**Switch Mode Power Conversion**
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**Lecture - 30**
**Implementation on PID controller**

Good day to all of you. We shall continue with our discussion on design of controllers specifically for DC-DC converters, as you recall we have done the modeling of the DC-DC converters, and then last few classes we have been discussing the basic principles of the controllers reviewing them in fact and trying to understand the operations of the PID components of a controller. The PID controller is one of the most robust controllers, and very popular in the industry too. And that is what we would be using for ultimately to close the loop for the DC-DC converters too.

So, in the last class we had discussed, we had completed our discussion on the PID components and had just begun to look at how the P I and D components can be implemented using op amp. So, we have started with the integrator and then we shall continue on towards the other components, and see how we can integrate it with op amp's. Because if you are using a digital controller, if you are using a digital processor like a microcontroller then you have to implement the equations the PID equations within them.

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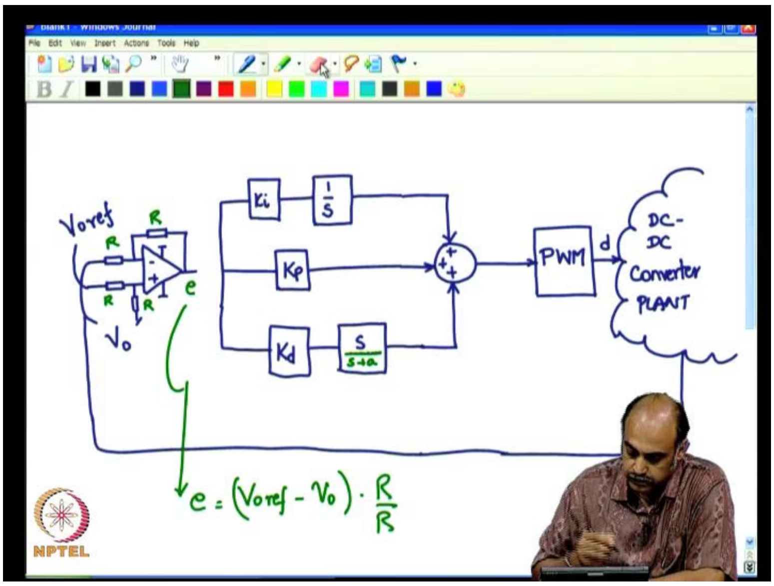

So, coming to our topic here of implementing the controller, let me again bring you back to our block diagram, you may be already knowing this block diagram, but let us write it down once again, we have k i the integrator portion the integrator, I am going to write it as 1 by s, you have the k p portion, the proportional gain and you have k d, the scaling for the differentiator, and I am going to write the differentiator as s, and the denominator I am going to write it in dotted or another color as s plus a implying that you cannot escape s plus a, even though s is the only thing that is required.

So, s plus a is a pole which is a very far in the frequency access, and all these outputs are added up in this fashion plus plus and plus, and the output of this goes to pulse width modulator, we will call that one as pulse width modulator PWM, and output of that goes as the control input d to the DC-DC convertor, this is the plant. The sensed output could be V naught is fed back, and this is let us say V naught reference, V feedback V naught feedback or just V naught. So, that you have less number of subscript to worry about.

So, we had the last class mentioned that this is the reference, it could be any reference could be current reference, voltage reference depends upon what you actually want to control, what you actually want to control. Now, let us say for an example that we want to control the output voltage of the DC-DC converter. So, that is the one which is fed back, and as suitable reference for that is the one which we need to apply the desired reference. Now, this is our control structure in brief, there are still lot of lot of details that we need to worry about which we will do that as we progress, we had been trying to replace these blocks, we have been trying to replace these blocks with op amp's.

So, first what we did was that in the last class, we replaced the comparator portion with an op amp, a differential op amp, let say this is the plus and this is the minus. So, a diff amp is written in this form, you can refer to any book on op amp's, and you can get host of op amp circuit idea from them. So, this is the positive is connected there, the negative is connected to V naught. So, what we shall do is connect it in this fashion, now all these resistances are R for now let us maintain it as same values. So, you will get an error e which is nothing but V naught ref minus V naught, this e equals V naught ref minus V naught into R by R, but as the values of resistance are equal they actually cancel out and this would go. So, it is just V naught ref minus V naught.

