# A Universal Modeling Framework for Real and Virtual Energy Storage

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***Abstract*—Energy storage equivalent circuit models are commonly used in design as they represent various physics or chemistries in a way familiar to power system engineers. However, the wide variety of employed circuits makes it challenging to identify the capability and transient response of energy storage and convolutes the comparison of storage options. Virtual energy storage, an aggregation of controllable loads, also currently lacks a modeling approach analogous to real storage. This paper proposes a universal energy storage model that represents both real and virtual storage—abstracting away the virtual storage power electronics while maintaining the system dynamics. This work demonstrates how the universal model can represent virtual energy storage and how existing battery and supercapacitor models can convert into the universal model. A comparison to switching models demonstrates the efficacy of the proposed universal model.**

***Index Terms*—energy storage systems, virtual energy storage, mathematical modeling, battery, supercapacitor, thermal storage, HVAC**

## I. Introduction

Energy storage (ES) is critical in modern power systems as the switch to renewable energy sources amplifies the mismatch between energy generation and consumption, creating the need to temporarily store and release energy. The search for ES solutions has uncovered many approaches spanning various physics domains (e.g., electrochemical, thermal, mechanical). Each ES option has pros and cons that make them optimal for specific applications. A relatively recent solution has gained attention called virtual energy storage (VES), which is an aggregation of controllable unidirectional loads inherent to the system. These loads have inertia or energy capacity and can act as effective bidirectional storage by modulating the power consumption dynamically using power electronics. Examples of VES include a building's HVAC system [1], [2] or a hot water tank heater [3].

Given that power distribution primarily occurs within the electrical domain, electrical equivalent circuit modeling is a popular approach for ES system design. This allows electrical engineers to evaluate the feasibility of various ES options, including system stability, power efficiency, and sizing/cost. However, the wide variety of available ES equivalent circuit models makes direct comparisons and trade-off studies challenging, especially when involving multiple storage types within an application. The distinction between circuit components that affect power dynamics and energy storage capabilities can also be unintuitive. This paper aims to define a universal energy storage model (UESM) framework capable of accurately modeling any ES, both real and virtual. This universal representation allows all ES mediums to be directly compared to each other, simplifying design studies and comparisons.

Existing ES electrical equivalent circuit models often include Thevenin equivalents with a dependent open-circuit voltage and a series of impedance networks to track responses to transient loads [4]–[9]. VES models are either high-level that abstract away many of the dynamics and losses of the system [2], [10] or use switching circuit models [1], which are costly to simulate or offer little value for long-term system-level design. Existing literature lacks an attempt to formulate the VES in the same model framework as real ES. Here the UESM framework identifies the standard methods to represent ES time constants and dynamics and defines a generalized template that applies to any ES device. Power electronics within a VES are abstracted away while maintaining the system dynamics relevant to real ES. To present a simple generalized ES model, not all equivalent circuit models in the literature fit within the UESM framework. Instead, common topologies among ES models are identified and used within the UESM.

This paper is organized as following. Section II provides a high-level overview of an HVAC-based VES. Section III presents the proposed UESM, ES metrics using the UESM, and the UESM representation of a battery, supercapacitor, and VES. Section IV compares and discusses the UESM and switching models of a VES, followed by a comparison of each ES medium using the provided ES metrics. Lastly is a conclusion with proposed future work.

## II. Virtual Energy Storage Concept

The VES concept utilizes controllable thermal and inertial loads inherent to a system that can behave as an energy buffer.

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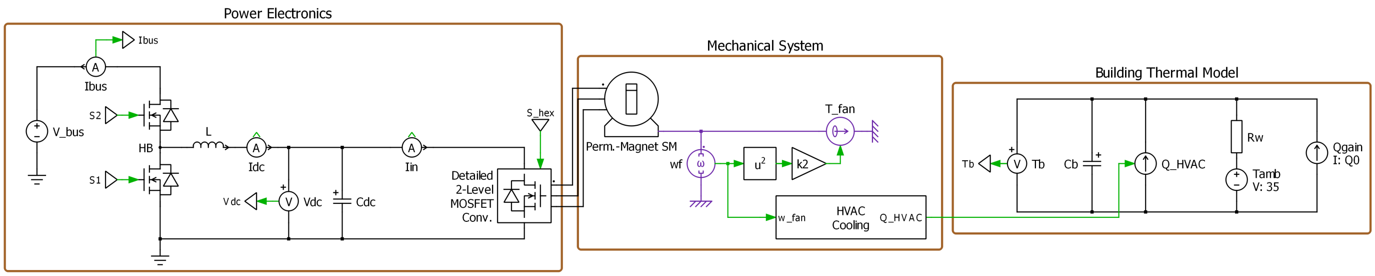


Fig. 1: HVAC-based virtual energy storage in electric circuit representation.

