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Revisiting battery modeling using the energy power supply concept

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Abstract

Using the energy power supply concept, this paper proposes a DC voltage source with limited energy storage capacity, which models: the energy storage capacity of the batteries, the involved energy transfer process and the constant voltage output behavior when the battery has storage energy. Further, this circuit source is used for understanding the combined electrical–circuit based battery model (CECBM), which is commonly used (i.e. for designing of: portable electronic devices, hybrid electric vehicles and smart grid systems), because it is capable to predict accurately the DC voltage response, the runtime, the transient, and some nonlinear behaviors. These models have been used without a comprehensive development about the inspiration of its topology, and the simple energy flow process that models. This work uses the novel electric Energy Power Supply concept for understanding the behaviors captured by the CECBM.

INTRODUCTION

The energy storage devices have a wide application span. Recently, the battery technologies have been receiving huge attention because three commercial applications: portable electronic devices, hybrid electric vehicles and smart grid systems [1]. Without battery models in hand, circuit designers cannot predict nor optimize either battery runtime or circuit performance.

I. Energy flow process

$$P_L(t) = \frac{dE_L(t)}{dt} = v_L(t)\, i_L(t); \tag{1}$$

II. EPS model

$$E_S(t) = \begin{cases} E_{st} & E_L(t) \leqslant -\eta_s(E_{st}-E_0) \\ E_0 - \frac{E_L(t)}{\eta_s} & E_0 - E_{st} < \frac{E_L(t)}{\eta_s} < E_0 \\ 0 & \eta_s E_0 \leqslant E_L(t) \end{cases}; \tag{2}$$

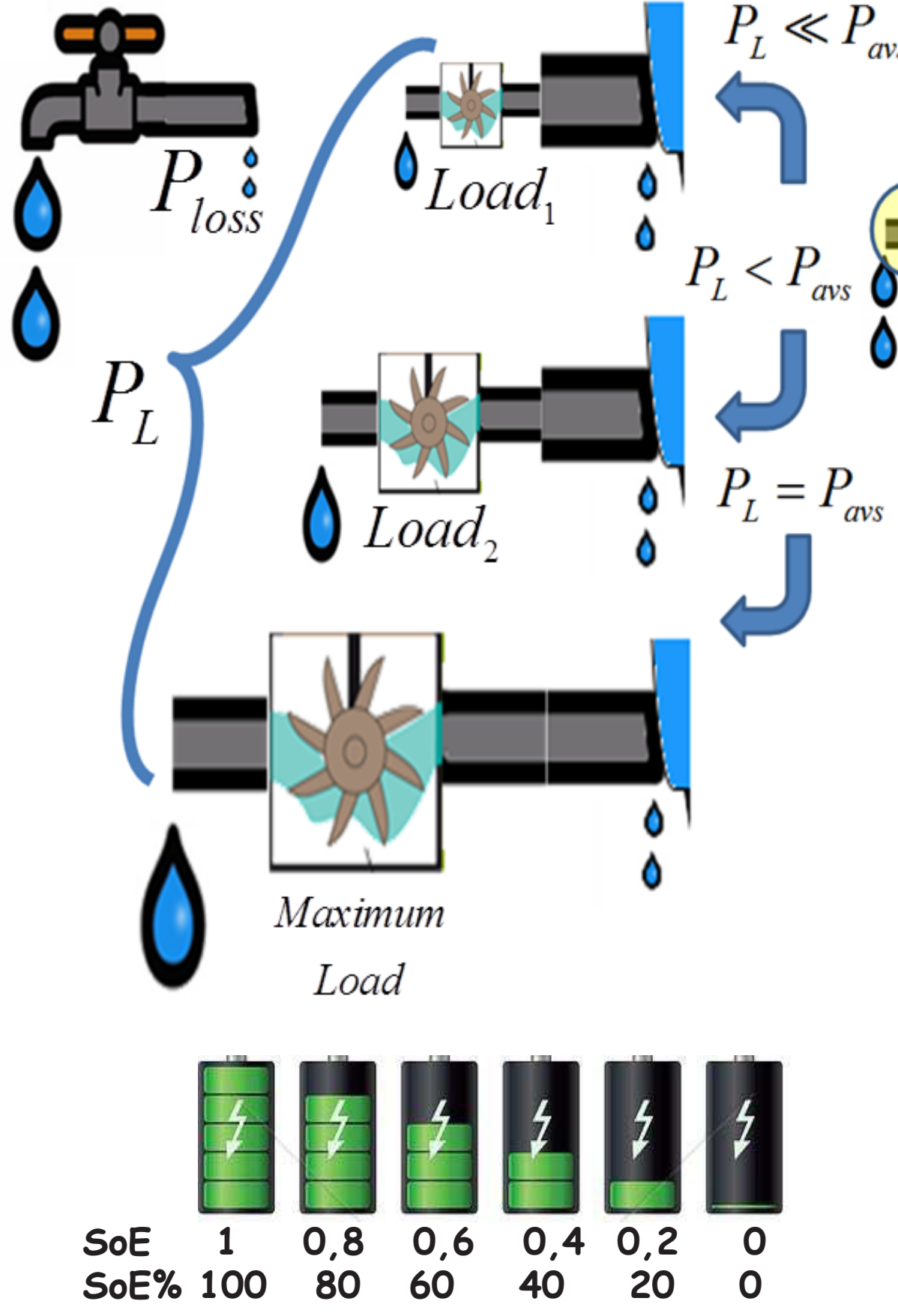
$$P_S(t) = -\frac{d}{dt}\left(\frac{E_L(t)}{\eta_s}\right) = -\frac{P_L(t)}{\eta_s}; \tag{3}$$

