DC Microgrid and Control System
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Lecture - 15
Modeling of Energy Storage System

Welcome to our lectures on DC Microgrid and Control System. Today we shall discuss in detail about the modeling of the energy storage that will be ultracapacitor and the batteries mainly.

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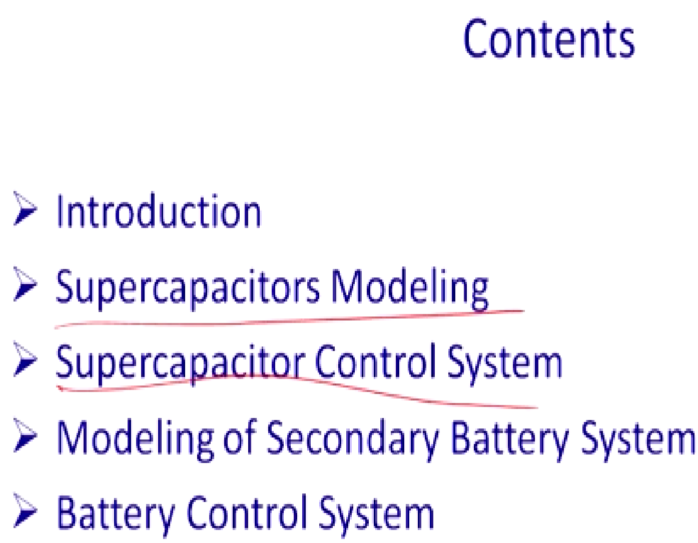

So, this will be our presentation layout today. We shall discuss about this ultracapacitor or the supercapacitor and its modeling or thereafter uh how you will be charging and discharging the ultracapacitor and that is it will be essentially related to the control charging that we will talk about the control and modeling part of it. Thereafter we will have a modeling of the secondary battery system and battery management system on the battery control system that will be discussed. We will try to convert this topic in our course content today.

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Introduction

- It is well known that energy storage devices provide additional advantages to improve stability, power quality, and reliability of the power-supply source.
- The major types of storage devices being considered today include batteries, supercapacitors, and flywheel energy systems
- The performances of batteries, supercapacitors, and flywheels have, over the years, been predicted through many different mathematical models.
- Some of the important factors that need to be considered while modeling various energy storage devices include storage capacity, rate of charge/discharge, temperature, and shelf life.

So, what we know that we have seen that since erratic creates actually uncertain nature of this energy sources in case of the renewable energy, we require to store the energy. So, storing element is essentially is one of big part of our microgrid. So it is well known that energy storage device provide additional advantage to improve stability, power quality and reliability of the power supply sources and most of the and in a microgrid also there might be a big demand there might be a big demand and also there might be some time while you are you are generating the source at its peak output.

So there is a mismatch between these 2 peaks but it may cater the average power throughout a day, but there will be an instantaneous mismatch between the big demand, as demanded by the consumer and thus supply generated by the renewable energy sources and for this reason it necessitate to introduce this storage element. The major type of storage devices being considered today includes batteries with the advent of the lithium ion batteries, thereafter other batteries. We will see that there is a lot of advantage to it.

Thereafter supercapacitor and flywheel energy system and you know actually this this storage element will have its requirement depending on the time. Battery can supply power in hours, ultracapacitor will last for the generally in minutes, and flywheel also almost same thing depending on the site of the flywheel because you know if energy storage capability is actually is rotational mass, its inertia, constant and all those things matters.

So, you will have you will require different kind of utility for support different kind of if it is a voltage fluctuation kind of application. Generally ultracapacitor or the or actually what is fluctuation kind application you got used voltage saxs sometime and this is the issues related to the power quality, then we will go for the ultracapacitor and the flywheel systems and if you wish to shift or manage your peak power demand because of mismatch between your peak demand and the peak generation, battery generally preferred nowadays.

Of course, your technology is emerging and men many are working on it, so of course what we are making a statement in 2019, it can change within 5 years. The performance of the batteries superconductor and flywheel have over the years have been predicted through the through many different mathematical models, so we shall come into its mathematical model. We shall take few simple mathematical model to analyze a storage element and ultimately overall control system we will understand the mathematical mode only.

So, we required to develop the mathematical model of this storage element. Some of the important factors that need to be considered while modeling various energy storage devices include its storage capacity, mostly it is the NH, so battery will have a stored charge in the form of chemical energy. Ultracapacitor or supercapacitor will store the energy 1/2 CV square. Here it will be storing the energy of 1/2 MS square x omega.

Also the rate of, that is also the power part of it, rate of charge or discharge, this is basically if you differentiate energy you get power and which rate it can deliver power into the system and the temperature sensitivity because battery has a huge temperature sensitivity, we need to consider it and its whole life, how many years it will last that also required to be considered while choosing a storage device.

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Supercapacitors Modeling

- Supercapacitors can be modeled by the equivalent electrical circuit shown in Fig.1.
- The Supercapacitor is characterized by the capacitance *C* and two resistances:
  - The series resistance R_s, commonly called the equivalent series resistance (ESR), which is the main contributor to power loss in charging and discharging processes; and
  - The dielectric leakage resistance, R_l.

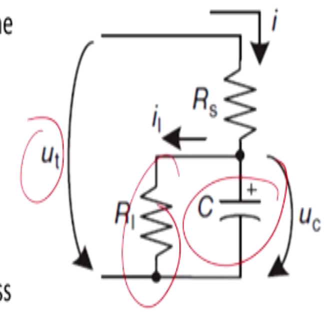

Fig.1: The equivalent electrical circuit of a Supercapacitor

- The voltage at the Supercapacitor terminals can be deduced from the equivalent electrical circuit in Fig.1.

