Fundamentals of Power Electronics
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Lecture - 91
Close looping dc-dc converters

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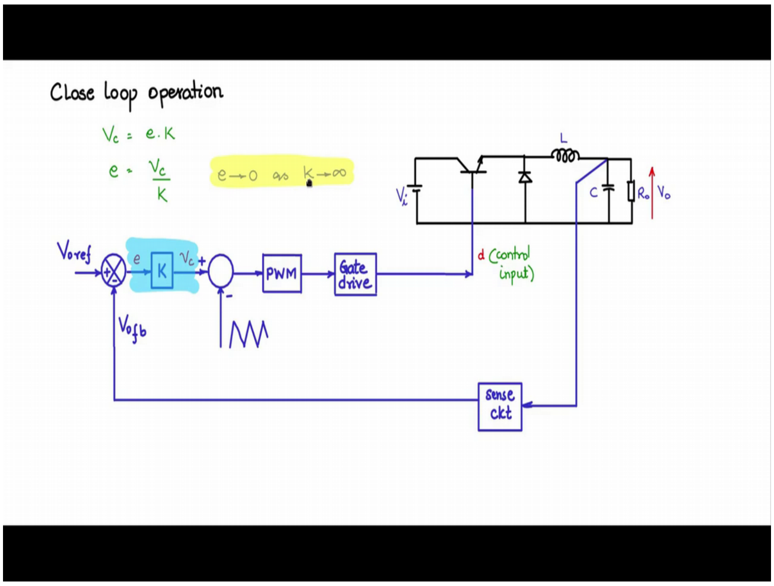

In this session let us look at Close loop operation of dc-dc converter. Let us take an example of a buck converter, this is a buck converter we are familiar with this topology, but note that you can work with any converter the principle of closed loop operation is the same. Call this V i, L, C, R naught V naught and we would like to regulate V naught and the control input is here in the form of duty cycle dts.

So, let us say that is the control input d. Now, let us build the control portion of the schematic. So, let us have a reference a feedback quantity plus and minus we are comparing it and let us pass it through a control block and how about the control block will give you the control signal which will be compared with the triangular waveform, triangular career to generate pulse width modulation and pulse width modulation and steering that we have discussed.

And then from the pulse width modulation it will go to the gate drive circuit, we have discussed the gate drive circuit on protection and then goes to a drive the switch. Now, this feedback here will be the output feedback. So, we are sensing the output if we are controlling output we have to sense the output pass it through a sense circuitry which means, it could be made up of op amps for stepping down, filtering and then scaling and the output of the sense circuit is given here to this compare for to this compare circuit in order to do the control.

So, you have V naught reference and V naught feedback. So, how it operates is that now let us say V naught here increases this will increase, here it will increase V naught feedback increases. So, V naught feedback increases V naught ref minus V naught feedback will decrease so error will decrease. And the output of this will decrease the pulse width modulation signal will change in such a direction to decrease the drive duty cycle and therefore, once that duty cycle decreases output will decrease and come back to its original position operating point.

And this is the close loop action for one direction where V naught increases starts with some V naught increase and the V naught increase could have occurred due to any disturbance, disturbance in the load in input voltage or even temperature.

If V naught decreases also the action will be in similar way, here it will decrease V naught feedback decreases error will increase this will increase pulse width modulation pulse width decreases increases d will increase and then therefore, V naught will increase and it will populate to normal operating point.

So, this is the control action that you will see. It is now required that we design the value of this controller gain K. So, if we properly choose this controller then we can ensure that the error here will be 0 and the V naught feedback will match V naught reference and your output will be regulated as per the reference desired reference. So, let me introduce some variables, this is error e and output of the controller will call it as a control voltage V c.

This control voltage in fact, will be comparing with the carrier triangular carrier to generate the pulse width modulated waveform. Now, let us focus on this part irrespective of all the other parts of the system. Now, if we see here the relationship is V c is nothing, but e into K error into controller gain. So, let us say e error is equal to V c by K, when can we get the error as 0? There are only two possibilities, either V c should be 0 or K should be infinite.

