Control and Tuning Methods in Switched Mode Power Converters
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Module - 01
Switched Mode Power Converters and Simulation
Lecture - 02
Overview of Voltage Regulators

Welcome. So, today is our 2nd lecture and it is on the Overview of Voltage Regulators.

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In this lecture, we are going to discuss about linear voltage regulators, then introduction to switch capacitor converters, then basic understanding of hybrid switch capacitor converter followed by switched mode power converters.

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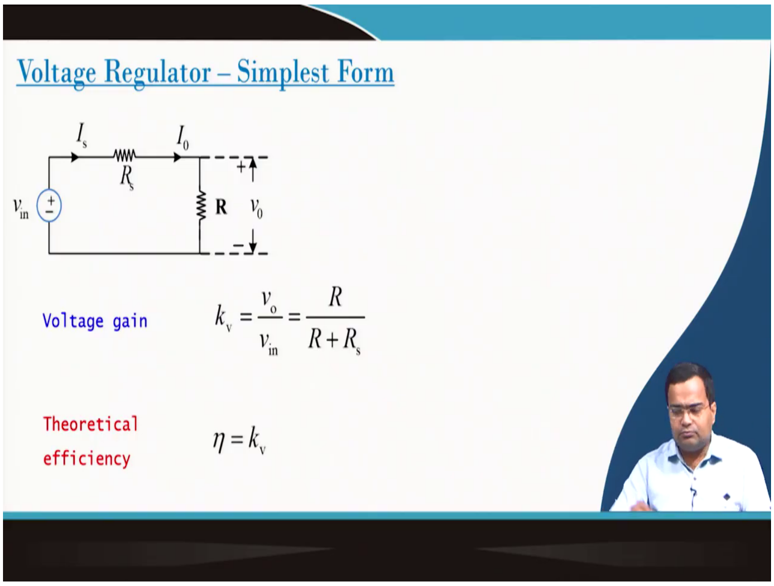

So, in voltage regulator, if you start from very basic, it starts with a simple a resistive divider, where we have a series resistance R_s and load resistant R. The voltage across the load resistance is simply R by R plus R_s. What can happen? Here, the input voltage can vary, the load resistance can vary, but we need to regulate the voltage.

So, in order to regulate the voltage what degree of freedom we have in our hand is the variation of the source resistance. So, we can vary the source resistance in a way such that output voltage is maintained at its desired value, in spite of variation in input voltage and/or in load resistance.

But, if we look at the efficiency of this voltage regulator, its theoretical efficiency is same as the voltage conversion ratio, which is practically even less. If you want to achieve higher voltage conversion, your efficiency will get degraded significantly, because the most of the voltage drop across the R_s will be dissipated as heat energy.

So, if you want to achieve a lower voltage as v_o, then the maximum voltage will be dropped across the series resistance. And, higher this drop voltage is lower the efficiency and higher power dissipation; consequently, temperature goes up. So, this process is not an efficient way of regulating output voltage.

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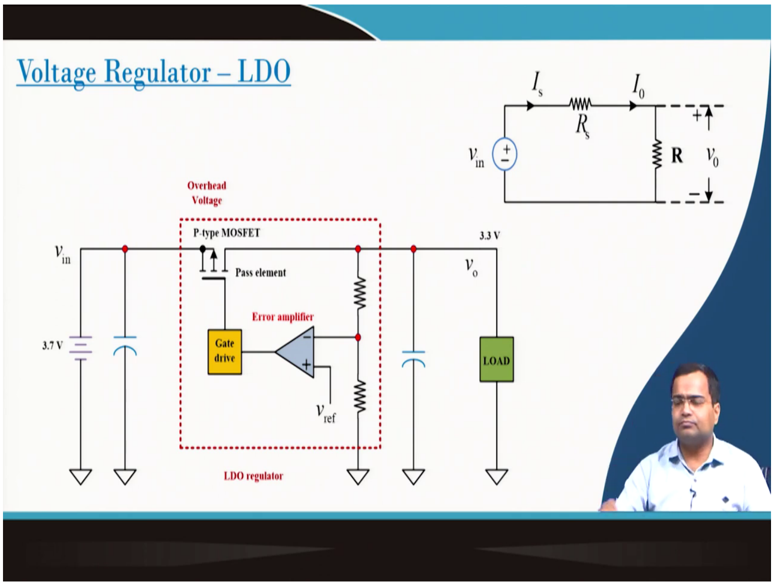

In general, this variable source resistance can be achieved by using a transistor. This is a drop out regulator, linear drop out regulator, what we have discussed? We want to drop certain voltage across the series resistance such that the output voltage is maintained at its desired value.

So, we want to use a transistor, which will act like a variable resistance. And, how can we adjust the resistance of the transistor? By varying the gate voltage. And, for gate voltage the input for this gate drive is the feedback voltage of the output feedback voltage, we will generally put a resistive divider.

And, then we need to compare with the desired reference voltage and accordingly we generate the gate voltage. Such that, the output, I mean, the drop across the PMOS transistor, what we are using PMOS, is the drop which created in such a way the output voltage is maintain. And, here we also use input capacitor and output capacitor in practical linear drop out regulator.