Let us take the ultracapacitor or the supercapacitor past. Supercapacitor can be modeled by the equivalent electrical circuit because you know it is a capacitor only it has to be a capacitor, ideal capacitor followed by the series and the parallel resistances. The supercapacitor is characterized by the capacitance C and 2 resistances. The series resistances Rs commonly called the equivalent series resistance or ESR.

And ESR should be very small, which is the main contributor of the power losses in the charging and discharging process and the dielectric leakage then that will be mottled as a resistance Rl. The voltage at the supercapacitor terminal can be deduced from the equivalent circuit of this figure. So, you can have what is the voltage available to you, you can calculate.

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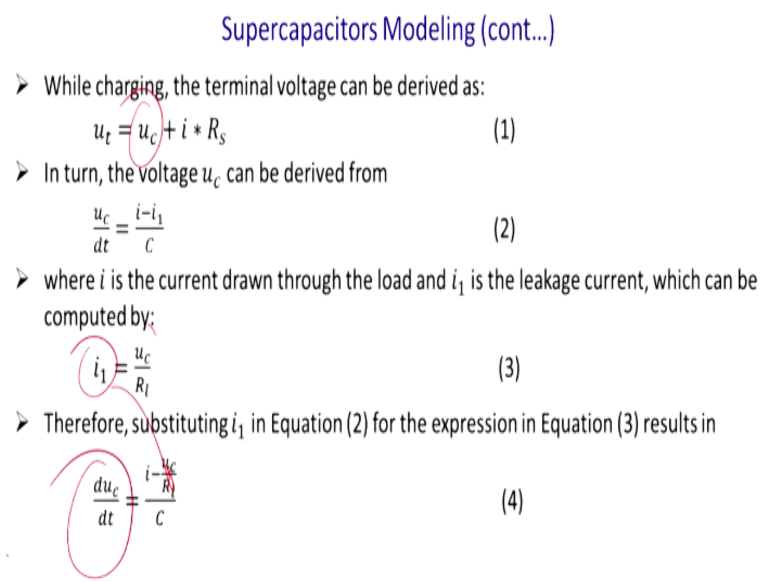

So, while charging, the terminal voltage can be derived at ut = uc that is the capacitor voltage + the drop across the ESR and in turn the voltage uc can be actually derived from this uc/dt = i1- i-i1/c. Most of the cases you know actually this resistance is quite high and this resistance value can be neglected also where the current through the load i is the leakage current which can be expressed as i1 = uc/Rl, generally this current is pretty small and thus therefore we can also substitute that this I here and ultimately you get uc/dt = i-uc/R/C.

So, this will be the actually the divinity across the capacitor, essentially this will be the current which will sink through while charging. So, let us take a buck converter, which will be actually storing the ultracapacitor, will be charging and will be discharging by the bidirectional Dc to DC converter in a boost mode.

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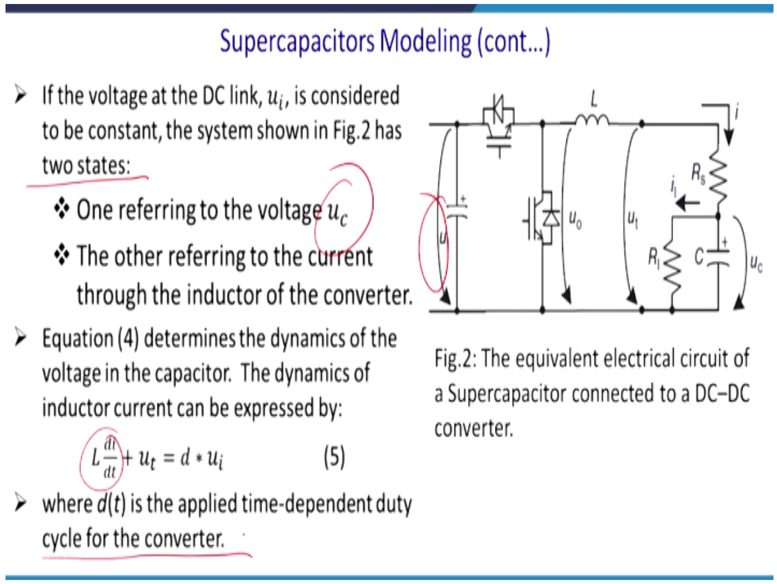

So, in this configuration, the voltage DC link, ui, that is this one, is considered to be constant and as shown in the figure 2, it has two states. One referring to the voltage uc, other referring to the voltage through the in, uh other actually this will be the current through the inductor. There are 2 states always, is the voltage across the capacitor and current through the inductor. So, we can rewrite the equation for determining the dynamic voltage of the capacitor.

The dynamics of the inductor current can be expressed as Ldi/dt + ut = duty cycle when it is on or d is the duty cycle of it into ui where ui is the input to the buck converter where dt is applied to the time dependency of the converter.

