

**Fundamental of Power Electronics**  
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**Lecture - 67**  
**Inductor example**

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EXAMPLE

$V_{i,max} \cdot d_{min} = V_{i,min} \cdot d_{max} = V_o$   
 $11 \cdot d_{min} = 9 \cdot d_{max} = 3.3 \text{ V}$   
 $d_{min} = 0.3 ; d_{max} = \frac{1.1}{3}$

L

Let us now take an example and see how to design an Inductor. Consider a buck converter, we have discussed and studied the buck converter at some length, we know how it operates. This is  $V_{naught}$ , let say  $V_{naught}$  we want is 3.3 volts and  $I_{naught}$  is 5 amp load requirement. The switching frequency is 20 kilo Hertz; 20000 Hertz,  $V_i$  input voltage 10 volts plus or minus 10 percent varies from 10 volts minus 10 percent to 10 volt plus 10 percent. This is Q D L C and R  $naught$  and our job is to design L inductor.

So, let us try to find the duty cycle  $V_{i,max}$  into  $d_{min}$  is equal to  $V_{i,min}$  into  $d_{max}$  should be equal to  $V_{naught}$ , buck converter relationship. Now,  $V_{i,max}$  10 volts plus 10 percent 10 percent of 10 volt is 1 volt. So, 11 volts into  $d_{min}$  or 9 volts into  $d_{max}$  is equal to 3.3 volts;  $d_{min}$  from that relationship  $d_{min}$  will turn out to be 0.3,  $d_{max}$  is 1.1 by 3.

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The image shows a handwritten derivation for the inductor value L. It starts with the equation  $V_{max} \cdot d_{min} = V_{min} \cdot d_{max} = V_o$ . Then, it substitutes values:  $11 \cdot d_{min} = 9 \cdot d_{max} = 3.3 \text{ V}$ . From this, it finds  $d_{min} = 0.3$  and  $d_{max} = \frac{11}{9}$ . The main equation for L is  $L = \frac{V_o \cdot (1 - d_{min})^{0.3}}{\Delta i_L \cdot f_s}$ . The result is boxed as  $0.23 \text{ mH}$ . Annotations include:  $\Delta i_L$  is labeled as 10% of 5A, and  $f_s$  is labeled as 20 kHz. A small 'A' is written at the bottom left of the slide.

We will need the d min value, L is equal to V naught into 1 minus d min divided by delta i L into f s. While, we discussed the buck converter we had use this equation; we had developed this equation L is equal to V naught into 1 minus d by delta i L into f s. I am now including it has d min because, d min is worst case when d is minimum this value in the numerator within the brackets is maximum and I will get the larger value of L.

So, that would be the worst case. So, let us plug-in these values as 10 percent of 5 amps which is 0.5 amps. Here first is 20 kilo Hertz, this is 3.3 volts 0.3 and you will land up with L 0.23 milli Henry. So, this is the value of L, that is the first step in the design of inductor, find the value of L which we have done from the understanding of how the buck converter operates.

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Area product:

$$I_m = I_o + \frac{\Delta i_L}{2} = 5.25A$$

$$E_L = \frac{1}{2} \cdot L \cdot I_m^2 = 3.1834 \times 10^{-3} \text{ joules}$$

$$A_p = \frac{2 \cdot E_L}{K_w \cdot K_c \cdot J \cdot B_m} = 1.34747 \times 10^{-8} \text{ m}^4$$

$$= 13474.7 \text{ mm}^4$$

$0.6$  (under  $K_w$ )  
 $\left(\frac{I_m}{I_o}\right)$  (under  $K_c$ )  
 $3 \times 10^6 \text{ A/m}^2$  (under  $J$ )  
 $0.25T$  (under  $B_m$ )

SELECT POT CORE  
**P36/22**  
 $A_c = 201 \text{ mm}^2$   
 $A_w = 101 \text{ mm}^2$   
 $A_p = 20100 \text{ mm}^4$   
 $l_m = 55.2 \text{ mm}$

Next let us try to find the area product. So, for finding the area product we need these values, what is  $I_m$  because in the energy equation we have  $L$  is equal half  $L I_m$  square. What is  $I_m$ ?  $I_m$  is you know that the current in the inductor the average value is  $I_{naught}$  and there is superimposed on that  $\Delta i$  ripple peak to peak. So, the peak value will be  $I_m$  plus  $\Delta i$  by 2. This we know, we have studied 5 plus 0.25, 5.25 amps.

Then the energy in the inductor at peak current will be half  $L I_m$  square which will turn out to be 3.1834 into 10 to the power of minus 3 joules. And, now the area product can be calculated  $2 E_L$  divided by  $K_w K_c J B_m$ . We know all the values here,  $I_m$  am going to take  $K_w$  as 0.6 and experienced winder will wind this,  $K_c$  is the crust factor which is  $I_m$  by  $I_{naught}$ ,  $I_{naught}$  is the rms value.

