CHAPTER 4

DESIGN OF HYBRID STORAGE SYSTEM

This Chapter explains the design of Hybrid Storage System for the Electric Vehicle. The selection of various parameters of the Supercapacitor and Battery ratings for the Simulations is described in detail. The necessary parameters in context to market availability are observed and calculated in this chapter.

4.1 EV BATTERY SYSTEM :

In EV applications, desirable attributes for the battery system are high specific power, high specific energy, faster rechargeable, safe in harsh operating environment and a high number of cycle life as well as a long calendar life. There are basically two categories of battery systems that are accordingly termed as primary batteries and secondary batteries. Primary batteries are non-rechargeable and are discarded at the end of a single full discharge. Secondary batteries however are rechargeable with the number charge-discharge cycles varying for diverse battery technology. It is the secondary battery that finds application in EVs.

4.1.1 Basic configuration of secondary batteries:

“A basic secondary battery cell consists of two electrodes immersed in an electrolyte. The anode is the electrode where oxidation occurs whereby electrons are transported out of the cell to the cathode via the load circuit. The cathode is the electrode where reduction takes place and where electrons from the external load return to the cell. The electrolyte however serves as a path for completing the electrical circuit inside the cell. Electrons are transported via ion migration from one electrode to the other through the electrolyte, thus creating a potential across the cell. During a battery cell charging operation, the process is reversed and the negative electrode becomes the cathode while the positive electrode becomes the anode. Electrons are externally injected into the negative electrode to perform reduction while oxidation takes place at the positive electrode. The reactions that take place during charge and discharge do not necessarily occur at the same reaction rates. The unsymmetrical reaction rates are expressed as the charge acceptance rate during a charging process and a charge release rate during discharge. Generally, the charge release rate of a battery system is higher than the charge Acceptance Rate, which is why secondary batteries require a longer time to recharge”, is explained in the Handbook of Batteries[61]. Fig.4.1 explains the basic battery cell construction and operating principle.

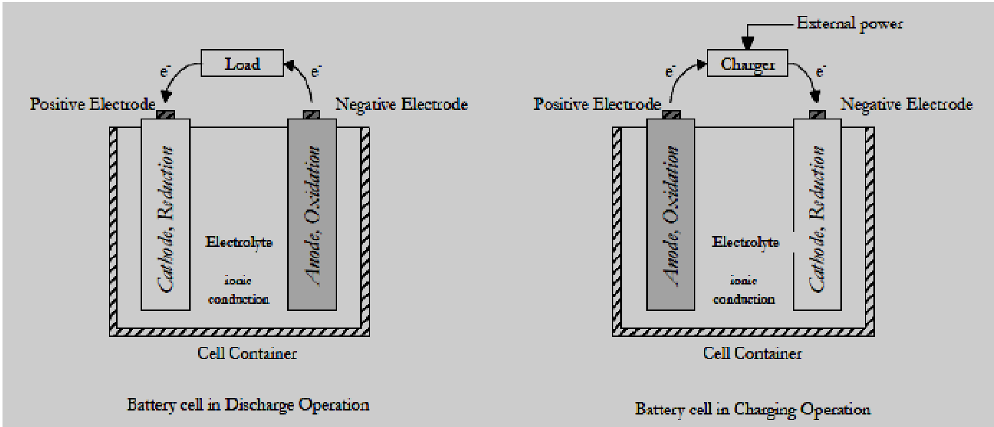

Fig. 4.1 Operating Principle of a Secondary Type Battery Cell

"Only in an ideal battery cell, the electrons only flow when the external circuit is completed. However, in all battery systems, a slow discharge does occur due to diffusion effects. This open circuit discharge is known as the self-discharge of the battery, and is a parameter that is used as one of the long-term performance descriptors of a particular battery type. Fig.4.2 explains the basic equivalent circuit model (Thevenin model) of a secondary battery, the consequent voltage characteristic as a function of the battery stored charge capacity and the power characteristics. The battery is represented by an ideal open circuit voltage source (V_{oc}) and a series internal resistance (R_i)." explained by Crompton [76].

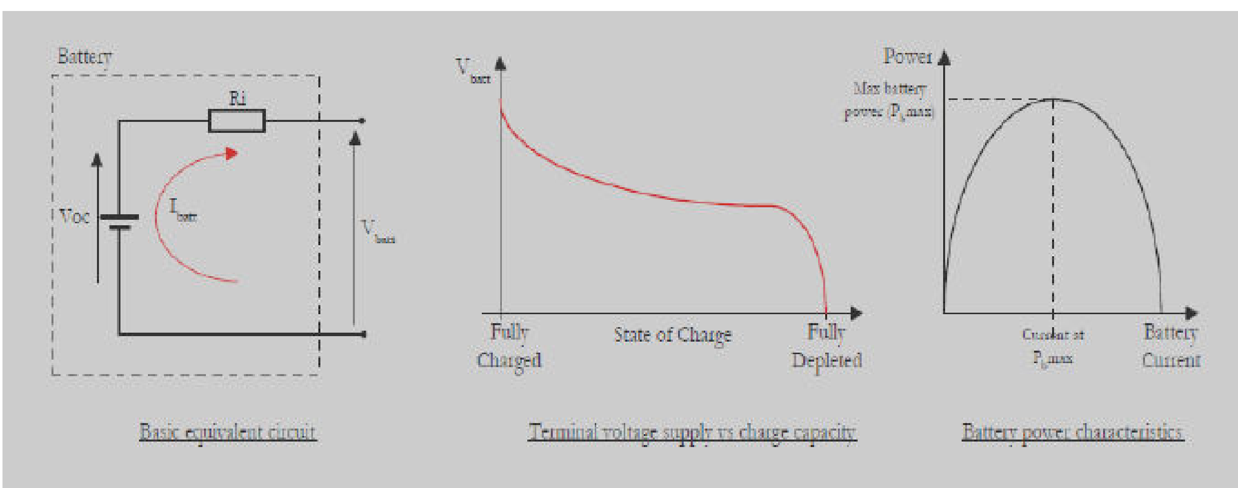

Fig. 4.2 Battery Basic Equivalent Circuit and Voltage Characteristics

The equivalent circuit loop holds true to Kirchhoff's voltage law to produce a terminal voltage expressed as,

$$V_{bat} = V_{oc} - I_{bat}.R_{\text{i}} \qquad \text{(4.1)}$$

Where, both V_{oc} and R_i are dependent upon the instantaneous state of charge. [79, 80]. Here, V_{oc} represents the open circuit voltage of the battery and R_i is internal resistance of the battery. Extensions to the basic circuit model can be made to account for the difference in charge acceptance and charge release rates [77].