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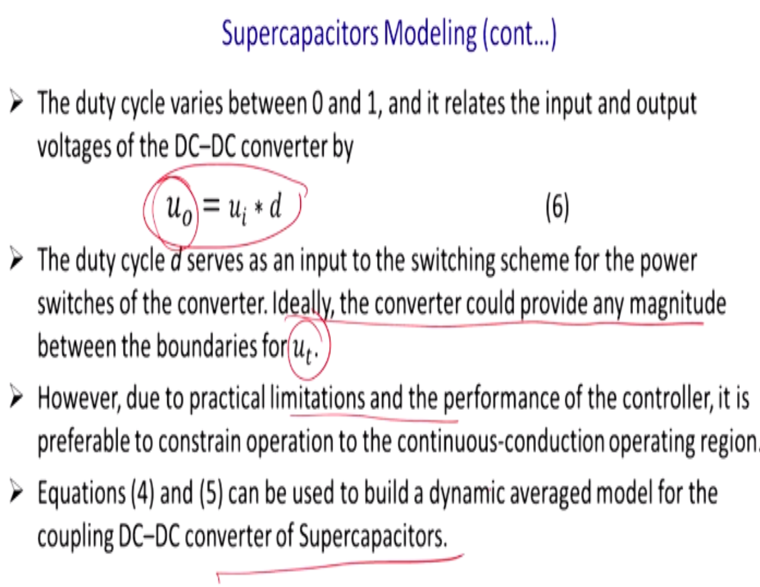

So that is what happened. The duty cycle varies between 0 to 1 and it relates the input and the output voltage of the DC to DC converter, so U = ui x d. The duty cycle d serves as an input to the switching schemes for the power switches of the converter. Ideally, the converter could provide any magnitude between the boundaries of ut. However, due to the practical limitations and performance of the controller, it is preferable to constrain the operation to the continuous conduction operation region because control is always better in a continuous conduction mode.

Then actually this equation will hold, otherwise it doesn't hold, and the equation 4 and 5 can be used to build dynamic average model, please refer to the Advanced Power Electronics NPTEL courses in DC to DC converter. I have discussed in detail about the average modeling of the DC to DC converter and model of the coupling of the DC to DC converter for the supercapacitor.

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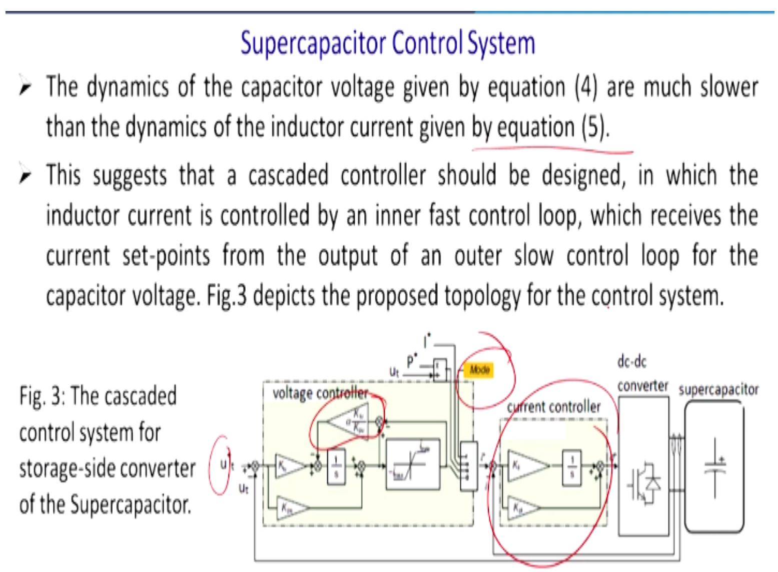

Now this is a scheme of charging ultracapacitor. You got ut, that is the reference ut, the cascade control of the storage side of the super ultracapacitor and you will decide the mode from here and ut you have got the ut reference that is basically the desired voltage is the ut of the ultracapacitor and essentially you have a PI controller and PI controller will have also a feedback mechanism that a limitor and ultimately that gives you effectively the value of the R. So this reference will be actually compared with the average current controller.

You can have a peak current controller also, but it is better to use the average current controller and ultimately that will decide the duty cycle of the buck converter in this case. So this is the explanation of this figure. The dynamics of the capacitor voltage is shown is given equation in 4 must lower than the dynamics of the inductor current given on equation 5. So for this reason, you have a first controlling current loop that is this one and thereafter you have a slow controlling voltage loop.

This suggest that a cascade controller should be designed in which the inductor current is controlled by an inner fast current loop which received the current set point from the output of an outer slow control loop for the capacitor voltage. Figure 3 depicts the proposed topology for the control system. This is the figure 3.

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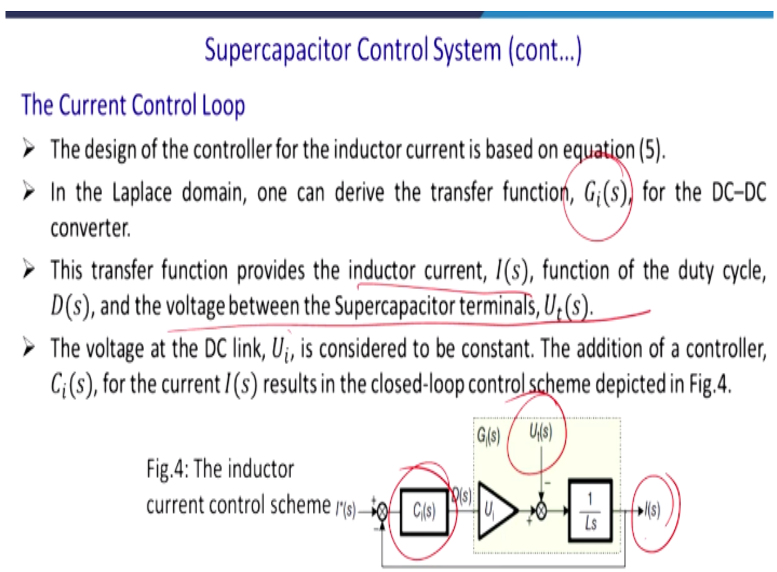

Let us split it into the slip it and we shall here discuss about the inner current loop of the inducted current loop. The design of the control for the inductor current is based on the equation 5, please refer to the equation 5. It is the inductor current, so this is the equation 5. The lap in Laplace domain, one can derive the cascade function that is Gis for the DC to DC converter, essentially it is a discontinuity for switching on and switching off.