$$E_{st} = \lim_{t\to\infty} \int_0^t P_L(t)\cdot dt \quad , \text{ assuming } \lim_{t\to\infty} E_s(t) = 0; \tag{4}$$

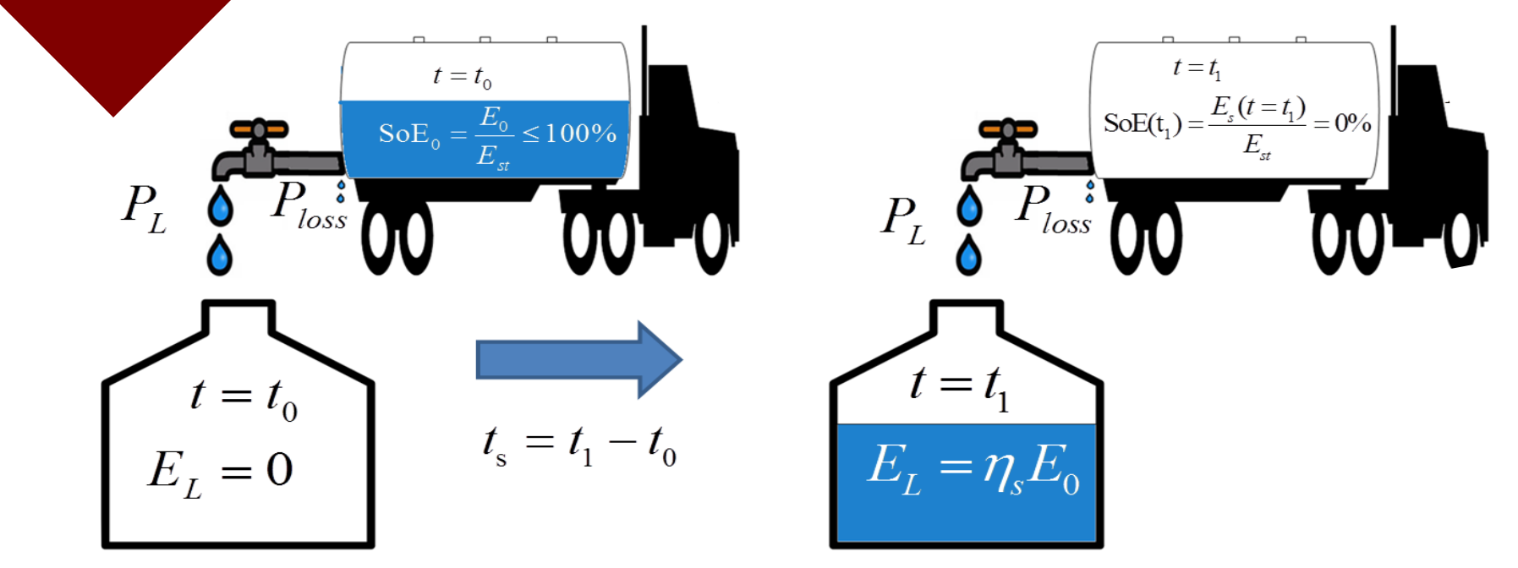
$$P_{avs} = \max\{P_L\}; \tag{5}$$

$$SoE = \frac{E_s(t)}{E_{st}}; \tag{6}$$

