BATTERIES: CLASSIFICATION AND REVIEW OF ELECTRIC CIRCUIT MODELS FOR ELECTRIC VEHICLE

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Abstract.

Traditional Transportation system is used fossil fuels which created Green House Gas Emission (GHE) and exploited the environmental conditions. Now days the initiative is reflected in many countries of transforming from traditional gasoline based transportation system towards Electric Transportation. There are two types of Electric Transportation system such as Retrofitting based Electric vehicle system and Battery operated Electrical Vehicle (EV) system. Mostly Battery operated Electric Vehicles are attracting to users. Utilisations of EV are day by day increasing and hence there is need to enhance the entire performance of EV by designing the optimistic internal parameters of Battery used in sub systems of EV. The entire performance of battery is depending upon the various factors of battery such as specific energy, specific power, life cycle, safety, charge time, internal resistances, charge and discharge time, temperature, cost, and toxicity. Hence there is need to deals with the above mentioned factors and internal parameters of battery for improvement in performance of Battery. The main objective of proposed research paper is to study and analyse the electric circuit model (ECM) of Battery that used in EV to find the internal parameter by using Algorithm. The various models of ECM such as Simple Model, Enhanced Simple Model, Dynamic Model, Thevenin based model, Modified generic model, Tremblay model are critically reviewed and all are mentioned the elaboration of Internal parameters of Battery. During the study of Thevenin model, it has been highlighted that third order is responsible for creating the huge transient response in ECM and hence to reduce the transient response there is need to design and developed the optimistic R, C parameters of ECM. Detailed studies of comparative analysis of various models are highlighted by considering the uncertainty analysis.

Keywords. Electric, Vehicle, Battery, Modelling, BMS.

1. INTRODUCTION

Due to increasing the cost of oil and gas at International level, the transportation cost is increasing day by day. Fossil fuels based transportation system produces huge Green House Gases (GHE) emission and polluted the entire environment. Electric Vehicle is rapidly acquire conventional automobile market, due to its efficient and easily availability in market[1]. World people's community focus on maximum use of renewable energy for daily use, because of conventional transport system produced huge carbon dioxide, air pollution, impact on ozone layer, climate changes (flood, storm) condition. Today transportation industry work on fuels first and manpower is the second requirement of it. India import crude oil from USA 1.9, 6.2, 10.3, 10.8 million metric ton of spend ₹4138, ₹11398, ₹18915, ₹16614 crore respectively for the year 2017-2018 to 2020-2021. Reducing reliance on foreign oil, a researcher looking for other alternatives sources of energy such as hydrogen storage, a battery, solar PV, Fuel Cell (FC), biofuel and huge injection of various Energy Storage systems (ESs) like batteries, ultra capacitors (UC), etc[2]. Due to limited resources of fuels, huge cost and GHE are the causes for transformation of traditional transportation to sustainable is obtained by using Electric Vehicle (EV) [3]. In EV energy storage system is playing very important role and out of many storage systems are available [4-7], battery is most reliable one. Most suitable, most reliable and more flexible to recharge the battery is nothing but the secondary battery i.e. Rechargeable Battery. The primary battery is a single used battery, the application of this cell is in wrist watch, toy, torch, gas water heater etc.[8] Main focus on internal parameter estimation of battery, the parameter of battery are directly affect on the performances of battery, once we find the perfect value for parameter of battery then it is used in simulation. Various algorithm are developed and explain by researcher for battery parameter [9]. Like an AC system, Battery is not facing the integration issue like reactive power, harmonics, power factor, frequency monitoring and control, synchronisation, etc [10]. Battery charging is hot issue in recent decade, many researcher proposed different charging circuit for differential battery with insight effect on it [11].

Battery has basic source of storage of electricity having different type (Table I) having advantages and disadvantages, Li-ion batteries lead in market for his recent development and performances [12]. DC storage system (Battery) is also facing several issues like life cycle, cost, weight, uncertainty issue, performance, safety, interfacing with electronic component and protection and hence it is indeed to deal with above highlighted issues in EV storage battery system [13-16, 31]. DC storage system (Battery) controlled and operate through power electronics circuitry, the dynamic model of battery as well as charging circuit are discussed [17]. The modelling and simulation give idea about system performances, characteristic, and nature of responses in advanced. Through the simulation we find the behaviour of battery for charging and discharging mode, inserting some critical condition in it. Once we find dynamic responses virtually and it is implement on real time physical system [18-20].

The main objective of this paper is to look upon, the various equivalent electrical circuit's models of lead acid battery, Nickel metal hydride and Lithium Ion battery for enhancing the performance efficiency of battery by using internal parameter identification techniques.

2. BASIC OF BATTERY SIZING.

The battery is a constant source of power, there are three types of Battery packing system are available such as individual battery cell, number of cells are combined in a module and no of modules are combined in a pack [22]. Battery is used in EV and during its normal operation it is discharging in non linear acceleration and variable braking operation. Hence to maintain the stability during the running operation of EV, Energy storage system is ensure the tolerable values of performance parameters by maintaining the stability, reliability and optimum operation of EV.