4.1.2 Specific Energy (SE_{batt}):

The amount of energy per unit of battery mass is termed as the specific energy of battery. This parameter is an intensive property of a battery system and is expressed in watt-hour per kilogram (Wh/kg). The actual energy that can be extracted from a battery system depends on the temperature and discharge rate. As a general expression, the battery specific energy is,

$$SE = \frac{\text{Discharge Energy}}{\text{Total Battery Mass}} = \frac{E_{dis}}{M_{bat}} \qquad \text{(4.2)}$$

Since the discharge energy varies with the discharge rate of the battery, the specific energy of the battery also varies accordingly. [89]

4.1.3 Specific Power (SP_{batt}):

The specific power of a battery system is the parameter that quantifies the magnitude of power obtainable per unit mass. Expressed in watt per kilogram (W/kg), this parameter also serves as an approximation of the power level available from a battery system [89].

$$SP_{bat} = \frac{\text{Discharge Power}}{\text{Total Battery Mass}} = \frac{P_{diss}}{M_{bat}} \qquad \text{(4.3)}$$

4.1.4 Battery Capacity:

"The capacity of a battery system is the measure of the amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode. This parameter is measured in Coulombs (C) but is usually expressed in Ampere-hour (Ah). Ideally, the Ah rating for a specific battery would be the same for any discharge current. However, in all practical battery systems, the actual capacity is depended on the magnitude of the discharge current. In usual, for most battery types, the higher the discharge current, the less will be the resultant Ah measurement. This change in capacity is due to excess side reactions inside the battery cell. To take the discharge current magnitude into account when specifying battery capacity, a parameter termed as the "C rate" is included when expressing of battery capacity", explained by P. C. Luk and Rosario. [89] The following equation provides a more detailed perceptive for the discharge current.

$$I = k\,C_n \qquad (4.4)$$

Where,

I is the charging or discharging current

C is the battery rated coulometric capacity in Ah

k is multiplication factor of C,

n is the *Capacity* rate.(C rate)

Since the value of C usually decreases as the C-rate increases, the constant discharge current magnitude along with rated battery capacity must be stated together in order to accurately describe the actual battery capacity and hence its usable energy.[78, 81, 82]

4.1.5 Self Discharge:

This parameter causes the energy stored in the battery to be wasted due to ion flow within the electrolytes i.e. self discharge, which continuously discharges the cell over a long period. The flow rate depends on the several factors, predominantly the temperature of the cell, where higher temperatures result in higher self-discharge rates. The energy loss due to self-discharge of a battery, E_{SD} is expressed in percentage per hour and is stated as[76,89],

$$E_{SD} = \alpha_{SD}.E_{b\ Norm} \quad \text{……(4.5)}$$

Where

α_{SD} is the battery 24 hour self discharge coefficient

$E_{b\ Norm}$ is the battery nominal energy capacity in Wh.

4.1.6 Faradic Efficiency (Ampere-hour Efficiency):

The Faradic efficiency or Ampere-hour efficiency or charge efficiency of a battery is defined as the ratio of discharge capacity (Ah) to the charge capacity (Ah). It does serve as a guide in comparing the efficiencies of various battery technologies. The ampere-hour efficiency of a battery is expressed as [89],

$$\eta_{Ah} = \frac{\text{Ah(discharge)}}{\text{Ah(recharged)}} \quad \text{……(4.6)}$$

4.1.7 Battery Energy Efficiency:

"The battery energy efficiency is defined as the ratio of electrical energy delivered by a battery from a particular state of charge to the electrical energy required to return the battery to the same state of charge. Although the battery efficiency is not a straightforward parameter to quantify the performance of a battery, it is effective as a comparative measure of the various power and energy management strategies. As a usual definition, the battery efficiency can be expressed under constant current tests (Peukert's Test) as follows. For a discharge time t_f, the battery discharge energy E_{dis} can be expressed as a function of its open circuit voltage V_{oc}, its internal resistance R_i and a constant discharge current I_b as follows", derived by Rosairo. [89]

$$E_{dis} = \int_0^{t_f} P_b(t)\,dt = t_f(V_{oc} - I_b.R_i)I_b \quad \text{……(4.7)}$$

Charging the battery for the same duration as the discharge duration t_f with the same magnitude of charging current as the discharge current gives a charging energy E_{chg} as,

$$|E_{chg}| = \int_0^{t_f} |P_b|(t)dt = t_f(V_{oc} - |I_b|.|R_i|) \quad \text{.......................................(4.8)}$$

Therefore, the battery efficiency expressed as a function of the battery current can be stated as,

$$\eta_{bat} = \frac{E_{dis}}{E_{chg}} = \frac{V_{oc} - R_i|I_b|}{V_{oc} + R_i|I_b|} \quad \text{..(4.9)}$$

4.1.8 Battery State of Charge (SoC):

The battery state of charge is a unit less parameter that represents the current capacity in relation to the nominal capacity of the battery. As the battery is discharged and charged, the SoC indicates the relative amount of energy that has been removed or added into the battery in respective processes. Expressed in a normalized ratio, the SoC of a battery system is stated as [89],

$$SoC_{bat} = \frac{Actual\ Battery\ Charge}{Total\ Battery\ Charge} \quad \text{..(4.10)}$$

4.2 BATTERY MODELING :

It is shown in [81, 82] that, "The widely excepted empirical relation between capacities (Q), discharge current (I) and time (t) is Peukert's equation, formulated in 1897 by W. Peukert.[81, 82] Peukert's equation under constant current discharge is:

$$I^n . t_{cut} = \lambda \quad \text{..(4.11)}$$

Where I is the constant discharge current, t_{cut} is the time taken to reach the battery specified cut-off voltage, λ and *n* are curve fitting constants, with $n \rightarrow 1$ for small currents and $n \rightarrow 2$ for large currents. The Peukert exponent, n relates to the battery construction".