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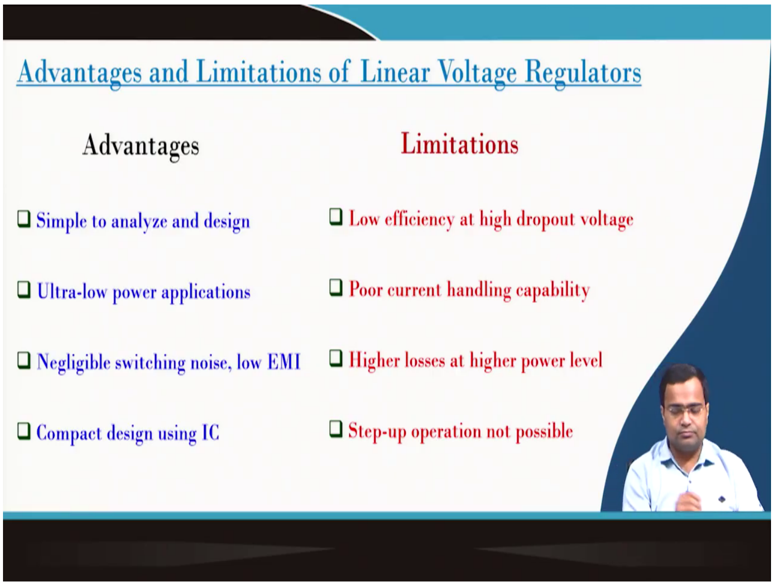

So, what are the advantages of this linear voltage regulator? The advantages is that this is very simple; that means, is it is like a resistive divider very simple to analyze and design, I mean relatively simple. In transistor level, it can be somewhat more challenging, but in general from system level these are simple.

And, these are reused for ultra low power applications in which the current requirement is very low such that the current going through the series resistance will also be low. So, that the I^2 square loss will be low. Even though it is not very highly efficient, but we still need to limit the losses across the resistance, and the power loss will be converted into heat energy and it can heat up. So, in low power applications, heat can be maintain. However, it has negligible switching noise, because there is not much switching what we will be discussing in subsequent voltage regulators, in which there will be inherent switching.

So, it is less susceptible to switching noise. So, as a result the EMI is low. And, also it can the design can be made compact using an integrated circuit. But, what are the disadvantages? As we discuss the efficiency is very low and it depends on the drop out voltage, higher the drop out voltage the lower the efficiency.

In fact, if we want to you know step down let us say from 12 volt to 3.3 volt, in such cases, linear voltage regulators are not recommended. We should use more than one stage. The first stage it can be 12 to let us say 8 volt and the second stage 8 to 3.3 or even we can divide into multiple stages.

Because, at each stage the drop out voltage across the transistor should be smaller, so that the heat dissipation can be distributed among multiple stages, but as we increase the number of stages efficiency further reduces. It also has a poor current handing capacity, because as I said if we try to use it for high current, then the losses will be really significantly higher and it will be unmanageable.

And, it is also very lossy at high power level, which means, if we have variable load current and if it is designed for a certain load range, it is good to use at lower current level. As the current level increases then the losses increase. And, third one I mean another drawback is that, this is generally not used for step up applications, because it is used only for step down applications.

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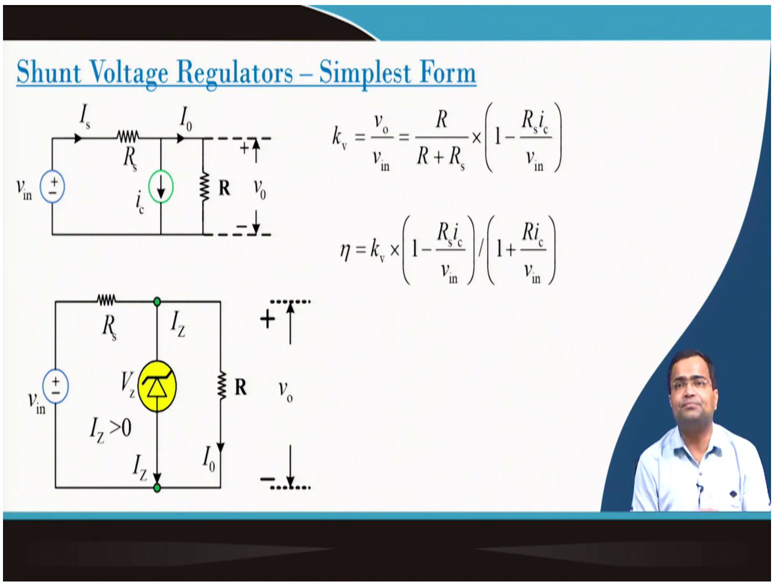

We can also use a shunt voltage regulator, where in addition to series voltage regulator, we generally consider an additional current shunt path across the load resistance. This is generally a control current, and in this case, in the voltage gain, another factor will come due to the current sinking path.

So, the efficiency can be shown to be even lower than the series voltage regulator. But, because of this current shunt path, this gives an additional degree of freedom and that helps to improve voltage regulation over a wider range of load current.

For example, we can replace this control current using a Zener diode where, the voltage across Zener diode can be maintained and whatever the residual current. I mean there will be a load resistance and that current. The Zener diode voltage drop will be constant, and the current passing through the Zener diode will be such that the voltage across output voltage will be maintain.

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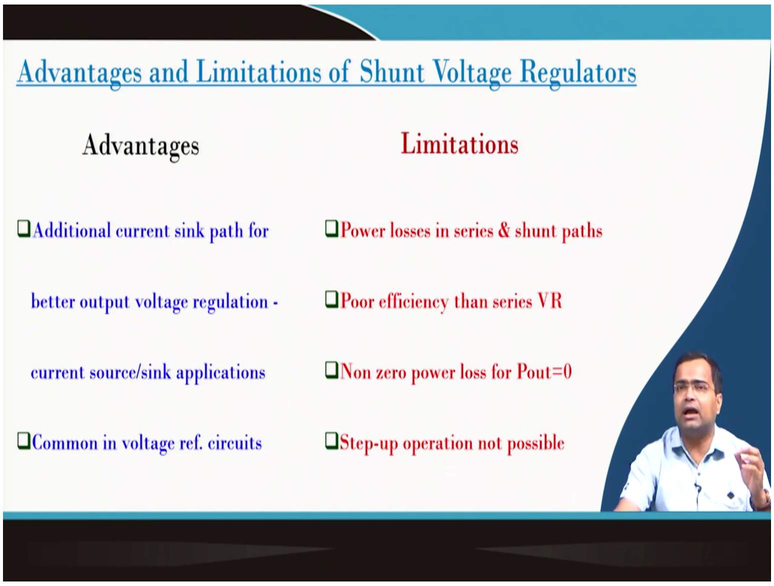

So, a shunt regulator has an additional current sink path, which can offer better output voltage regulation. Such regulators are common in voltage reference circuits, where a Zener diode is replaced by a transistor for current control, but, its losses are more. Even the voltage gain is lower than the series voltage regulator.