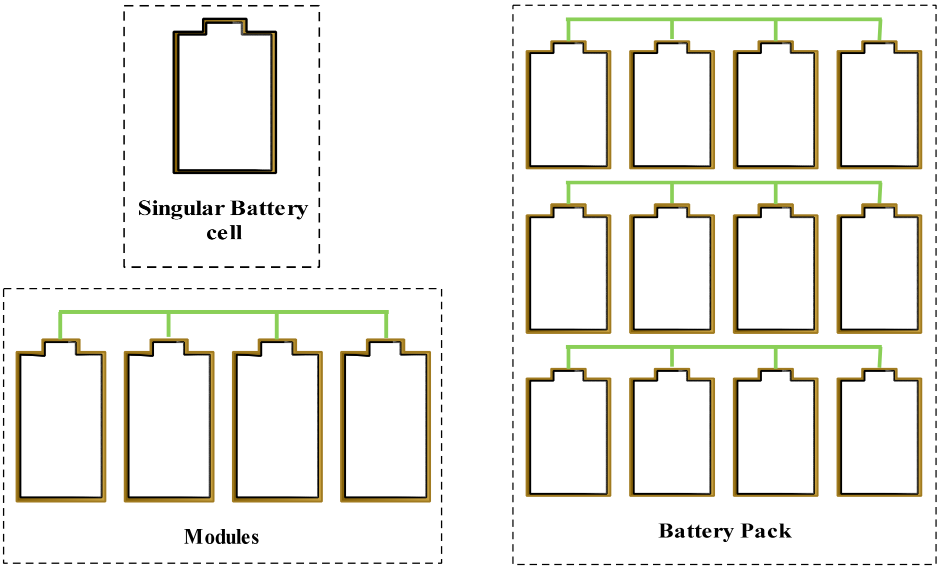

Figure 1: Level of battery pack.

Hence by proper planning and selection of battery above mentioned parameters can be enhanced [5]. Electro mobility needs lightweight batteries which are having enough capacity to fulfil the need under fast charging and discharging mode of operation. Fig. 1 shows the proper battery pack system in singular cell, modules and level of battery packing system.

2.1 Selection criteria of Battery

The selection of battery is deciding upon the efficiency, safety, charging and discharging time, cost, life cycle, etc and following factors are consider in systematic selection approach.

1) Proper selection of battery according to load. (Few KW to 100 KW): According the size of chassis, weight and load to be carrying, the motor rating is selecting. According to motor rating the battery rating to be decided[30, 31].
2) Shape of Battery. There are three types of shapes of battery are available such as Cylindrical, Pouch, Prismatic. According to size of vehicle, it is decided the particular shape.
3) Topology for charging and discharging: There are different types of charging and discharging topologies are available (seen section 5) such as stable current, stable voltage, combine stable current and voltage, etc.

4) Battery Management System: During the continuous operation of battery, the sudden charging and sudden discharging of battery affected the voltage profile of cells and unequal voltage available in different cell and in battery. Hence the entire performance of battery is affected. Hence it is needful to maintain balance voltage throughout the different cell. Hence BMS is used in battery to maintain stable constant voltage in entire battery[31].

2.2 Development of Battery

Battery has long history Figure 2 give idea about evolution in it. The progress has happen in electrode, electrolyte solution, life of cell, charging and discharging rate, safety and its application in various industrial, commercial and domestic use. In early era of battery used for limited application but recently development in technology and limited sources of conventional energy sources and its impact on environment is key point to use it. Battery can be charged through renewable energy source (i.e. sunlight), from solar panel we got DC power to store this power into battery [4, 13, 17].

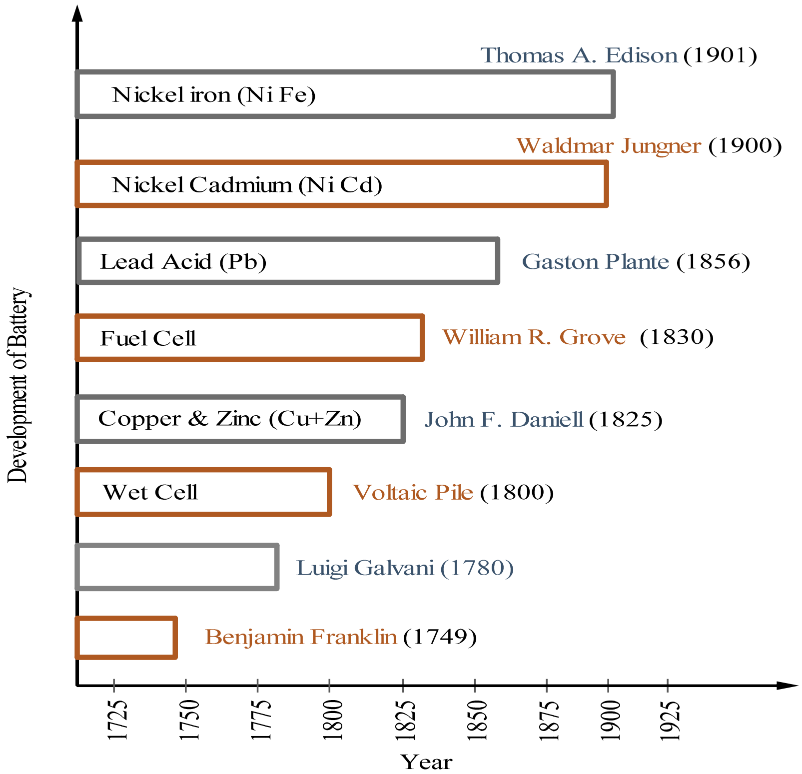

Figure 2: Development of battery.

