2026 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING
AND TECHNOLOGY SYMPOSIUM
POWER AND MOBILITY (P&M)
AUGUST 11-13, 2026 - NOVI, MICHIGAN

TIME-DEPENDENT POWER FLOW MODELING FOR NON-PASSIVE LOADS IN BATTERY ELECTRIC PROPULSION ARCHITECTURES

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ABSTRACT

Traditional Linear Circuit Analysis (LCA) relies on steady-state voltage assumptions that are fundamentally incompatible with battery-exclusive propulsion architecture. Whilst LCA remains valid for hybrid systems, where an auxiliary source actively regulates the State-of-Charge (SOC), it fails when analyzing non-passive, constant-power loads. In pure electric architecture, the time-dependent decay of the discharge voltage forces a continuous, non-linear increase in current to satisfy mechanical power demands. A time-dependent power flow methodology is introduced to resolve this theoretical divergence. Using the conservation of energy operating explicitly within the power domain, the time-dependent coupling of current and voltage can be modeled. This approach supersedes steady-state approximations for higher fidelity predictions for component efficiency, system heat generation, and battery capacity requirements for pure electric propulsion systems.

Citation: N. Ingarra, K. J. Kobus, J. G. Kobus “TIME-DEPENDENT POWER FLOW MODELING FOR NON-PASSIVE LOADS IN BATTERY ELECTRIC PROPULSION ARCHITECTURES” In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 11-13, 2026.

1. INTRODUCTION

Modern energy storage systems are used in a variety of platforms, including aviation drones, hybrid and electric vehicles (BEVs), and military silent-watch applications. Within each of these applications, the time-dependent behavior of the battery varies significantly, necessitating use-case-specific modeling. Accurate, context dependent modeling is critical for proper sizing, thermal management, and development of not only the battery pack, but also its supporting power electronics. Relying on a universal analytical approach is fundamentally flawed; the broad application of standard Linear Circuit Analysis (LCA) is only mathematically valid under specific operational conditions.

Although the origins of battery cell technology date back to the late 18th century [1], modern electromechanical systems represent a complex convergence of chemistry, solid-state physics, and electromechanical engineering. Despite this inherent complexity, contemporary electrical engineering practices often oversimplify system-level models. When a battery serves as an exclusive energy source in an architecture, conventional analysis methodologies typically, and incorrectly, characterize the battery as an ideal component capable of supplying a constant input voltage to its load. Unless an auxiliary power source is actively maintaining the battery's State-of-Charge (SOC), true constant input voltage conditions are physically impossible to sustain.

Unfortunately, this results in a potential divergence of the expected results of electrical and electronic system performance when using the theoretical model compared to what may be experienced in actual real-world applications. For example, in the instance where an electrical motor is evaluated at a constant input voltage, the performance of that motor would vary if the input voltage changed. To help engineers better understand these conditions, this paper will go to the fundamental modeling of electrical modeling of components powered by a battery system. The proposed modeling will provide better correlation with testing as well as sizing batteries packs to meet the power and energy demands.

In electrical circuit design, development, and testing, linear circuit analysis (LCA) is typically a standard methodology used for electrical systems [2]. With the recent development and widespread global production of electric propulsion methods for transportation systems, a comprehensive test design approach that complements LCA can be valuable. There are many benefits of having "up-front" test data that has high correlation to a system's actual performance. These new methods can be based on the fundamental principles of the conservation of energy principle when a battery is used as a system's primary power source compared to having the battery assist the main power source. Instead of a battery having a constant, unchanging energy delivery rate (with constant current and voltage depending solely on the load's power demand), a battery's behavior will be impacted by the type of load it supplies power to, which will then change the characteristics of a battery's discharge conditions.

There are two types of electrical loads: passive and non-passive. A passive load does not have a specific power requirement. This load could consist of an LED, for instance, which reacts to different power inputs. An LED would then be dim with a lower input power. A non-passive load is an electro-mechanical load, such as a motor connected to a pump, fan, or driveline. The pump, fan, or driveline requires power from the mechanical domain (shaft work), and the motor must meet the mechanical power required. This mechanical power must come from the electrical domain.

When a battery is delivering energy to non-passive loads, where the power demand must be satisfied (such as a motor driving a pump), battery modeling can be designed to provide test results that have a higher correlation with other types of electrical components (such as common power electronics like capacitors and inductors).

In electrical engineering, there are four types of dependent sources: Current Controlled Voltage Source (CCVS), Voltage Controlled Voltage Source (VCVS), Voltage Controlled Current Source (VCCS), and Current Controlled Current Source (CCCS). [2].
A fuel cell is an example of a CCVS where its output voltage depends on the discharge current. An example of a VCVS is a non-inverting amplifier. An example of VCCS is a field effect transmitter. An example of a CCCS is Bipolar Junction Transistor.