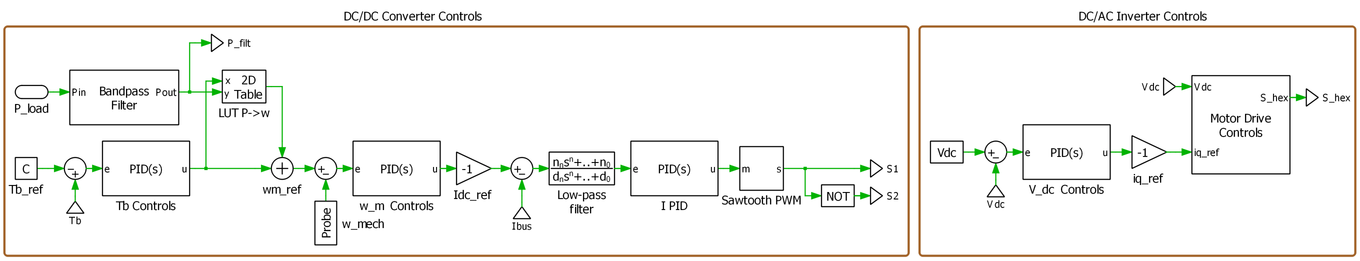


Fig. 2: VES control system.

While these are usually unidirectional loads, they behave in the same manner as real ES. Neither real nor virtual ES *creates* energy, they only *store* energy for a later time. From an energy management perspective, reducing the amount of power the inherent load draws is equivalent to supplying an amount of power for some duration.

To demonstrate that the UESM framework applies to VES, this section will cover a building's HVAC cooling system configured to behave as a VES. The primary energy storage medium is the thermal capacitance of the air within the building. While in cooling mode, energy is expended to maintain a comfortable temperature. External air temperatures and internal heat generation sources, such as from humans, electronics, and lighting, counteract this cooling effort. While remaining within a nominal temperature threshold, the HVAC system can modulate its power consumption to act as a power bandpass filter. The lower frequency limit of the filter ensures temperatures remain within the comfort zone, and the upper frequency limit prevents unwanted acoustic noise and equipment wear caused by the speed adjustment of the HVAC system [1]. HVAC modeling is based on [1], [2] where the mass flow rate $\dot{m}$ of the air is proportional to the fan speed $w_{fan}$ (1), and the power consumption $P_{fan}$ of the motor is proportional to the fan speed cubed (2). The lumped thermal model of the building is given in (3).

$$\dot{m} = k_1 w_{fan} \tag{1}$$

$$P_{fan} = k_2 w_{fan}^3 \tag{2}$$

$$C\frac{dT_b}{dt} = \frac{1}{R_w}(T_{amb} - T_b) + c_p\dot{m}(T_l - T) + Q_0 \tag{3}$$

A power electronic-based architecture of the HVAC system is shown in Fig. 1. It consists of a dc/dc converter connected to a dc-microgrid, hex-bridge inverter motor drive, 3-phase permanent magnet synchronous motor (PMSM) driving a fan, the lumped-capacitance thermal equivalent circuit model of the building, and the associated controls for the power electronics. The motor-driven fan pumps cold air through a refrigeration unit into the building to maintain nominal temperatures. Note that the refrigeration unit power is ignored in later discussions, as it is a relatively constant load and thus minimally impacts the power filtering ability of the VES [11].

The dc/dc converter controls the temperature regulation and power filtering while the hex inverter regulates the dc-link capacitor voltage between the two converters by adjusting the input current of the motor. The roles of the two converters are interchangeable, but this control approach conforms to the UESM concept, as will be shown later in the paper. The control system is shown in Fig. 2. The dc/dc converter controller includes two inputs: a building temperature PI controller and a power bandpass filter. The bandpass filter output is fed into a 2-D lookup table that calculates the necessary fan speed reference bias to achieve the power filtering command output of the bandpass filter. The resulting fan speed reference is fed into a cascaded speed and current PI control loop, generating the PWM duty-cycle signals for the boost converter. The dc/ac inverter controller input is the dc-link capacitor voltage, which is regulated using a PI controller feeding into the dq-frame current controllers. The commanded currents are achieved using space vector modulation. For additional control details, readers can refer to [1] for the detailed control scheme used for the VES.

## III. Universal Energy Storage Model

The UESM consists of two isolated but coupled circuits: the state of charge (SOC) domain circuit and electrical domain

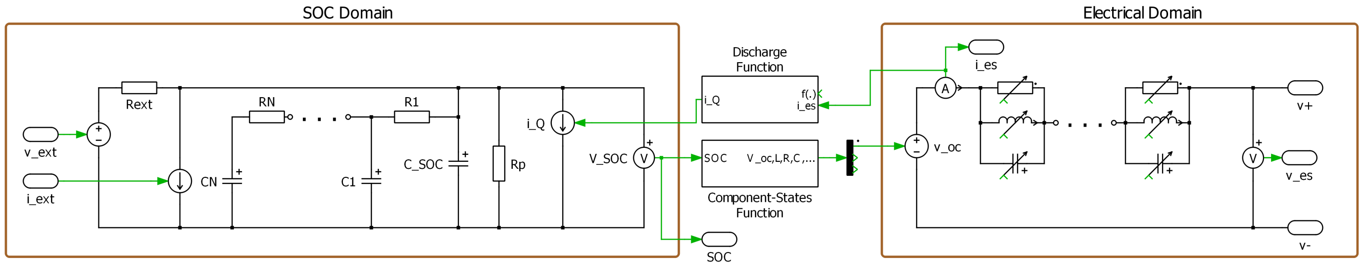


Fig. 3: Universal energy storage model.

circuit, both shown in Fig. 3. The domain coupling occurs through the discharge function and the component-states function, both specific to the modeled energy storage medium.