Now, if we take the case where V c is 0 which means you are grounding this portion. So, if you are grounding this portion and making V c always permanently 0 then there is no close loop, becomes an open loop system.

So, it cannot be that V c has to be allowed to vary and make K infinite. If you make K infinite whatever may be the variations in V c e is always 0, the error is always 0 which means that the output is regulated the output V naught feedback and V naught reference are the same and which means that the output here V naught is as per the desired reference V naught ref. So, in order to achieve desired control we have to make e going to 0. So, if e tends to 0 which means that you have made K tending to infinity. Now, this is the important rule or important control principal that you have to remember whichever be the system you have to make the controller gain as high as possible to achieve error tending to 0.

However there are many problems and trying to make controller gain infinite. So, we need to apply some constraints and under some operating conditions we will try to make K tending to infinity. So, let us have a look at how we go about doing that.

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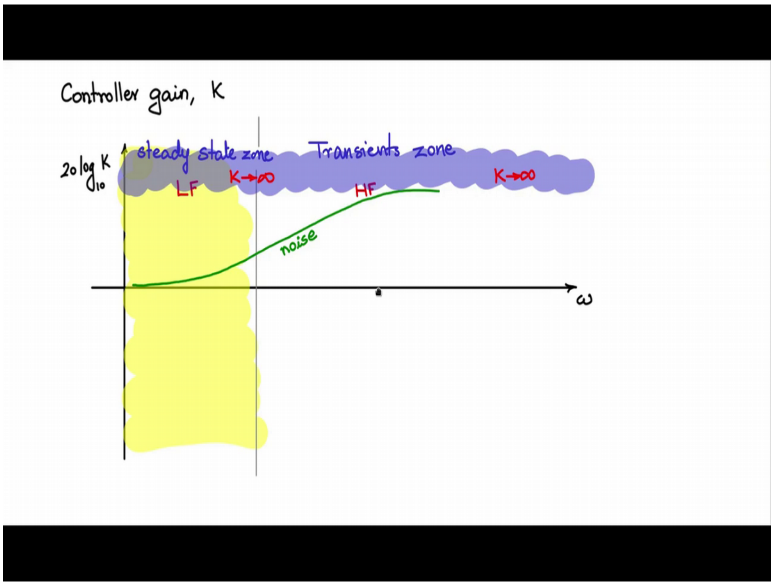

So, now, let us look at the controller gain K, now I am going to draw a graph of frequency on the x axis you have frequency, on the y axis you have the gain the magnitude or the gain of the controller and I am going to express as 20 log base 10 K in the dB scale.

So, now let us use this graph to understand K a bit better. The system is going to be in various states it will be in the steady state it will be in a transient state and it will be transiting on transition state to the steady state. So, when you say steady state it means omega is 0, that is it is this area here near omega 0 will be the steady state zone. And as omega is as we are going more towards the right part of the x axis or the omega axis frequency is high which means that you are in the transient zone here. So, let me mark this portion, this is roughly this steady state zone closer to the dc and therefore, low frequency region.

Therefore, we can call this as the steady state zone or the low frequency zone All this portion the higher frequency region can call the transients zone all the dynamics they are all occurring in this region of the omega scale. We can call this as LF Low Frequency region or this as high frequency region. I have drawn here a curve a green curve here and this is the noise curve, see from here that the noise is low in the low frequency region and the noise is more in the high frequency region the systems are more sensitive to noise the high frequency region. So, therefore, if we go by this rule that K should be infinite the controller gain should be infinite it will amplified noise throughout all the frequencies.

So, if I place the; if I place the K controller gain infinite here means this is very high gain it is going to amplify not only the signal. It is going to amplify even the noise everywhere and the noise which is pretty significant in the high frequency region especially the measurement noise, sensor noise you will see that they will get also amplified to very high value large value and V c will be mostly noise it will be swamped by noise and then you will not get any meaningful control.