Even, there can be some additional losses under no load conditions. So, the efficiency is poor then even a series voltage regulator. Also, we cannot achieve step up voltage conversion.

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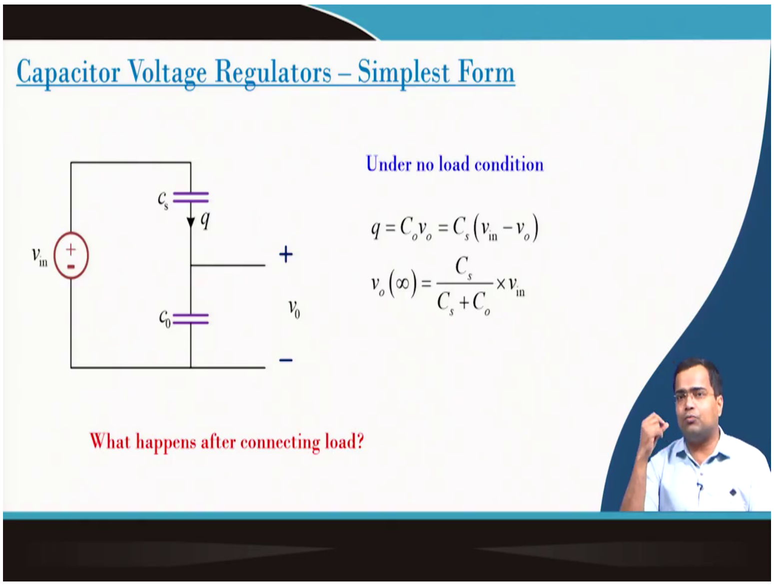

So, you have to think something using energy storing element, rather than dissipative element to further improve the efficiency and also to achieve voltage regulation. So, one of the way we can use capacitive network. Here we are using two capacitance they are in series.

And, if we take the voltage across one capacitor, which is the output voltage, it can be represented by the ratio of like a C_s by C_s plus C_o times the input voltage. But, what is the problem here? The first problem if there is any variation in the input voltage, the output voltage will vary since the ratio is constant. So, it has a poor line regulation, which means that any changed in supply voltage will also affect the variation in the output voltage. I mean it will lead to variation in the output voltage.

Another problem is that here we have not connected any load. If you do not connect any load, then the charged balance will happen in such a way, that we can get the output voltage in terms of input voltage and the ratio of capacitance.

But, what happen? If we connect a load; that means, we connect a load resistance across the output capacitance C 0.

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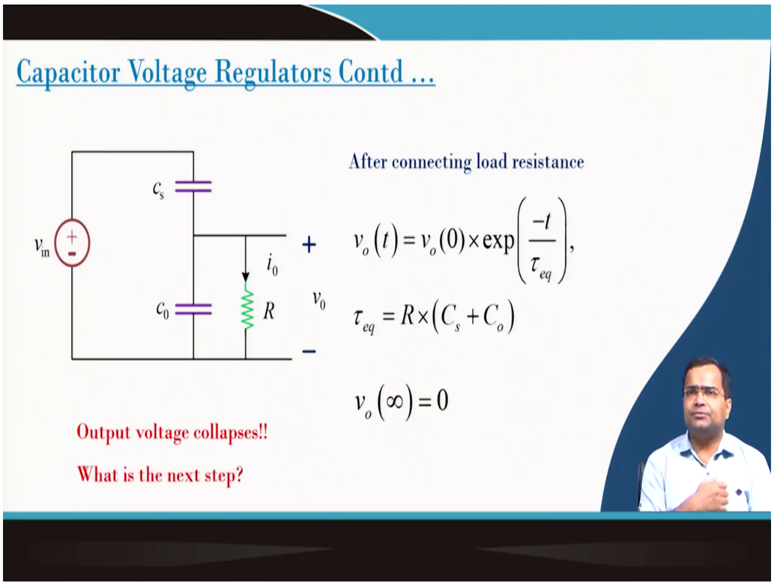

What happens if we connect a load. Once we connect a load, we can write the equation which is very simple. In fact, it can be represented by a first order system, where the output voltage can be written as the initial voltage into e to the power of minus t by tau equivalent, a tau equivalent is written.

And, what we see if you wait for some time; that means, when t increases the output voltage starts falling. What happens? Because, when you start drawing current, I mean the current is going through the load resistance; that means, that current should come from the supply voltage. If that current comes from the supply voltage that means, the rate of change of charge is nothing, but the current.

Since the current is flowing, the charge is no longer constant, i.e., the charge is varying. If the charge varies what happen? The source capacitance is actually getting more and more charge. So the voltage across source capacitance will grow up, whereas, the voltage across load capacitance will comes down. And, ultimately the voltage will become 0 at steady state. So, the voltage will collapse.

So, such circuits cannot be used for a voltage regulator while considering a load. And, of course, it has a line regulation problem and what is the next solution? How can we solve this problem?