The SOC domain represents the primary storage system of the ES and defines how effective it is at storing energy for a period of time and how fast it will passively lose charge. The circuit captures charge capacity, charge redistribution, self-discharge, and external inputs from other non-electrical energy domains. It is a normalized circuit such that voltage $v_{soc}$ is equivalent to the SOC (i.e., $v_{soc} = 0.5$ when $SOC = 50\%$). The conversion from the original physics domain to the SOC domain is achieved by using (4)-(6), where $x_1$ is the original domain value associated with a $SOC = 100\%$ and $x_0$ with $SOC = 0\%$ (e.g., for a supercapacitor $x_1 = 2.7V$ and $x_0 = 0V$). $C'$ is a capacitance, and $R'$ is a resistance of the original domain.

$$SOC = \frac{x - x_0}{x_1 - x_0} \tag{4}$$

$$C = C'|x_1 - x_0| \tag{5}$$

$$R = \frac{R'}{|x_1 - x_0|} \tag{6}$$

The electrical domain captures the dynamics of the ES within an electrical power system. This includes the equivalent open-circuit voltage $v_{oc}$ and series impedances that capture traits such as response time, transient stability, and the control implementation of the ES system. $v_{oc}$ and impedance values can either be functions of SOC or constant, depending on the ES medium and the chosen fidelity. For real ES, the dynamic traits are often inherent to the physics or configuration of the storage medium and limit the energy bandwidth that the ES can supply effectively. For VES, the electrical domain circuit can be customized to an extent but also represents its limitations in supplying power.

Determining what equivalent circuit components of existing models belong in the SOC or electrical domains comes down to identifying the RLC impedance network with the largest time constant. Equivalent circuit models often consist of several series-connected RLC parallel impedance branches. However, only one group is associated with the storage of energy long term as observed in [4][8]. The group with the largest time constant belongs in the SOC domain, while all other parallel branch groups belong in the electrical domain. A capacitor or inductor in the electrical domain may have a relatively large value, but they cannot store energy for long due to the small time constants caused by a low parallel resistance. Instead, those branch groups better represent the transients of the ES device. Both parallel RC and RL branches represent frequency-dependent resistance to current draw and the ES capability to respond to a change in load.

Linking the two domains of the UESM is achieved using a discharge function and a component-states function. The discharge function outputs the discharge current $i_Q$ for the SOC domain, and is a function of the ES output current $i_{es}$ in the electrical domain and the SOC. The component-states function, a function of SOC, outputs the electrical domain impedances and sometimes SOC domain impedances. The specific models for the discharge and component-states functions are ES medium dependent. Due to the potentially complex relations the functions must represent, this paper uses a mathematically or experimentally derived lookup table for simulations. However, any approach to modeling these functions can be used, given that they do not contain any internal states.

### A. *Energy Storage Metrics for UESM*

Accompanying the UESM framework are some general definitions of energy storage metrics: SOC, charge capacity, energy capacity, power capacity, and self-discharge rate. Many different interpretations and methods exist to characterize these traits in the literature, and it is out of the scope of this paper to discuss them. The purpose of these definitions is for a standardized way to calculate these values for direct comparisons between different energy storage options.

The most trivial metric is SOC, the voltage across $C_{SOC}$ in the SOC domain circuit. In some literature, SOC represents the state of *energy* rather than the state of *charge*. There is a distinct difference between the two; for example, the energy stored in a capacitor is $E = \frac{1}{2}Cv^2$ while the charge stored is $Q = Cv$. In the UESM framework, SOC represents the state of *charge*.

The self-discharge rate (SDR) in this paper is defined as the RC time constant of the SOC domain circuit. Or equivalently, the time it takes for the SOC to go from $100\%$ to $36.8\%$. Power capacity $P_{rated}$ is defined as the nominal power an ES can supply while discharging from $100\%$ to $0\%$ SOC and is determined using (7).

$$P_{rated} = i_{rated} \int_0^1 v_{oc}(SOC) dSOC \tag{7}$$

Charge capacity $Q_{rated}$, determined by (8), is the total charge the ES can supply to a load at the rated current $i_{rated}$ while discharging from 100% to 0% SOC. This approach accounts for the SDR of the ES, while discharging at the rated current minimizes the SDR impact.

$$Q_{rated} = i_{rated} \int_{0|_{SOC=1}}^{t_f|_{SOC=0}} dt \tag{8}$$

The amount of energy an ES can supply in real application is challenging to specify as it depends on many variables such as discharge rate, frequency, temperature, and state of health. While a single value cannot wholly encapsulate the energy capacity of an ES, it is still a valuable metric for comparing different ES devices and commonly used in literature, sometimes represented as energy density [12] [13]. A popular approach to estimating the energy stored in a battery is the product of the charge capacity (Amp-hour or Coulombs) and the nominal open-circuit voltage $v_{oc}$, and is used to define the energy capacity $E_{rated}$ in the UESM framework. This is given as (9). This approach to calculating energy capacity ignores the power losses of the ES medium since power losses are highly dependent on the use-case factors including temperature and power demand.