So, therefore, we cannot just put K equal to infinite throughout spanning all the frequency regions, you need to have K is equal to infinite only during steady state let us say at more closer to the dc here and then K should become lower, smaller at higher frequency regions. So, now that is the technique that we will adopt to shape the K curve as frequency changes as a function of frequency.

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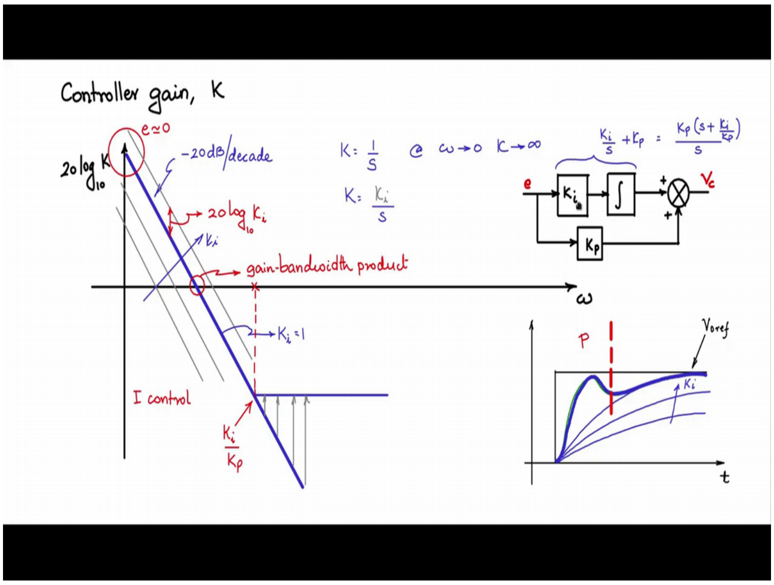

Controller gain, K

$K = \frac{1}{S}$ @ $\omega \to 0$ $K \to \infty$

$K = \frac{K_i}{S}$

$\underbrace{\frac{K_i}{s} + K_p}$ = $\frac{K_p\left(s + \frac{K_i}{K_p}\right)}{s}$

Let us begin with the gain of infinity near dc in the near the steady state part. So, if there is a gain of infinity then the error is 0 so you will get 0 steady state error. To start from here, let me draw a gain curve K like this which means it is going down at minus 20 dB per decade. So, here it is infinite and this type of shape of the gain curve is given by our familiar integrator which is written as 1 by S in the as a transfer function. So, as omega tends to 0 omega is tending towards dc the gain K will tend to infinite value.

So, around this region it is infinite gain is very high error is 0, almost close to 0 and you have steady state accuracy of 100 percent. Now, as the system moves towards higher frequency zones during different points on the operating; different points in the operating region, you would like to have the gain K lesser and lesser as the frequency goes higher. The reason being as I told before the noise is larger as you start going towards high frequency on therefore, you have to reduce the gain attenuate the gain if you want to get meaningful control signals.

Now, this is just plain I control, you just have 1 by S integral and that is I control; I could have chosen instead of this minus 20 dB per decade line, I could have chosen this line. This also is a 20 minus 20 dB per decade line starting from another infinite value, it is a family of infinity or I could have chosen another minus 20 dB per decade line like this or I could have chosen a 20 dB per decade line above the one that I have chosen.

So which one should I choose? So, let us introduce one more degree of freedom K is K i by S. So, I have put one more variable instead of 1 by S I put K i by S; K i is equal to 1 is this take blue line which I have chosen. For any other value of K i you have this parallels.

Now, if I have to include K i into this figure the difference between this and this would be 20 log base 10 K i. So, I know which parallel to pick if I start picking parallels as it starts to intersect the omega axes towards the right the bandwidth is higher. So, this is K is equal to K i is equal to 1; now you see the points of intersection this is the unity gain bandwidth product. So, the gain bandwidth so when you compare this parallel intersection with respect to the blue line that we have selected you see that this parallel is having a higher gain bandwidth, the one here as a lower gain bandwidth.