- Benjamin Franklin an American researcher was introduced the concept of storage energy using battery in 1749.
- Luigi Galvani was suggested some modification in battery in 1780.
- Voltaic Pile [28] was introduced the concept of wet cell in 18^{th} century.

- John F Daniell [28] continue the work of V. pile and remove the error in previous research of battery. He introduced the combine copper and zinc electrodes in battery during 1825.
- William R. Grove was described the concept of fuel cell in 1830-39.
- Gastone Plante [28,29] was lunched the concept of Lead acid battery in 1856.
- Waldmar Jougener [29] was developed the concept of Nickel Cadmium during 19^{th} century.
- In 1901, [29] Nickel Iron battery was introduced by Thomas Edition.

Battery is performed well during static load operation but during the dynamic load of operation it's discharging mode of operation affects the overall performance of battery. During the charging and discharging mode of battery operation, the overall temperature of battery increases and it is indeed to control the temperature within the tolerable predefined values. Aging and de-rating effect of battery needs to consider during performance analysis of battery under charging and discharging mode of operation.

Table I: Comparative Study Of Various Batteries Parameter (24).

Specification	Lead Acid (PbO_2)	Nickel Cadmium (NiCd)	Nickel Metal Hydride (NiMH)	Lithium Ion		
				Cobalt (Co)	Manganese (Mg)	Phosphate (PO_4)
Specific electric Energy(Wh/kg)	35-55	40-85	55-125	155-255	110-155	95-125
Charge Time (Hr)	6-10	1-2	2-3	2-4	1-2	1-2
Internal Resistances	Very low	Very low	Low	Moderate	Low	Very low
Life Cycle	200-300	1000	300-500	500-1000	500-1000	1000-2000
Self Discharge / month (%)	5	20	30	Less than 5		
Battery Cell Voltage (V)	2.1	1.30	1.30	3.5	3.6	3.1-3.4
Charge Cut off voltage (V/cell)	2.40	1.5	1.5	4.2	4.2	3.6
Discharge Cut off voltage (V/cell)	1.75	1	1	2.50-3	2.50-3	2.50

Specification	Lead Acid (PbO_2)	Nickel Cadmium (NiCd)	Nickel Metal Hydride (NiMH)	Lithium Ion		
				Cobalt (Co)	Manganese (Mg)	Phosphate (PO_4)
Charge Temperature (°C)	-20 to 50	0 to 45	0 to 45	0 to 45		
Discharge Temperature (°C)	-20 to 50	-20 to 65	-20 to 65	-20 to 65		
Maintenances Required	4-5.5 months	2-4.5 months	2.5-3.5 months	Free		
Safety	Temp is controlled and it is stable	Temp is controlled and it is stable using fuse protection system		BMS protection is required		
Cost	Low	Moderate		High		
Toxicity	Very High	Very High	Low	Low		

3. MODEL OF BATTERY

To understand the nature and operation of battery, modelling of battery is indeed. Battery consist of Anode, cathode and electrolytic solution which is shown in Figure 3. Operation of battery is established by electrochemical process, Lithium ions are travel from Anode to cathode under charging process and electrons are travelled through wire to form a electric circuit. During discharging process, Lithium ions are moved out in extraction mode to form electric circuit. Ions are travel form anode to cathode under intercalation mode and neutralize the charges. In battery operation movement of Li ion is important process, In discharge mode the electrolyte solution in neutralised mode therefore ion not travelled from it, in the chemical action water is form as by-product and its reduces specific gravity of electrolyte. For fully charged battery specific gravity of acid is 1.26 and for fully discharge battery is 1.17, it is measured by hydrometer. In Charging mode in the battery electrolyte for a chemical reaction in it and ion travelled from it and we get power from battery [6, 8].

The viscosity of electrolytes is an important parameter for SoC calculation. Lithium technology is heavily used among the batteries option because of its upper electric energy density and decreases the electric discharge rate.

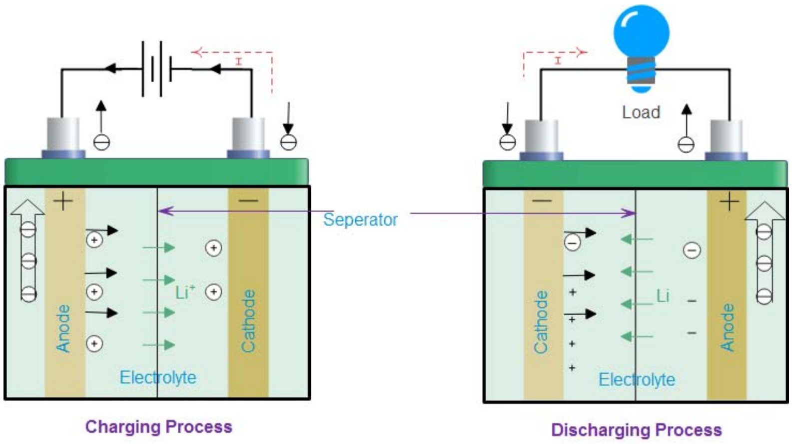

Figure 3: Charging and discharging process[32].

