Fundamentals of Power Electronics
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Lecture – 94
Instability in current control and slope compensation

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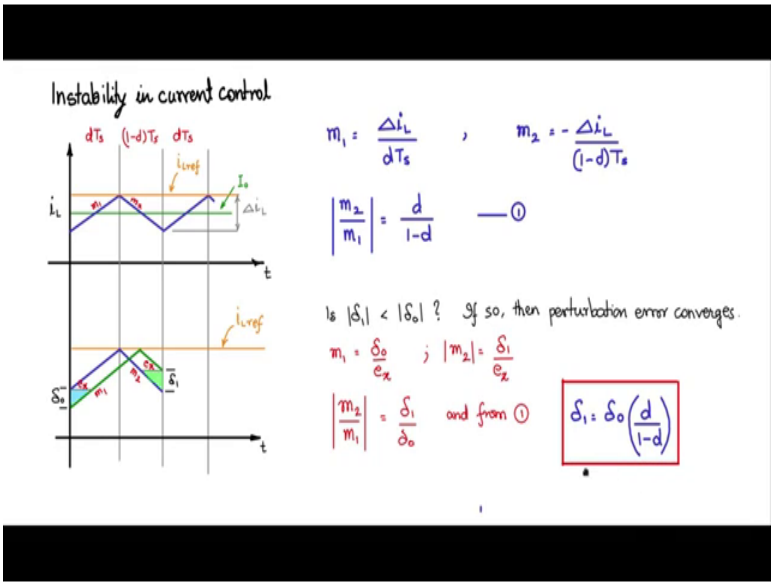

In current control there is a problem of instability that will occur for duty cycle operations greater than 50 percent. For duty cycle operation less than 50 percent the current control is stable inherently. But for greater than 50 percent any error or any perturbation can get amplified and this is a problem that you will see in most of the current control type of topologies.

We will have a look at that, we will study this and then also see how we will solve this problem and there is a standard solution for this called slope compensation. So, let me draw the time line and I will split the time line into various periods dT s 1 minus d T s dT s so on. So, let us take the inductor current, now this the current that we need to study. So, let me draw this average inductor current which is I naught and let me superimpose on that the actual inductor current which will be in this form of a linearly rising, linearly falling wave shape.

So, this slope rate you know the voltage across the inductor during dT s period divided by L the voltage across the inductor during the 1 minus dT s period by L, but I am going to use generic slope turns. So, let me say that this is the i L reference; this is i L reference. So, whenever the inductor current rises up to i L references, hits the i L reference then the switch will be turned off and the inductor current starts to fall and then at this point the new period starts and the clock will reset the we will restart the switch and the switch will turn on and the inductor starts to charge up.

So, this operation we just now had a look at how current control operates. Now, let me indicate the slope, the rising slope as m 1 this is a generic slope term it can be used for representing the slope on any converter whether be buck converter or the work boost converter or the boost converter or any other isolated converters as well. So, this is the m 1 is nothing, but delta i by delta t during that time which is the voltage during that time divided by the value of L and then here on the down slope also you have m 2. So, let me indicate that peak to peak is the ripple current delta i L.

So, now with these let us just formulate the problem. So, m 1, this slope m 1 the slope rising slope is nothing, but delta i L divided by this time period dT s and m 2 is this slope; the falling slope which is minus delta i L by 1 minus dT s. So, this is pretty evident from this waveform wave shape. So, let me write m 1 by m 2, I will take the modulus I am going to take out the minus sign out of it which is d divided by 1 minus d we will call this as equation 1 this is the ratio of the slope which is d by 1 minus d.

Now, let us look at the m 2 by m 1 in from a different perspective, let me draw the inductor current waveform once again inductor current i L and this is i L reference, this i L reference. And let me draw the m 1 slope part of the current waveform and then this is the m 2 slope part the current waveform, I am just going to draw for one cycle. Now, I am going to perturb let us say due to some reason whatever the reason there has been a perturbation and that has come at this point, it may have occurred previously it may be accumulated.