So, this will have an average model and this transfer function provides the inductor current Is and the function of duty cycle Ds and the voltage between the ultracapacitor terminal voltage

Uts. The voltage of the DC link Ui is considered to be constant. The addition of the controller Cis of the current Is results in closed control scheme as depicted in figure 4.

So this one is basically the Cis, this is additional controller, that is basically you know compare this current loop that you will feed to this a gain element to match this dimensions as well as its magnitude, that you will control with the battery sorry. This ultracapacitor output voltage and then you got a 1/Ls that is inductor and ultimately this current is the current through the inductor. This is the inner current control scheme.

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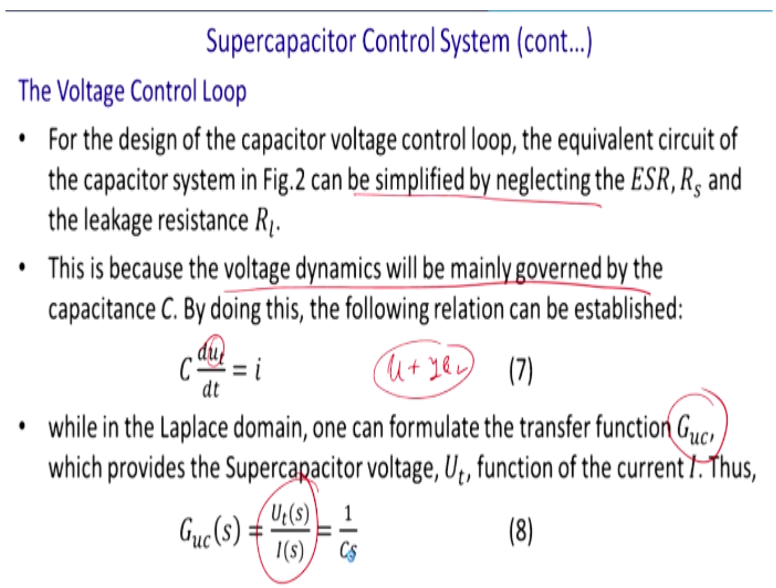

Now let us come to the voltage control loop. The design of the capacitor voltage control loop, the equivalent circuit of the capacitor in the figure 2 can be simplified by neglecting the ESR and Rs and the leakage current Rl. So we just neglect the ESR and the Rl and just you write C dut/dt = i. This is because the voltage dynamics will be mainly generated by the capacitance C and only it will add up this value of the voltage.

So, rate of change of voltage is you differentiate, it is it has no sensitivity on the resistance. So for this reason, it is eliminated. If you have Ut + some I x Rl, so you know actually if this part is constant, so it does not make any sense. So by doing this, following relation can be established. While in a Laplace domain, we can formulate the transfer function that is Guc and which provides the supercapacitor voltage Ut, so that can be written as Ut/Is, essentially it will be it is 1/Cs.

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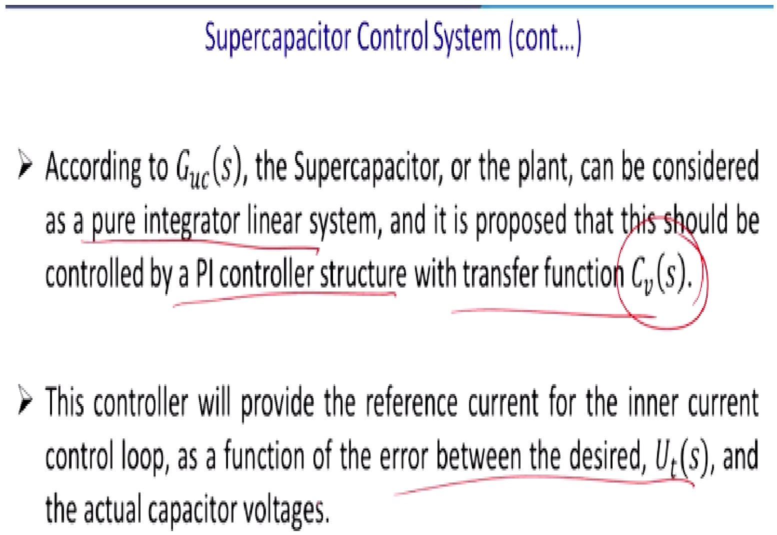

So according to this Guc, the supercapacitor or the plant can be considered as pure inductor linear system and it is proposed that this should be controlled by a PI controller structures with the transfer function of Cv. So, this is the by this analysis, we now understood what kind of controller is required here. This is Ci and we require another controller so that we have to go back to this slide so since this is a this is this is basically the voltage controller and this is essentially what you can see that it is a PI controller.