$$Q = I . t_{cut} \quad \text{..(4.12)}$$

In practice, the exponent n is never equal to 1. n values of commercial batteries are 1.05 to 2, with about 1.2 being a common value [34]. From above equations, the relationship between the charge capacity Q and the current I can be derived as;

$$I^n . \frac{Q}{I} = \lambda \qquad (4.13)$$

The state of charge (SoC) of a battery corresponds to the present battery capacity. It defines the remaining capacity throughout a discharge time. [89]The SoC follows,

$$SoC(t) = Q - \int_0^t i(t)d\tau \qquad (4.14)$$

The state of discharge (SoD), defined as the measure of charge drawn from the battery is represented as,

$$SoD(t) = \Delta q = \int_0^t i(t)d\tau \qquad (4.15)$$

The depth of discharge (DoD) of a battery is the percentage of capacity to which it is discharged and is given by equation 4.16,

$$DoD(t) = \frac{Q - SoC(t)}{Q} . 100\% = \frac{\int_0^t i(\tau)d\tau}{Q} . 100\% \qquad (4.16)$$

For a small interval dt, assuming that the battery is fully charged at $t=t_0$, and with (4.15) and (4.16), it follows that;

$$d(DoD) = \frac{d(SoD)}{Q(i)}, where\ d(SoD) = i(t)dt \qquad (4.17)$$

Referring to Piker's equation, $0 < n-1 < 1$, for $I > 1$, Q decreases as I increases. From (4.13),

$Q = \lambda / I^{n-1}$ for constant current discharge. Allowing for time varying currents, $Q = \lambda / I^{n-1}$. Therefore;

$$d(DoD) = \frac{\frac{idt}{\lambda}}{i^{n-1}} = \frac{i^n}{\lambda}dt \qquad (4.18)$$

Integrating both sides from t_0 to t,

$$\int_{t0}^{t} d(DoD) = \int_{to}^{t} \frac{i^n}{\lambda}dt,$$

$$\blacktriangleright\ DoD(t) - DoD(t0) = \int_{t0}^{t} \frac{i^n}{\lambda}dt \qquad (4.19)$$

Since DoD (t_0) = 0 when the battery is fully charged at t=t_0, the factional depletion model (FDM) is given by 100%.

$$DoD(t) = \int_{t0}^{t} \frac{i^n}{\lambda}dt.100\% \qquad (4.20)$$

To predict the workable range of an EV, either the SoC or DoD may be used. With (4.14)

and (4.14), the SoC at time t is,

$$SoC(t) = Qt - SoD(t) \qquad (4.21)$$

The accuracy of Q_t is expected since a predicting error in Q_t results in a incorrect SoC estimation, DoD measurement are sometimes used since it is expressed as a fraction of Q_t and can be expressed as[89],

$$DoD = \frac{SoD}{Qt} \qquad (4.22)$$

4.3 SUPER CAPACITOR:

"Supercapacitors function as per secondary batteries in terms of storing and delivering energy. However, the charge storage methods itself is very diverse compared to batteries. As opposed to batteries, which produce electric charge through chemical processes, supercapacitors store energy in the form of static charge. Since the energy is stored in the same from that it is used, supercapacitors offer faster charging and discharging rates compared to batteries of similar volume. The energy densities of supercapacitors are however comparatively less than that of batteries by a factor of 10 to 20", modeled by Surewaard and Tiller [83, 84].

A supercapacitor cell structure consists of two electrodes, a separator, and an electrolyte as illustrated in Fig.4.3. The separator permits the mobility of charged ions but prohibits electronic conduction. An electrolyte is either a solid state, organic or aqueous type [89].

The decomposition voltage of the electrolyte determines the maximum operating voltage of a supercapacitor. Owing to the very small separation distance between the electrolytes, as well as the large effective surface of the active material, large capacitance magnitudes in terms of Farads are achieved but voltage capacity is highly reduced. The magnified insert in Figure 4.3 explains the large surface area of the active material.

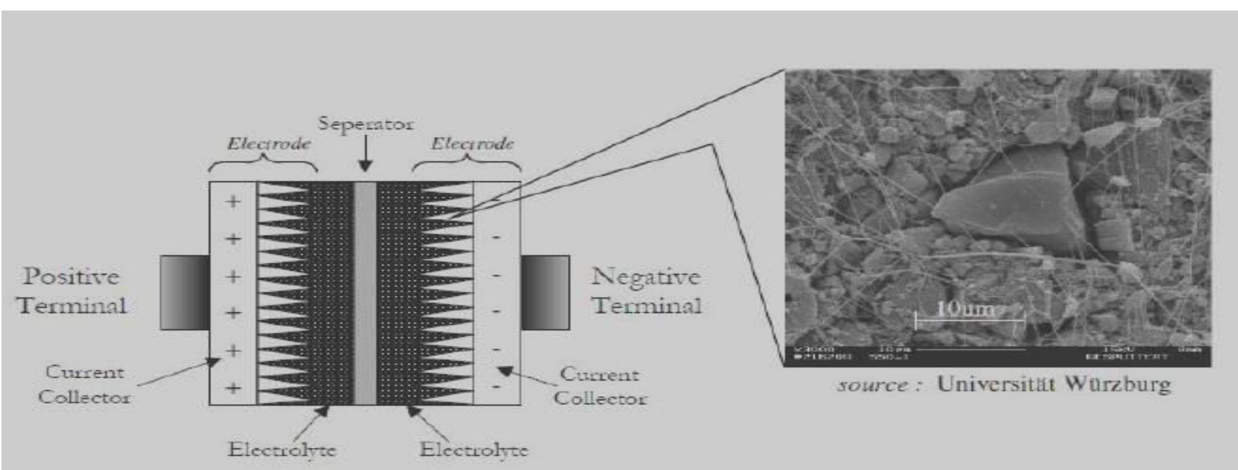

Fig. 4.3 Basic Cell Construction of a Supercapacitor[89]