There is a perturbation it should have started from this, but it is going to the operating point are shifted and then there is going to be the inductor current going in this fashion because of this perturbation this error. And then once it goes in this point, at this point it will not turn back because it has not at hit the current reference.

So, it will go further hit the current reference here and then the switch turns off and then you will see the inductor current going in this fashion this is the end of the period. So, if I say this is the perturbation del 0, now this perturbation goes on to here and then appears on the side as del 1. Now, the question that we need to ask is del 1 higher than del 0 or lower than del 0; is del 1 less than del 0 if del 1 is less than del 0 then I know that it is decreasing and then the next cycle it will further decrease the next cycle further decrease and actually it will converge.

So, if the perturbation error converges, so if del 1 is less than mod del 1 is less than mod del 0 then the perturbation error will converge and ultimately it will decay down to 0. But the problem is if del 1 is greater than del 0 then you are going to have an instability situation. So, let us check that out. So, now, here I am going to draw this line and I am going to shade this triangle look at this triangle and this is having a slope of m 1 and then I will mark this horizontal error as e x. Now, you can express this from basic trigonometry m 1 is nothing but del naught by e x.

Now, let me draw the triangle this distance is the same it just rises up, this is the same distance horizontal distance still remains the same e x. So, now, from this let me shade this triangle. So, you can now say m 2 is del 1 by e x I have taken mod absolute value and now with these two you can formulate m 2 by m 1 which is del 1 by del 0. And from here we can substitute m 2 by m 1 with d by 1 minus d so, you can say del 1 is del 0 into d by 1 minus d. Now, this is the important relationship that we have here.

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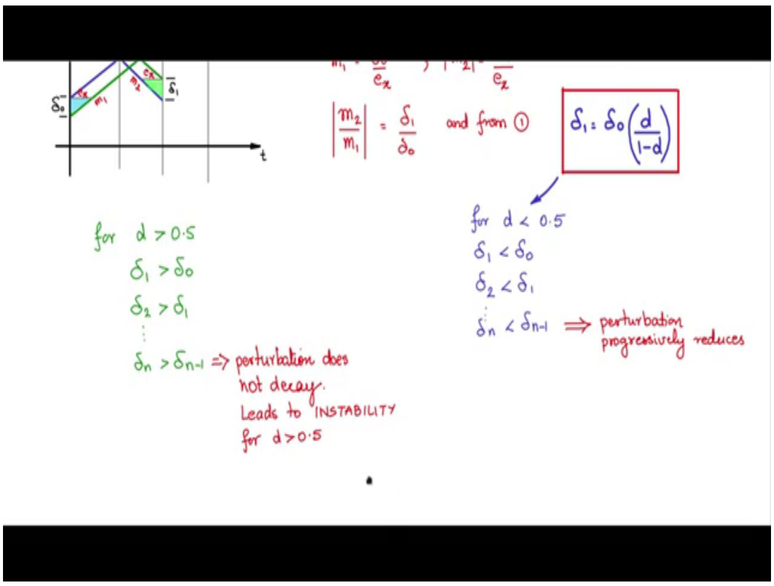

So, what does this mean? Means that for d less than 0.5, this 0.5 and this is greater than 0.1 minus d is greater than point 0.5 and therefore, this term is less than 1 and del 1 is less than del naught. So, therefore, del 1 is less than del naught del 2 is less than del 1. So, on del n is less than del n minus 1. So, therefore, gradually from del naught you will see the perturbation decreasing to del n and it is converging to 0 therefore, it is decay. So, this implies that the perturbation progressively reduces to 0.

Now, for d greater than 0.5 del 1. So, 0.5 divided by something less than 0.5 this is greater than 1 and del 1 is greater than del naught del 2 is greater than del 1. So, on del n greater than del n minus 1 which means the perturbation is progressively increasing and it does not decay. So, therein comes the instability issue. So, this leads to instability for d greater than 0.5. So, this is what we mean by saying instability in current control for duty cycles greater than 0.5. So, there is a solution for this; there is a standard solution for this which we call slope compensation. Let me let us also discuss about that.