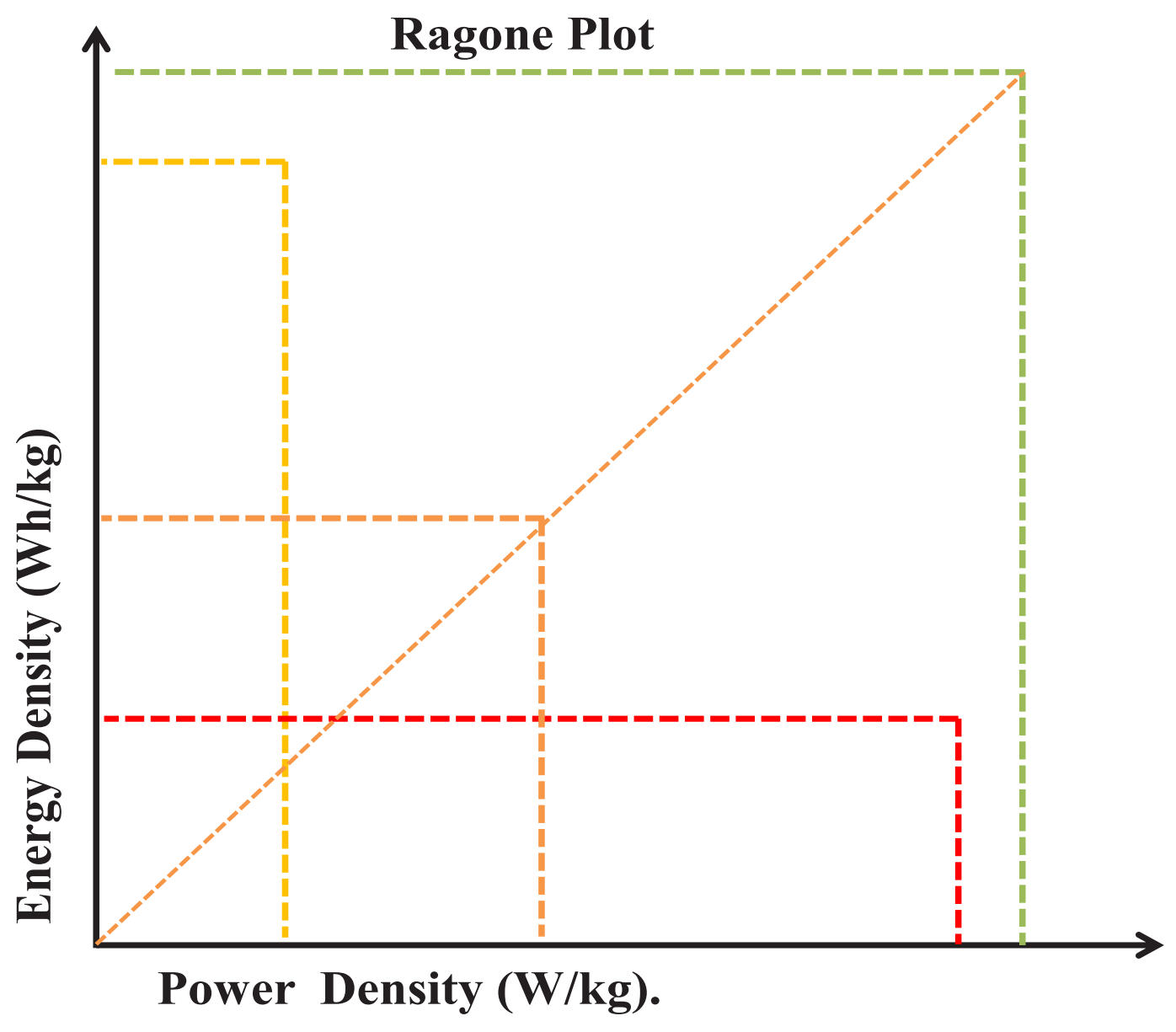
$$SoE = \begin{cases} 1 & E_L(t) < -E_{st}\eta_s(1-SoE_0) \\ SoE_0 - \frac{E_L(t)}{E_{st}\eta_s} & E_0 - E_{st} < \frac{E_L(t)}{\eta_s} < E_0 \\ 0 & \eta_s E_0 \leqslant E_L(t) \end{cases} \tag{7}$$