“Supercapacitors are not guarded to the same physical restrictions as dielectric capacitors. The discharge characteristics and equivalent circuits of supercapacitors are analogous to conventional low farad capacitors but there are some primarily unlike properties between the two. The large capacitance of supercapacitors arises from the very huge specific area available from the use of porous nano-carbon materials. Based on charging and discharging the interfaces of high specific-area materials such as porous carbon materials or porous oxides of some metals, these devices are able to store and releases immense amounts of electric charge and corresponding energy at high densities (expressed in Wh/kg). Hence, they can be operated at specific power densities (expressed in W/kg) higher than batteries”, found in Nesscap Manual [88, 92]. In addition, their capacitance for a given physical size of the device is much higher to electrolytic capacitors. Comparing a 350F - 2.5V supercapacitor (Maxwell BCAP 0350F, length = 62mm, diameter = 33mm, weight = 60g) with a 2200F –100V electrolytic capacitor (Evox-Rifa PEH200, length = 60mm, diameter = 35, weight = 85g) shows that the energy density of the supercapacitor is approximately 140 times greater than the electrolytic capacitor. For this reason proprietary terms such as Supercapacitors and Supercapacitors have been used to describe the high-energy storage capability of these devices. [89, 90]. Supercapacitors also demonstrate cycle lives up to one million under suitable conditions [91]. This is because only storage and delivery of electrostatic charge takes place at the extended two-dimensional interface of high-area materials. No slow chemical phase changes take places within the supercapacitors as does in the three-dimensional chemical materials within secondary batteries.

4.4 SUPERCAPACITOR MODELING

At present, there are several propositions of supercapacitor model representation. The simplest of all is the classical equivalent circuit with the lumped capacitance, equivalent parallel resistance (EPR) and equivalent series resistance (ESR). Figure 4.4 shows the classical equivalent circuit with the three parameters. Determination of these parameters provides a first approximation of a supercapacitor cell.

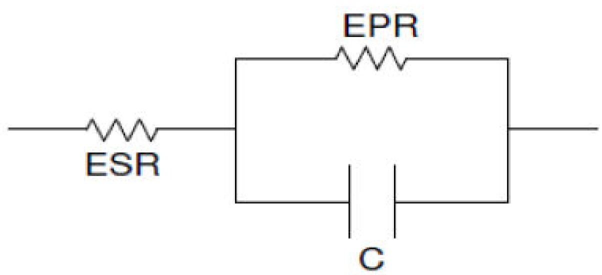

Fig. 4.4 Classical Equivalent Circuit of a Supercapacitor[89]

The EPR represents the current leakage and influences the long-term energy storage. In multiple series connections of supercapacitors, the EPR influences the cell voltage distribution due to the resistor divider effect. Using empirical methods, Sypker and Nelms [31, 52] showed that the EPR is related to the voltage decay ratio by,

$$EPR = \frac{-t}{\ln\frac{V_2}{V_1}.C} \qquad (4.23)$$

Where V_1 is the initial voltage, V_2 is the final voltage and C is taken as the rated capacitance.

Through experimental measurements of voltage decays of several supercapacitors having various capacitance values, it was shown that the EPR effects could be neglected for transient discharge calculations. However, the EPR value is important when cell balancing of series connected supercapacitors is considered. Examining the ESR effects, further empirical verifications by Describing a more detailed terminal representation model, Zubieta and Bonert [40] proposed and investigated a three RC branch network with one branch having a voltage dependent capacitance.

Each branch of the circuit shown in Figure 4.5 has a diverse associated time constant. The authors [45] assigned the first branch, containing R_i as the "immediate branch". This branch dominates the supercapacitor behavior in the order of a few seconds. The "delayed effect branch", with R_d has influential behavior in the range of minutes. The third branch is the "long-term" branch. This branch governs the long-term response of the circuit after periods exceeding ten minutes. Finally, the branch with resistance R_{Leak} represents the supercapacitor leakage current. The "immediate branch" contains a voltage dependent capacitor C_{i1} that reflects the voltage dependency of the cells double-layers capacitance.

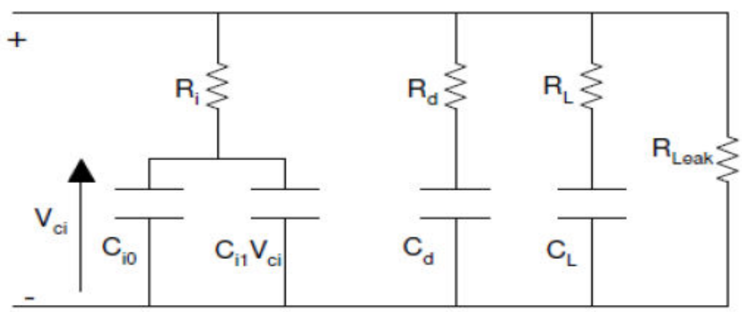

Fig. 4.5 Branch Representation of Supercapacitor model [83]

A hybrid modeling approach has been developed by Rizouge and Moigne [52]. It is to improve classical SC models. This approach has used frequency and temporal results for the representation of the model. The model based parameters tested with manufactured SC data taking cycling test and precise temperature readings. As with the battery model, Surewaard et al. [81] and Buller et al.[82] investigated a supercapacitor equivalent circuit though impedance spectroscopy measurements. The mathematical expression for $Z_{pore}(j\omega)$ has only two independent parameters (C, t). Including L and R_i, only four parameters have to be extracted from the measured spectra. The graph of Figure 4.6 shows a comparison between the measured impedance data and the simulated data obtained using the circuit model. In the depicted frequency range the best approximation shows nearly perfect agreement with the measured data[89].