Battery performances carried out by parameter are Specific Power, Safety, Performance, Life Span, Cost, Specific Energy, etc. (Figure 4). The average life of a battery is 7 to 10 years depending on the power consumption profile of the battery at the time of acceleration and braking mode [4].

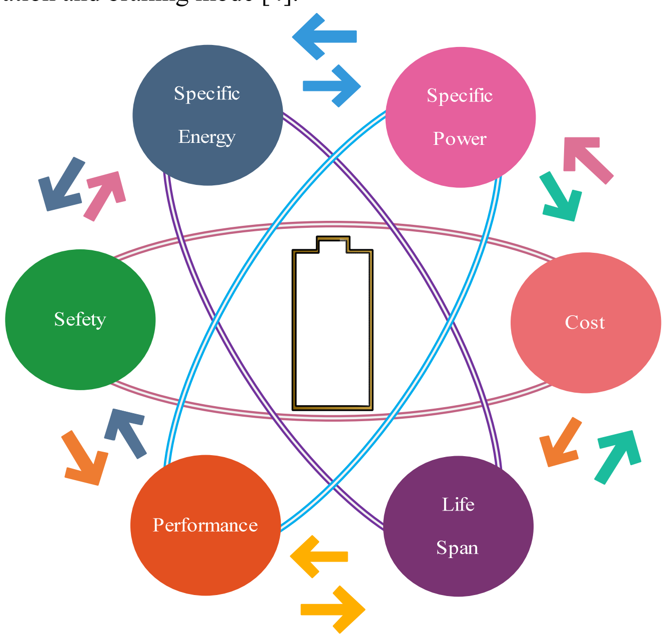

Figure 4: Battery performances major parameter[31].

Electrical circuit models are frequently transform into an equivalent circuit for the scientific model to produce the effect of the batteries under charging and discharging mode of operation. Electrical model, we know the mathematical model of battery, if ones we got dynamic model use different analysis tools such as Machine learning, Neural network, fuzzy logic, artificial intelligence to predict the batteries performance [15,32].

3.1 Classification of Battery Models.

Modeling of battery circuit, drive an important role in the research and blooming of any real-time problem. Modeling will help to change the thinking on subject in many ways for the same problem. Real systems can be transformed into physical models or a mathematical model which allows knowing the dynamics behavior of the system through simulation. Modeling helps to predict the responses of any real system, in advance before implementing it on the object. It is done by system theory and deep knowledge of particular object. Modeling is based on computer-based software and it gives optimum result and accuracy for the system.

As per the various internal factor, battery circuit are classify in many model are listed below

i. Electrochemistry models,
ii. Electrical models,
iii. Thermal (Heated) models,
iv. Mechanized models,
v. Atomic (Molecular) models,
vi. Interdisciplinary models (Electric-thermal-chemical, etc.)[18],

Distinct techniques or approaches of modelling:

i. Physical based models (Electrochemistry),
ii. Experiential models,
iii. Analytical based or mathematical model,
iv. Electrical circuit models,
v. Stochastic models,
vi. Compound models, [7, 19].

4. EQUIVALENT BATTERY CIRCUIT MODEL

Many researcher explain various battery model for different factor are present in the literature that is used in modeling of battery for a simple differential model to third order or 'n' number of order differential model. For the estimation of battery performance, various mathematical models play a significant role [20].

4.1. Simple Models

The first mathematical modeling is presented by M. A. Casacca [7] in 1992 for lead-acid batteries. Battery specifications of an ideal battery are given in capacity Ampere hour (Ah) and voltage (V). The present power of the battery calculate by the product of Current capacity and Voltage i.e Wh, Figure 5 shows a simple linear model it consists of internal resistances (R_{int}), Open circuit voltage (Voc), and battery terminal voltage (U_T). This model shows linear characteristics not contain any nonlinear element in this model. This model gives the steady-state response.

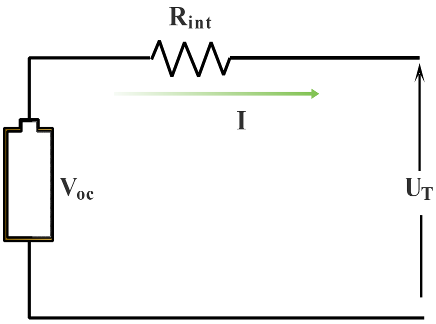

Figure 5: Simple linear model.