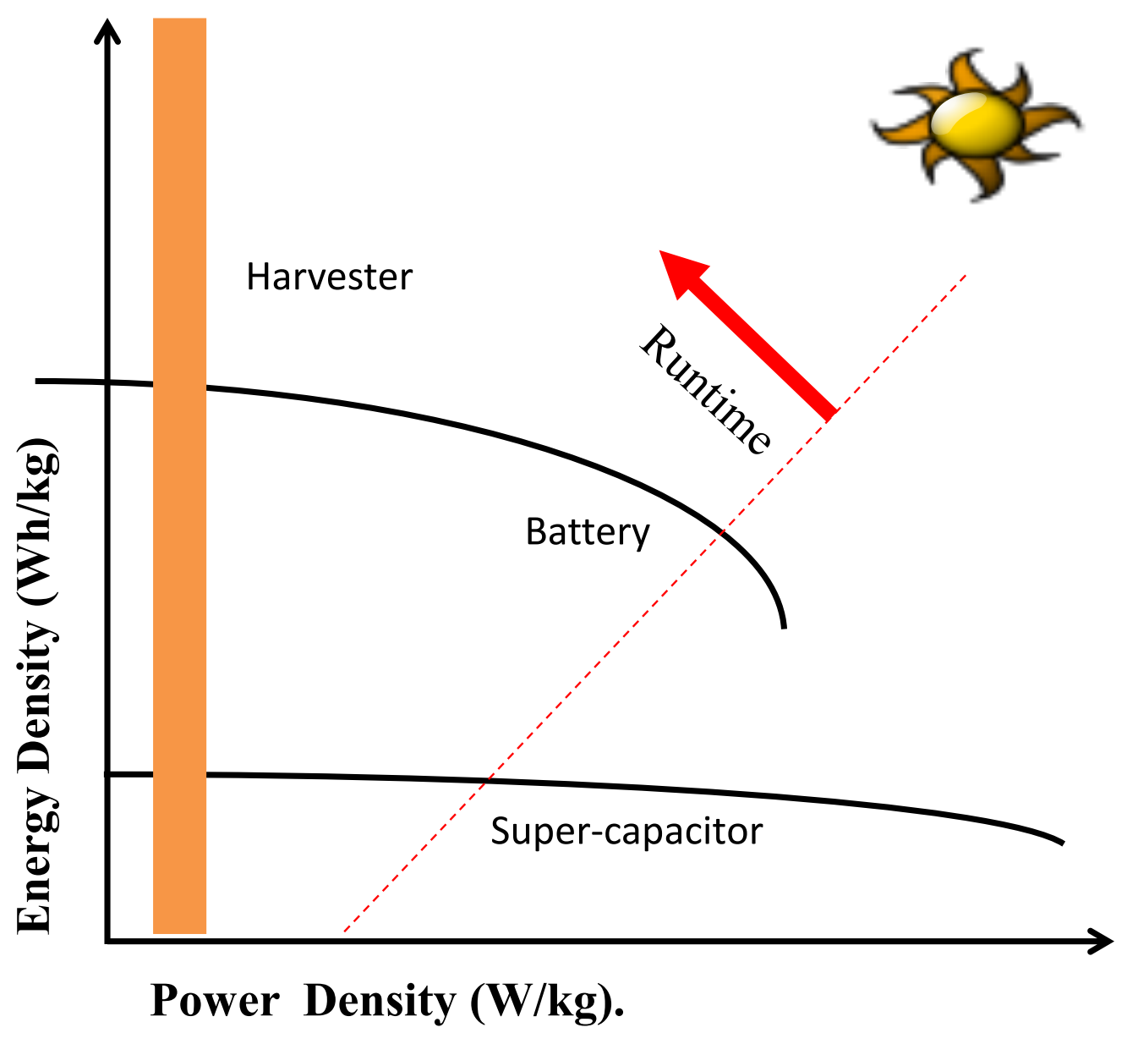


ENERGY POWER SUPPLY (EPS)