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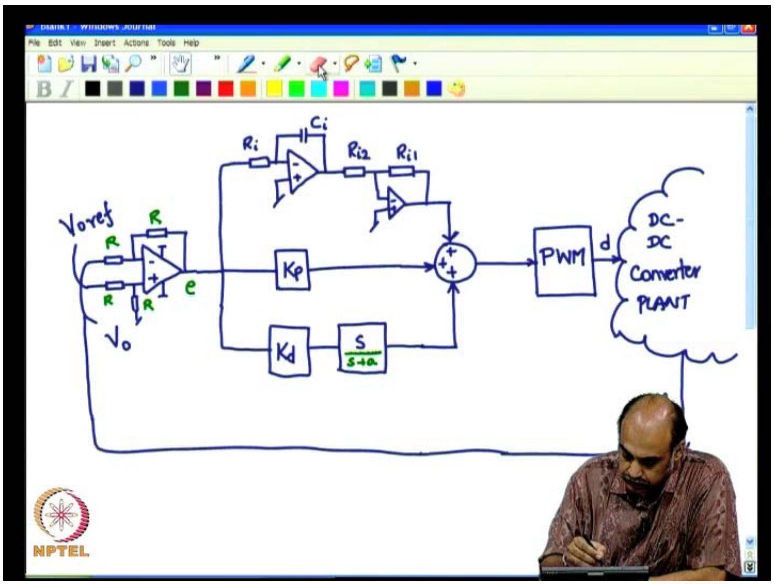


So, this is the first part compare comparison I am going to remove this. So, that we do not clutter up the board, and next we had replaced the integrated portion with op amp's. So, let me do that for you now recall go back to the circuit that we have discussed in the last class, it involve two op amp's; one for integrating and another for setting the gain, but you can reduce number of op amp's, but right now do not bother too much about the number of op amp's, we shall just try to just replace the equations with op amp's.

So, this is an integrator, let us say this is R i, C i, you can add one more gain stage here if needed and that is what we had included in the last class minus and plus. So, this R i 1 and R i 2 would give not only gain, but also the inversion, this portion gives addition gain plus inversion here. So, you have two degrees is basically setting the gain of this stage, and setting the integration gain at of this stage. You have an inversion here, you have one more inversion here. So, from to here there is no inversion. Are you could remove this stage and just set the gain integrated gain by choosing properly the value of this and this.

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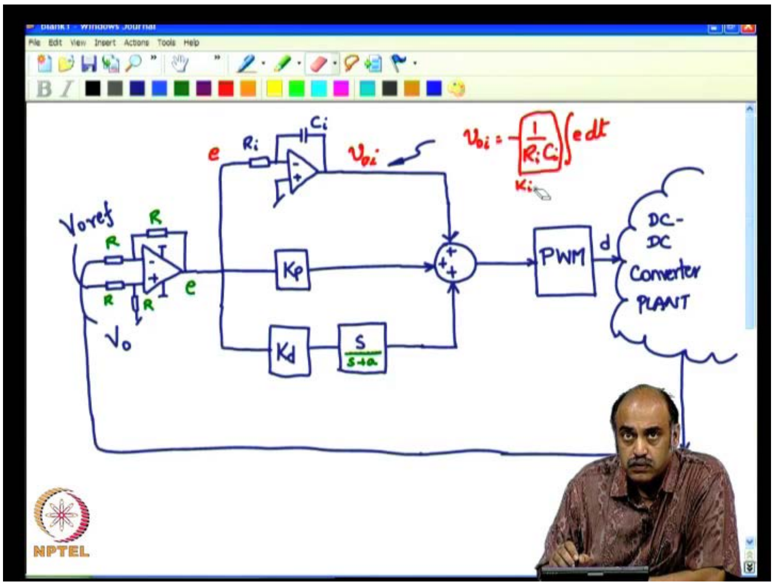


So, let us probably make thinks simpler for now let me remove this stage, one set of reduction. So, we have like this, what is the output here, you have e as the input, you have e as the input here, and let me call it as the integrator V naught i in the output of the integrator. So, V naught i is now there is an inversion we will keep it as minus 1 by R i C i integral of e dt, this is the equation of the integrator output. So, this essentially is the gain k i and the integration e. So, this would be your k i in your… So, properly choose or i C i product to achieve the value of the desired gain scaling.

So, let me again wipe out these portions, so that we do not clutter the board and look at the next portion. The next portion of course is k p, remember that we now have an inversion at this point, we will take care of this inversion while doing this summing. So, we will give inversion to all these and then take care by giving a summing point at the summing point.

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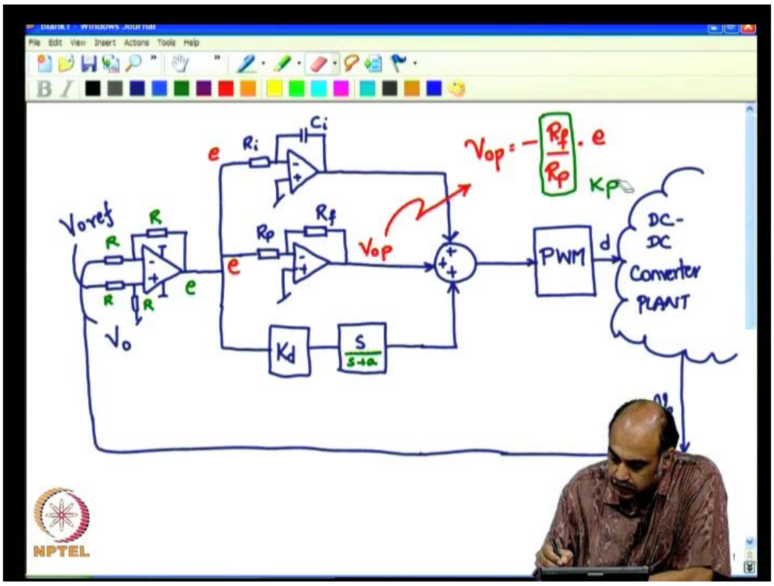