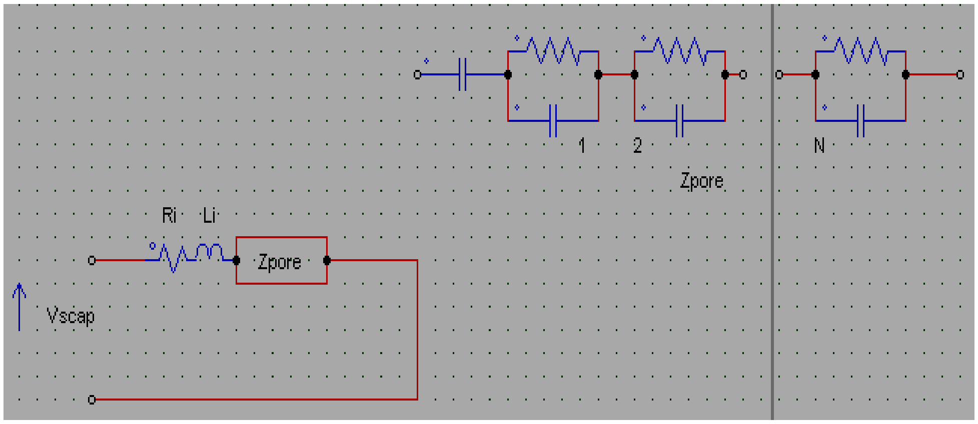

Fig. 4.6 Supercapacitor Model through Impedance Spectroscopy [82]

The nonlinearity of high "C" capacitors must be considered in the supercapacitor model as it has significant influence in the estimation of the exploitable energy. A complete derivation can be found in [84]; however the final solution is reproduced here to show comparison of the time constant difference between a dielectric capacitor and a supercapacitor.

$$t = \frac{2}{c}\left[\sqrt{b^2 - cq0} - b - \sqrt{b^2 - cq} + b.\ln\frac{\sqrt{b^2 - cq0}}{\sqrt{b^2 - cq}}\right] \qquad (4.24)$$

Where,

$$b \equiv \frac{C0}{2\alpha R}, \qquad c \equiv \frac{1}{\alpha R^2} \text{ and } C \equiv Co - \alpha V = \frac{q}{V}$$

V is the voltage across the supercapacitor, C_0 is the static capacitance at zero voltage α is an empirically determined constant and q is the stored charge.

4.5 PARAMETER SELECTION OF BATTERY AND SUPERCAPACITOR

4.5.1 Electrical Machine :

Vehicular propulsion system always prefers machine based on initial cost, drivers possible, efficiency, torque ranges, weight, volume, reliability as well as load and no load characteristics. Various machines are available, among them PMSM – Permanent Magnet Synchronous Machine suits the best. The machine has main two parts electrical and mechanical parts. The electrical part of the PMSM is modeled in the dq frame:-

$$v_d = R_s\, i_d + L\frac{di_d}{dt} - w_e L_q\, i_q$$

$$v_q = R_s i_q + L_q\frac{di_q}{dt} + w_e L_d i_d + w_e \lambda_{pm}$$

$$P_{EM} = \frac{3}{2}\,(v_d i_d + v_q i_q)$$

Where,

v_d	[V]	d axis voltage
v_q	[V]	q axis voltage
i_d	[A]	d axis current
i_q	[A]	q axis current
Rs	[Ω]	Stator phase resistance
L_d	[H]	d axis inductance
L_q	[H]	q axis inductance
λ_{pm}	[Wb]	Permanent magnet flux linkage
w_e	[rad/s]	Angular frequency of the stator
P_{EM}	[W]	Electric input power

The model of mechanical part of the PMSM is as follows:-

$$\tau_e = J_s + \frac{dw_s}{dt} + B_v w_s + \tau_c + \tau_s$$

$$p_s = \tau_s w_s$$

Where,

J_s	[kgm^2]	Shaft moment of inertia
τ_e	[Nm]	Electromechanical torque

τ_c	[Nm]	Coulomb Torque
B_v	[Nms / rad]	Viscous friction coefficient

The coupling between the electrical and mechanical part is given by:

$$\tau_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{pm} i_q + \left(L_d - L_q\right) i_d i_q\right)$$

$$w_e = \frac{P}{2} w_s$$

Where, P = number of Poles

4.5.2 Battery:

The source "battery" is the lever of an EV. It provides the necessary energy to the electric machine and other utilities. Eventually, this energy is converted into the other required energy like mechanical and thermal energy. Out of many diverse types of batteries existing the lithium ion is the researchers first preference due to its relatively high specific power and energy. In this research work - the battery model is based on Lithium Ion Cell. (VL 37570)[94, 97].

4.5.3 Electric Model:

The battery is modeled in steady – state. The electric equivalent circuit diagram is given in Figure 4.7 the battery model consist of an internal voltage source and to inner resistances used for charging and discharging and two diodes. Charging currents are considered negative and hence the discharging currents are positive[97].

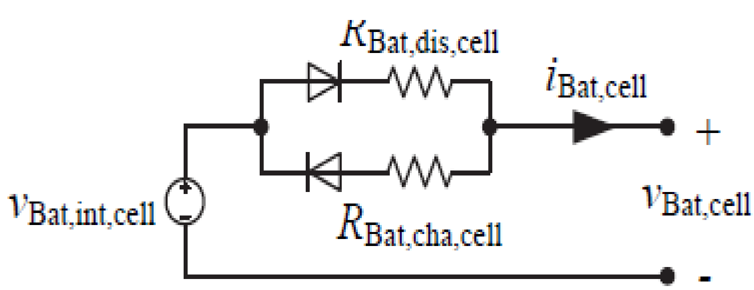

Figure 4.7 Battery Model

From Figure 4.7 the unit cell voltage is represented by:-

$$v_{Bat,cell} = \begin{cases} v_{Bat,int,cell} - R_{Bat,cell,dis}\, i_{Bat,cell}, & i_{Bat,cell} \geq 0 \\ v_{Bat,int,cell} - R_{Bat,cell,cha}\, i_{Bat,cell}, & i_{Bat,cell} < 0 \end{cases}$$

Where,

$v_{Bat,cell}$	[V]	Battery cell voltage
$v_{Bat,int,cell}$	[V]	Internal Battery cell voltage
$i_{Bat,cell}$	[A]	Battery cell current
$R_{Bat,cell,dis}$	[Ω]	Inner Battery cell resistance during discharging
$R_{Bat,cell,cha}$	[V]	Inner Battery cell resistance during charging

Resistances and voltage sources shown in Fig. 4.7 depends on the particular depth of discharge of the battery. The battery cell has been modeled by the curves given in the data sheets [61].