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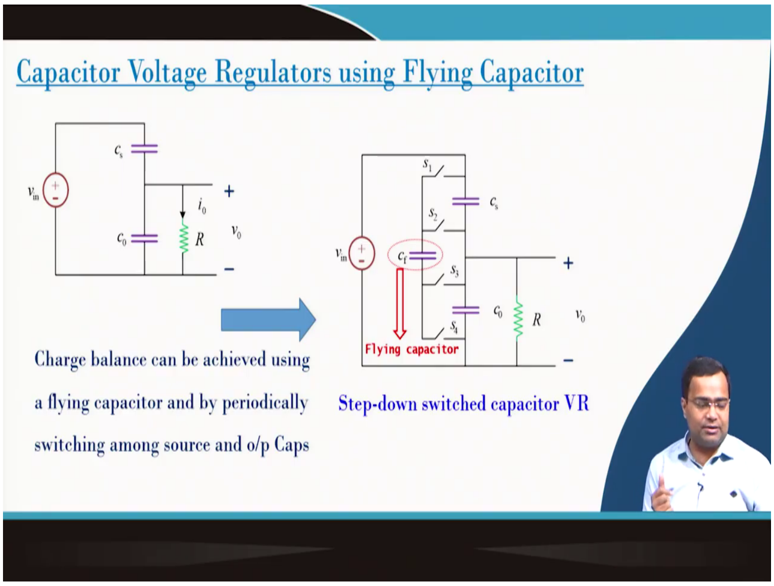

So, now, instead of that fixed capacitance, what we consider earlier, what was our problem? Our problem is that the charge balance. When we are operating at steady state without load, the charge is balance, but when you connect a load the current is flowing and the charge balance is getting hampered. As a result, you have an asymmetric voltage across the capacitor and the output capacitor collapses.

But, now suppose if we find a mechanism by which we can try to maintain the charge balance by means of a switching action. This is exactly how the charged balance can be achieved using a flying capacitor by periodically switching back and forth this capacitor between source and the load output capacitor.

And, this is the flying capacitor, and there are four switches. In some cases, I will show you that you do not need even a source capacitance, because the flying capacitor itself can be connected between the output capacitance and the input voltage. This means that the c_f can be connected in series with the load capacitance and output capacitance, which can also be connected across the output capacitance.

So, it can be periodically connected back and forth between supply and the load such that the charge balance is maintained. So, in order to get a voltage balance, we need to do charge balance. This can achieve step down voltage conversion, and the converters belong to step down switch capacitor voltage regulator.

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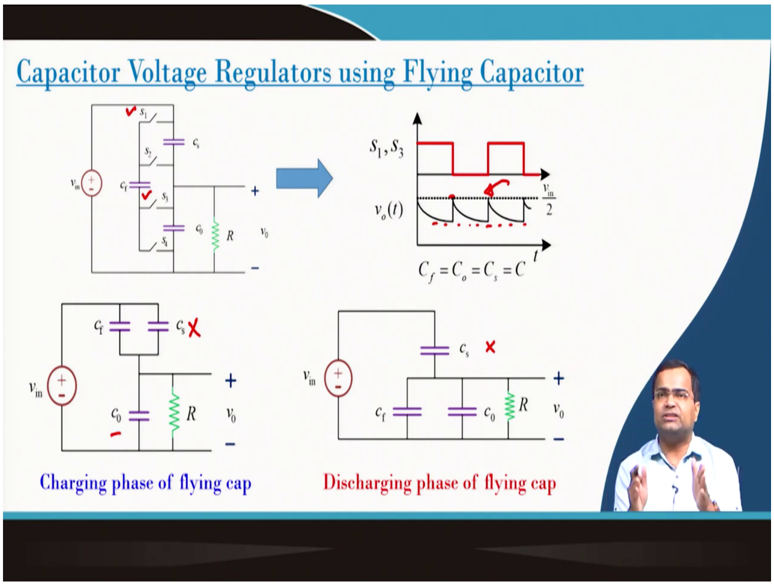

So, now, we understood that flying capacitor can achieve voltage balance, but again this is only when you connect that flying capacitor in series with the input voltage and the output voltage. I am talking about various configurations, when the switches are turned on and off, and the flying capacitor is connected across the source capacitance. And, if the source capacitance is not there, the flying capacitor is connected between the supply and the output capacitor.

And, it is now getting charged ok, but the moment we connect flying capacitor, there will be a discrete jump, and the voltage will reach v_in/2, which can be proved using charge balance equation. But, if we wait for some time then the same problem happen.

The voltage across flying capacitor will build up and the voltage across output capacitor will go down, but the total voltage across the two capacitor will be constant which is nothing but the input voltage. So, we need to quickly take this capacitor back and connect to the load capacitance which is the output capacitor. Again when we connect the output capacitance, the next time again it will reach to v_in/2.

And, the flying capacitor and the output capacitor come in series. If the source capacitor is not there, the input supply is disconnected and the both the capacitors are supplying the load. So, naturally they will get discharged. So, you cannot connect keep this configuration for long time. So, none of the charging phase or discharging phase should continue, in each of these phase the output capacitor will discharge.

So, we need to do it periodically and we need to do rapidly. So, that the voltage deviation can be reduced to keep within a certain limit. But, such frequent charging and discharging also put a limit that is called high frequency switching limit.

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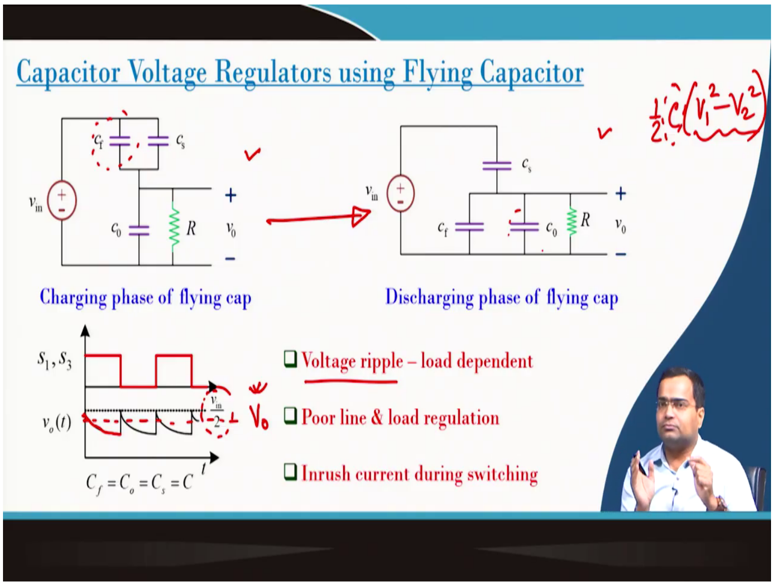

So, we have discussed about two configuration. In one case, the flying capacitor is connected between the input voltage and the output capacitor. And, in second case the flying cap is connected across the output capacitor. So, one is the charging phase, and the other is the discharging phase. And, what I found? This rate of discharge that means, if we talk about this particular profile, who decide this rate of discharge?