$$E_{rated} = Q_{rated} \int_0^1 v_{oc}(SOC) dSOC \tag{9}$$

### B. UESM: Battery

Representing a lithium-ion battery using the UESM is the most straightforward as it requires minimal adjustments to existing dynamic models in literature, such as [4]–[6]. It is common to represent the dynamics of a lithium-ion battery using several series connected RC parallel branches. This series impedance captures the change in resistance from the charge depletion and recovery effects [5]. The electrical domain of the UESM models the same dynamics. In fact, there is little difference between the UESM battery model shown in Fig. 4, and the model presented in [4]. Each RC branch's resistance and capacitance are both a function of the SOC. The open-circuit voltage source is also a function of the SOC, being a linear relation in simple models and a nonlinear relation in more detailed models. The voltage source and RC branch impedance parameters are calculated in the component-states function of the UESM, a function of SOC and discharge current $i_Q$. Note that the UESM component-states function generally does not depend on $i_Q$. For this battery model, the electrical domain impedance changes whether the battery is charging or discharging. The sign of $i_Q$ is used instead of the derivative of SOC to help with modeling.

The SOC domain is also similar to existing battery models [4][5], where a battery's capacity is commonly defined as stored charge in units of amp-hours (Ah). The SOC is thus a ratio between the maximum charge and the charge stored in the battery. Or equivalently, the integration of discharge current $\int i_Q dt$. Given the direct relation between discharge current and SOC, the SOC domain model is simply a single capacitor in parallel with a current source, as shown in Fig. 4. This is also the approach used in [4]. The SOC capacitance is defined as the charge capacity in Coulombs (i.e., $C_{SOC} = Ah \cdot 3600$). The voltage across $C_{SOC}$ is equivalent to the battery's SOC, as with all implementations of the UESM. In both [4], and the UESM, the SOC domain current source $i_Q$ is equivalent to the ES output current $i_{es}$. Some battery models also capture the self-discharge rate, which can be modeled as a resistor in parallel with $C_{SOC}$. However, this paper omits the battery's self-discharge as it involves a relatively large time constant.

### C. UESM: Supercapacitor

Numerous supercapacitor (SC) equivalent circuit models exist in literature with various topologies. An in-depth discussion on each modeling approach is out of the scope of this paper, but readers can refer to [8][9] for review and comparisons. In general, SC equivalent circuit models are grouped in RC parallel branch dynamic models, multi-stage RC ladder (or transmission line) models, and multi-branch RC series models, or a combination of them found in [7]. Aside from the multi-branch RC series model with an incompatible circuit topology, any of these model types are compatible with the UESM. The RC parallel branch dynamic model [8] uses a similar topology as the dynamic battery model used in section III-B, thus is not discussed further in this paper.

The remainder of this section will demonstrate how the SC model presented in [7] can be transformed into the UESM framework. The model is shown in Fig. 5 for the reader's convenience. However, the parallel leakage (self-discharge) resistor $R_leak$ is moved to the left side of the series resistor $R_s$, and into the SOC domain, to fit the UESM. Given the resistance magnitude, this minor change in model topology results in a negligible error.

The dotted line in Fig. 5 marks the separation between the SOC and electrical domain. The resulting UESM representation is shown in Fig. 6. All circuit elements in the electrical domain are identical to the corresponding elements from [7]. The SOC domain circuit elements are derived by transforming the circuit elements shown on the left side of Fig. 5 using (5)(6). Similar to the battery UESM, the SOC domain discharge current $i_Q$ is equivalent to the ES output current $i_{es}$. The relation between $v_{SOC}$ of the SOC domain and $v_{oc}$ of the electrical domain is $v_{oc} = v_{max} v_{soc}$ where $v_{max}$ is the rated voltage of the SC.

### D. UESM: Virtual Energy Storage

For an HVAC-based VES, energy is stored using the thermal capacitance of the building's air. Therefore, the SOC domain models the building's thermodynamics, where the SOC is equivalent to the temperature $T_b$ scaled. Feeding power into the VES results in the charging of the ES. Since the HVAC system in this scenario provides only cooling to the building, an $SOC = 1$ occurs at its minimum temperature limit

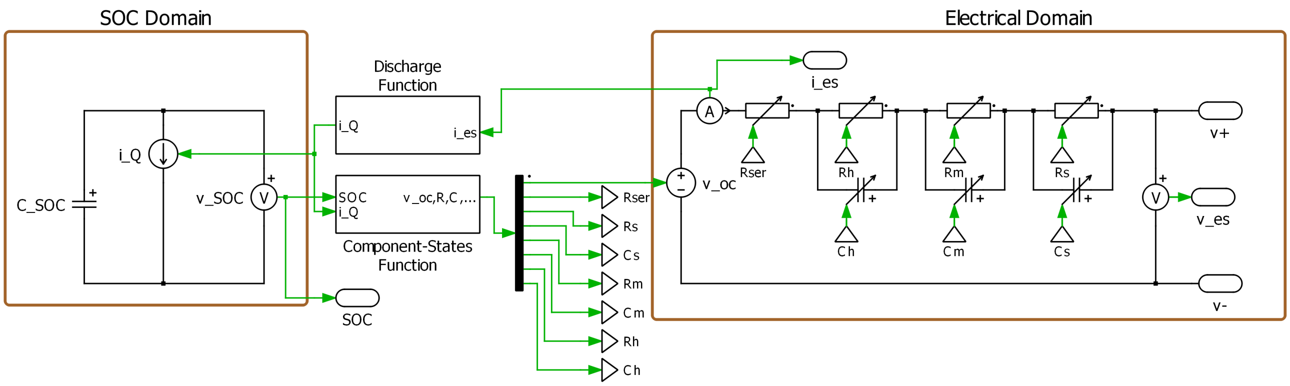


Fig. 4: Battery UESM.