4.5.4 Battery Capacity Model:

The below equation are derived [61] for understanding the values of DoD and SoC as they are the key parameters to identify the battery capacity. The state of charge and depth of discharge depend on the integral of the current drawn or delivered to the battery, i.e.,

$$DoD_{Bat} = DoD_{Bat,ini} + \int \frac{i_{Bat,eq,cell}}{Q_{Bat,1,cell}} dt$$

$$SoC_{Bat} = 1 - DoD_{Bat}$$

Where,

DoD_{Bat}		Depth of Discharge
$DoD_{Bat,ini}$		Initial Depth of Discharge
SoC_{Bat}		Battery State of Charge
$i_{Bat,eq,cell}$	[A]	Equivalent Battery cell current

The equivalent battery cell current depends on the sign and amplitude of the current. Therefore;

$$i_{Bat,eq,cell} = \begin{cases} I_{Bat,1,cell} \left(\frac{i_{Bat,cell}}{i_{Bat,1,cell}} \right)^k, i_{Bat,cell} \geq 0 \\ \eta_{Bat,cha} i_{Bat,cell}, i_{Bat,cell} < 0 \end{cases}$$

$$k = \begin{cases} 1, i_{Bat,cell} \leq I_{Bat,1,cell} \\ 1.125, i_{Bat,cell} > I_{Bat,1,cell} \end{cases}$$

Where,

K = Peukert Number

$\eta_{Bat,cha}$ = 0.95 Charging Efficiency

It is seen that the peukert number has two diverse values depending on the amplitude of the discharge current. For currents higher than the nominal 1 hour discharge current $I_{BAT,1,cell}$ the capacity is therefore reduced significant.

Based on the above modeling and the estimation of the power rating, the Table 4.1 shows the observations for the two wheeler driver train.

Table 4.1 Observations of the two wheeler driver train

Mode	Initial Speed (Km/Hr)	Final Speed (Km/Hr)	Time (Sec.)	Energy Generated (Wh)
Braking I	25	0	2	15
Braking II	55	25	6	48
Acceleration I	0	25	2	-18
Acceleration II	25	55	6	-48

The above observations have been done practically using the Brush Less Direct Current (BLDC) Drive by measuring the speed using speedometer and the Energy required at the battery side for the estimate of the Energy rating of the SC using energy meter. The measured data shows that the approximately 50 Wh SC. To generate the 50Wh energy from the braking period and to supply the 50Wh energy for the accelerating mode, the losses of the system must be included in the energy estimation. The energy utilization from the SC will be only 70 – 75 % of the maximum capacity of the SC. Using the equation of the efficiency as shown here:

η = Energy required / (Energy Required + losses)…………………………………………....(4.27)

As the SC can be discharged up to the half of the voltage supplied to it:

η = 2 * Energy Required / 0.75 (Energy required + losses)………………………………..(4.28)

Here, η is the efficiency for the energy conversion from the SC to the wheel, which includes the energy conversion from chemical to electrical and electrical to mechanical, which is equal to 80%. The sum of energy required and losses will be nothing but the energy rating desired for the SC.

Energy desired = 2 * Energy required / 0.75 * η = 2 * 50 / 0.75 * 0.8 = 166.67 Wh ≈ 168 Wh

The power rating of the SC must be such that it would not overload the motor and the regeneration also can be achieved efficiently. To get the maximum utilization of the traction system, the SC should be able to handle the peak power demand to drive the electric motor. Of course, due to this limit, SC may be over loaded for a short period. The power ability will also be depended on the temperature rise due to power loss of internal resistance [88]. Thus, the power rating will be of the order of the converter and the motor rating only. In this case, motor rating is of 200 W maximum. For this, the SC power rating will be of 200 W.

It is preferable to have high voltage as far as possible to reduce the resistive losses thorough out the system. It is compulsion that wherever current is supposed to flow, there will be some resistance in its path, and when current flows through the resistance power will be dissipated though the heat generation. Although, it is also possible to transfer the same amount of energy with less current if the voltage is kept higher. On the contrary, very high voltage will increase their issues such as electromagnetic interference, insulation requirement and the safety. The systems nominal voltage in case of two wheeler electric vehicle is observed to be 48 V and in case of four wheelers, it is 110 V dc. The SC unit will comprise several interconnected SCs cells which each has a maximum voltage of the range 2 to 4.2 V. With a given energy requirement and cell type, the total number of cells is already determined. The SC module configuration is to be determined. If they all are connected in series, the voltage will be maximum but the SC unit will have more fluctuations because of smaller effective value. If they are connected in parallel, the highest voltage of a single cell with maximum capacitance may be achieved. Hence, the series – parallel combinations of the SC cells are to be studied such that the characteristic between the extremes can be achieved. Similarly, the converter is constructed to operate with a lower voltage at one side, to which the SC must be connected to enable full operation [90]. If the highest voltage of the SC exceeds that of the battery, the capacity is not fully utilized. It could be argued to install such a system as a safety issue; the converter can never raise the voltage over the input voltage, hence, the SC can never be overcharged. Thus, the SC unit maximum voltage is selected to be the same, or almost near to the battery supply voltage. The problem of variation of the voltage of the SC from battery voltage to zero voltage can be handled by converter.

The design criterions above are to be met with as low weight, volume and cost. It should also be able to have high efficiency as far as possible. Its design can be done using: i) reference and survey for the figures of merit from the market data available ii) design of interconnection of cells.[87, 88, 93].

Table 4.2 Available range of ratings for SC cell

Capacitance	ESR	Voltage	I_{max}	Weight	Cost ('000 Rs.)
1 – 3.6 KF	0.3 – 4 mΩ	2 – 3.2 V	0.5 – 1 KA	0.1 – 0.9 kg	2.4 – 3.6

The energy stored in case of series parallel connections of the SC is:

$E = (N_s * N_p)\ C.V_{sc}$ …………………………………………………………………...(4.29)

Where,

N_s = number of SCs connected in series.

N_p = number of Ns series SCs connected in parallel.

C = capacitance of one unit cell.

V_{sc} = Voltage across an SC cell.