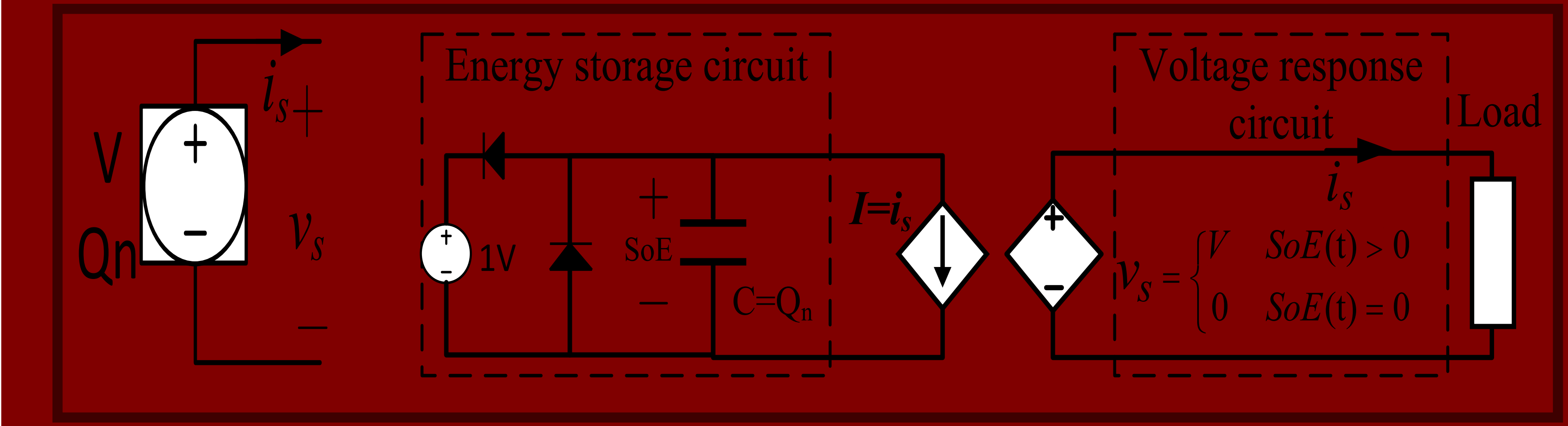
Proposed Taxonomy		
E_{st}	P_{avs}	Name
Infinite	Infinite	Ideal EPS
High	Low	Power EPS
Low	High	Energy EPS
Finite	Finite	Real EPS





Taxonomy Example	
Name	Example
Ideal EPS	The sun
Power EPS	Harvester
Energy EPS	Super-Capacitor
Real EPS	Battery

