Cañizares, "Ground source heat pump modeling, operation, and participation in electricity markets," *IEEE Trans. Smart Grid*, pp. 1–13, 2021.
- [62] N. Padmanabhan, M. Ahmed, and K. Bhattacharya, "Battery energy storage systems in energy and reserve markets," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 215–226, 2020.
- [63] "Electric storage participation in markets operated by regional transmission organizations and independent system operators, Order No. 841," Tech. Rep., Federal Energy Regulatory Commission

- (FERC), Washington, DC, Feb. 2018. [Online]. Available: <https://ferc.gov/sites/default/files/2020-06/Order-841.pdf>
- [64] "Frequency regulation compensation in the organized wholesale power markets, Order No. 755," Tech. Rep., Federal Energy Regulatory Commission (FERC), Washington, DC, Oct. 2011. [Online]. Available: <https://www.ferc.gov/sites/default/files/2020-06/OrderNo.755.pdf>
- [65] B. Xu, Y. Dvorkin, D. S. Kirschen, C. A. Silva-Monroy, and J.-P. Watson, "A comparison of policies on the participation of storage in us frequency regulation markets," in *IEEE PES General Meeting*, Boston, MA, 2016, pp. 1–5.
- [66] M. Z. De Souza, C. A. Canizares, and K. Bhattacharya, "Self-scheduling models of a CAES facility under uncertainties," *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 3607 – 3617, 2021.
- [67] F. Calero, C. A. Cañizares, and K. Bhattacharya, "Detailed and average battery energy storage model comparison," in *IEEE PES Innovative Smart Grid Technol. Europe (ISGT-Europe)*, Bucharest, Romania, Oct. 2019, pp. 1–5.
- [68] "Regulated price plan, price report," Tech. Rep., Ontario Energy Board, Toronto, Canada, April 2021.
- [69] B. Cleary, A. Duffy, A. O'Connor, M. Conlon, and V. Fthenakis, "Assessing the economic benefits of compressed air energy storage for mitigating wind curtailment," *IEEE Trans. Sustainable Energy*, vol. 6, no. 3, pp. 1021–1028, 2015.
- [70] "EPRI-DOE handbook of energy storage for transmission & distribution applications," Tech. Rep., EPRI and U.S. Department of Energy, Palo Alto, CA, and Washington, DC, 2003.



Chioma Anierobi (S'12, M'17) received the B.Sc. degree and M.Eng degree in electrical engineering from Nnamdi Azikiwe University Awka, Nigeria. She also holds an M.Sc. degree in Electrical and Computer Engineering from University of Waterloo, ON, Canada. She was a Lecturer with the Department of Electrical Engineering, Nnamdi Azikiwe University Awka, Nigeria from 2012 to 2016. Currently, she is a Power Consultant at CPCS Transcom Ltd, ON, Canada. Her research interests include energy storage systems, power system optimization and renewable energy investments in developing countries.



Ivan Calero (S'17, M'20) received the diploma in electrical engineering from Escuela Politécnica Nacional (EPN), Quito, Ecuador, in 2008, and the Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Canada, in 2020. From 2009 to 2010, he was with the National Electricity Council of Ecuador. He is currently a Postdoctoral Fellow at the University of Waterloo. His research interests include modeling, analysis and control of power systems.



Fabian Calero (S'18, M'21) received the diploma in electrical engineering from Escuela Politécnica Nacional (EPN), Quito, Ecuador, in 2007. He obtained his Ph.D. degree in Electrical and Computer Engineering at the University of Waterloo, ON, Canada, in 2020. His research interests include power system modeling and control, and artificial intelligence applications for dynamic modeling.



Matheus Zambroni de Souza (S'21) Received the diploma in electrical engineering from Universidade Federal de Itajuba (UNIFEI), Itajuba, Brazil, in 2015. Master in electrical engineering from UNIFEI in 2017. He is currently a PhD candidate in electrical engineering in the University of Waterloo, ON, Canada. He had experience working with power systems stability during his undergrad, and power quality and signal processing during his master's. Today, his research focuses on compressed air energy storage participation in the electricity market, using robust optimization and/or affine arithmetic to model uncertainties.



Claudio A. Cañizares (S'85, M'91, SM'00, F'07) is a University Professor and Hydro One Endowed Chair at the ECE Department of the University of Waterloo, where he has been since 1993. His highly cited research focuses on modeling, simulation, computation, stability, control, and optimization of power and energy systems. He is the IEEE Trans. Smart Grid EIC; a Fellow of the IEEE, the Royal Society of Canada, and the Canadian Academy of Engineering; and is the recipient of the 2017 IEEE PES Outstanding Power Engineering Educator Award, the 2016 IEEE Canada Electric Power Medal, and of multiple awards and recognitions from PES Technical Committees..