The equation shows that the energy stored doesn't depend on the method of interconnections. The peak voltage will vary with number of series connected cells according to:

$V_{sc}\ max = N_s * V_{max}$ / Cell……………………………………………………………….(4.30)

Total Capacitance will vary according to:

$C_T = \{N_p/N_s\} * C$ / Cell…………………………………………………………………(4.31)

Table 4.3 Observations of a SC cell

C	ESR	$V_{initial}$	V_{max}	I_{max}	Weight	E_{sc}
1837 F	1.8 Mω	2.0 V	3.2 V	0.36 KA	0.881 kg	10.24 KJ

The minimum number of cells required to reach the voltage demands are 15 with a cell voltage of 3.2 V. If more energy is needed another such series strain could be connected in parallel or cells with higher capacity can be utilized. [90] If both cell types have the same internal series resistance, the added series strain strategy would be preferable since the total resistance will be less, as per the equation:

$ESR_T = \{N_s/N_p\} * ESR/Cell$……………………………………………………………….(4.32)

Once the voltage is fixed, the selection of SC cell depends only on the unit weight and the need of total energy. Since, the cell voltage as per the market data available for cells is 2 – 3.2 V, the minimum number of cells required in this case is 15 – 24. It is to keep in opinion for designing that larger the value of capacitance, the more energy can be stored but with heavier module of the SC. As per the data taken for the capacitance the weight will be of the order of 13.5 – 27 kg. For two wheeler of the BLDC drive the weight of the carriage can reach up to 90 + 27 kg (approximately). Hence, the BLDC drive is capable of the 117 kg weight (excluding the weight of the vehicle itself) to drive with. In this system, the capacitor is therefore simulated with diverse practically feasible solutions which are shown in Table 4.4. Out of all the calculations that consist of 2 strains of 15 series connected 3.2 V cells is more suitable. The calculations is done with a cell capacitance of 2KF, weight of 0.9 kg, 0.36 KA peak current and the ESR = 1.8 mΩ. There are more suitable solutions if the two wheeler is 24 V battery operated. The remaining parameters of the module will be as per Table 4.4:

Table 4.4 Calculations for SC

N_s	N_p	E_{sc} (Joule)	ESR_T (mΩ)	C_T (Farad)	V_{sc} (Volt)
15	2	307200	13.5	266.67	48
20	2	409600	18	200.00	64
18	2	368640	16.2	222.22	57.6
16	2	327680	14.4	250.00	51.2
14	2	286720	12.6	285.71	44.8
12	2	245760	10.8	333.33	38.4
10	2	204800	9	400.00	32
8	2	163840	7.2	500.00	25.6
6	2	122880	5.4	666.67	19.2

4	2	81920	3.6	1000.00	12.8
2	2	40960	1.8	2000.00	6.4
8	3	245760	4.8	750.00	25.6
8	4	327680	3.6	1000.00	25.6
8	5	409600	2.88	1250.00	25.6

4.6 CONVERTER DESIGN:

The converter should be able to handle all the power between the electric BLDC Drive to the SC. Here, due to State of Charge (SoC) of SC is allowed to change so does the voltage over the SC. If SoC of the SC is low and there is a need to transfer power, the current will increase. Thus, the converter must be designed to handle both high current and high voltage on the SC side. [92] As per the characteristics of the SC it is allowed to discharge up to 50% of the maximum voltage, in order to handle full power at all times. [86] The current rating should be:

$I_{rating} = P_{sc\ max} / 0.5\ V_{sc\ max}$,…………………………………………………………...…….(4.33)

The power rating of the converter should be at least twice the rating of the SC if the maximum SC voltage is equal to the battery voltage according to:

$P_{rating} = V_{rating} * I_{rating} = P_{sc\ max} / 0.5\ V_{sc\ max} * V_{rating} = 2*P_{sc\ max}$ ……………………………….…………..(4.34)

Here, V_{rating} = Voltage of Battery.

4.6.1 Bidirectional DC-DC converter design :

DC/DC converter must be able to do active power sharing of multiple energy storage system and enhance implementation of energy system. Battery and Supercapacitor hybrid storage system, active and passive component sizing and methodology are presented. Bidirectional two input DC-DC convertor is adopted in this framework, bidirectional converter are more efficient and flexible of all present interfacing topology. [85, 86]

4.6.1.1 Battery Discharging (boost mode)

$v_{in} - L_{batt}.\frac{di_{batt}}{dt}$ =0……………………………………………………………………(4.35)

$v_{in} - L_{batt}.\frac{\Delta i_{batt}}{Dt_2}f_{sw} = 0$ … …………………………………………………………….(4.36)

Rearranging,

$v_{in}(D_{t2}) = L_{batt}.\Delta i_{batt}.f_{sw}$…………………..………………………………………….(4.37)

Where D_{t2} is the duty cycle of the T_2 and f_{sw} is the fix switching frequency of the converter.

During conduction period of D_1 and when T_2 is off,

$v_{out} - L_{batt}.\frac{di_{batt}}{dt_{off}} - v_{in} = 0$ …………………………………………………………..(4.38)

$v_{out} - L_{batt}.\frac{\Delta i_{batt}}{(1-D_{t2})}f_{sw} - v_{in} = 0$ …………………………………………………….(4.39)

Rearranging,

$(v_{out} - v_{in})(1 - D_{t2}) = L_{batt}.\Delta i_{batt}.f_{sw}$……………………………………………..(4.40)

Equating terms $L_{batt}.\Delta i_{batt}.f_{sw}$ in (4.39), (4.40) and factors give the voltage transfer function:

$\frac{v_{out}}{v_{in}} = \frac{1}{(1-D_{t2})}$………………………………………………………………………..(4.41)

The terminal voltage of battery is at its maximum open circuit voltage at 100% SoC, where the unit terminal voltage is 12 V (Approx.). The duty cycle is minimum at this condition and is calculated as,

$$D_{t2min} = 1 - \frac{v_{batt\ dis\ max}}{v_{out}} = 0.5 \quad \ldots\ldots(4.42)$$

The lower boundary of battery operation occurs when the unit battery terminal voltage drop to 9V. In this type condition duty cycle is maximum it calculate as,

$$D_{t2max} = 1 - \frac{v_{batt\ dis\ max}}{v_{out}} = 0.625 \quad \ldots\ldots (4.43)$$

Thus, the boost mode of operation on battery side as only input to output voltage transfer function resultant in boost duty cycle range.

$0.50 < D_{t2} < 0.625$

This boundary condition is used to calculate the steady state operation of the converter and is not the duty cycle limit imposed in the converter control loop.