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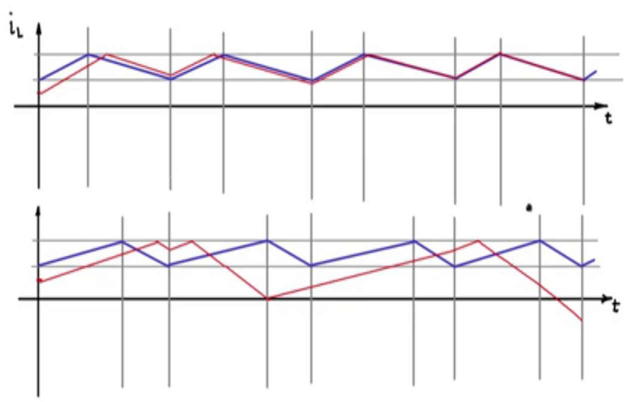

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The inductor current I will draw the time verses inductor current and I will keep the markings in such a way that the duty cycle is less than 0.5. I want to show few cycles. Now, let us say this is one cycle, second cycle, third cycle, fourth cycle now, these are the duty cycle gaps. So, in the first cycle duty cycle less than 0.5 second cycle same duty cycle less than 0.5 third cycle like that.

So, let me mark the upper tip and the bottom tip of the inductor ripple. So, let me mark it like that and the inductor current will stay within this ripple. So, during the time of this duty cycle, d t inductor current is going to rise like this and during the time of the 1 minus d t it is going to fall; rise fall rise fall rise fall so on. Now this would be the normal expected steady state value of the inductor current. Now, let us see what happens if there is a disturbance.

Now, I will introduce a disturbance here, I will just offset it disturbance could have occurred due to any number of reason I will say if this disturbance occurs the inductor current will start on from here, it is an integrateral start on from here with the same slope v in minus v b divided by L.

So, it go parallel to this line. So, let me draw it parallel to that line and then after it hits this top limit it will go parallel to the down slope of minus v b by L then up slope, down slope so on you see that it progresses in this fashion. And what is the take away from this is that whatever there is the disturbance finally, decays to 0 and then it the disturbance is removed and the normal inductance steady state value current flows.

Now, take the example of another case t versus i L. Now, I am going to increase the duty cycle to beyond 0.5, same time periods duty cycle is higher same time period duty cycle is higher and so on. So, now, when the duty cycle is greater than 0.5 what happens? Let me again mark the top and bottom of the inductor ripple, I will keep it same and what is the steady state normal expected value the inductor current let me first draw that.

So, this will be v in minus v b by L, this will be minus v b by L negative slope, positive slope, negative slope, positive slope, negative slope so on. So, this is the normal expected steady state value the inductor current under duty cycle greater than 0.5 also.

Now, here also like here we will introduce a disturbance, the disturbance has occurred due to whatever the reason. So, when you introduce the disturbance, now from this point onwards it will start going parallel to this line, it will have the same inductor slope. So, let us say it takes this line it hits the top value here that is the i L reference value, then goes down resets again. Where this is the time duration when the queue of the flip-flop is low, hits the time the end of t s when the clock again gives a small pulse and sets the flip-flop, again it will rise then goes down continues going down here it will get reset so on.

And you see that the disturbance starts growing, cycle by cycle it starts growing becomes unstable.

So, it never converges to the expected steady state value of the inductor current. So, when the duty cycle is greater than 0.5 the inductor current will start diverging and it will not be stable when you do current controlled operation in this fashion where this is the i L reference, the top of the inductor current ripple is the i L reference. How do we solve this problem let us seek a solution and try to find out how to do that and implement that.