So, this controller will provide the reference current for the inner current control loop as a function between the error between the Ut and the actual capacitor voltage. So accordingly you will charge that and this is the analysis of this ultracapacitor and it is used for stabilization of the loop as well as it is used for stabilization of the transient disturbance for the load change or the dropping and other phenomena also, and a DC microgrid ultracapacitor, now a days is an integral part as a storage device.

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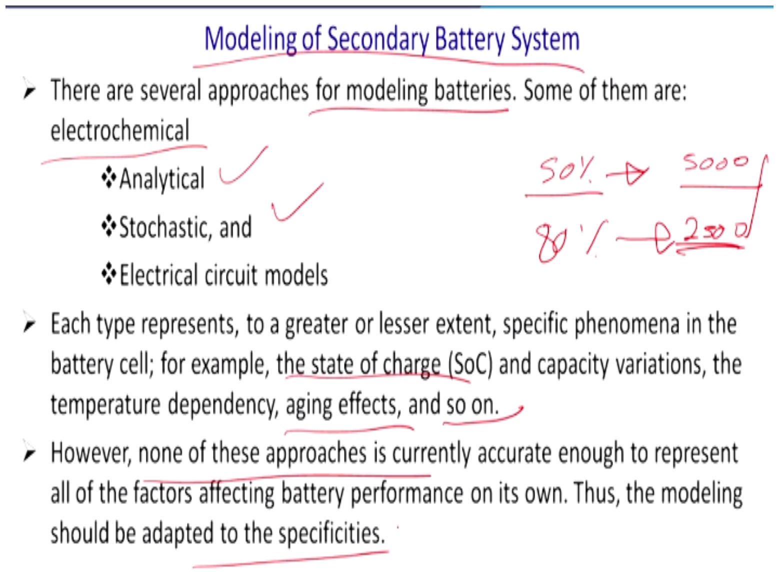

Now let us come into the modeling of the second storage element that is battery. Battery essentially is a slow element. It takes lot of time to charge as well as discharge. So its phenomena will be (( )) (18:33) but essentially your energy conservation and all those things will be balanced by these batteries only. So, there are several approach for modeling the batteries and some of them are electrochemical, so we cannot ding into that because our limited knowledge in the electrochemical processes, but we shall do the analytical study, stochastic study and its electrical circuit models.

So each type represents, to a greater or lesser extent, specific phenomena in the battery cells; for example state of charge and the capacity variation, the temperature dependency, aging effect and so on. So life of the battery also depends how much cycles you have charging and more over how much you are discharging in each cycle. So, this model should accurately represent, for example if you go for the 50% depth of discharge and you may able to actually you can refer to the data sheet of any battery companies, you can have a charging cycle of 5000.

If you go to depth of discharge by 80%, you will find that you may be limited to go to the level of 2500. More the depth of discharge and less will be the number of cycles you can use. So, your model should validate those all phenomena, chemical phenomena, mathematically, but there is a great challenge in it. However, none of this approach is currently accurate enough to represent all of the factors affecting the performance of its own.

Thus, modeling should be adopted for the specific requirement or specific needs, and for example, if you keep in the if you keep the battery into the sensitive temperature controlled environment, you will find that it will last long. If you put that batteries in non-ac environment, you will find that that going to decay faster.

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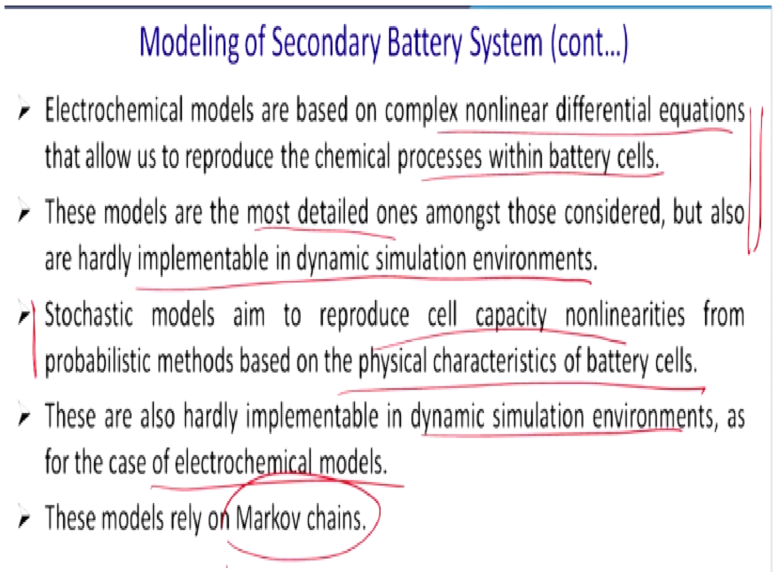

Electrochemical models are based on the complex nonlinear differential equations and that allow us to produce the electrochemical process within the battery cells, but that is totally the domain of the chemical engineers. These models are most detailed ones amongst those considered, but also hardly implementable in a dynamic simulation environments. Of course, it is a perspective of an electrical engineering, so maybe actually a person with a, we have we have a definitely limited knowledge with the chemical processes, chemical thermodynamics, and for this reason we are making this statement.

What problem lies, they don't understand electrical engineering, we don’t understand a good amount of the chemical engineering. So, for this reason, the solution we wanted to see here is a stochastic aim to reproduce cells capacity nonlinearities from probabilistic method based on the physical characteristics of the battery cells. So, there are people still working on it, but we try to have simplify our problem and try to address it.