Now, this portion the proportional gain portion can be addressed by putting one single op amp here, we can introduce op amp here minus plus and a gain, this is an inverting amplifier recall from your op amp process. So, if this is R f and R p, we have the input as e here and output as V naught proportional, and what is V naught proportional? V naught proportional equals minus, there is an inversion R f by R p that is the gain into e the input. This portion is the proportional gain k p, that we have been using till now. So, that is the implementation of the proportional part in using op amp's, notice is the change of sign inversion there, we are using inverting amplifier.

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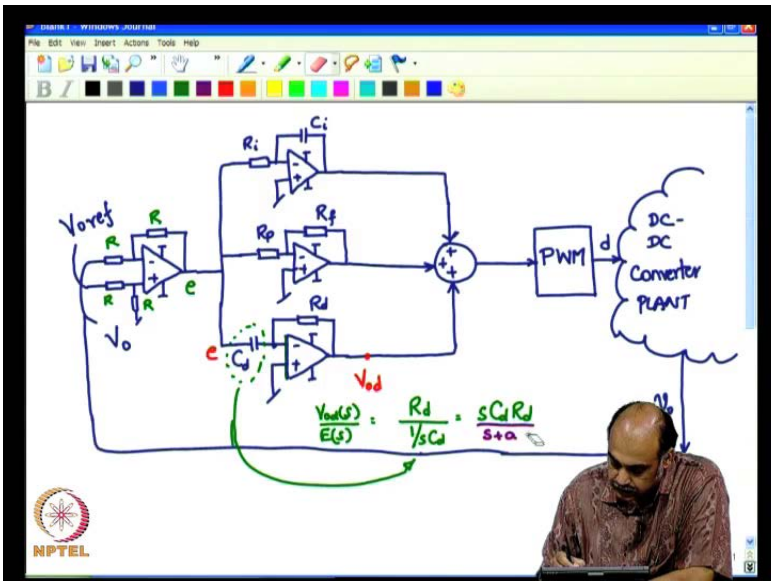

And let me again erase this portion to clear this board, and let us see what we do for next component which is the derivative component. So, let us erase this part, and include another op amp, let me use the minus and plus inputs, now look at the integrator; integrator is having R here, and see there we just have to interchange that we put the c on the input side and use R for the feedback portion. So, you have C d, R d all the op amps have power supply pins, power supply inputs. So, you should not forget that. Now, the output of the differentiator is given to the summing, now the input to the differentiator again is e at this point you have V naught of the differentiator - output to the differentiator.

So, what is the transfer function of this, look at if you look at the Laplace domain V naught d s by E of s equals R of d by 1 by s C d, this is... So, 1 by s C d which is nothing but s C d R d. So, apparently here you see the transfer function appears ideal where you do not you have an ideal s and scalar C d R d. However, understand that you are using a practical op amp, the practical components op amp has a pole very far in the frequency domain very far in the frequency access it is, it is nothing but low pass filter. So, this will introduce that high frequency pole the op amp; op amp is an low pass filter that op amp's pole will be the high frequency pole, which actually is implicit and that is there we do not write it, but it is there remember that it is never ideal.

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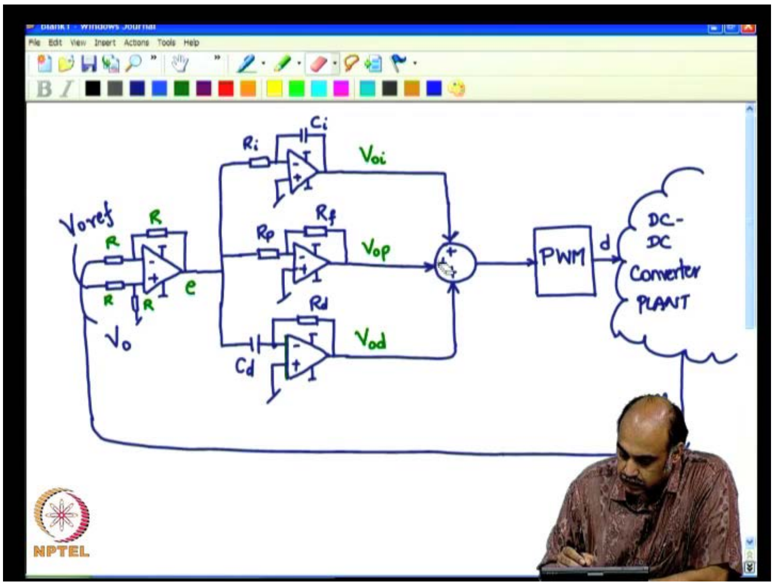

So, we shall clear out this portion of the board and keep the rest C d and yeah… So, you have the outputs from the integrator, from the proportional part, and the derivative part; output of all these need to be summed up.