A battery's SOC and current draw will impact the discharge voltage. If a battery is assumed to be an independent voltage source, its voltage is constant, but batteries' properties change with its SOC and discharge voltage it does not fall into any of the existing dependent source categories.

The fundamental element of a battery is a cell, and multiple cells make up a pack. A cell is typically characterized, and its individual data is applied, at a pack level. A cell is typically characterized by a constant current discharge otherwise known as a C-rate. As the discharge current increases, there is an energy loss within the cell itself which also increases, as shown in Figure 1.

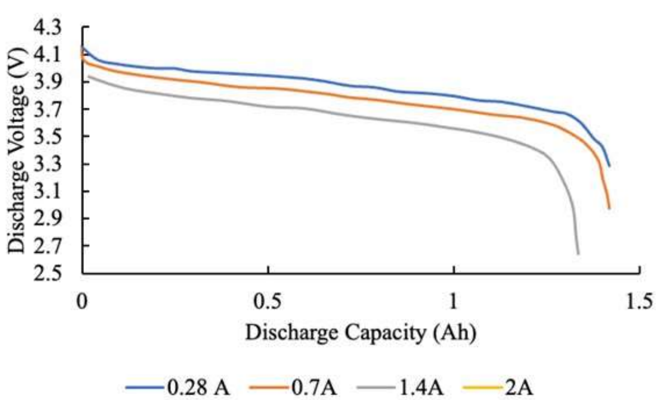


Figure 1: Sample Cell Discharge Curve [3]

The discharge voltage changes as the battery discharges. The decreasing discharge voltage will reduce the power the battery is producing the discharge current will also impact the battery capacity. A real battery is not an ideal voltage source because its voltage changes with the state of charge and current. It is in fact a dependent voltage source. The cell has less capacity as the current increases due to the increase in Ohmic losses. Based on the behavior shown in Figure 1, a cell is sometimes believed to have an unchanging effective resistance. However, the cell discharge voltage will change based on its state of charge, as well as the current it is delivering. In this mode of discharge, the power output will not be constant, it will decrease as the state of charge decreases. The current will remain constant, but the cell voltage will decrease and therefore reduce the output power of the cell. If a cell is discharged differently then, there will be different characteristics out of the battery.

When a battery is the only power source like in a Battery Electric Vehicle (BEV), its voltage will not be constant and as a result, the current will be dependent on the battery voltage, and the system will never be in steady state. It will not behave as a constant voltage source.

There are several types of battery models and each one attempts to understand battery behavior, but each one is using a linear circuit analysis to predict the relationship between open circuit voltage and discharge voltage. The battery models are shown in Table 1.

The basic battery model is a simple/linear battery model as shown in Figure 2. To improve the simple model, it is assumed the battery resistance is changing with state of charge as shown in Figure 3.

Table 1 Types of Battery/Cell Models and Applications [4]

Model Nature	Model	Data	Suited Application
Electro-chemical	Pure Electro-Chemical	P	Battery Design
Electro-chemical	ECM/Reduced Order	SE	Battery Design
Electro-chemical	Electro-Chemical	SE	Battery Design
Electrical -Analytical	Peukert's Model	E	Prediction
Electrical -Analytical	Rankhmatov and Vrudhula	SE	Prediction
Electrical -Analytical	Sheperd and other Interations	SE	Prediction
Electrical -Analytical	State-Space	E	Prediction
Electrical -ECS-Simples	Simple Rint	E	Real time control and SOC Estimation
Electrical -ECS-Simples	Enhanced Rint	SE	Real time control and SOC Estimation
Electrical -ECS-Simples	RC	SE	Real time control and SOC Estimation
Electrical -ECM-Thevenin	1st Order	SE	Real time control and SOC Estimation
Electrical -ECM-Thevenin	2nd Order	SE	Real time control and SOC Estimation
Electrical -ECM-Thevenin	3rd-nth Order	SE	Real time control and SOC Estimation
Thermal	Analytical Thermal	P-SE	Real time
Thermal	ECM Thermal	SE	Real Time
Combined Models	Electro-Thermal	SE	Real Time
Combined Models	Thermo-electromechanical	P	Real Time
Combined Models	Thermo-mechanical	SE	Real Time

There is not one model that predicts cell performance and heat generation. Each of the models does use linear circuit analysis to predict the behavior of the battery and each one approximates the circuit differently. The models are trying to determine the relationship between open circuit voltage and discharge voltage.