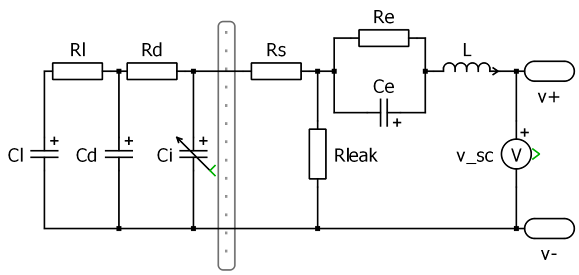


Fig. 5: SC model from [7].

($T_b = T_{min}$) and $SOC = 0$ at its maximum ($T_b = T_{max}$). The thermodynamic parameters of (3) are scaled using (4)-(6), with $x_0 = T_{max}$, $x_1 = T_{min}$. This VES has both an external voltage source $v_{ext}$ and current source $i_{ext}$. $v_{ext}$ is equivalent to $T_{amb}$ scaled using (4), while $i_{ext}$ is $Q_0$ and not scaled. The SOC domain circuit for this VES is shown in Fig. 7.

The electrical domain for real ES consists of an SOC-dependent voltage source and series impedance intrinsic to the storage physics. The series impedance, in turn, defines the transient response of the output voltage $v_{es}$ for a change in load current. For this VES, the transient response of $v_{es}$ primarily depends on the implemented control system. As discussed in Section II, temperature regulation and power filtering is controlled by the dc/dc converter while the motor drive regulates the dc-link capacitor voltage. The electrical domain circuit should then represent the behavior of the voltage PI controller, which outputs a command current $i$ based on the error between referenced and measured voltage ($e = v^* - v$). This is analogous to a current through an impedance between two voltage sources (i.e., $e = i \cdot Z$ where $Z^{-1} = PI(s)$). The voltage controller circuit representation uses methods derived in [14]. The electrical domain for this VES thus consists of a voltage source with a magnitude of the reference dc-link voltage and a parallel $RL$ impedance. $R$ represents the inverse proportional gain and $L$ represents the inverse integral gain. This circuit representation is shown in Fig. 7.

The UESM discharge function handles the conversion between the electrical domain $i_{es}$ and SOC domain $i_Q$. For HVAC-based VES, $i_Q$ is the heat transfer induced by the cooling system. From (3), $i_Q = c_p\dot{m}(T_l - T)$, where $\dot{m}$ is a function of $w_{fan}$ given in (1) and is indirectly controlled by $i_{es}$. A steady-state equation for $i_{es}$ as a function of the fan speed $w_{fan}$ is derived below.

The rotational dynamics of a PMSM driving a fan operating with no flux weakening (i.e., $i_d = 0$) is modeled as

$$J\frac{d}{dt}w_{fan} = \frac{3}{2}\lambda_m i_q - k_2 w_{fan}^2 - Bw_{fan} \tag{10}$$

where $J$ is the combined motor and fan rotational inertia, $\lambda_m$ is the PMSM flux linkage, $i_q$ is the q-axis current, and $B$ is the frictional loss coefficient of the motor [15]. Combining the active power dq-frame equation $P = v_q i_q$ (reduced from $P = v_d i_d + v_q i_q$ since $i_d = 0$), inverter input power $P = i_{es}v_{dc}$ and the steady-state q-axis equivalent circuit voltage formula (11) yields the relation (12)

$$v_q = \frac{p}{2}\lambda_m w_{fan} + R_s i_q \tag{11}$$

$$R_s i_q^2 + \frac{p}{2}\lambda_m w_{fan} i_q = i_{es}v_{dc} \tag{12}$$

where $R_s$ is the stator resistance, $p$ is the PMSM pole count, and $v_{dc}$ is the dc input voltage of the inverter. Solving (12) for $i_q$ results in the quadratic equation

$$i_q = \frac{-\frac{p}{2}\lambda_m w_{fan} + \sqrt{(\frac{p}{2}\lambda_m w_{fan})^2 + 4R_s i_{es} v_{dc}}}{2R_s} \tag{13}$$

Inserting (13) into (10) under steady-state conditions ($\frac{d}{dt}w_{fan} = 0$) and solving for $i_{es}$ results in a quartic equation dependent on only two time-varying components, $w_{fan}$ and $v_{dc}$, where $w_{fan}$ is present to the fourth order. For the VES UESM discharge function, $v_{dc}$ is assumed to be constant, thus the quartic equation for $i_{es}$ is solely dependent on $w_{fan}$, or $i_{es} = f(w_{fan})$. Due to the size of the quartic equation, it is omitted from this paper. Solving for $i_Q$ as a function of $i_{es}$ requires the inverse solution to the quartic equation. Since solving such an equation is a time-intensive procedure, an inverse-function lookup table is generated by evaluating $i_{es} = f(w_{fan})$ for a range of $w_{fan}$ values between 0 and the fan's rated speed. This lookup table serves as the UESM discharge function.