The one here are still lower gain bandwidth. So, the speed of response is the one that is going to be affected by choosing the parallels. So, let us now write down our controller has a K i here then passed through an integrator and you have the control signal, this whole put together is K i by S. Now, let me draw the time graph. So, this is time t and then let me have a step response what is the step response to a step in V naught ref, this is V naught ref. So, what happens to the output, the output can be like this depending upon what value of K let us say I have chosen a K i which is corresponding to this line.

So, you have a very slow response and let us say I choose this line which is having slightly higher gain bandwidth product. So, it will be slightly faster. So, you see that as K i you choose the parallels with K i moving increasing you will have faster and faster response so here also K i increases in this fashion. So, let us say the one that we have chosen we could probably have a K i coming like this and you can see it reaching steady state quicker.

Like that if we choose a higher one it would probably go much quicker and then you choose one that satisfies you on the oscilloscope. Then let me now introduce one more component, a component like this in parallel I will call that one as K p just a proportional gain and this proportional gain is added up to the proportion the integral one also.

So, you add it up in this fashion. So, this is error and this is we see the control signal. Now together you see this is K i by S plus K p will be that transfer function between V c and e. So, this can be written as S in the denominator K p into S plus K i by K p. So, you see that there is as 0 coming into the picture. So, this is an integrator that is the integrator that continues to stay, there is 0 at some frequency point on this x axis K i by K p; now let us say at some point I design and place this as the K i by K p. So, at this K i by K p value of frequency I place the 0.

So, what should happen? The pole is giving a minus 20 dB per decade 0 will give plus 20 dB per decade the plus 20 dB per decade and the minus 20 dB per decade here will cancel and flattened out in this fashion. So, what have I achieved with this. So, you see if I had not put this K p the gain would have fallen down like that, but now I am gaining extra gain as frequency changes. So, I am improving the high frequency gain in this fashion, the result is that in the time axis this is the high frequency part the transient that is the high frequency part transient part this is the steady state part.

So, you will be pulling up the transient part because the gain has increased you will pull up the transient part and then after it goes starts going to the steady state part you will see it is only I control that comes into the picture the batten is handed over to the I control. So, if you see the whole response may look like this with a PI initially the p comes into the picture, that p is actually improving the transients and then after the transient has pass going to the steady state the batten is handed over to the i control then you will see a response something like that.

So, this way you try to include a PI controller. How do I choose the values of K i and K p? The step is very simple you do not include K p firs, you only start with K i and K i very low value start with very low parallel.

So, keep on increasing K i gradually keeping K p 0 K i gradually in you increase till you get to a response with pure i control that is best and then you stop at that value and then K p is only going to improve the dynamics. Steady state K p is not going to touch because K p comes only at the higher frequency zone as the low frequency comes into the picture that is only I control. So, you have taken care of I control first you have to take care of the I control and fix your study state response. So, that is these responses.

So, once the steady state response is fixed then you try to pull up the dynamics by introducing K p. So, K p also you try to increase from 0 onwards gradually increase K p that keeps adding up here the improvement in the dynamics and then it will try to pull it up and then at some value you will see that it is best beyond that it will start to probably have damped responses.

So, do not go over to that and then you probably may have over shoots do not go over to that. So, you stop at the best response you think you can achieve by looking at the scope and at that value you stop at the value of K i and K p and those values of K and K p you plug in and you have your PI controller.