Ideal battery model

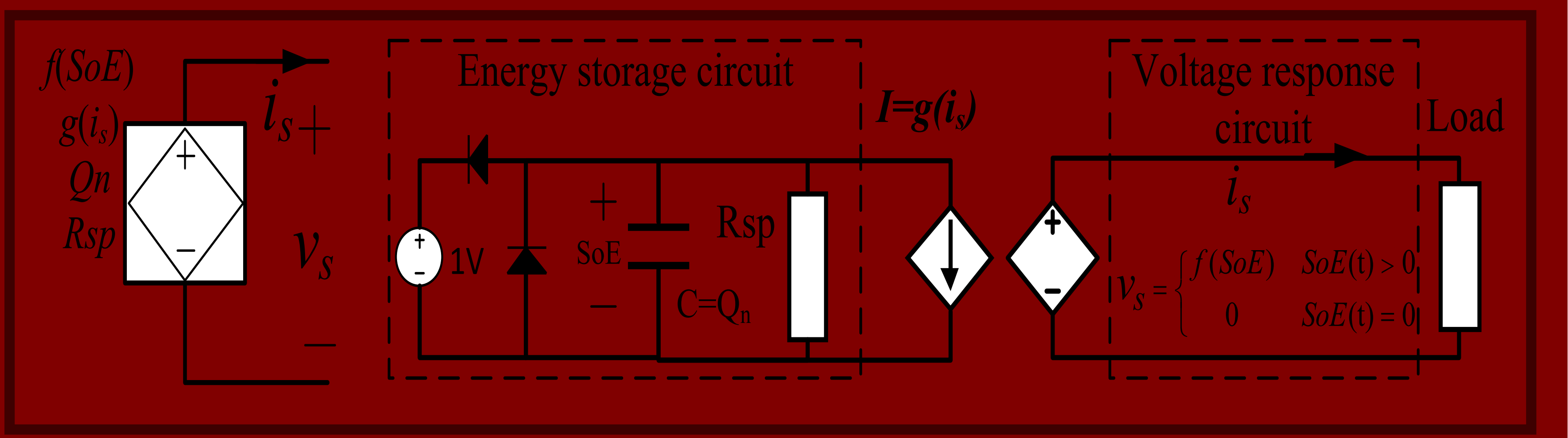


$$v_S(t) = \begin{cases} V & SoE(t) > 0 \\ 0 & SoE(t) = 0 \end{cases}; \tag{8}$$

$$SoE = \begin{cases} 1 & \frac{\int_0^t i_L(\tau)d\tau}{Q_n} \leqslant (SoE_0 - 1) \\ SoE_0 - \frac{\int_0^t i_L(\tau)d\tau}{Q_n} & \frac{SoE_0-1}{SoE_0} < \frac{\int_0^t i_L(\tau)d\tau}{Q_n SoE_0} < 1; \\ 0 & Q_n SoE_0 \leqslant \int_0^t i_L(\tau)\,d\tau \end{cases} \tag{9}$$

In conventional circuit theory the voltage source models can supply unlimited energy, therefore a direct battery model is unavailable, but using the circuit shown for modeling the battery, both its runtime and its DC I-V performance are captured.

General ideal batery model



In order to increase the model accuracy, tracking of the SoE is modeled by non linear relations (g and f) for describing the energy flow process. This approach allows capturing some nonlinear behaviors as: the C-rate effect and capacity fading effects.

TABLE II. Significant electric battery behaviors

Battery behavior	Description
1) I–V performance (IVP)	I–V performance is the estimation of the battery output voltage for any load.
2) DC–IVP	DC I–V performance is the estimation of the steady state battery voltage variations
3) Open circuit voltage (V_{oc})	Is the voltage of battery during equilibrium state when the load is a open circuit
4) Internal resistance on DC–IVP	The internal impedance of the battery, when it increases the battery efficiency decreases and thermal stability is reduced.
5) N on DC–IVP	The DC–IVP changes with N, e.g. The Rss increase when N increase.
6) T on DC–IVP	The DC–IVP changes with the ΔT, e.g. the V_{oc} increase when N increase.
7) Transient response	Battery output voltage response when the load current is a rectangular current pulse.
8) State of Health (SoH) tracking	The SoH is a measurement of the ageing of the battery that reflects the general condition of a battery compared with a new battery. The accuracy estimation of the SoH by the model is referred as tracking the SoH.
9) SoC tracking	The SoC is more common than SoE in battery literature, but they describe the same energy flow process. The accuracy estimation of the SoC by the model is referred as tracking the SoC.
10) Capacity loss (i.e. storage energy loss)	Changes in the useable capacity (storage energy) can be either a result of irreversible capacity loss or reversible capacity change. Capacity fading depends on many stress factors such as temperature, C-rate, SoC and depth of discharge.
11) Capacity fading due to cycle number	Irreversible capacity loss (storage energy) as a result of cell ageing due to cycling.
12) Capacity fading due to time	Irreversible capacity loss (storage energy) as a result of cell ageing due to storage time.
13) capacity loss due to T	Reversible capacity change as a result of Δ T.
14) C-rate effect (rate capacity effect or current recovery effect)	Reversible capacity change as a result of the C-rate. The current recovery effect is the recovered capacity by discharging at a lower current.
15) Runtime prediction	The continuous period of time during which the battery operates as an energy source for its load (i.e. output voltage bigger than end-of-discharge voltage).
16) Self-discharge effect	The storage energy (called usable capacity) declines as storage time (self-discharge) increases.
17) AC response	I–V performance when the load current is an AC current.
18) Charge (Ch) and discharge (dCh)	Typically, the behaviors for discharging are not equal to charging behaviors.