So, the faster discharge corresponds to higher current when the output capacitor is delivering to the load. If the load current increases, the rate of discharge will be faster, and if the load current decrease the rate of discharge will be slower.

This means that the output voltage ripple is load dependent. So, it has a poor output voltage load regulation because of load dependent ripple voltage. Thus the average voltage varies with the ripple voltage, varies and when load current varies, so, output voltage also changes.

So, it is a poor voltage load regulation. It also as the poor line regulation, because voltage conversion ratio depends on the input voltage. If the input voltage increases these voltage goes up, if the input voltage decreases this voltage goes down.

So, if we want to maintain this voltage constant then really this voltage this peek voltage is v_in by 2; that means, it can achieve voltage half of the input voltage. If you want to achieve higher step down then we need to connect sub cell multiple flying capacitor cell.

So, each conversion stage can achieve ½ step-down voltage conversion. And regulation point depends not only that step down factor; it also depends on the rate of discharge profile; that means the value of the capacitance, output capacitance. So, if you take a larger capacitance, then you can reduce this voltage ripple and achieve higher better regulation, but again larger capacitor has a penalty in terms of power density.

Secondly, if you look from this to this configuration, when this flying cap was initially connected to the supply, this voltage was different than the output capacitor voltage. When you reconnect back if the output capacitance is large initially there is a voltage difference between the flying capacitor and the output capacitor. Flying capacitor is sitting at a higher voltage whereas; the output capacitor is sitting at a lower voltage.

So, this voltage mismatch will cause a huge inrush current; that means, huge inrush current will go from flying capacitor to the output capacitor and it is important to limit the current. So, as a result we also want to make sure that very large voltage variation is not desirable and also the amount of current also depends on the size of the output capacitor.

So, if you have a take a larger capacitor, the difference in the voltage is large. So, for the same voltage different, if this capacitor is large, if this capacitor is large; that means, the energy difference will be large and as a result the shoot through current inrush current can be higher.

So, that is why we have to keep in mind, that this capacitor size also has a constant, the selection and as I said there is a inrush current during switching, ok.

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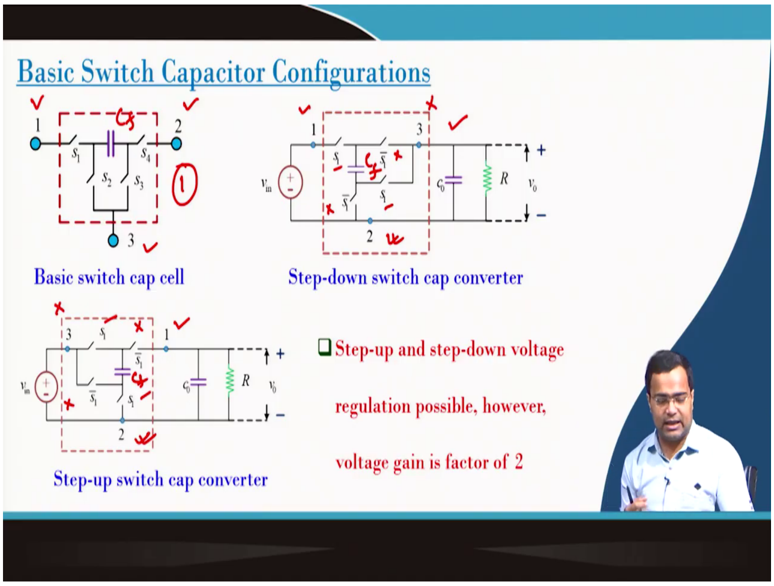

So, in order; that means, now we talk about step down switch capacitor converter. So, if we look at a basic switching cell it has 3 terminal, the terminal 1, terminal 2, and terminal 3 and this is my flying capacitor and there are 4 switches. Now, we can connect this 3 terminal in a different way to achieve various functionality like, you can achieve step down operation, you can achieve step up operation, even you can achieve voltage inversion, like a inverter.

So, I am just showing here 2 cases. One is step down and step up. I am not showing voltage like a voltage inversion that is also possible. So, in step down we connect 1 terminal 1 here, terminal 2 here, terminal 2 here, sorry terminal 3 and terminal 2 here. And, we set the switch S 1 and S 1 identically. They operate identically. S 1 bar and S 1 bar they operate identically and S 1 and S 1 bar they operate in a complementary fashion.

So, here if you, that means, this particular step down converter we saw in the previous example. Here, we have eliminated the source capacitance so; that means, the flying cap can get connected in series with the input voltage and the output capacitor and it also gets connected reconnected to across the load capacitance.

That means, in the second phase in the discharged phase it is disconnected from the supply and connected across output capacitance. In the other case, if you say just step up we rotate this cell in such a way; that means, we change the inter connection, terminal 1 is here, terminal 3 is here and terminal 2 is here. And, we set this S 1 here, S 1 and S 1 bar here S 1 bar here; that means, when the switches on S 1, the flying capacitor which is the flying capacitor it is connected across the input voltage.

In the next cycle you turn on S 1 bar switch and turnoff S 1 switch then this supply; that means flying capacitor voltage actually comes since series with the input voltage. And, with a polarity such that, the output voltage becomes input voltage plus flying capacitor voltage, by that way we can achieve step up conversion.

So, we can actually achieve step up and step down voltage conversion. However, in these two cases, we can achieve either step up or step down in a factor of 2 using one cell module. Using another module, one can achieve step down one-fourth using 2 such modules. Similarly, if you want to achieve step up of 4, we need 2 cells like that.