Look, it would have been a great you know actually now what happened in your battery mobile, it gives the state of charge, how you estimates is generally actually estimates by the output voltage, but it is silent about that how many years left it will has to be replaced, so how many charging and discharging cycle you have followed. So, battery management system is a huge process and warning system for trigger that require to replace this battery within this period of time, something like that.

Like you know your oil gives an indicator that I have to fill oil once once actually the level of this oil goes low, but battery when need to be replaced, it is difficult to give a warning. Anyway, we adopt some probabilistic method to forecast on it. These are also hardly implementable in dynamic simulation environment as for the case of the electrochemical model. These models rely on Markov chains.

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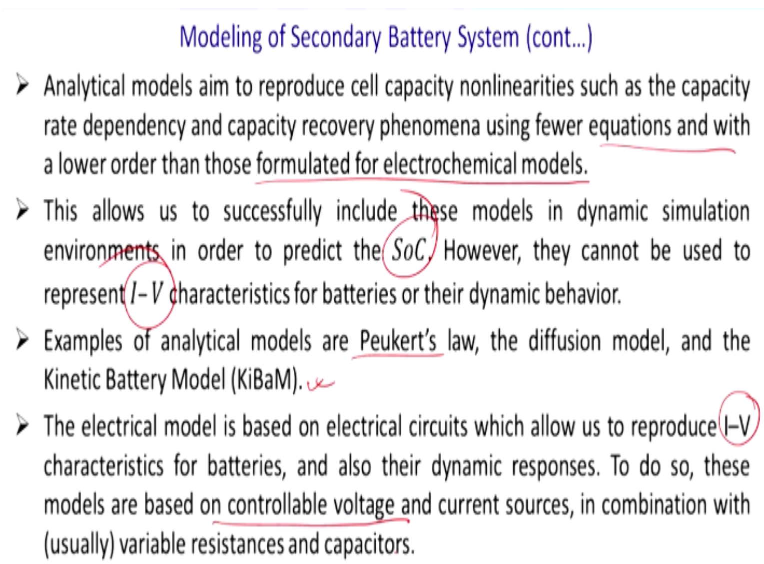

So, this is altogether a chemical process, and for this reason, analytical model aim to reproduce the cells' capacity. Nonlinearity such as the capacity of the rate of dependency and the capacity recover phenomena using fewer equations and with the lower order than those formulated in electrochemical models, and thereafter, it allows successfully to include these models in dynamic simulation environment in order to predict the SoC. SoC generally if you wish to predict rightly, we require to uh calculate the specific gravity.

Specific gravity generally changes of the battery due to the chemical reaction. However, they cannot be used to represent the I-V characteristics for the batteries or their dynamic behavior. For example, analytical model of Peukert's law, the diffusion model, and the kinetic battery model can be used here. The electrical model is based on the electrical circuits, which allows to represe, which allows to produce I-V characteristics that we required to know for the batteries and also their dynamic responses.

To do so, these models are based on controllable charge and current sources in combination with usually variable resistance and capacitor, letter C.

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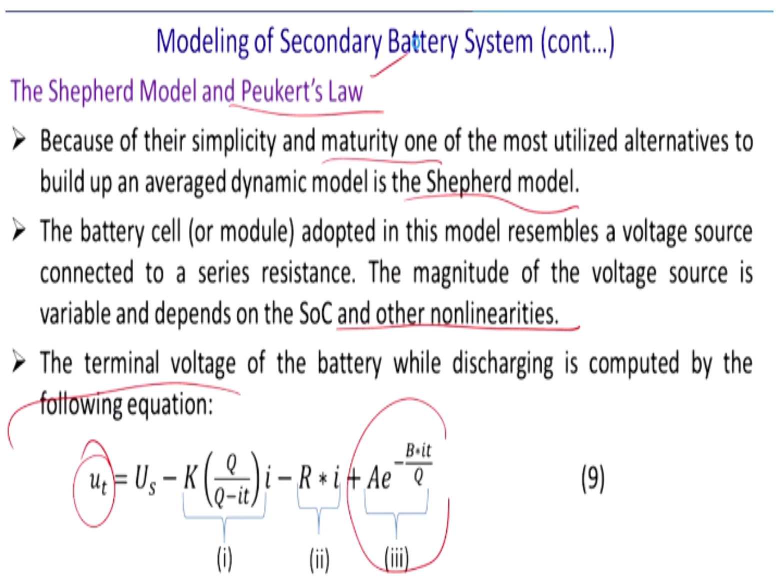

So, this is Shepherd Model and Peukert's Law. Because of their simplicity and maturity, one of the most utilized alternative to build up an average dynamic model is the Shepherd model. The battery cell or the module adopted this model resembles a voltage source connected in series. The magnitude of this voltage source is variable, depend on the Soc and other nonlinearities. So, terminal voltage of the battery while discharging is computed by the following equation.

So, this is the terminal voltage Us, K which shall escalate Q/Qit x I – Ri x Ae to the power Bit Q. So, it is a complex relation, it is called this law, Peukert's law.

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The Shepherd Model and Peukert's Law

- For charging processes the terminal voltage can be computed by:

$$u_t = U_S - K\left(\frac{Q}{Q-it}\right)i - R*i - Ae^{-\frac{B*it}{Q}} \qquad (10)$$

- Where u_t is the terminal voltage (in volts), i is the electric current (in amperes), Q is the maximum amount of charge for the battery (in Ah), it is the actual battery charge (in Ah), and U_S, K, R, A and B are Shepherd parameters.
- These Shepherd parameters are defined as: U_S is the constant voltage (in volts); K is the slope of the polarization curve, or the polarization resistance (in V/Ah); R is the internal resistance of the cell measured in the charged state; A and B are empirical parameters.