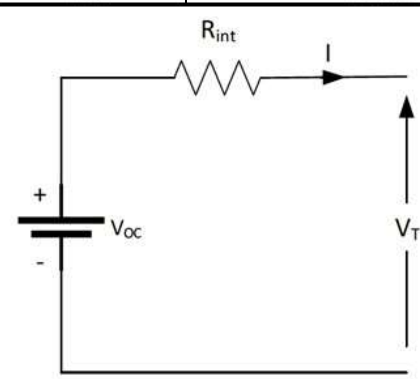


Figure 2 Simplified Battery Cell Model [4]

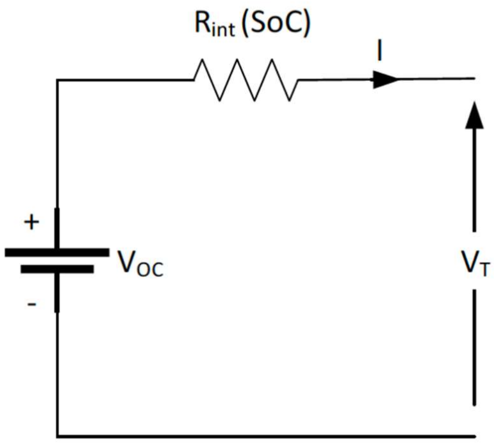


Figure 3 Enhanced Battery Cell Model [4]

Both cell models can be used to predict electrical performance, and both models use linear circuit analysis, but these models are not used to compute the heat generation unless they are combined with other models. The enhanced battery model allows for the cell's resistance change based on the state of charge of the battery.

Another detailed model with the second order Thevenin Model as shown in Figure 4.

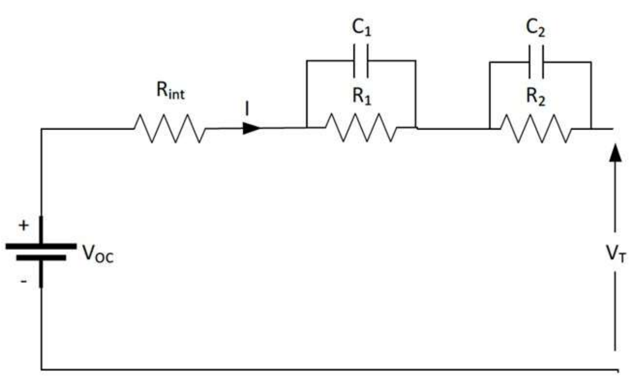
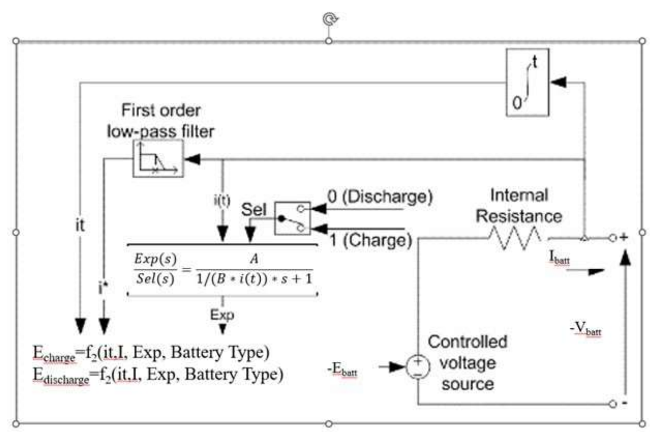


Figure 4 Second Order Thevenin Model [4]

The anode and cathode are approximated with capacitors and resistors. This type of model is used to provide better fidelity than the other models, but it cannot provide heat generation unless it is coupled with other models. Like the other two models it does use linear circuit analysis. It should be noted that cells should model both electrical and thermal together because the cells performance does depend on their temperature.

Some of the commercially available software like MATLAB/SIMULINK also use linear circuit analysis. The SIMULINK Battery Model in Figure 5 shows the correlation between discharge voltage, current, resistance, and the cell's State of Charge (SOC).

Figure 5 SIMULINK Battery Model [5]



What the model in Figure 5 (with the coefficients that have been obtained from experimental data) shows is that a generic cell model can be used that will incorporate the ability to determine the cell state of charge, as well as the computation of discharge voltage and resistance. The SIMULINK model also uses linear circuit analysis.

In Figure 5, it can be seen then that the battery is considered a controlled voltage source. The open circuit voltage (OCV) is a function of the SOC of the battery. The open circuit voltage will decrease as the state of charge decreases. As a result of the SOC decreasing, the discharge voltage will also decrease. The decrease in system voltage will lead to lower discharge of power. In this case the system power requirement may not be met. In fact, it is not just the resistance that is changing, it is also the open circuit voltage as shown in Figure 6.