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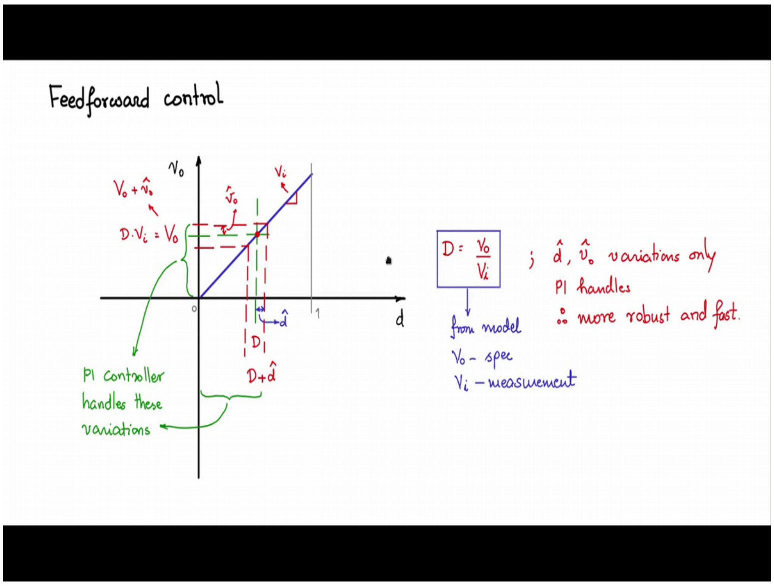

Feedforward control

$\boxed{D = \frac{V_o}{V_i}}$; $\hat{d}$, $\hat{v}_o$ variations only

PI handles

∴ more robust and fast.

from model

V_o – spec

V_i – measuement

We saw that the controller K can be a PI controller and how we can get p parameters of the PI controller K i and K p we just now discussed. I want to introduce one more concept call the feed forward control which will help the PI controller to be more robust and faster.

So, let me how this x y axis on the x I am going to have the duty cycle d, on the y axis it is V naught. So, V naught and d are related; V naught is the output of the buck converter and that is the controlled variable d is the input to the buck converter it is the control input. So, the relationship is d is control input this is the controlled output and actually when you talk of transfer functions it is V naught by d s in the Laplace domain.

So, these two have a relationship so let me draw that the slope is V i. So, V i into d so let us say for example, d varies from 0 to 1 and let me take an operating point where this is the operating point and this x intercept is d I will put it as uppercase D and the y intercept is uppercase V naught. So, the relationship between V naught and d is V naught is equal to D into V i. This slope of this transfer curve is V i which is fixed constant.

So, V naught is d into V I, D is actually the control input. So now, let me say that due to many reasons V i itself can vary. So, therefore, the slope of the blue line can vary or there could be a disturbance in the output or there could be some disturbance which is reaching the output and V naught can vary. So, therefore, this operating point can vary in the neighborhood of this steady state operating point that we have shown here.

So, let me say that D is actually not D, but D plus or minus D hat this small indicating the small variation about the neighborhood; about the neighborhood of the operating point as d hat. And likewise on the V naught side also on the y axis I will say that this is V naught plus v naught hat where v naught hat is nothing, but the variations in the neighborhood of the operating point. So, in the normal PI control that we discussed till now without the feed forward control, the controller this I will just write down D is V naught by V i and this is coming from the model where V naught is a specification and V i is measured from the circuit.

Now, why this is important is that all these variations all the variations in control input variation d is supposed to handle the complete variation of V naught. So, the PI controller that we discussed till now is supposed to handle all these variations which means that the operating point can swing between 0 to the actual operating point. And the PI controller is supposed to handle this large signal variations as opposed this with feed forward control what is it that we are going to do we are going to use this. We said that this is the model of the system we know that V naught is equal to D V i we have derived develop this model earlier while starting the buck converter.

So, I know V naught; V naught is coming from the specs user specs V i is coming from the measurements instant by instant measurement. So, V naught by V i is known. So, this is the nominal operating point or the steady state operating point that the system should be for that given V i for that measured V i and a specified V naught. So, this information is available to me, let me use that information which the PI controller was not using before. So, you use this information and set the operating point at this, then due to any disturbance if there is any variation in the neighborhood the operating point the PI controller should only handle this small deviations.