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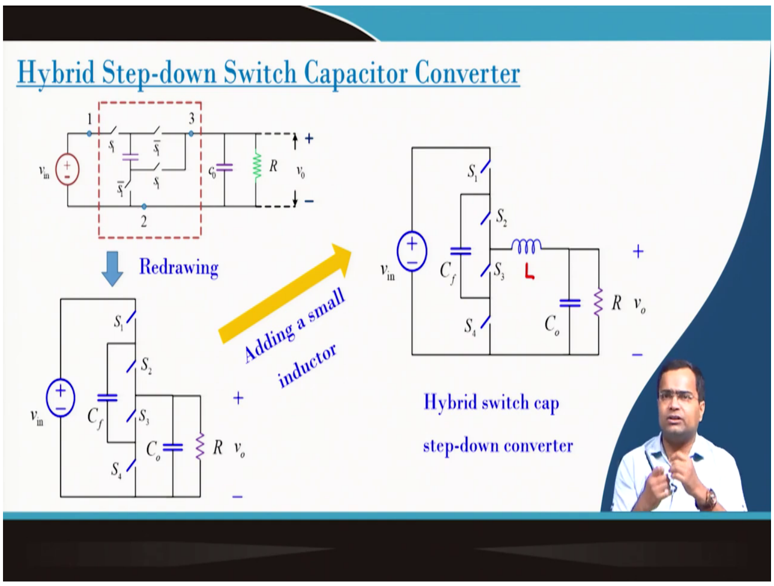

So, there are certain difficulties in switch capacitor converters, because of you know we are switching back and forth switches capacitor with different voltage level and that can lead to high inrush current. One way to avoid you know or to reduce this inrush current effect we need to put a current limit so that the current should not change drastically or immediately. We need to put a slew limit, and you know in order to do that we need to put an inductor.

So, if we redraw this circuit the first circuit, which is a step down converter. Then, if we add a small inductor to limit the slew rate of the current, then this inductor is connected here, which is a small inductor. This inductor is primarily used to reduce the slew rate of the current. So, that you know we can reduce the effect of high inrush current. And, this can also achieve better regulation than pure switch cap converter. These are called hybrid switch cap converters. In a hybrid step down DC-DC converter, the primary energy transfer element still remains the capacitor, which can achieve high energy density.

The capacitor offer higher energy density than inductor, because it can store more energy with a smaller size, whereas, a small inductor is used to limit the current. It is not used primarily for energy transfer, that is why its value is very small.

But, if you want to go for on chip application, we can go for a higher switching frequency to reduce the flying capacitor value and if the power level is low the switches can be integrated inside the IC. But, typically this inductance actually we consider either off chip and if they are very small, even we can consider on chip inductance also.

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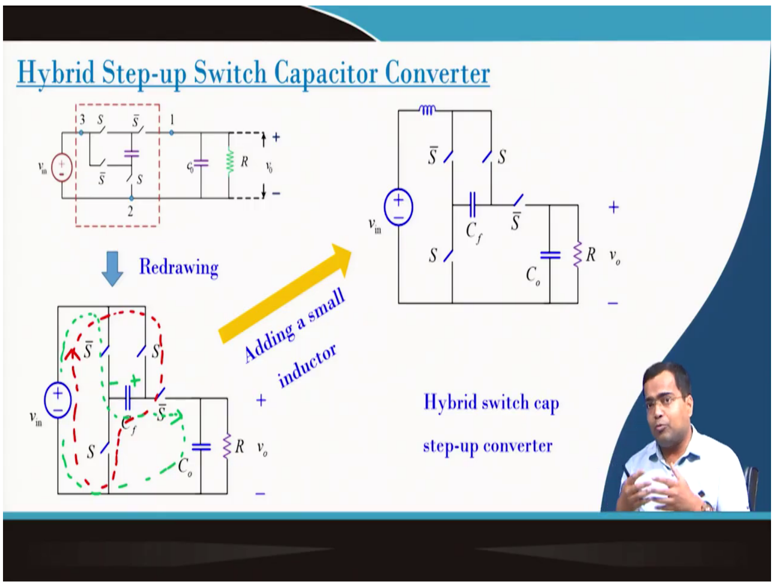

Now, what will happen for hybrid step up converter? We talk about hybrid step up converter, where it has 3 cell, like a 3 terminal 1, 2, 3, and we have discussed if we redraw this circuit.

What do we discuss? Initially, this flying cap; that means, in the charging phase, it is connected between this terminal, so, this is the connection. In the second phase, if we go for the second phase, this is connected like this way; here it is connected, this way it is connected across this terminal.

So, this is the second phase of the circuit. Here, you see when it was charging the red color, then the flying capacitor voltage this voltage is positive and this is negative. So, it was getting charged to the input voltage, ok and just a minute, ok.

So, this is positive terminal, this is negative terminal, in the discharge phase this positive terminal and negative terminals again they come in series with the input voltage. That means, v in then flying cap voltage, if we add them together that is equal to the output voltage.

So, the output voltage can achieve twice v_in. Now, again if we add a small inductance in order to reduce the voltage difference of the flying capacitor; that means, if you want to reduce the inrush current, then you can add a small inductance. And this makes a hybrid step-up DC-DC converter. This means, we can achieve higher step-up conversion by using hybrid switch capacitor converters. And, at present these hybrid switch converters are getting more and more popularity.