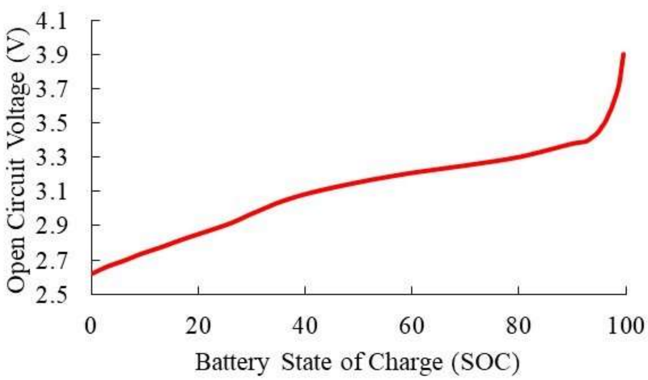


Figure 6: Sample Cell Open Circuit Voltage vs. State of Charge [6]

The theoretical (open circuit voltage) is the theoretical voltage of the cell and it is the starting voltage without any losses, and it cannot be violated. There are three types of losses in the battery, and these losses are charging transfer which is also known as activation losses, Ohmic losses and the last type of losses are known as concentration losses. If the losses are subtracted from the open circuit voltage, then the discharge voltage is obtained as shown in Figure 7. Note the discharge curve Figure 1 and Figure 7 do have non-linear regions along with a linear region.

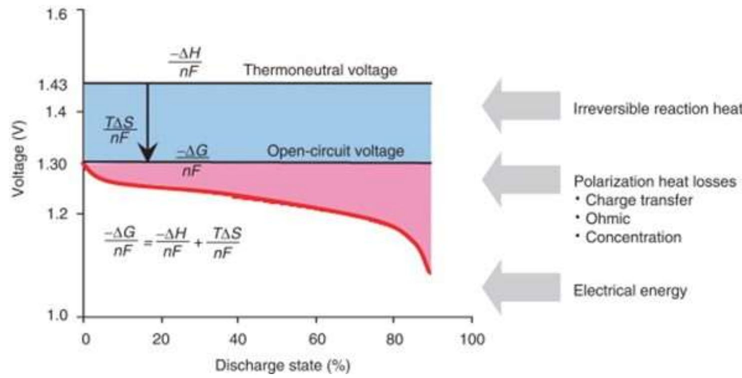


Figure 7: Relationship Between Open Circuit Voltage and Discharge Voltage [7]

The system analysis must be performed where the current depends on the cell voltage and the load. Linear Circuit Analysis is not applicable when the voltage source is not constant because the constant power will not be maintained. If the discharge voltage is constant, then the power discharge will be constant.

Not all the losses in the cell are linear, as shown in equation 1. The natural log does appear in activation loss and concentration loss term as shown in equation 1.

$$E_D = E^o - \frac{R_u T}{\propto nF}\ln\left(\frac{j}{j_o}\right) - rj - \frac{R_u T}{nF}\ln\left(1 - \frac{j}{j_l}\right) \qquad (1)$$

This is the main reason the voltages losses in a cell are non-linear, but in the cell models they are being approximated with resistors and/or capacitors to predict transient behavior. The activation losses and concentration losses are electro-chemical losses which explain their non-linear behavior. The only way a cell can give a constant voltage is if its state of charge can be held constant and this will occur only in a hybrid application. The other power source can maintain the state of charge of the battery.

2. Theory

A cell can have up to three (3) types of discharge characteristics: constant current, constant resistance, or constant power. In Figure 8, we see that during constant current discharge, the cell discharge voltage continuously decreases with the state of charge. As a result, the power delivered by the cell also decreases due to the falling voltage. Cells are currently characterized by a constant current, computing the state of charge much easier and as a result the discharge power will not be constant.

With constant power discharge, the cell discharge voltage decreases faster than the constant current discharge. This is mainly due to the increase in current. In this case, the cell adjusts to meet the power demands of the load. Keeping track of the cell capacity is not as easy because of the continuously changing current.

In the case of constant resistance, the cell maintains its voltage longer during the constant resistance discharge. The cell will adjust the current to maintain a constant resistive load. The more dominant discharge modes are constant current and constant power.

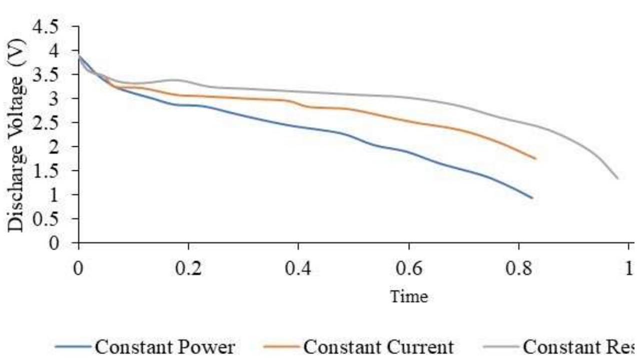


Figure 8: Discharge Voltage Impact Based on Discharge Mode [3]

As shown in Figure 8, in constant current discharge, the discharge voltage decreases along with the SOC. In the constant power discharge, the cell run time is lower than that of the constant current. The constant resistance discharge profile shows the cell running for the longest time. To better understand this, the discharge current needs to be further examined.

Electrical power is a result of the discharge current and discharge voltage; the discharge current is also examined in each of the three cases as in Figure 9.