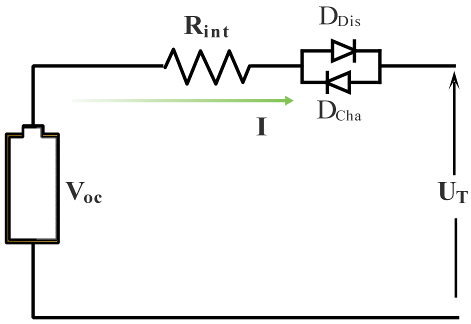

Figure 6: Charging and discharging circuit.

The R_{int} decides the heat generate in a battery. Basically battery temperature is majorly depends on internal resistances, so every researcher has air to nullify the resistances of internal parameter of battery. Whenever a load is connected the terminal voltage is:

$$U_T = V_{oc} - R_{int} * I \tag{1}$$

In the Simple linear model is neither U_T nor V_{oc} vary with state of charge (SoC). Internal resistance of this simple model does not consider into account because the state of charge, electrolyte concentration, and electrolyte formation not dependent on it i.e Rint.

Resistances for figure 6 shows different for charging and discharging condition, For charging condition $U_T > V_{oc}$, the charging Diode is in forwarding bias and discharge Diode in reverse bias and vice versa in discharged condition.

For Charging, Terminal Voltage,

$$U_T = V_{oc} + R_{int} * I \tag{1a}$$

For Discharging, Terminal Voltage,

$$U_T = V_{oc} - R_{int} * I \tag{1b}$$

4.2. Enhanced/Amplify Simple Battery Model

In the amplify battery model, the voltage source is replaced by the state of charge (SoC) controlled voltage. The effect of open circuit voltage (Voc) is dependent to SoC.

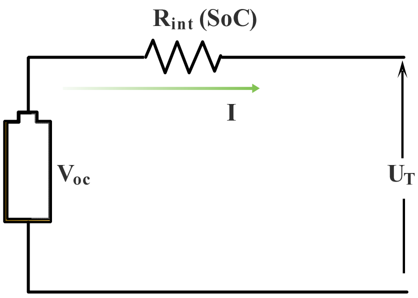

Figure 7: SoC simple battery model.

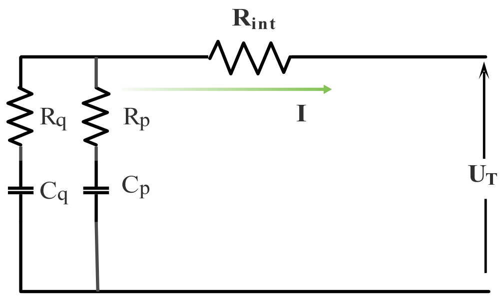

Figure 8: Dynamic model with RC.

In figure 7 shows the amplify circuit model for battery, from this model the new terminal Voltage (U_T), is,

$$U_T = V_{oc} - R_{int}(SoC) * I \tag{2}$$

Where internal resistances can be calculated as,

$$R_{int}(SoC) = R_0/S^k \tag{3}$$

Where SoC, R_0, and k are present charge status of the battery, initial internal resistance and a capacity factor respectively.

$$SoC = 1 - \frac{\sum Ah}{C_{10}} \tag{4}$$

Where A indicate value for current, h is time and C_{10} is battery capacity for 10 hours.[8]

4.3. Dynamic Model

The RC or dynamic model is consist of polarisation (p) and capacity of battery (q) parameter shown in Figure 8. It was first invented in 2000 by the SAFT Battery Company for the NREL.

Figure 8 it having two resistances and two capacitances (R_p, R_q, C_p, and C_q). where 'p' is polarization and 'q' is the capacity of the battery respectively, C_q is indicating SoC capacity of the battery, and the value of C_q is very high. R_q indicates limiting resistances.

The equation are as:

$$V_T = V_{oc} - I_q * R_q * R_{int} * I \tag{5}$$

$$V_T = V_{CP} - I_P * R_P - R_{int} * I \tag{6}$$

4.4. Thevenin-Based Battery Models

Thevenin model is considered for finding nonlinear responses of the system. This model gives a valid solution for the transient state. To simulate transients result in computer based software, some phenomena as polarization must be considered.

Thevenin model are categories between

i. First (I^{st}) order Thevenin model
ii. Second (II^{nd}) order Thevenin model
iii. Third (III^{rd}) order Thevenin model
iv. N^{th} order Thevenin model

According to the cell connected in series and Parallel for constant output Voltage.

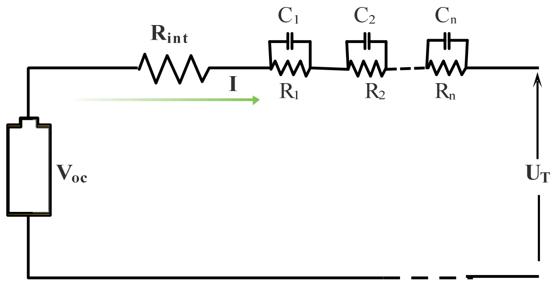

Figure 9: N^{th} order thevenin model

In figure 9 consist the battery model with n number of pairs of parallel resistors and capacitors, (R1, C1), (R2, C2), . . . , (Rn, Cn), The Equivalent Output Voltage of thevenin model is,

$$U_T = V_{oc} - R_{int} * I - \sum_{K=1}^{n} R_k I(1 - e^{-\frac{t}{R_k C_k}}) \quad (7)$$

For n^{th} order battery model, we calculate the value of Resistances and capacitances for SoC and SoD. The Value of n pairs of parallel resistor and capacitor can be calculated by [10, 11].