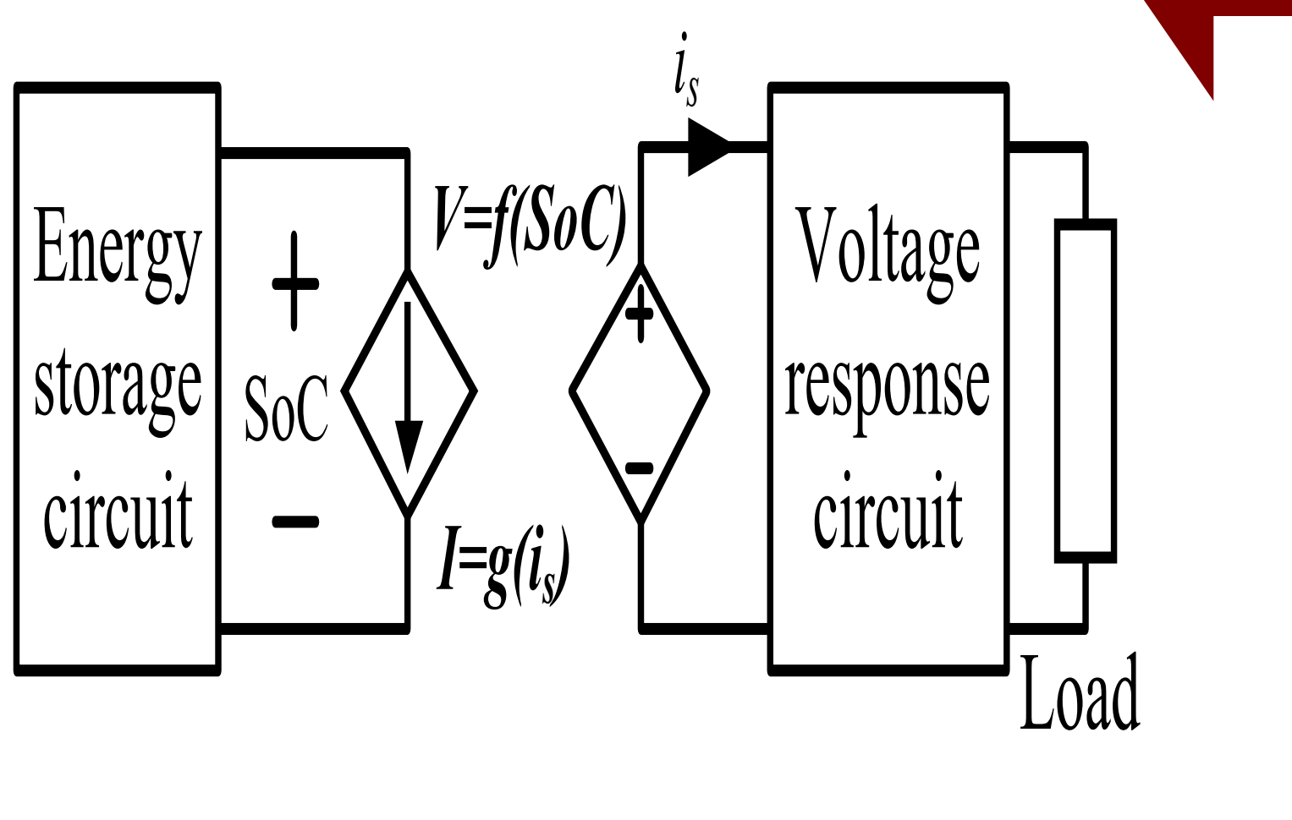
STATE OF ART OF THE CECBM

TABLE I. Comparison of the circuit values dependences on the analyzed models

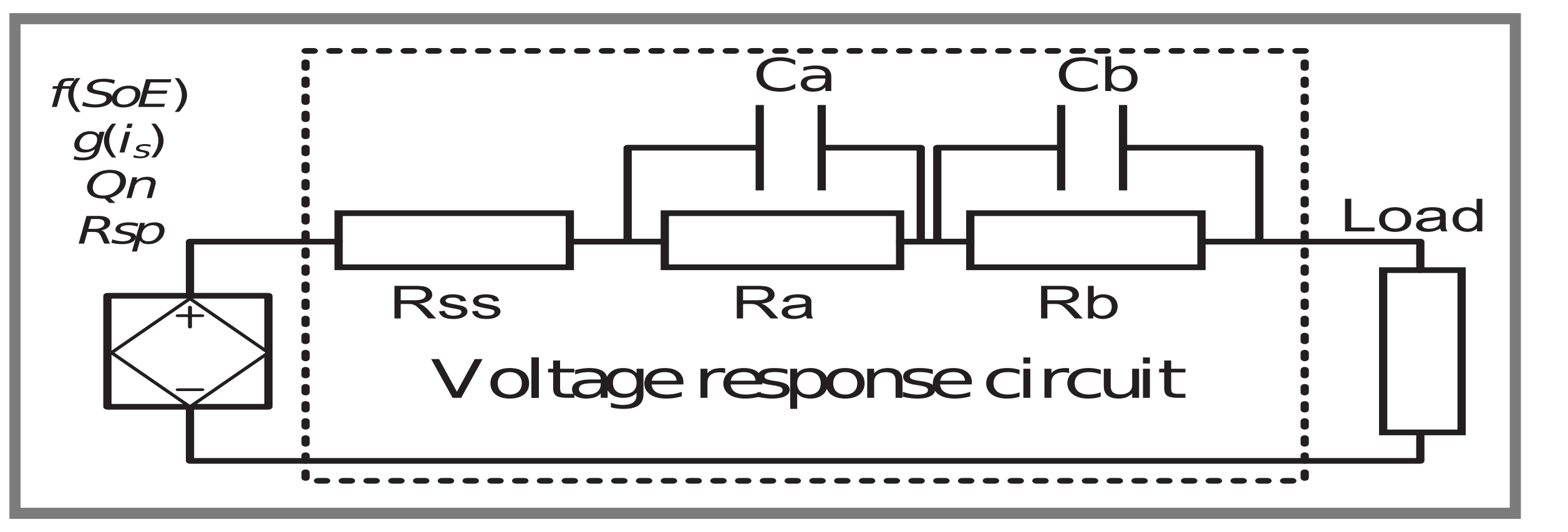
Model param.	Ideal	Gen.	Real.	2006 [7]	2009 [14]	2010 [8]	2012 [9]	2013 [10]	2011 [11]
Qn	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal
Rsp	infinite	Nominal	Nominal	infinite	infinite	infinite	infinite	infinite	infinite
Rss	0	0	Nominal	$h(SoC)$	$h(SoC)$	$h(SoC)$	$h(SoC)$	$m(SoC,is)$	$q(SOC,T,abs(is),sgn(is))$
Ra, Rb	0	0	Fixed	$h(SoC)$	$h(SoC)$	$h(SoC)$	$h(SoC)$	$m(SoC,is)$	$q(SOC,T,abs(is),sgn(is))$
Ca, Cb	infinite	infinite	Fixed	$h(SoC)$	$h(SoC)$	$h(SoC)$	$h(SoC)$	$m(SoC,is)$	$q(SOC,T,abs(is),sgn(is))$
g	$g(is)=is$	$g(is)=is$	$g(is)=is$	$g(is)=is$	$g(is)=is/CF$	$l(is,t)$	$l(is,t)$	$l(abs(is))$	$n(abs(is),sgn(is),T)$
$\frac{f}{sgn(SoE)}$	$f(SoE)=V$	$f(SoE)=V$	$h(SoE)$	$h(SoE)$	$p(SoE,T)$	$h(SoE)$	$h(SoE)$	$h(SoE)$	$h(SoE)$

TABLE III. Comparison of the proposed CECBMs

Behavior Table. II	Ideal	Gen.	Real	2006 [7]	2009 [14]	2010 [8]	2012 [9]	2013 [10]	2011 [11]	2010 [15]
Item 4	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
Item 5	no	no	no	no	yes	no	no	no	no	no
Item 6	no	no	no	no	yes	no	no	no	yes	no
Item 7	no	no	very lim	lim	lim	lim	lim	lim	lim	yes
Item 9	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Item 11	no	no	no	no	yes	no	no	no	no	no
Item 12	no	no	no	no	yes	no	no	no	no	no
Item 13	no	no	no	no	yes	no	no	no	yes	no
Item 14	no	no	no	no	no	yes	yes	yes	yes	no
Item 15	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Item 16	no	yes	yes	no	no	no	no	no	no	no
Item 17	no	no	no	no	no	no	no	no	no	no
Item 18	Ch&dCh	Ch&dCh	Ch&dCh	dCh	dCh	dCh	dCh	dCh	Ch&dCh	dCh



Real Battery model



Adding three resistors and two capacitors to the model, the following behaviors of the real battery were captured: limited output power, relaxation effect, transient response, and internal voltage drop when it is loaded.

Conclusions

The proposed DC voltage source with limited energy storage capacity was used for understanding the combined electrical circuit-based battery model. Further, it was presented a comprehensive state-of-the-art review of the progress that has been made on this battery model. Furthermore, a comprehensive development of the energy power supply concept and the energy flow process was presented and used for comparison of the analyzed models.

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