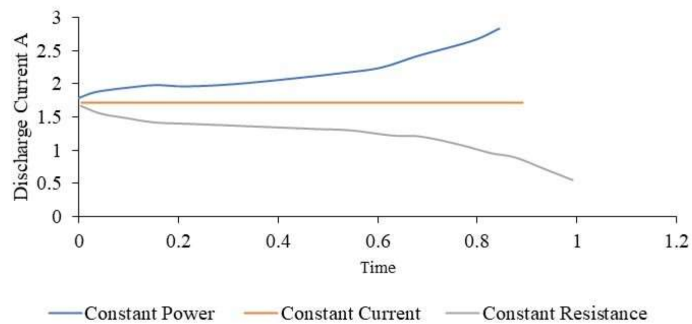


Figure 9: Discharge Current Impact Based on Discharge Mode [3]

As shown in Figure 9 in constant current discharge, the current remains constant and does not change with time, and it has the second longest run time. The decreasing current will produce lower power, because of the decreasing voltage. The constant power case does have the shortest discharge time out of the three cases, and it shows the current is increasing with time. This is due to falling discharge voltage. In the case of constant power discharge, the current is low initially when the voltage is high and the current increases as the cell discharge voltage decreases to maintain the power. Note that during constant power, the power discharge remains constant at the expense of decreasing voltage and increasing current. The constant resistance case does have the longest discharge time; in this case the current is decreasing with time to maintain constant resistance.

Also, the capacity of the cell will decrease faster during constant power discharge and must be sustained by integrating the current. In the case of constant resistance, the current decreases as the voltage drops to maintain the resistance of the load. The last step is to look at the different power discharges as shown in Figure 10.

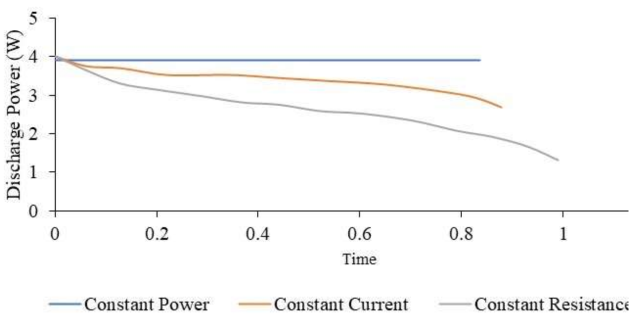


Figure 10: Discharge Current Impact Based on Discharge Mode [3]

As shown in Figure 10 the constant power does have the shortest discharge time, and it provides the most power. The constant current discharge will have the discharge power decrease because of the drop in discharge voltage. The constant resistance case has produced the least amount of power mainly because of the changes in the voltage and current. In each of these cases the cell heat generation will be completely different due to the change in voltage and current.

The discharge mode of the battery will also impact the battery heat generation from Joule heating. The properties of the battery are temperature dependent and thus the electrical and thermal system must be coupled together to improve battery modeling.

Based on the battery/cell models in Table 1, and the SIMULINK model shown in Figure 5, these models will use a Linear Circuit Analysis (LCA). Kirchhoff's Voltage Law (KVL) is used to solve for current. The battery block itself does not hardcode a constant power, instead this behavior could be enforced by the load block connected to the battery model. To obtain a constant power result, the required power is divided by the voltage to yield current. To keep the model stable there must be a voltage cut off. This process makes it difficult because the discharge voltage is not always known.

In the scenario where the battery is the main power source, like in a BEV, the system voltage will naturally decrease with time, and if a constant current method is used, the output power of the battery will be decreasing. In this case the current will be dependent on the cell discharge voltage.

In case of a hybrid, the battery state of charge can be maintained by the other power source, and the system voltage can be considered constant. In this case the cell voltage can be held, and the properties of the battery will remain constant. Cell manufacturers will characterize batteries at constant current or C-rate to determine their characteristics. A cell is limited in that it can provide constant power but not constant voltage.

The constant current discharge and constant power discharge may impact the applicability of LCA and need to be assessed to confirm whether it is applicable. This can be determined by examining the characteristics of the system's source, load, or both.

This theory can also be applied to a DC motor and a resistor, inductor, and capacitor (RLC) circuit. The circuit model of the DC motor is shown in Figure 11.

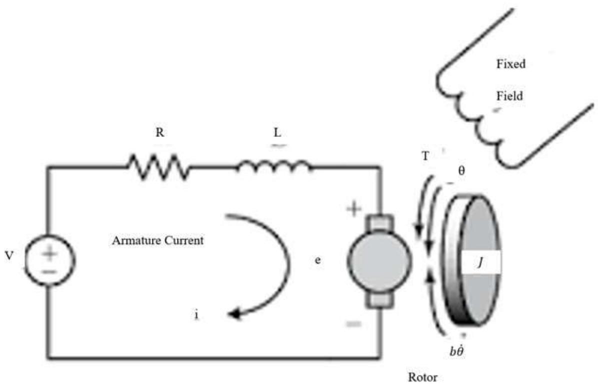


Figure 11: Circuit Schematic of a Motor Error! Reference source not found.