4.5. Modified generic battery model (Shepherd Model)

C. M. Shepherd elaborate a battery model in 1965. His research he find a mathematical equation that explain the discharging processes of different cells by calculating the cell voltage during discharge [3]. Shepherd's find that the relation between battery terminal voltage and current, Shepherd's model derive the interaction between the terminal voltage of the battery and the discharging current. These experimental models give the best result for stable characteristics performances of the battery on a certain discharging current (exponential current). Figure 10 give the idea to build-up nature in simulation [11].

$$U_{dis} = E_0 - K\left(\frac{Q}{Q-it}\right)i - R_0 i + A\exp(-BQ^{-1}\, i\, t) \quad (8)$$

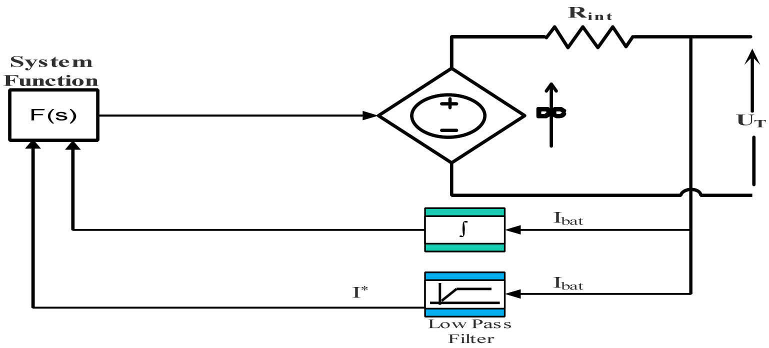

Figure 10: Modified generic battery model.

4.6. Tremblay Model

Olivier Tremblay presented an easy-to-use battery model using dynamic simulation software. To avoid the problem of forming an algebraic loop, this model only used the SOC of the battery as a state variable [2]. The controlled terminal voltage (U_T) is depended on current consumed by battery, for proposed battery model it assume R_{int} and thermal characteristic are kept constant.

$$U_T = E_0 - K\left(\frac{Q}{Q-i*t}\right) + A\exp(-B * i * t) \tag{9}$$

Tremblay model have two constraints
First, the minimum no-load battery voltage was zero V, whereas the most battery voltage wasn't restricted. Second, the minimum capability of the battery was zero Ah, whereas the most capability wasn't restricted. Therefore, the most SOC is larger than 100 percent if the battery is overcharged. Once the parameters were well determined from the discharge curve provided by the makers. The Tremblay model might accurately represent the behavior of the many kinds of batteries. The electric circuit models square measure enforced in dynamic simulation studies like wind energy conversion systems, electrical phenomenon systems, and electric/hybrid vehicle systems [10, 11].

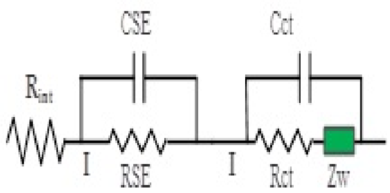

Figure 11. Impedance based battery model.

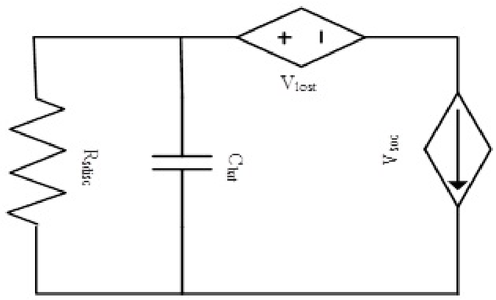

Figure 12. Run time based battery model

4.7. Impedance based battery model

Figure 11 show circuit for electrochemical impedance spectroscopy (EIS), for calculating battery parameter this technique are commonly used. Impedance are depends on applied voltage and its result take on nyquiest plot[6].

4.8. Run time based battery model

Figure 12 Simple run time model for estimate the parameter. In circuit R_{sdisc} is self discharge resistances, C_{bat} is the capacity of battery, V_{bat} is battery voltage is depends on SoC .

4.9. Combine or Hybrid Model

In this model combine two different model to check the parameter of battery using high computation method. Combination of two model open number of algorithm for nding real time State of Charge SoC , State of Health SoH , Depth of Discharge DoD for further information of battery. Figure 13 give simple view of hybrid model.

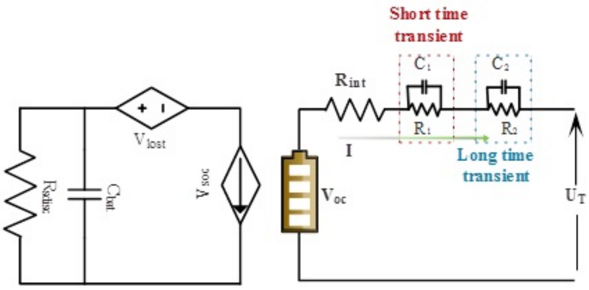

Figure 13. Combine or Hybrid Model.