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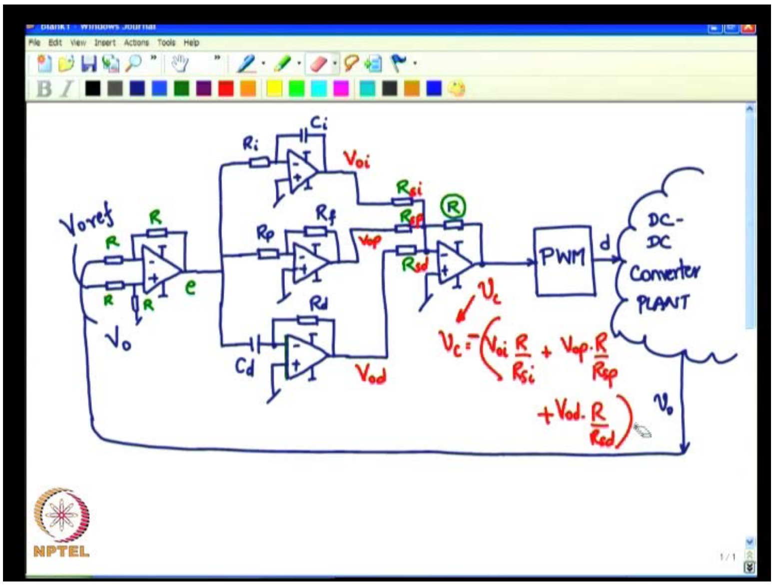


So, let us do that summing again using one more op amp. So, this portion we shall try to remove and replace it with the summing op amp. So, this is removed, and let us incorporate an op amp here. So, these are ground points, these are ground points so on. Now, let us erase these make some space for some resistance. So, let us put the summing resistances here. So, we have three summing resistances, and the output of that. So, let us say for simplicity, we keep all these resistances R, R, R, R. So, this feedback R divided by this R will be the gain part this high stage, this feedback R divided by this R would be the gain for the proportional stage and so on and all will be summed up.

Now, let us connect them. So, to one end of the summing R you connect the integrator output than to the other another R, you connect the proportional controller part output, and then to another R you connect the differential output part. You see that you can further have control on the gains for each of each of these parts by having a control on these values of resistances. So, let us give different names for that for these resistances. So, it would be let us say R summing i, R summing p, R summing d.

So, the gain for V naught i. So, what will be at this point, this the inverting which will further invert this, so therefore from here to here there is no inversion. So, at this point we have V c. So, what is V c? I shall write it below here, V c equals V naught i it goes through this gain R by R s i, then adds up V naught p R by R s p plus V naught d into R by R s d, each individually scaled. Now, all these some together and there is an inversion, do not forget that this inversion.

For again I am going to remove this flatter. So, you have 1, 2, 3, 4, 5 op amp's. So, this five op amp's together are basically implementing your PID block, the input comparator, the error is the output of that which goes through each of these i p and d blocks, output of them are summed up to give you V c are the control voltage which goes to the PWM and then gets converted into time, and then goes as input to the DC DC converter. Now, this PID block is not complete, if you do not include the and the wide up when the value of V c goes beyond a particular threshold what do we want to do? We do not want the integrator to integrate or we want to just stop the value stop the capacitance from accumulating any further charge. So, you just clamp it.

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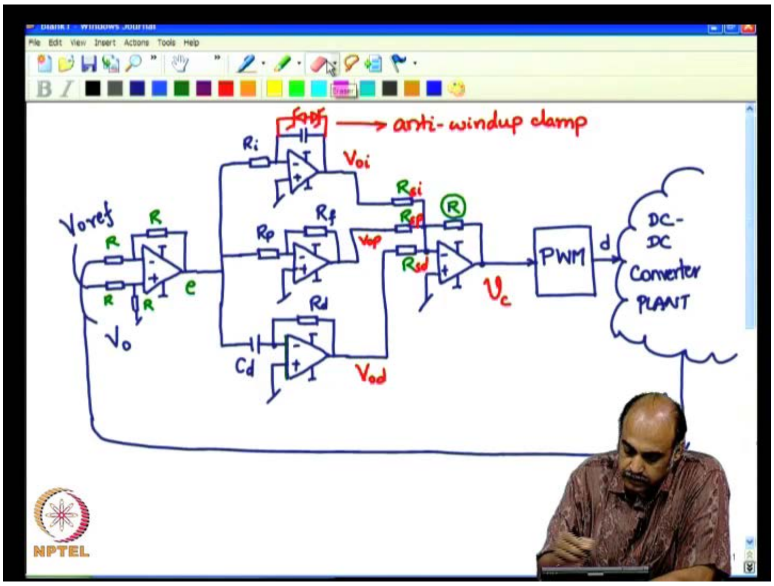


So, how does one do the clamping it is by putting let me create some space. So, you can implement it by putting two zeners back to back like this. So, let us say you want to set the threshold at around three volts, you need to use three volts zeners, you want to set the threshold at five volts, you need to use five volt zeners. So, these zeners one for the positive direction, another for the negative direction, because you do not know what is the direction of the error and will act as the anti wind up clamp.