An electric motor can be mathematically represented by use of two (2) differential equations, as shown in Equation 2 and Equation 3:

$$J\ddot{\theta} + b\dot{\theta} = KI \quad (2)$$

$$L\frac{dI}{dt} + RI = V - K\dot{\theta} \quad (3)$$

The first equation as shown in equation 2 is the torque balance of the motor. The second equation as shown in equation 3 is the result of KVL applied to the motor. In a steady-state solution, the current would remain constant along with the voltage and a solution can be obtained with the constants known. To solve the transient case, the discharge mode of the type of cell discharge needs to be known. If the cell is discharging constant current the power of the motor will not be met and the voltage and current will be a function of time. If the cell is discharging constant power, the voltage and current will be continuously changing and the voltage and current will also be a function of time also.

The standard method of Kirchhoff's Voltage Law (KVL) could be used if the power does not need to be satisfied, but if the power needs to be met then a new approach is needed. The current can be solved since the voltage is constant. This is true only when the battery is in a hybrid application since the battery voltage is controlled with the other power source. If the time-based element is introduced like in a battery only power system, the motor speed and torque will be continuously changing as shown in equation 4 and 5.

$$J\ddot{\theta}(t) + b\dot{\theta}(t) = KI(t) \quad (4)$$

$$L\frac{dI(t)}{dt} + RI(t) = V(t) - K\dot{\theta}(t) \quad (5)$$

2.1. Kirchoff's Voltage Law

The current method involves using KVL to predict the current. Where Equation 2 is Newton's Second Law and Equation 3 is Kirchhoff's Voltage Law, the voltage of the source is known and kept constant in the current model. If the voltage is not constant, then the model would not be applicable since the voltage is continuously changing. If the cell is discharging constant power, the voltage and current will ***not*** remain constant. Therefore, examination of the motor model will be required with variable input voltage, starting with the conservation of energy in its raw form as shown in Equation 6:

$$V_B(t)I_B(t) - V_R(t)I_B(t) - LI_B(t)\frac{dI_B(t)}{dt} - P_m = 0 \quad (6)$$

The conservation of energy assumes the voltage and current are a function of time. Note that the differential equation is not homogenous, and current (I_b) only appears in three terms. The required power comes from the mechanical domain. To simplify the process, Equation (6) divides the equation by I_b:

$$V_B(t) - V_R(t) - L\frac{dI_B}{dt} - \frac{P_m}{I_B(t)} = 0 \quad (7)$$

The resistor voltage can be further simplified through Ohm's Law, as shown in Equation 8:

$$V_B(t) - I_B(t)R - L\frac{dI_B(t)}{dt} - \frac{P_m}{I_B(t)} = 0 \quad (8)$$

The last term of the equation contains power and current. The required power is known; the current and voltage are changing. Therefore, we cannot solve the equation for voltage and current simultaneously. First, we must solve the current, and then we can solve the voltage. To get the original motor model back with the conservation of energy approach, the motor power can be broken down into torque and angular speed as shown in equation 9.

$$P_m = \tau\omega \quad (9)$$

If the relationship of torque and current are used from Equation 2 is substituted into equation 9 then the mechanical power can be expressed in with current as shown in equation 10.

$$P_m = KI\omega \quad (10)$$

If Equation 10 is substituted into equation 8 then the current in the denominator is eliminated and Equation 2 is obtained.

$$V_B(t) - I_B(t)R - L\frac{dI_B(t)}{dt} - K\omega = 0 \quad (11)$$

The approach does eliminate the current in the denominator. This approach also shows KVL, and the conservation of energy are the same. With a decreasing system voltage, the question now comes into play whether the same performance can be obtained or if performance will decrease because of the lower cell voltage.

In the case of the electric motor, the load will be non-passive because the motor must provide power to satisfy the mechanical load. As the current changes, the required voltage will also change. When the voltage decreases, the required current will increase, and this increasing current will further reduce the battery's SOC. To further complicate the issue, the efficiency of electronics changes with input voltage as shown in Figure 12 and Figure 13:

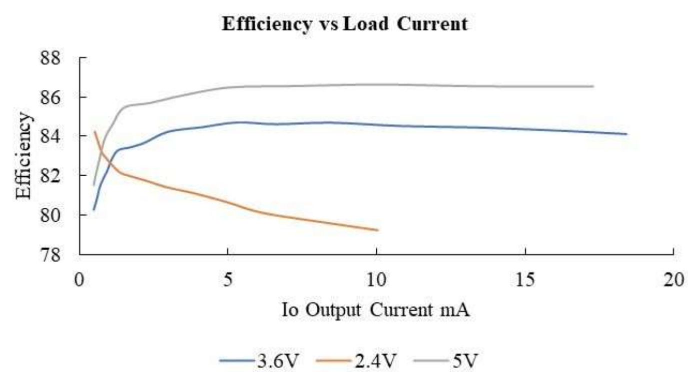


Figure 12: Electronic Module Efficiency Based on Load Current [9]