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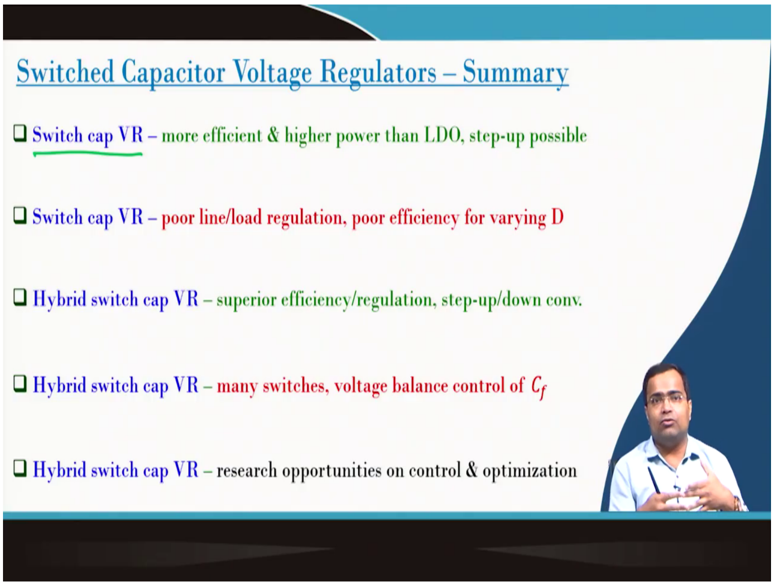

So, if we summarize I mean we know about voltage regulator using resistive divider and this we are using capacitive divider. And, at the end we added small inductance and which offer benefit in terms of regulation, which is better than poor switch capacitor converter. So, switch cap voltage regulator, they are more efficient and higher power it can handle, higher power than linear drop out regulator and here you can achieve step up voltage conversion also.

But, we saw that switch capacitor voltage regulators suffer from poor line regulation, because if you take one cell of switch capacitor converter we saw the peek voltage that we can achieve at the output is v_in by 2. That means, if there is any variation in the input voltage, that peek voltage also varies.

We also saw the ripple voltage, which depends on the load current. As a result the average voltage which is nothing but the peek voltage minus half of the ripple that depends on all that also depends on the load current. That means, if the load current increases then the ripple increases as a result output voltage decreases. So, it also suffer from poor load regulation and line regulation.

Another important factor; that means, we generally since we achieve the peek voltage is v in by 2 for 1 cell, if we want to set output voltage much lower than v in by 2, then we need to allow larger and larger ripple and that kind of ripple can also degrade the efficiency.

That means, if you operate this voltage regulator you know (Refer Time: 31:29) ratio different than the v in by 2 for step down, for step up to v in when it suffer from poor efficiency. So, for the best efficiency you should operate close to the you know v in by 2 for 1 cell, that means the voltage step up and step down generally, we can achieve in a factor of 2 for 1 cell, factor of 4 like a factor of 2 to the power sorry a factor of 4 for 2 cell, factor of 8 for 3 cell and so on.

Hybrid switch capacitor converter voltage regulator they offer superior efficiency as well as regulation compare to pure switch capacitor converter. But of course, at the cost of inductance which also decreases the power density. And, you know whereas, the pure switch cap we can go for fully on chip implementation, for hybrid switch cap depending upon the inductance value we may not be able to always on chip.

So, we need to keep the inductor outside the chip. And, here also you can achieve both step up and step down conversion. Then hybrid switch capacitor voltage regulator, it require more switches you know compared to LDO. So, you need more switches. It also require, I mean the flying capacitor voltage also has to be maintained, because if the flying capacitor voltage deviates significantly, then the regulation problem occur and if you do not balance.

Because, we are just showing a stage step down conversion. And, if we use multiple such stages, we can achieve a voltage step down of 1 8. So, you can connect 1 by 2, 1 by 2, 1 by 2, this in cascade. And, this is very important to maintain the voltage regulation, that voltage across the flying capacitor the voltage balance is very important.

If you do not regulate, you know that can lead to because the switches are designed based on the voltage rating. So, if there is a significant deviation across the voltage of the flying cap, it can actually deviate, it can lead to overvoltage, which may lead to the voltage going beyond the device voltage ratings.

So, I mean we have to keep that in mind, the voltage balance voltage control of the flying cap is also important. The hybrid switch capacitor voltage regulators are gaining a lot of attention for high step down high step up operation, where we need to achieve high power densities.

Smaller size higher efficiency converter, which can achieve higher step down as well as higher step up.

And, these are you know is a current research topics and where the control optimization is also a very important factor. Because the voltage balancing issue, there are multiple issues are involved.

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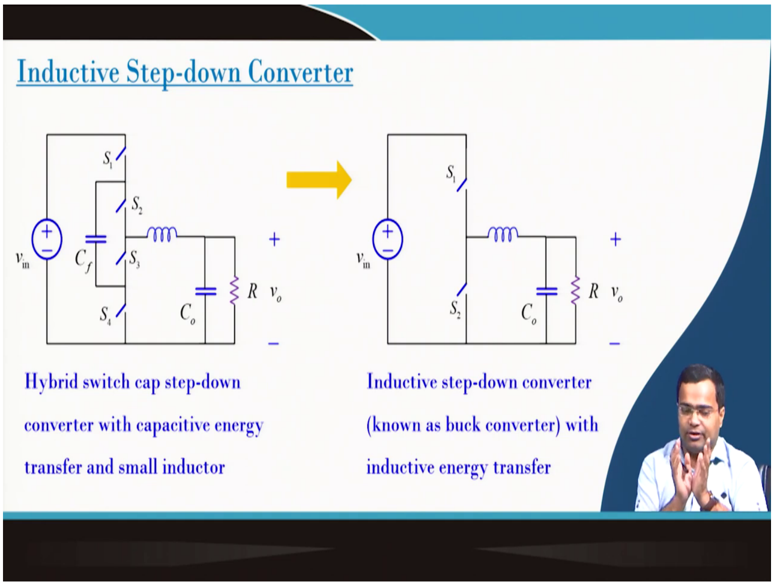

Now, you would go to inductive DC-DC converter which are primarily known as switch mode power converters. Suppose, if you start from our hybrid switch capacitor converter, where we have consider the flying capacitor to be responsible for energy transfer process, and a small inductor is used to limit current slew rate. Here, we need 4 switches, one flying capacitor, one inductor. Now, if we replace this primary energy transfer element by inductor and remove the flying capacitor and simply 2 switches are enough.