In charging process, just see that what is the difference between charging and discharging process, so it is almost same, just it will change little bit, you will have ut = Us – K Q/it x Ri A to the power of this. So, let us introduce this nomenclature here one by one, where ut is the terminal voltage involved, i is the electric current in amperes, and Q is the maximum amount of charge in the battery that will be actually your ampere hour capacity of the battery.

Generally, it has been denoted by the manufacturer and it is the actual battery charge in Ah and Us, K, R, A, B are the Shepherd parameters. These Shepherd parameters are defined as Us, the constant voltage in volts, K is the slope of polarization curve or the polarization resistance, and R is the internal resistance of the cell which you talk about many time from class 2 level of the cells measured in the charged state, A and B are the empirical parameters.

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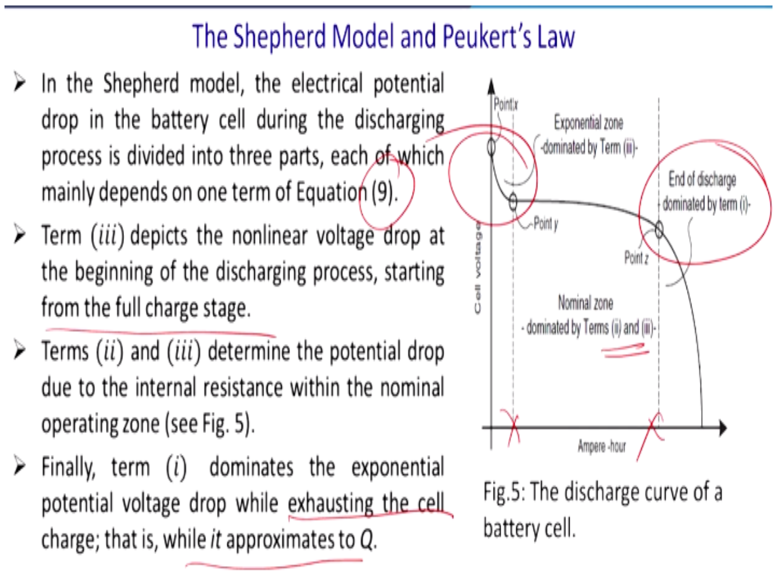

The Shepherd model of the electrical potential drops in the battery cell during the discharging process is divided into the 3 parts, each of which depends on one term of the equation 9, that we have seen there. The term 3 depicts a nonlinear voltage drop at the beginning, so this is the case, beginning of the discharging process, starting from the full charging state, this is the process. The term 2 and 3, just go back please, so this is the term 1, this is term 2 and this is the term 3.

Nonlinear voltage drop at the beginning of the discharge process starting from the full charge, and experimentally you can find it out A and B. So, the terms 2 and 3 determines the potential drop due to the internal resistance and you can see the figure B that is the nominal zone and this is for the term 2 and term 3. Finally, the end of the discharge, so it will be very fast and you required to operate in this region only, this is called your safe zone of operation.

You will see that, actually you may see that when you got a 40% battery charge, it goes to the 30% battery charge in the end of time and the battery chargers, it goes to ten pes 10% to 0% almost in no time. So, this defines this characteristics and finally uh the the first part of the equation determines the exponential potential drop while exhausting the cells charge s and it appears to approximate the value of the Q. So based on this model, we require to first design the battery charging process.

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Battery Control System

- As in the case of Supercapacitors, a cascaded control system based on PI controllers can be proposed for the batteries.
- In such a structure, the inner control loop would be in charge of controlling the currents exchanged by the battery.
- The control loop topology and tuning are identical to those for Supercapacitors, since they solely depend on the inductor included in the DC–DC converter and the voltage at the DC link that couples the storage side converter to the dc-bus.
- However, the outer control loop is in charge of providing the inner one with the reference profile of the current.
- The reference current is limited by the battery management system (BMS) for protection purposes.

In case of the ultracapacitor, a cascade control system based on the PI controller can be proposed for the batteries, so same model can be used. In such a structure, the linear control loop should be in charge controlling current exchange by the batteries. The control loop topology and tuning are identical to those of the ultracapacitor, please refer to the capacitors. Since this only depend on the inductor included, the DC to DC converter and the voltage at the DC link that couples the storage side of the converter to the DC bus.

However, the outer control loop in charge in charge are providing the inner one with the reference profile of the current. The reference current is limited by the battery management system for the protection purpose, and generally if it is a lead acid battery, so your maximum charging current cannot cross uh 10, 10% of your AH value. So that kind of limitation will be put by the battery management system.