Now, this is this is a circuit that we developed from the block diagram as such, there is no reduction in the number of op amp, but this is the rather unwieldy circuit, you can do lots to reduce the number of op amp's and keep things simple.

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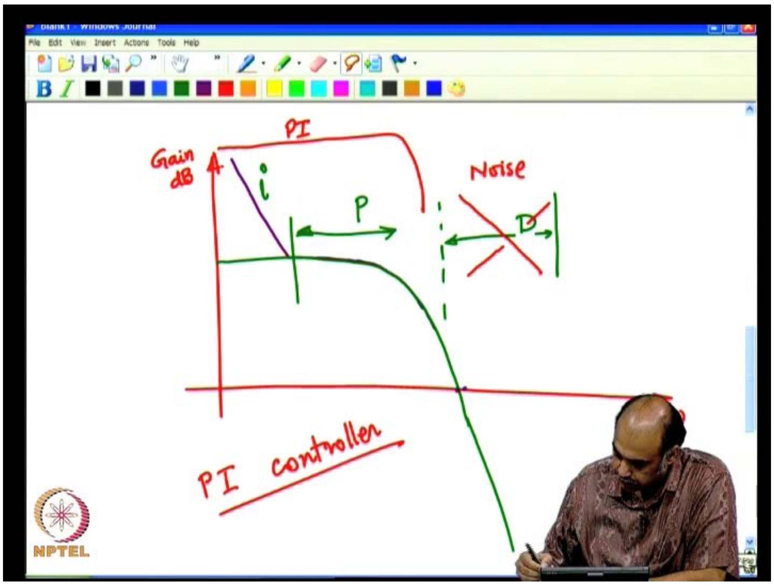


So, let us try to improve this circuit; first and for most you can try to see if your controller can be restricted to just be an i. Meaning if this is your omega axis, and this is your gain in dB, and let us say your plant has the low pass characteristics like this, it is going down and to this low pass characteristics we have the controller; controller is trying to pull up here. So, the controller the integrator portion tries to pull up here then the proportional portion is trying to maintain it at this point let us say, and because it is not changing with frequency and the differential portion is trying to pull up the gain at much higher frequency.

So, if it does not make difference in the bandwidth if the system is already slower then it makes good sense not to have the derivative just to have the proportional the integrator portion - the integrator portion i, and after some point the p proportional portion, after some point actually that is where the D portion comes in, because these are noise sensitive zones, it is always good to see avoid the D, the first iteration if your system works well with just the and I then stop with it do not go further to include the D. Only when your dynamics are not really up to the mark and really what to improve the dynamics you try to put in the D, most of the controller will just have this. The P and the

I part and therefore you have what is called the PI controllers? For the PI controllers are the ones which are more popular most popular, and most of the plants seemed to be with just PI controller the (( )), and meet the specification's include the D part only if absolutely necessary.

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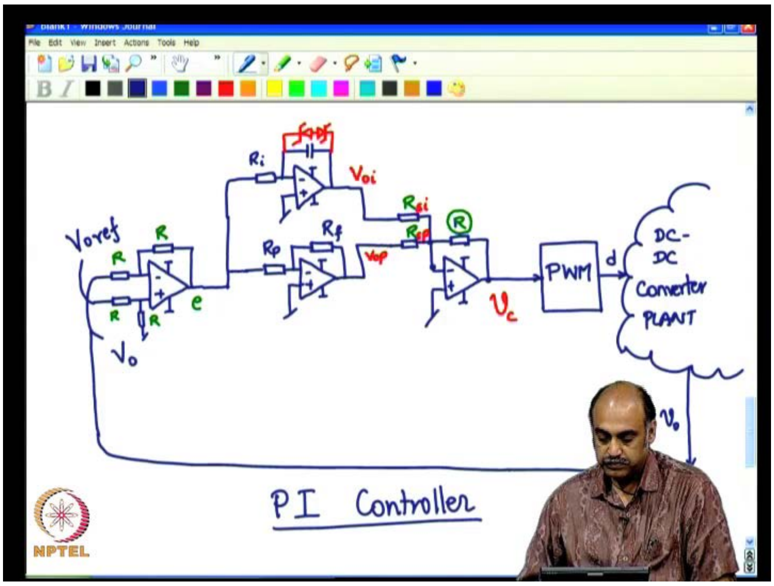


So, if we if we look at this system plant, let me copy this portion. And shift it to another page here, and let us erase the derivative part, we do not want the derivative part. For most of the controller, it is to do over the derivative part, just the PI is sufficient line. So, this would be PI controller. So, we have reduced one op amp, of course with the reduction in the feature that is the de-component.