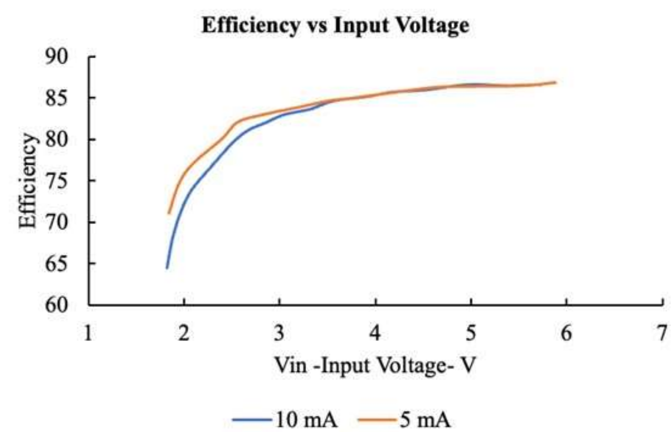


Figure 13: Electronic Module Efficiency Based on Input Voltage [9]

Based on Figures 12 and 13, as input voltage decreases, so does reported efficiency which will lead to additional input power required as shown in Equation 12.

$$P_i = \frac{P_r}{\eta} \qquad (12)$$

Where P_i is the input power, P_r is the power required, and η is the component efficiency, as input voltage decreases, the required power delivered will increase. With changes in the efficiency of electronics, the input voltage and current must be known to compute the power needs. As input voltage drops, the input current will increase to meet the power demands. This makes the required power more dependent on voltage, current, and the battery.

Equation 7 and Equations 2 and 3 are not the same, but Equation 7 can be simplified by using Equations 2 and 3 assuming a constant voltage. In the case of Equation 7, LCA cannot be used. However, the insights derived by the current in the denominator can help explain inrush current. The new equation is non-linear and non-homogenous and would give a different solution to the existing model. The next step involves examining a battery in a resistor, conductor, capacitor (RLC) circuit. The current equation obtained from Kirchoff's Voltage Law (KVL) is shown in Equation 13:

$$V_s(t) - \int_0^t \frac{i(t)}{c}\, dt - iR - L\frac{di}{dt} = 0 \qquad (13)$$

The conservation of energy is applied to the RLC circuit, as shown in Equation 14:

$$V_s(t)i(t) - V_c i(t) - V_R i(t) - V_l i(t) = 0 \qquad (14)$$

Note the current is in each term and the equation is homogenous and linear. The current can be factored out of each of the terms as shown in Equation 15:

$$V_s(t) - V_c - V_R - V_l = 0 \qquad (15)$$

The equations for voltage and current for capacitors, resistors, and inductors can be substituted into Equation 13, resulting in Equation 16:

$$V_s(t) - \int_0^t \frac{i(t)}{c}\, dt - iR - L\frac{di}{dt} = 0 \qquad (16)$$

Note that the conservation of energy shown in Equation 16 is the same as in Equation 13. Therefore, linear circuit analysis can be used, which is why we propose the use of the electrical matrix, as it illustrates the typical approach for all source and load characteristics, as shown in Table 2. LCA is a special case of the *conservation of energy***.**

Table 2: Typical Use Cases of Linear Circuit Analysis

Source	Load	Linear Circuit Analysis
Steady State	Passive	Yes
Steady State	Non-Passive	Yes
Dynamic	Passive	Yes
Dynamic	Non-Passive	Yes

The next step involves examining our current circuit analysis as shown in Table 2. Based on our dynamic motor modeling with a battery as the main power source, we propose adding an additional tool to the toolbox and limiting the use cases of LCA. The new proposed matrix is shown in Table 3:

Table 3: Proposed Change for Applicability of Linear Circuit Analysis

Source	Load	Linear Circuit Analysis
Steady State	Passive	Yes
Steady State	Non-Passive	Yes
Dynamic	Passive	Yes
Dynamic	Non-Passive	No

The next point involves defining a passive and non-passive load. The main components integral to passive loads are capacitors, resistors, and inductors. In each of these cases, a voltage-current relationship can be applied to the electrical power equation, as shown in Equations 17, 18, and 19. The first case that is examined is the capacitor. In Equation 17, the electrical power is computed by voltage and current.

$$P = VI \tag{17}$$

In the capacitor, there is a relationship between the current and the derivative of voltage with respect to time, as shown in Equation 18.