So, d hat and v naught hat only the deviations about the neighborhood the operating point that the PI controller has to handle. So, these are small deviations and therefore, the PI controller is much faster to handle the small deviation and also because of the feedforward term this is the feedforward term which is giving a guidance or direction to the controller that any major deviation it is supposed to come and settle there it will be more robust. So, this way it is more robust and faster. So, let us see how we include this feedforward term into our control.

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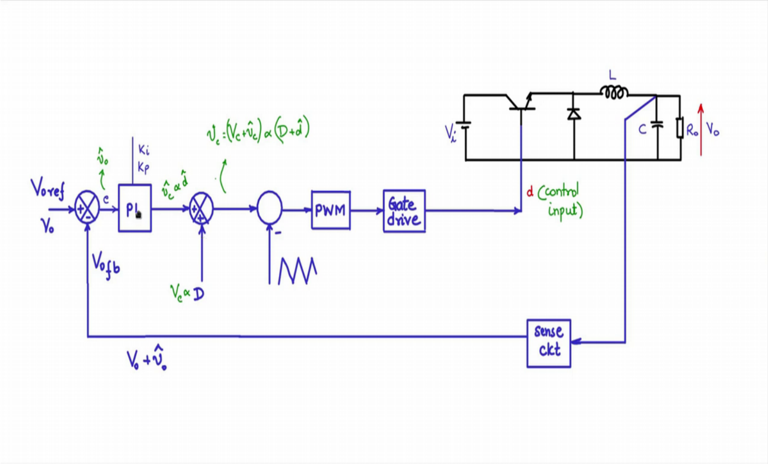

Let us now incorporate the feedforward part of the controller into this system. So, I have the controller as it is existing now. Now you see that K is nothing, but the PI controller and this PI controller is handling the entire large signal swing of V naught. Now, I will remove that because I need to include feedforward portion, also apart from PI let me extend that make the connection and here I will include the PI controller.

Now, this PI controller has two parameters K i and K p which we need to select just like as i told you first make K p 0 K i you gradually increase from a very low value to take the parallel with low bandwidth and keep on increasing till you get a very good response time response and then fix that and after that increase K p from 0 gradually to pull up the transient response performance.

So, this is the error and the output of this is connected to another sub merge and that is where we attach the feedforward term and that feedforward term is the steady state duty cycle the uppercase duty cycle steady state duty cycle which will decide the nominal operating point or the steady state operating point. Now, what is being fed back is V naught the nominal or the steady state V naught plus the disturbance or the variations then V naught. Deviation in that V naught, V naught reference has to contain only the nominal steady state operating point V naught, it does not contain the deviation because this is the reference.

So, this minus this would give you the error which is basically the deviations about the nominal operating point about the normal steady state operating point and the controller is supposed to take care of this and make this deviations 0. So, you see that PI is now only handling v naught hat deviations small deviations in the neighborhood of the operating point. And what is the output of the PI controller? The output of the PI controller is v c hat. Now, V c uppercase V c which is a voltage which is proportional to the nominal duty cycle is given at this point and this v c hat is proportional to d hat which is deviations about the nominal because they are all proportional to time.

Now, on adding these two you have V c plus. So, I have V c plus v c hat the voltage proportional to the nominal duty cycle plus v c hat which is the voltage proportional to the deviation in duty cycle, is together proportional to D plus d hat. So, that is the voltage signal which is actually going to get modulated with this particular carrier triangular carrier and that PWM is driving this gate and switching on and off this buck converter transistor.

So, you see here the PI controller is only handling the hat terms; it is only handling the deviation terms which is small signal terms and the nominal steady state operating point is given from the model was D is equal to V naught specified by V i measured.

So, D is a feedforward term here this handles the steady state part and the deviation any deviations any disturbance PI takes care and it is handling only small signal deviations. And therefore, this PI will be very robust and very fast because the deviations are small. So, in this way you can introduce the feedforward term and make the controller fast and reliable.