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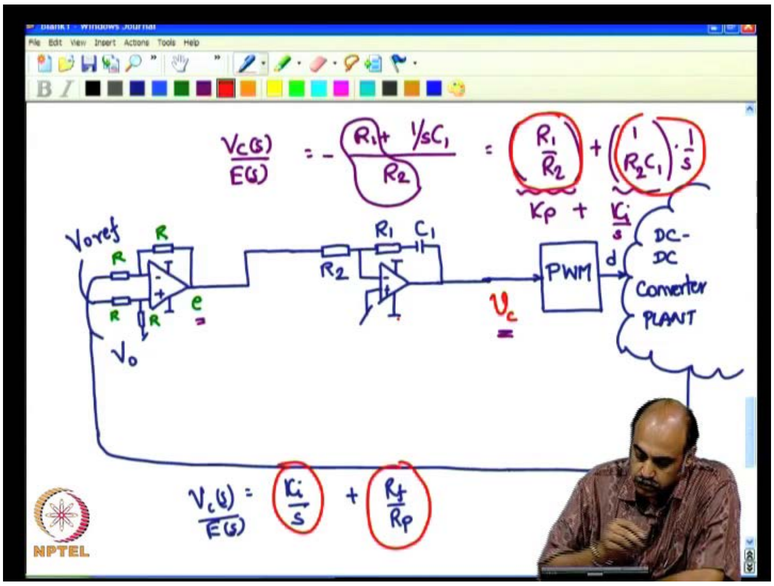


Now, look at look at this two parts look at these two parts, what is the transfer function? The transfer function of V c is nothing but V naught i and to keep in simple, let us keep these R value gains, the summing gains unity. So, that we can just say that plus V o p and which is nothing but and I shall assume that the R going to put this anti clock diodes always, but I want to clear up some space to include. So, you have 1 by R i C i integral of e dt plus R f by R p e, this is nothing but if I say this is k i by s plus R f by R p, then this becomes E s E s V c s.

So, the transfer function is nothing but V c s by E s the error which is nothing but k i by s plus R f by r. So, this is the transfer function of this INP block, now can we replace it with single op amp having similar transfer function. So, if we are able to do that then we can eliminate many of these op amp's, and make the circuit simpler. So, let us check, let us check, if we can do something like this. So, we have an op amp, and to the op amp; the input is e like before and let us say this is called R1, R2 and this is C 1. Now, let us try to find the transfer function of this new op amp circuit V c s by E of s, that is output to the input.

So, the s… So, the s domain this is nothing but R1 plus 1 by s C1 divide by R2, there is an inversion yeah. So, taking (( )) inversion always going to the gain, this is the portion which is like R1 by r2 plus 1 by R2 C1 into 1 by s. So, this is… So, this is your k p plus let say k i are if you take the inversion like here we have not include the inversion, this is understood to be there, then you can keep it separately with the input. Then you see that this is of a form this gives the transfer function of a from similar to the earlier circuit, if it is k i by s and this portion is similar to this portion. And therefore, we can as well use this circuit.

Let me clear up this yeah, because this gives exactly the same a kind of output as this, except here there is no inversion. In the earlier case, there is an inversion with this op amp, and then followed by a summing op amp which provides an inversion. So, there is an inversion here, and then inversion here leading to double inversion, therefore positive. Now, in the case of in the case of this single op amp, this single op amp which gives an inverted output. So, there is just an inversion here which means it is going to be negative. So, you can introduce one more inversion any where either within this block are here.

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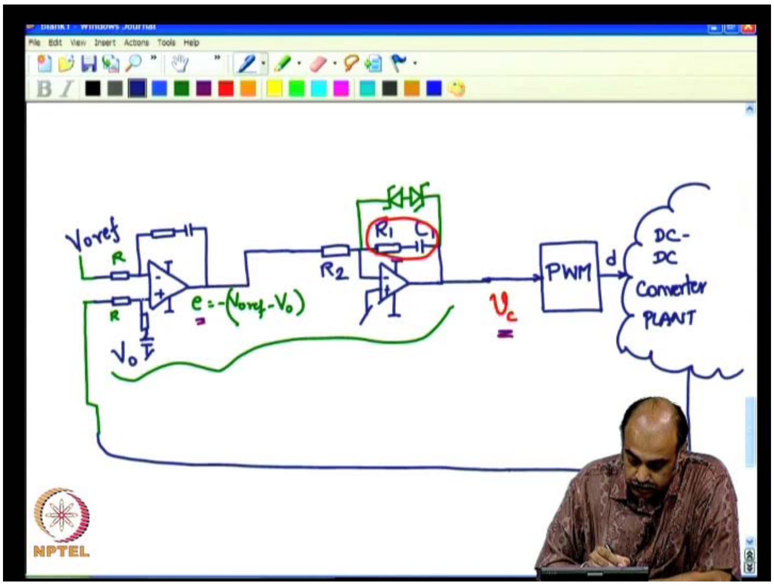


So, if you give an inversion here, it would mean that we interchange we interchange this to that, and this to that here. So, we have an inversion here which is now minus V naught ref minus V naught. So, this inversion followed by an inversion here, followed by an inversion here would again reach here with no inversion, and the phase would been proper context. So, be careful about the inversion whenever you do changes in the circuit keep track of the number of inversion are like as we will later on do in a practical case, if you lost count of number of inversion, we shall when we do on line tuning first check whether the phase relationships are ok, end to an and then do closing of the loop.