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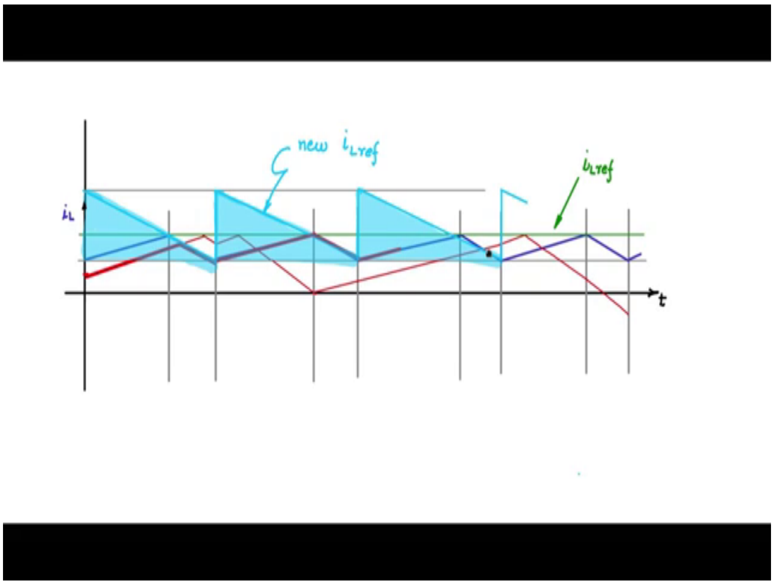

Let me consider the problem case waveform. Here the duty cycle is greater than 0.5 and we see that if we give a disturbance, the disturbance keeps growing and leads to a unstable inductor current waveform.

Now, this line here, this top line here where the inductor current is comparing with that line is the i L reference line. So, let me highlight that with a different color and let me indicate that. So, that is i L ref. So, whenever the inductor current reaches i L ref and tries to cross that then the error changes direction becomes negative and then resets the flip-flop, but that is not happening in a proper way when the duty cycle is greater than 0.5. Now, let us try to change the shape of this i L reference line instead of being a straight flat line let us introduce some slope.

So, what I will do is try to extend this axis and then let me draw a line which is having the same slope as the falling slope of the inductor. Now the falling slope of the inductor here is minus v naught by L or minus v b by L for the case of the buck converter. So, we will trying to use that same slope continue it upwards, now this is the slope line that we will use for this time period t s we will repeat the same sloped line for every time period. So, using that as a marker let me repeat the same slope line for the next time period then the next time period too and so on. Now, this sawtooth type of waveform will become the new i L ref. So, when you use the i L ref of this nature you see something nice happening.

Now, let us take the same disturbance and let me allow the inductor current to go parallel to what is supposed to be the steady state value. So, it goes parallel, now hits the boundary here it hits the i L reference here and at this point it tries to cross over. And the comparator goes; the error goes negative the comparator will, output will see to it that the reset of the s r latch resets is asserted and resets the q value. So, thereby it will then start having a down slope and the down slope is going to be along the same parallel because the falling slope for the inductor current is minus v naught by L or minus v b by L in this case.

So, you see that in just one switching cycle the error has been reduced. So, the error is from there on continues to follow the steady state value. So, you see that any error quickly converges and the error is removed within a switching cycle, this is the beauty of having this type of a sloped saw tooth shaped i L ref. So, you should give the slope here for the i L ref same as the falling slope of the inductor current then you are safe and the error will be removed within a cycle. So, how to give a slope now this was the old i L ref to this old i L ref you have to compensate and see that you have this kind of a slope so this is called slope compensation.

So, current control with slope compensation will give you the best results where even if there are errors, the errors will be removed within a cycle and the system will be stable. So, this can also be proved mathematically what I have just shown by graphs, you can refer to literature on dc-dc converters or any of the NPTEL courses on dc-dc converters.

We shall now see how we can generate an i L reference which is of this form. It should be in this kind of a saw tooth form and the slope being same as the falling slope of the inductor current. And once we generate that then our current controlled converter is ready for performing battery charging operation with MPPT.