Switching frequency for 1 KHz (1 ms period), switch T2 is in conduction for the maximum of:

$$t_{2max} = \frac{1}{f_{sw}} . D_{t2max} = 0.625 \text{ ms} \quad \ldots\ldots (4.44)$$

Calculation of minimum time of conductionD_{T2},

$$T_{2min} = \frac{1}{f_{sw}} \bullet D_{T2}\text{min} = 0.5 \text{ ms} \quad \ldots\ldots(4.45)$$

Conduction period of T2battery

$$V_{battdis} = L\frac{di_{batt}}{dt} = L\frac{\Delta L}{\Delta t} \quad \ldots\ldots(4.46)$$

Design of inductor and its ripple current rating: Ripple current contributes iron losses copper losses and introduces audible noise, its value ideally kept low. [96] Current variation is more than 1% and a mean current, I_{mean} of 8A, total pick-to-pick current variation is 0.08A.

$\Delta I = (0.01 \cdot I_{mean}) = 0.08$ A

Induction required at maximum time $V_{battdis}$ is,

$$L = \frac{(Vbatt_{dis}\max)(\Delta t_{\min})}{\Delta I} = 0.48 \text{ mH} \quad \ldots\ldots(4.47)$$

Induction required at minimum time $V_{battdis}$ is,

$$L = \frac{(Vbatt_{dis}\min)(\Delta t_{\max})}{\Delta I} = 70 \text{ mH} \quad \ldots\ldots(4.48)$$

4.6.1.2 Calculation of load:

When convertor maximum power rating P_{max}, and nominal DC bus voltage V_{DC} nominal voltage (V_{DCnom}), maximum load current is,

$$I_{load\ max} = \frac{P\max}{V_{DC}nom} = 200/24 = 8.34\text{A} \quad \ldots\ldots(4.49)$$

4.6.1.3 Battery buck mode:

In the buck mode, DC bus voltage doing work as input voltage (v_{in}) and the battery voltage is out put voltage (v_{out}) of the convertor. Switch T_1 operate and diode D_2 is opposite direction,

$$v_{in} - v_{out} - L_{batt} \cdot \frac{di_{batt}}{dt_{on}} = 0 \quad \ldots\ldots (4.50)$$

$$v_{in} - v_{out} - L_{batt} \cdot \frac{\Delta i_{batt}}{D_{t1}} f_{sw} = 0 \quad \ldots\ldots (4.51)$$

Rearranging,

$$(v_{in} - v_{out})D_{t1} = L_{batt} \cdot \Delta i_{batt} \cdot f_{sw} \quad \ldots\ldots (4.52)$$

During the conduction period of Diode D_2 (T_1 is off), the KVL loop is,

$$(v_{out})(1 - D_{t1}) = L_{batt}.i_{batt}.f_{sw} \qquad \text{(4.53)}$$

Equating terms $L_{batt}.i_{batt} \bullet f_{sw}$ in (4.52).and(4.53) gives,

$$(v_{in} - v_{out})\, D_{T1} = v_{out}(1-D_{T1}) \qquad \text{(4.54)}$$

The output voltage is related to the input voltage,

$$v_{out} = v_{in} D_{T1} \qquad \text{(4.55)}$$

when voltage V_{in} is maximum duty cycle occur minimum, and when voltage is minimum duty cycle is maximum,

$$D_{T1min} = \frac{V_{out}}{V_{in}} = 0.437 \qquad \text{(4.56)}$$

$$D_{T2max} = \frac{V_{out}}{V_{in}} = 0.5 \qquad \text{(4.57)}$$

The duty cycle rang is maintain a mean charging current of 8A with a current ripple of no more than 1% and then calculate as:

$$L_{batt} = \frac{(V_{out})(1 - D_{T1})}{\Delta i_{batt} \bullet f_{sw}} \qquad \text{(4.58)}$$

Hear high induction require for a lower output voltage and duty cycles, calculation of minimum inductor value is

$$L_{batt} = \frac{(V_{out})(1 - D_{T1})}{\Delta i_{batt} \bullet f_{sw}} = 4.504\text{mH} \qquad \text{(4.59)}$$

The inductor is connected with battery in series and capacitor is connected with parallel, After Simulation Results the better output was coming with 12 mH so Inductor was designed with that Value and the Maximum current at that time was 2.7 Amp so taking Safety Limit of 1.3 Inductor was designed for 4 Amp Rating.[96]

4.6.2 Control Pulses Design

The Control Pulses are designed to simultaneously drive both the MOSFETs according to the need as shown before the calculation of providing boost operations we have to give 50 % duty cycle hence the pulses are with 50 % complementing each other and programmed in controller using the T_{mod} operation.

The output is taken in two pins of the controller but not given directly to the device as isolation is required for safety purpose.

The Isolation is provided by the Optocoupler Circuit as shown below

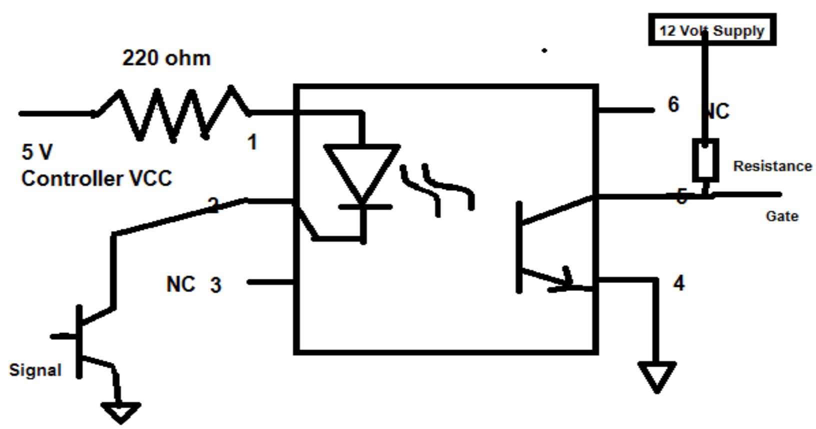

Fig. 4.8 Optocoupler Circuit

The Driver IC Used is 4N 33/35 which was easily available in market.