We will kept to that later by right now account an number of inversions. Now, we would further reduce the controller, if you want to of course here do not forget that we shall always put two diodes, zeners back to back to take care of the wide up; these are the anti wide up plants. Now, if you observer can we do something, such that these two op amp's are can be combine together and made into single op amp, this is nothing but a difference amplifier and this is nothing but an inverting amplifier with impedance gain gain varies with frequency, not it is a resistive gain. So, if we look at these two resistances convert them to impedances of this type both here, then they become difference amplifier and additionally they can also do the integration. So, let us let us have look at whether we would do something like that, now if we replace now if we replace this by this here.

One should arrive at single op amp solution, but how ever this is not very good implementation or strategy; first of all you, you need to you need to have you a resistance across to provide a check up and path which will introduce a low pass filter and change the equations habit. So, it is better to not to an over simplification and having everything in a single op amp, it is easy also for you to debug to keep the earlier, two op amp structure, let us go to the earlier two op amp structure like this.

So, that it is clear and easy for debugging and separately tuning, otherwise even equations become very complicated and trying to adjust one value of resistance would affect not only k i, but it may affect k p also k d also, and therefore decoupling is lost. So, it is preferred that you just keep it in this structure as shown here. Now, this is the circuit implementation part of the PID controller, keep this in mind because you will try to if you want to implemented with DC-DC convertor, you need to remember and reconstruct them in this form. Now, here there is one black box which is this, the PWM which we have not discussed so far implementing it with op amp's. So, we shall also discuss that gradually and see how we implemented with op amp's.

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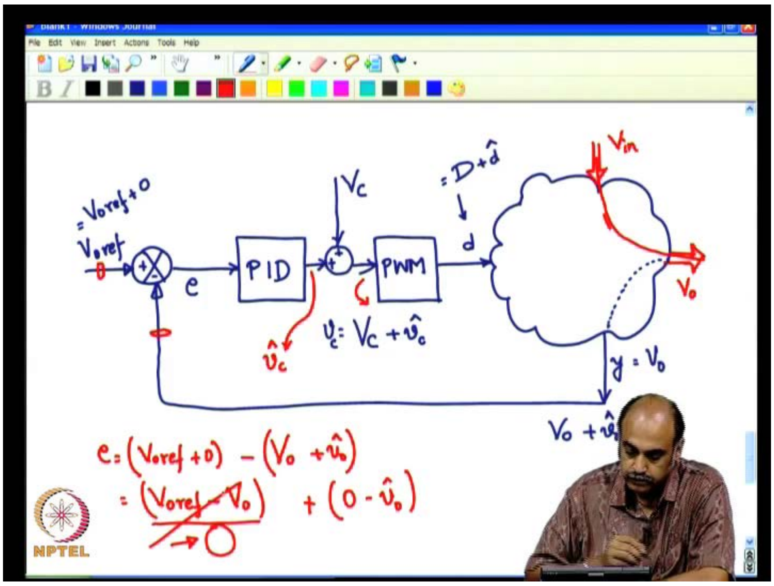

So, (( )) now coming back to this PI controller, we now know how to how to implement the varies parts or blocks of controller, now we can put it as one single PID block knowing fully well that they contain op amp's, this also contain op amp's and the output of that goes to PWM block, and the output of that goes to that controller sorry, the plant which acts as a input of the plant, the d input of the plant. The output from the plant y or V naught sensed output, always remember that there is power input and power output you are actually controlling the flow of power from here to here this is from V in to V naught do not forget that and that V naught which is sensed that V naught which is sensed from there through an opto isolated or through a hall sensor or through resistive division that sensed output is fed back here.

We will see about how we do this sensing and feedback also later, now we have this V naught reference and V naught we have error output of the PID controller Vc, which is the PWM. Now, in the in case of the DC-DC converter, we are doing the modeling which is small signal, but all the signals that you get here are having two parts. So, let me say it is having steady state part plus a V naught hat, now this reference is something which is set by u. So, this is having a steady state reference part plus small signal deviation is zero. So, the hat part is zero, then here the D is having steady state D plus a d hat part.