Mostafa Farrokhhabadi (S'12, M'17) received the B.Sc. degree in electrical engineering from Amirkabir University of Technology, Tehran, Iran, in 2010, and the M.Sc. degree in Electric Power Engineering from KTH Royal Institute of Technology, Stockholm, Sweden, in 2012. He obtained his Ph.D. degree in Electrical and Computer Engineering in 2017 at the University of Waterloo, ON, Canada, where he was a Postdoctoral Fellow from 2017 to 2018. He is currently the VP Technology at Bluwave-ai, Ottawa, Canada. His research interests include modeling, control, and optimization in microgrids.



Kankar Bhattacharya (M'95, SM'01, F'17) received the Ph.D. degree in electrical engineering from the Indian Institute of Technology, New Delhi, India, in 1993. He was with the Faculty of Indira Gandhi Institute of Development Research, Mumbai, India, from 1993 to 1998, and with the Department of Electric Power Engineering, Chalmers University of Technology, Gothenburg, Sweden, from 1998 to 2002. In 2003, he joined the Electrical and Computer Engineering Department, University of Waterloo, Waterloo, ON, Canada, where he is currently a full

Professor. His current research interests include power system economics and operational aspects. He is a Registered Professional Engineer in the province of Ontario.



Noela Sofia Guzman E. (S'13) received the B.Sc. degree (Summa Cum Laude) in electrical engineering from Escuela Politécnica Nacional (EPN), Quito, Ecuador, in 2014. From 2014 to 2016 she worked as technical assistant at the Electricity Corporation of Ecuador - Business Unit Transelectric, Quito, Ecuador. She obtained the Ph.D. degree in 2021 at the Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada. Her current research interests include power systems, modeling, optimization, frequency regulation, and energy storage systems.



systems.

William Mendieta (S'20) received a diploma in Electrical Engineering from the University of Cuenca (Ecuador) in 2013 and completed his MASc in Electrical and Computer Engineering at the University of Waterloo (Canada) in 2019. He is currently pursuing the Ph.D. degree in the School of Electrical & Electronic Engineering at University College Dublin. He has previously worked as a protection and control engineer for generation, transmission, and distribution system networks. His research interests include modeling, analysis, and control of power



Walter Violante received the Bachelor's degree and the Master's degree in Electrical Engineering from the Politecnico di Bari, Bari, Italy in 2016 and 2019, respectively. His research interests include modeling, simulation, control and optimization of power systems. He works in O&M of High Voltage and HVDC plants for Terna, the Italian Transmission System Operator.



Dario Peralta (S'17) graduated as an Electrical Engineer from the Escuela Superior Politecnica del Litoral (ESPOL), Guayaquil, Ecuador in 2009, obtaining a specialization in Electric Transmission Protections. He obtained in 2017 a MASc degree in Electrical Engineering at the University of Waterloo, ON, Canada, where is currently a PhD candidate. His research interests include energy storage system modeling and application to power grids and electricity markets.



Bharatkumar V. Solanki (S'14, M'18) received the Bachelor's degree in electrical engineering from Gujarat University, Ahmedabad, India in 2009, and the Master's degree in Electrical Engineering from the Maharaja Sayajirao University of Baroda, Vadodara, India in 2011. He worked as an analog hardware design engineer in ABB Global Industries and Service Limited, India from 2011 to 2013. He completed his Ph.D. studies in Electrical and Computer Engineering at the University of Waterloo, Waterloo, ON, Canada, on April 2018. He is currently Technical

Lead for microgrid projects, Siemens Canada. His research interests include modeling, simulation, control and optimization of power systems.



Nitin Padmanabhan (S'05, M'08, S'15, M'20) received the B.Tech. degree in electrical and electronics engineering and M.Tech. degree in electrical engineering from the University of Calicut, Kerala, India, in 2007 and 2010, respectively. He obtained his PhD degree in Electrical and Computer Engineering at the University of Waterloo, Waterloo, ON, Canada, in 2019. He was a Lecturer and Assistant Professor with the Department of Electrical and Electronics Engineering, Vidya Academy of Science and Technology, Thrissur, Kerala, India from 2009

to 2014, and a Postdoctoral Fellow at the University of Waterloo from 2019 to 2021. He is currently a Consultant at NS Consulting, Kitchener, ON, Canada. His research interests include demand response, energy storage applications, electricity market modeling and design, and optimization of power systems.