$$I = C\frac{dV}{dt} \tag{18}$$

By combining Equation 17 and Equation 18, a relationship between voltage and power can be obtained. This function is continuous everywhere:

$$P = CV\frac{dV}{dt} \tag{19}$$

The next component that qualifies as a passive load is the resistor. The resistor has a voltage and current relationship, as shown in Equation 20:

$$V = IR \tag{20}$$

If Equation 17 is combined with Equation 20, two equations can be obtained for the resistor power, as shown in Equation 21:

$$P = I^2R = \frac{V^2}{R} \tag{21}$$

Like the capacitor, the power can be related to either voltage or current and is continuous everywhere. The last component is the inductor, and the voltage and current relationship for this component is shown in Equation 22:

$$V = L\frac{dI}{dt} \tag{22}$$

The voltage relationship of Equation 22 can be placed into Equation 17 to obtain Equation 23:

$$P = IL\frac{dI}{dt} \tag{23}$$

Like the capacitor and resistor, the inductor power can be expressed in terms of one variable and is continuous everywhere. A non-passive load involves loads in which power requirements must be satisfied and the voltage and current respond to the power needs. Power is known in the case of electrically generated power. But voltage and current are not known in cases in which the battery is the primary load. If KVL is applied, the power is divided by the current to convert into the voltage domain as shown in Equation 24:

$$V = \frac{P}{I} \tag{24}$$

If the power required is fixed, the required voltage the battery needs to be produced depend on the current, at high low current high voltage is required as current increases the required voltage decreases.

3. Discussion

Batteries have three distinct modes of discharge, and their mode of discharge is influenced by the load applied to the battery.

In cases of a hybrid power system, the other power source can maintain the state of charge of the battery and thus maintaining the system voltage and the current mode of LCA is valid.

On the other hand, if the battery is the only power source and it is required to meet the power demand, then the LCA is not applicable and thus the power must be mapped in and out of each component to meet the electrical load. This approach requires the raw form of the Conservation of Energy.

In addition, the battery will be discharging under constant power, and electrical system will have to be designed for increasing current.

In a battery only power system, if the power does–not need to be met, LCA can still be used, and the load will respond to reduced power. The battery must be modeled with the electrical system to properly determine the size of the battery as well as the heat generation of the electrical components to maintain the system at its proper temperatures.

4. Conclusion

In electric propulsion architectures, the operational behavior of the battery is dictated by its application. In hybrid architecture, where an auxiliary power source actively regulated the State-of-Charge (SOC), the battery can maintain a relatively constant discharge voltage. Under these controlled, steady-state conditions, constant current equates to constant power, and traditional Linear Circuit Analysis (LCA) remains a valid model.

However, in battery-exclusive applications, such as pure Battery Electric Vehicles (BEVs), the assumption of a steady-state voltage is invalid. Because the battery serves as the sole energy source for non-passive, constant power loads (e.g., traction motors), the time-dependent decay in discharge voltage forces continuous, nonlinear increase in current to satisfy mechanical power demands. Under these dynamic conditions, steady-state LCA fails to accurately model the system throughout its discharge.

The use of time-dependent power flow modeling, via conservation of energy operating explicitly in the power domain, rather than relying solely on Kirchoff's Voltage Law (KVL), is required to accurately predict the system's behavior. By continuously mapping the time-dependent current-voltage relationship, the flaws of steady-state assumptions can be bypassed, achieving higher-fidelity predictions of component efficiency, time-dependent heat generation, and a more accurate required capacity of the battery pack.

Whilst this theoretical model resolves the divergence between LCA and actual non-passive load behavior, further empirical validation is required. Future work may focus on the verification of this time-dependent power flow methodology against physical dynamometer testing throughout high diversity vehicle drive cycles. Furthermore, integrating this power-domain model with time-thermal degradation models will allow for a more comprehensive analysis of battery pack-level efficiency under extreme environmental conditions.

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7. ACRONYMS

GVSC	Ground Vehicle System Center
J	moment of inertia of motor
B	Motor viscous friction constant
K	electromotive force constant /motor torque constant
R	Resistance
L	Electrical Inductance
V	Voltage
P_m	Mechanical power required
η	Efficiency (P_{out}/P_{in})
k	proportionality constant relating output voltage to current
i,j	Current density

I	Current
t	time
C	Capacitance
V_{OC}, E_{OC}, E^{o}	Open Circuit Voltage
R_{int}	Battery Internal Resistance
SOC	State of Charge of Battery
V_T, E_D	Battery Terminal Voltage/Battery Discharge Voltage
R_u	Universal Gas Constant
T	Absolute Temperature
α	Charge Transfer Coefficient
n	Number of Moles
F	Faraday's Constant
j_o	Equilibrium current
j_l	Cell limiting current
r	Resistance area
ΔH	Change in enthalpy
ΔG	Change in Gibbs Free Energy
ΔS	Change in Entropy
τ	Torque
$\omega, \dot{\theta}$	Angular Speed
$\ddot{\theta}$	Angular Acceleration