5. CHARGING TOPOLOGY

Battery charging is important task in EV. Charger having two type according to power flow in battery unidirectional and bidirectional charger. In unidirectional mode only grid supply power to the battery through charger and in bidirectional charging mode grid supply power to the battery at rated current according to the charger design and in steady mode of devices flow power from battery to grid in peak load condition. A charging device has the subsequent 3 functions: 1) Delivering safe charge to the battery; 2) Optimizing and control the charge rate, and 3) Terminating the charge. In literature battery having different type according to his material used in it, chemical action, electrolyte, etc. Nickel batteries require solely constant current (CC), whereas Li-ion batteries need a continuing current/constant voltage (CC/CV). Pulse charging, which uses a pulse current for up to one second, followed by a rest period and a discharge pulse for milliseconds, is claimed to be best as a result of improves the charging speed and efficiency[11]. Design an economical charger are simple and reliable for charging of the battery, the literature compare and evaluate some charging algorithms because every battery having a limitation for nickel and lithium batteries (lead-acid batteries are escaped due to the nature of their applications, which is different from nickel and lithium batteries) [12, 13, 26].

6. PARAMETERS CALCULATION FOR OPTIMIZATION

First-order (RC) model, the parameters can be easily evaluated from the experiment. The models with two or more pairs of parallel RCs element, having different rating give the stable responses but increasing the RC pairs the order of model will increase and it directly affect on system responses. Therefore to find all values for RC is mandatory to minimize the error in physical model. According the research of the Tingshu Hu et al., give primary idea about to estimate internal parameter (R, C) of the Thevenin model. This battery model deal with nonlinear characteristics, because the voltage and current are depends on state of charge. The SOC will vary the battery performances characteristics. Figure 14 Flowchart give the accurate value for battery internal parameter for fast and most efficient SOC, to find battery model.

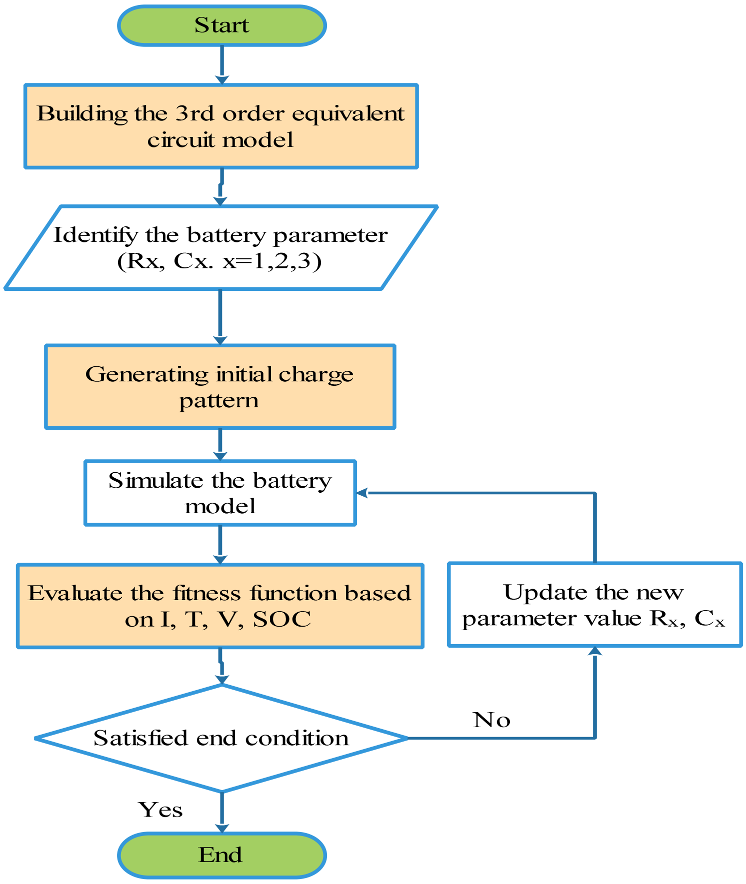

Figure 14: Flowchart for Parameter estimation[10],[25].

7. RESULT

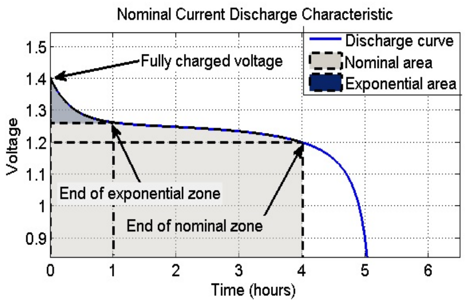

Figure 15. Typical discharge curve [3]