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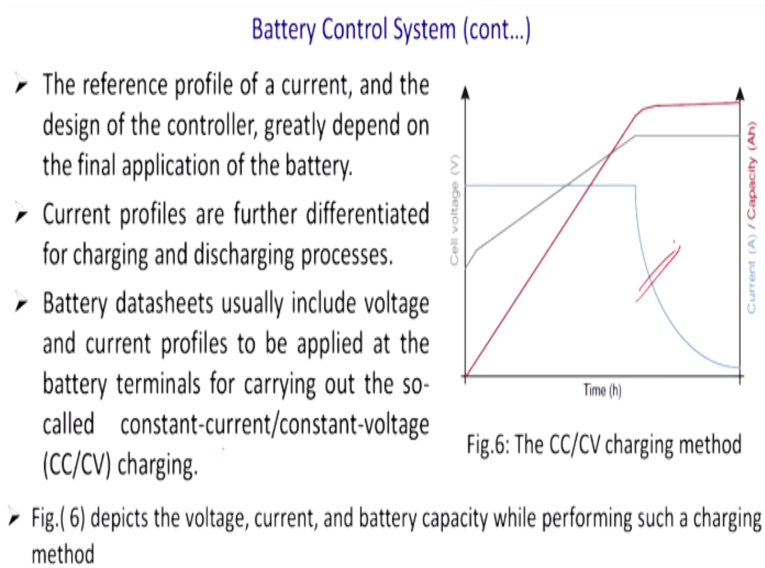

The reference profile of the current and the design of the control for controller greatly depend on the final application of the battery. You can see that there are different kinds of charging that is called CC or CV charging. The current profile are further differentiated by charging and discharging process. Battery datasheets usually include voltage and the current profile, profile to be applied at the battery terminal for carrying out so-called constant, voltage of the constant current charging.

So, this is the capacity Ah and you know this is the constant voltage charging, thereafter you can see that this is basically after that, this is called constant power charging essentially because voltage into current is constant. So there are different kinds of charging methodologies.

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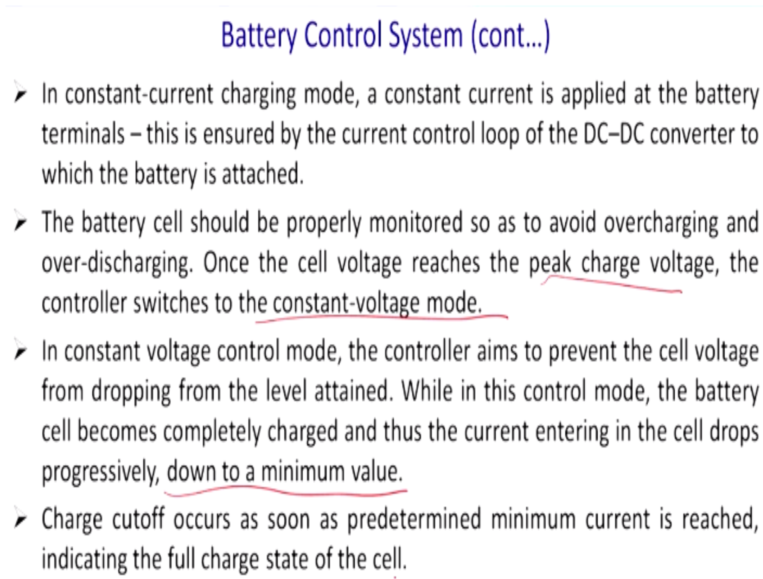

So, the constant-current charging mode, if you provide a constant current is applied at the battery terminal and it is ensured by the current control loop of the DC to DC converter, which the battery is attached. The battery cell should be properly monitored so that it avoid overcharging and over-discharging, that is we required to ensure that, otherwise there will be a fast fall and fast rise in voltage. Once the cell voltage reaches the peak charge, the controller switches to the constant-voltage mode.

In the constant voltage control mode, the control aims to prevent the cell's voltage from dropping from the level it is maintained. While is while in this control mode, the battery cells becomes completely charged and thus current entering into the cells drops progressively and lowers down to the max minimum value. Then there will be a charge cutoff occurs as soon as the predetermined minimum current is reached indicating that full charge the battery is fully charged. So, this is the way your battery management system will work.

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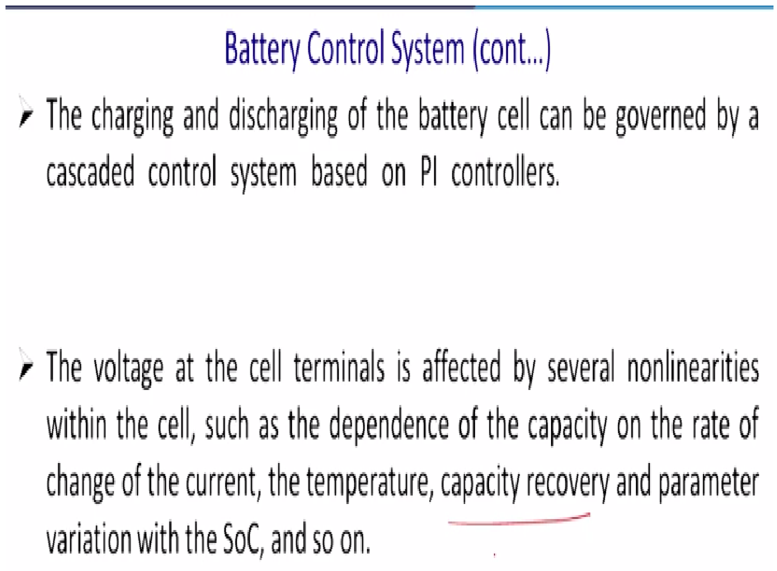

The charging and discharging of the battery cell can be governed by the cascade control system of the PI controller and the voltage cells the voltage at the cell terminals is affected by the several nonlinearities within the cells, such as that dependence of the capacity and at which the rate is charging and discharging, temperature, rs capacity, recovery, parameter variations, SoC, and so on. So, all cannot be fit into the modeling, for this reason, this formula is empirical one.

So, but while following that, we can successfully implement the battery management system. Thank you for your attention. We shall continue to our next discussion on the storage element.