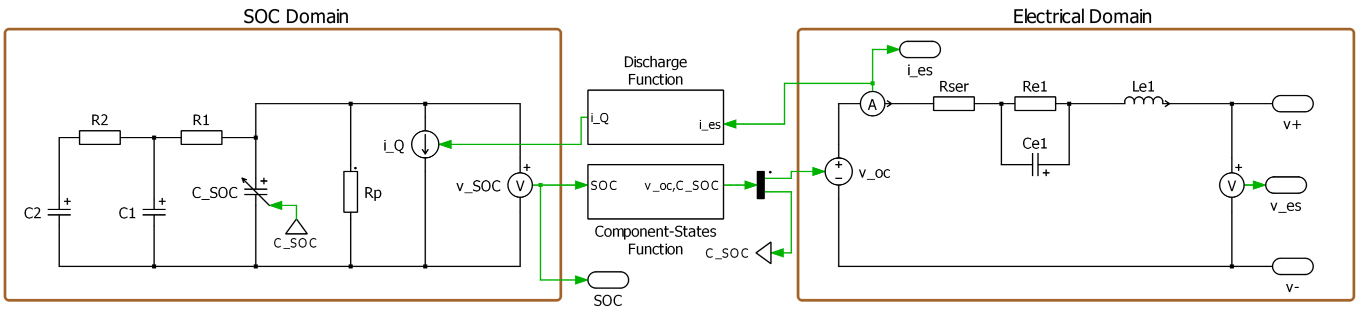


Fig. 6: SC UESM.

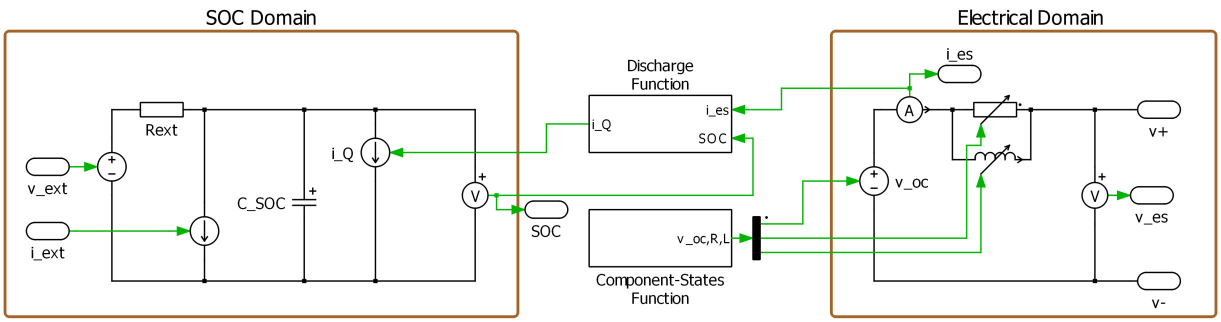


Fig. 7: HVAC UESM.

The component-states function of the UESM is constant in the HVAC-based VES while the control system parameters remain constant during operation.

## IV. Model Validation and ES Comparison

The parameters used for model validation and ES comparisons for a Li-ion battery, SC, and HVAC VES come from [4], [7], and [1], respectively. A single cell is used for the battery model, and the SC is a pack with 18 cells in series. The original HVAC system in [4] is scaled down to match the PMSM power rating of $15\,kW$. The building's volume and heat gain are scaled proportionally to maintain the same rate of heat gain when the HVAC is off. The building's external temperature $T_{ext}$ and heat gain $Q_0$ are for a hot summer day, thus providing a conservative scenario for the presented ES metrics. The UESM SOC domain parameters necessary for the simulations and ES comparisons are provided in Table I. All models and comparisons for this paper were built and performed using PLECS.

There is no validation section for the battery and SC UESM, as there is no need for model validation. The battery UESM is mathematically identical to the original model from literature, so comparison results in zero errors. Likewise, the UESM SC model is nearly identical to the original model. The relocation of the leakage resistance results in a negligible error; thus, comparison plots would serve no purpose.

### A. Validation of HVAC VES UESM

Typical switching models are fully validated with hardware in many literature and are trustworthy. This section validates the proposed HVAC-based VES UESM by comparing it to

TABLE I: UESM parameters.

| ES | SOC domain parameters | $i_{rated}$ |
|---|---|---|
| Battery | $C_{SOC} = 7920\,F$ | $4.4\,A$ |
| SC | $C_{SOC,0} = 3348\,F$, $C_{SOC,1} = 585.9\,F$, $R_p = 3.52\,k\Omega$, $R_1 = 0.1085\,\Omega$, $C_1 = 428.2$, $R_2 = 7.750\,\Omega$, $C_2 = 464.6\,F$ | $100\,A$ |
| HVAC VES | $C_{SOC} = 700\,kF$, $R_{ext} = 2.5\,m\Omega$, $v_{ext} = -4.5\,V$, $i_{ext} = 11.5\,kA$ | $11.16\,A$ |

the existing switching model covered in Section II. The VES UESM shown in Fig. 7 connects to the same dc/dc converter of the switching model shown in Fig. 1. The SOC circuit is mathematically equivalent to the thermal circuit in the switching model and thus behaves identically. The primary difference between the two models is the implementation of the inverter and motor. The switching model utilizes a hex-bridge inverter driving a 3-phase PMSM, both provided by the PLECS library. The UESM abstracts away the inverter by using a circuit representation of the voltage PI controller realized by the inverter, while the motor is part of the UESM discharge function. This approach means no direct feedback between the motor and the dc-link voltage regulator within the UESM. While this does introduce a modeling error, the impact is minimal.