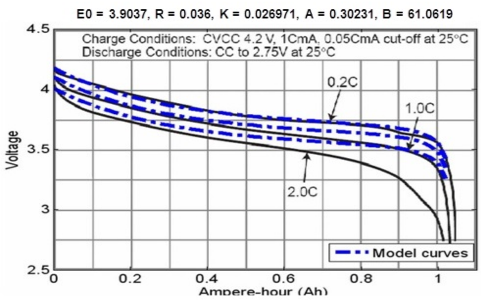

Figure 16. Li-Ion battery 3.6V, 1 Ah [3]

Figure 15 shows a typical discharge characteristic (TDC) which is referred from specific battery data sheet.TDC is supporting to calculate the various technical parameters such as Nominal Voltage (V) , maximum capacity (AH) , Rated capacity (Ah) , Fully charged voltage (V) , the internal resistance (R) , Nominal discharge current and end of exponential & nominal zone from manufacturer data sheet. Data sheet of battery contains ideal discharge characteristics which is consider as a reference and various technical parameters are refereed from data sheet and utilised in MATLAB simulation model. MATLAB simulation model results are validated with ideal reference discharge characteristics. It has been observed that the results are exactly matches with ideal reference discharge current. Figure 16 shows that Lithium Ion Battery having capacity of 3.6 V and 1Ah. Fig indicates that E_0 is important term and it is calculated by referring the various technical parametersfrom data sheet. E_0 is calculated for different batteries and it is varied according to TDC. Results obtained from simulation models are validated by considering Charge rate of 0.2, 1 and 2. Figure 17 (a) shows the relationship between Soc and time, Experimental and simulation result are compared and validated. In this plot, battery initially has fully charged i.e SoC is 1 and according to utilization of power present in battery, SoC is decrease. According SoC graph curve, It has been concluded that, Soc is predicted the approximate range in kilometer. Soc is decrease during discharging process and SoC increase during charging time. It has been observed that both curves are in same nature and 5% tolerance are expected due to certain constraints. Figure 17 (b) shows curve of voltage verses time. In this case both the simulation and experimental analysis shows satisfactory result. Figure 17 (c) shows relationship of current verses time. The nature of battery current is same during both the simulation and experiment result with maximum 5% tolerances are provided herewith. Current is varied according to SoC of battery. Plot C shows that initially more current is draw due to accelerating mode of electric vehicle and constant for rest period for 20-80% of SoC state.

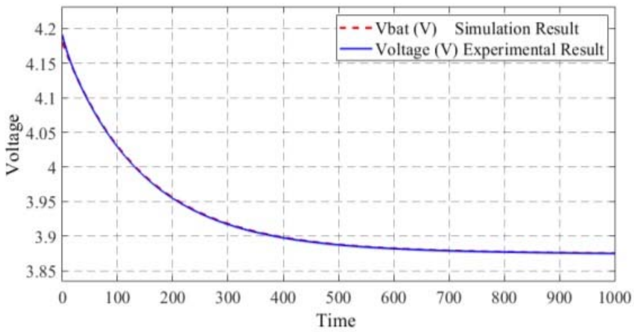

Figure: 17(a)

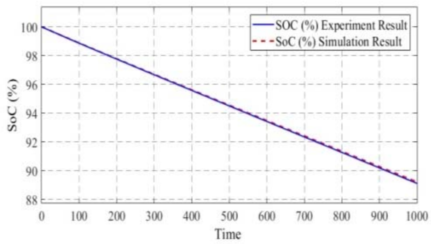

Figure: 17(b)

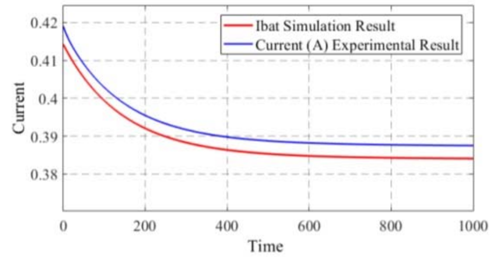

Figure: 17(c)

Figure 17. Experimental and Simulation Results.

8. Challenges of Electric Vehicle

- EV is best alternative for IC engine, To Drive EV, need of Battery, Supervisory Controller, Sensor, Decision controller, Alarm System.
- EVs are the least expensive compare to any other vehicle combination.
- Modern Electric Vehicle will be essential that develop supervisory control strategy and to study the performance of the vehicle under different driving conditions.
- Economical and safety issue, simulation of the vehicle control strategy is needed prior.
- Overcome of limited range problem of vehicle test different Configurations/architectures can be considered for converting the existing electric vehicle.
- The variety of battery chemistries available,[1,32]

9. Conclusion

In the development of electric vehicles the battery is the soul of the whole system, find the best battery for the system is a very important task. The battery performances, we know the internal parameter of the battery that directly affect the battery performances (SOC, SOH, SOP, Temp., Voltage, Current) In this perspective article we discuss different equivalent electric circuit model (ECM) for the simulation process having different pros and cons, Among them Thevenin third-order model has the good dynamic result for parameter estimation of the battery. Modified generic battery model has been developed in simulink and compare with experimental result. This model show very good result to apply for BMS algorithm. All this equivalent circuit model reduces the charging time of EVs, a safe and efficient electric model of the battery. Also, discuss charging topology for battery performances.

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