But, in this case we have to keep in mind that the inductance value will be higher, because to maintain sufficiently like within an acceptable ripple limit, ok. So, we need to this converter generally for the similar switching frequency, this hybrid switch capacitor converter, the inductance value can be reduced. You know and people talk about 3 switch, 3 level buck converter.

So, where for the same switching frequency we can reduce the inductance value; that means, as smaller inductance can allow to go for higher switching frequency. So, purely inductance, pure inductor, actually this these are now inductive step down converter or buck converter which is it you know is a good example of switch mode power converter.

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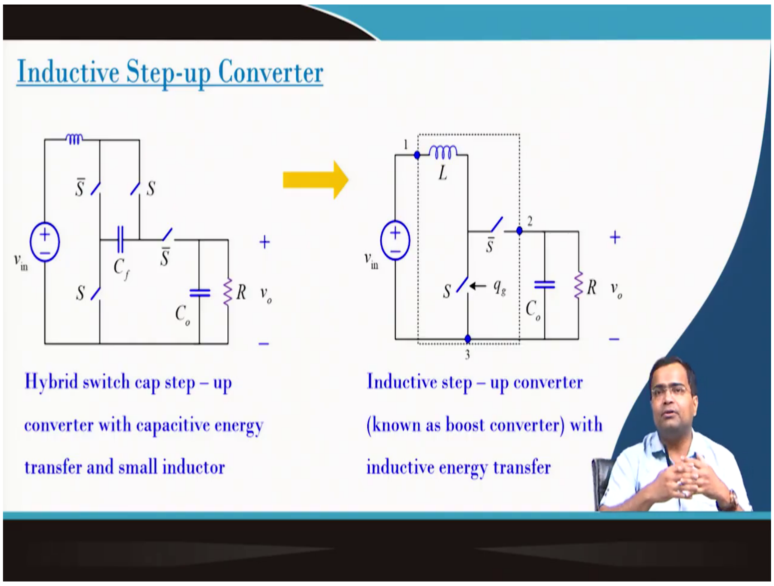

If you take step up DC-DC converters, we start with a hybrid switch capacitor boost converter, in which the flying capacitor is responsible for energy transfer process. But, now if we replace flying capacitor; that means, with the pure inductor as a energy transfer element, then it becomes a regular boost converter this is known as DC-DC boost converter. Where, inductor is responsible for energy transfer from inputs side to the output side.

Because, we want to achieve step up voltage which means that the output voltage is higher than the input voltage. And, we need to operate switch S and S bar in such a way that we make the desired step up performance.

Again in this case, the inductor value requirement will be somewhat higher and this converter is known as boost converter. And, this is also a good example of switch mode power converter.

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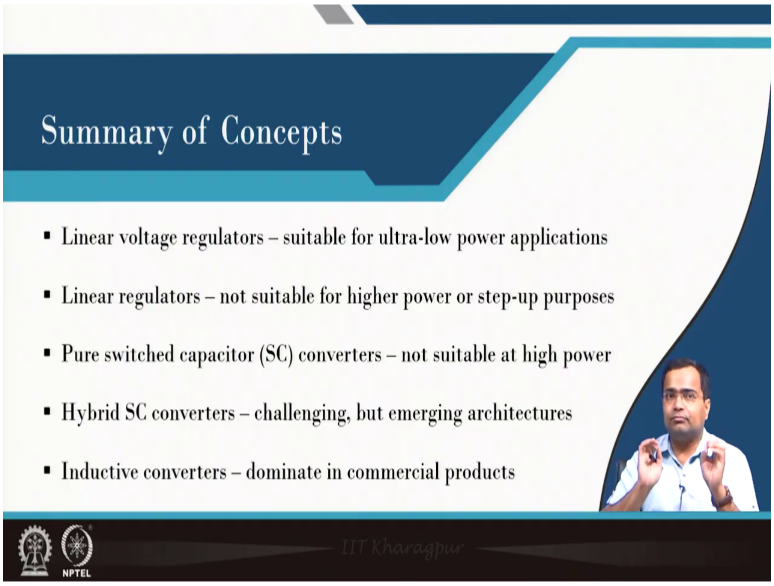

So, in summery today what we discuss? That means we talk about linear voltage regulator, particularly linear drop out regulator, which uses the basic concept of resistive divider network. And, these are use suitable for ultra low power application, where you know use of switches, inductor, capacitor will actually increase the size of the converter.

So, for very small size very low power still these linear regulators dominant in this segment. Maybe I am talking about less than few mW power levels. Linear regulators are not suitable when we are going for higher power, even for few hundreds of milli Watt and of course, few Watts or tens of Watt. This regulators can cannot achieve step up voltage, it can only achieve step down. That means, step up purpose cannot be achieve using this linear regulator.

Then, we discuss about pure switch capacitor converter, where the flying caps are used to achieve desired voltage regulation. And, we saw the voltage can be achieved like a factor of 2 for 1 cell, for 2 cell factor of 4 and so, and such converter suffer from load and line regulation problem and they are not suitable also for very high power. But, now people are also thinking of going for a higher power application, because the switch capacitor converters are used for even multilevel converter as well.

At hybrid switch capacitor converter where along with the flying capacitor, we consider smaller inductance and such converters are gaining lot of attention nowadays, for high frequency like a high power density switch mode power converter. Where we can achieve much smaller power supply, we can design a much smaller power supply, using hybrid switch capacitor architecture, and this is an emerging area of research.

But, still there are many aspects like optimization, modulation, voltage balancing, etc. which need to be addressed. And, finally, we discuss about inductive DC-DC converter which still dominate in most of the commercial product. And, in this course we will primarily consider switch mode power converter in particular.

And, we will discuss about modulation, control, modeling technique of this switch mode power converter. So, we will we take this switch mode power converter somewhat in depth discussion in the next lecture.

Thank you very much.