Fig. 8 compares the VES waveforms of the UESM and switching model from a 30-min simulation. The VES filters the power signal $P_{load}$ shown in Fig. 8a using a bandpass filter with corner frequencies $1\,mHz$ and $17\,mHz$. The VES input power $P_{es}$ of both models are shown in Fig. 8a, fan speed $w_{fan}$ in Fig. 8b, building temperature $T_b$ in Fig. 8c, and dc-link voltage $v_{dc}$ in Fig. 8d. The largest error between models appears in the input power, with a max absolute error (MAE) of $4.47\%$. However, the power error is not cumulative as the energy MAE throughout the simulation is only $4.37\%$. All other measurements have a MAE lower than $0.15\%$. These results demonstrate that the UESM can simulate the behavior of the HVAC-based VES to a high degree of accuracy, with the benefit of running much faster.

### *B. Using the Energy Storage Metrics*

TABLE II: Energy Storage Metrics.

| ES | SDR | $P_{rated}$ | $Q_{rated}$ | $E_{rated}$ |
|---|---|---|---|---|
| Battery | - | $15.84\,W$ | $2.2\,Ah$ | $7.92\,Wh$ |
| SC | $1.62 \cdot 10^7\,s$ | $2400\,W$ | $1.05\,Ah$ | $25.16\,Wh$ |
| HVAC VES | $32.6\,s$ | $6728\,W$ | $0.602\,Ah$ | $96.9\,Wh$ |

This section compares the three ES mediums presented in this paper using the energy storage metrics presented in Section III-A: SDR, $P_{rated}$, $Q_{rated}$, and $E_{rated}$. Calculating these metrics assume a full discharge depth of $100\%$, while recognizing such a discharge depth cannot be obtained in practice. The approach can be easily modified for a given SOC range. Since charge capacity $Q_{rated}$ depends only on $i_{rated}$ and the change in SOC, calculating each metric requires only the SOC domain and component-states function. This is a benefit to the UESM framework, which isolates the SOC model from the complex dynamics of the electrical domain.

Solving (8) is most straightforward for the battery model as the SOC domain consists of a single capacitor and current source. Thus, $Q_{rated}$ is of equal magnitude to $C_{SOC}$. $E_{rated}$ found with (9) involves the integral of $v_{oc}$ over the full SOC range. The high-order polynomial function from [4] averaged results in a voltage of $3.6\,V$. SDR is not considered for the battery as it is orders of magnitude larger than the other ES mediums in this paper. The ES metrics for the battery UESM is given in Table II.

The SDR and $Q_{rated}$ for the SC is found through simulation because the three capacitors present in the SOC domain involve solving a multi-variable integral. The integral part of (9) solves to $\frac{1}{2}v_{max} = 24\,V$. The ES metrics for the SC UESM is given in Table II.

A closed form solution for the time elapsed between two HVAC VES $v_{SOC}$ values, $v_a$ and $v_b$, assuming $i_Q = 0$ and external parameters, is given in (14). It is derived by integrating $dt$ using the SOC domain equivalent of (3) with respect to $dv_{SOC}$ (i.e., $t = \int(\cdot)dv_{SOC}$), while $\dot{m} = 0$. The SDR is solved for $v_a = 1.0$, $v_b = 0.368$, and the parameters given in Table I. Calculating $Q_{rated}$ for HVAC VES differs from the real ES calculations. Recall that a VES does not directly supply power. Instead, it modulates the amount of power from its nominal power to provide a buffer. So the calculated $Q_{rated}$ and $E_{rated}$ is the energy available by turning off the HVAC for a short period. Therefore, $i_Q = 0$ remains true for (8). The integral part of (8) is equal to (14) for $v_a = 1.0$ and $v_b = 0$. Solving for $E_{rated}$ is also unique for VES. $v_{oc}$ in the electrical domain represents the reference voltage for the dc-link voltage $v_{es}$; thus, it is not a function of