Now, coming to the input of the PWM, likewise V c equals a steady state V c part plus a V c hat part. So, let us do a minor modification here, in the control structure let us say that this point; we have a summer, this is summer. So, we are going to insert here a term a feed forward term which is based on the steady state part, so let us say I am going to insert V c here, steady state portion of the V c which means here what will be coming in would be V c hat. So, that at this point it is V c plus V c hat. Now, in this comparator when you subtract this and this, that is you have Vo ref plus 0 steady state part plus 0 minus again a steady state part plus V naught hat is your error, now that can be written as V naught ref minus the steady state part minus or that is a plus 0 minus V naught hat, this is the small signal part of the error.

Now, in the steady state, because we are using PID integrator this will tend to zero. So, this is not pair. So, this portion, because you are using PID controller will become 0, and we know that it is zero, we need to take care of the deviation; only the deviations then the PID can focus only on the deviation and the steady state portion can come directly from the reference, if you say you have V naught requirement of particular thing.

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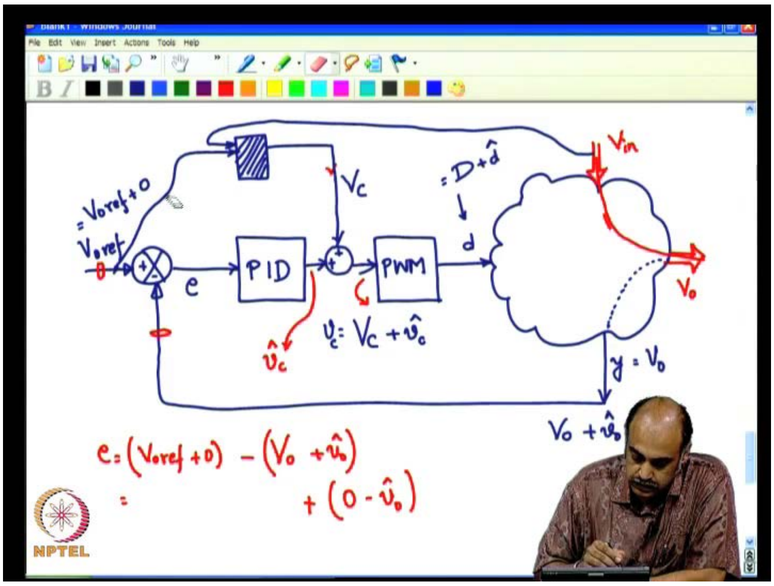


A value here can be given as a feed forward item let us say we put in a block pair, and this block goes in and it takes the value from there or much better, it can take the value from here and also by measuring the input, all from the steady state model. So, how we design this block, and how we take the inputs - various input and from the reference and then try to arrive it the value of V c, we definitely will see that later, but remember that we can separate in to the steady state portion.

So, the steady state portion can be addressed and taken care of by the feed forward term; the feed forward terms can be added either at this place or after that PWM appropriately you will get to understand the context in the nature by which way we will be adding once we know all the circuits put together. If we allow the PID or the controller portion to take care of only the small signal terms, then they will response much faster the dynamic will be much faster; however, you could allow the PID to take care of the entire signal both steady state plus small signal too. So, both are, but only thing is that dynamic will be slower.

So, this is the structure, structure and you can improve upon the structure's you can get many structures; control structures the simplest of course is to just allow the structure to be in this form, and allow the PID controller to take care of everything; of course, with constraints that the slower, the dynamic will be slower still that does not a matter. We have today seen how it looks like with op amp's.

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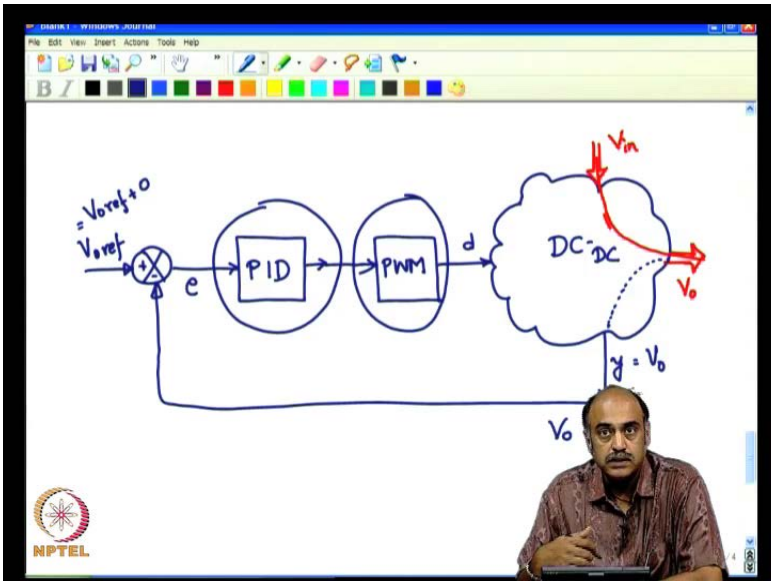


The next class we will see how this looks like, and then we will have a picture of every component in our mines, and then we can integrate all of them along with DC-DC converters here, and try to make the close loop operation possible for the complete integrated system. So, that is how we will progress.

Thank you for now.