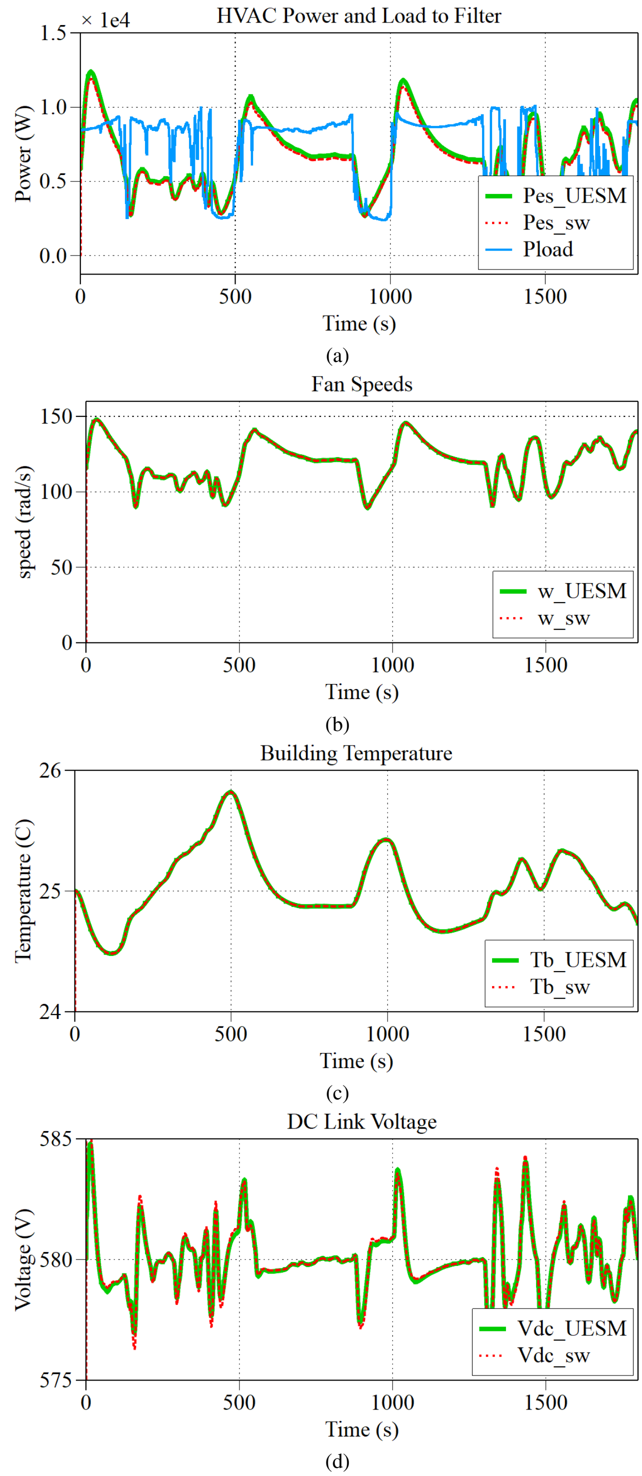


Fig. 8: Comparison between the UESM and switching model of the HVAC-based VES.

SOC but is constant. $E_{rated}$ is solved for $v_{oc} = 580\,V$. The ES metrics for an HVAC VES UESM is given in Table II.

$$t = C_{SOC}R_{ext}\ln\left(\frac{v_a - v_{ext} + i_{ext}R_{ext}}{v_b - v_{ext} + i_{ext}R_{ext}}\right) \quad (14)$$

Using the UESM framework methods to calculate these

ES metrics allows for a direct comparison between different ES mediums, summarized in Table II. Recall that the battery metrics are for a single Li-ion cell, and the SC metrics are for an $18$ cell pack. In practice, many battery cells are combined into a battery pack. A battery pack with a $P_{rated}$ comparable to the VES would require approximately $425$ cells, or $12$ cells for a comparable $E_{rated}$. These cell amounts do not account for the rectangular configuration constraint for cells connected in series and parallel, potentially increasing the required number of cells to match the VES. This highlights the benefit of VES over a battery pack when the criteria is high power capacity but relatively low energy capacity. Or the inverse for high energy capacity uses.

Similarly, approximately $50$ cells are required for a comparable $P_{rated}$ SC pack or $69$ cells for a comparable $E_{rated}$. The small difference between the number of SC cells for comparable $P_{rated}$ and $E_{rated}$ to the HVAC VES suggests these ES mediums have similar power and energy bandwidth applications. However, the fast SDR of the VES will significantly limit its applicable bandwidth. That being said, the HVAC VES equipment is inherent to the system, so its use should be prioritized, given that commercially available controls are available.

The ES metrics comparisons should serve as high-level comparisons between different ES mediums considered for a design. Their actual values will depend on the application and implementation and will be impacted by losses throughout the system. This holds especially true for the HVAC VES, where its SDR could be significantly improved if the HVAC system operates at a reduced power level instead of shutting down completely when providing power. While this increases the SDR, it would come at a cost of a lower $P_{rated}$. For example, reducing its $i_{rated}$ to $5\,A$ would increase its SDR to $127\,s$ while lowering $P_{rated}$ to $2900\,W$. The resulting $E_{rated}$ would be $186\,Wh$.

## V. Conclusion and Future Work

A universal energy storage model is proposed in this paper that is capable of modeling many types of real and virtual ES. The model utilizes common elements of ES equivalent circuit models to formulate a generalized framework separating energy storage mechanics from electrical dynamics. This universal representation allows all ES mediums to be directly compared to each other, using a common circuit topology and general definitions of ES metrics, making design studies and comparisons easier, especially in a hybrid ES system. The power electronics within a VES are abstracted away while maintaining their system dynamics, improving VES simulation speeds with minimal loss in accuracy. It is shown how the proposed model is compatible with HVAC-based VES and validates its performance by comparing it to a switching model. A high-level comparison between the different ES in this paper is provided using the ES metrics part of the UESM framework.

Future work includes extending the UESM framework to encapsulate the aggregation of multiple ES types into a single model. Currently, the model can represent different ES mediums but requires conventional modeling techniques to connect them. System control techniques utilizing the UESM concept can also be explored with an aggregated model. Additional work includes implementing other ES mediums into the UESM framework and characterizing model parameters directly from experimentation rather than converting existing models in literature.

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