You can find that out  $J$  is 3 into 10 to the power of 6 amp per meter square,  $B_m$  is 0.25 Tesla for ferrites we are using ferrites. And, this will work out to be 1.34747 into 10 to the power of minus 8 meter to the power of 4. Or, it works out to be 1 multiplied by 10 to the power of 12, you will get 13474.7 mm to the power of 4. Now, look into the core table and try to select a core which will give a value greater than this.

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Properties of Ferrite Cores					
Cores without air gap	Mean length per turn (mm)	Mean magnetic length $l_m$ (mm)	Core cross-section area $A_c$ (mm <sup>2</sup> )	Window area $A_w$ (mm <sup>2</sup> )	Area product $A_w l_m$ (mm <sup>3</sup> )
<b>Pot Cores</b>					
P1811	15.4	26	40	27	1061
P2606	32	57.3	76	51	4922
P3619	48	85.2	138	75	10300
P4622	75	132	240	101	20361
P6229	86	188.4	304	131	47784
P6676	130	133	715	118	170794
<b>EE Cores</b>					
E2005	38	42.8	31	47.8	1481
E2506	51.2	48.8	40	78	3530
E29107	52	57.5	55	87	4781
E36107	56	68.9	103.7	119	7963.2
E461813	78.4	78	138	140	18471
E421204	77.6	108.5	107	236	27392
E421215	81	87.2	182	236	40582
E421220	89	98	238	236	48568
E421213	100	146.3	246	337	142842
<b>SI Cores</b>					
SI115	44	48	32	39	1888
SI121	51	48	39	46	1961
SI132	68	75	41	136	8256
SI148	80	84	76	165	23840
SI166	25.3	308	440	204	107930
<b>Stack</b>					
T10	12.8	20.0	6.2	18.6	13132
T11	19.2	36.4	12	44.2	5364
T16	24.2	66.7	20	78.9	1579
T20	25.2	67.3	22	89	2090
T27	34.1	69.96	42	160.1	4042.2
T32	39.6	75	44	160.1	10873.2
T41	54.7	114.5	69	175.7	97360.3

23 mH

5.25A

$3.1834 \times 10^{-3}$  joules

$= 1.34747 \times 10^{-8} \text{ m}^4$   
 $\text{m} \rightarrow 0.25T = 1347.7 \text{ mm}^4$   
 $10^6 \text{ A/m}^2$

Now, let us look at the core table. Now, here is the core table I am now looking at the area product column, this is the area product column. Then look at this 1347, 13474 you are having 10200 P 30 power 19 greater than that 20301. Now, this is greater than the one that we have calculated. So, it may be good to choose P 36 bar 22 pot core of course, you can choose any other core shapes, but let us say for now for example, we choose this pot core. So, select pot core P 36 bar 22. So, this is the core that we have selected.

Now, what are the values for this core, the selected core? We have the core cross section area of 201 mm square. We have the window area of 101 mm square and we have the mean magnetic length of 53.2. So, let us write that down here; core cross section area of 201 mm square, window area 101 mm square, total area product which is the multiplication of this 20100 mm to the power of 4 and 1 m that is the mean magnetic length 53.2 mm. So, these are the parameters for the selected core which is the pot core P 36 bar 22.

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Permeance : From datasheet CEL HP3C grade ferrite

$$\mu_r = 2000 \pm 25\%$$

$$\mu_{r \min} = 1500$$

$$\Lambda = \frac{\mu_0 \mu_r A_c}{l_m + \mu_r l_g} = 4.717 \times 10^{-7} \text{ H/turns}^2$$

Turns :

Next let us calculate the permeance. See from the datasheet of CEL HP 3 C grade ferrite, I have obtained the value of relative permeability as 2000 plus or minus 25 percent, where the worst case permeability minimum value is 2000 minus 25 percent 1500. So, I will use this minimum permeability for the calculations in evaluating permeance.

So, in the permeance; if you look at the permeance equation  $\mu_0 \mu_r A_c$  by  $l_m + \mu_r l_g$ , this is what we had developed. We know  $A_c$ , we know  $\mu_r$ , we know  $\mu_0$ , we know  $l_m$ ,  $\mu_r l_g$ ;  $l_g$  the air gap. You pick up a piece of paper or mylar sheet, measure the thickness of that and then you can plug that in here. For now, I am going to take a paper of thickness 0.5 mm.

So, plug in the values; let us say  $\mu_0$  is  $4\pi$  into  $10$  to the power of minus  $7$ ,  $\mu_r$  is  $1500$  as given here,  $A_c$  is  $201$  into  $10$  to the power of minus  $6$  meter square,  $l_m$  is  $53.2$  into  $10$  to the power minus  $3$  meters,  $\mu_r$  is  $1500$  again and  $l_g$  is  $0.5$  mm so,  $0.5$  into  $10$  to the power minus  $3$  meters. So, this will work out to  $4.717$  into  $10$  to the power of minus  $7$  Henry per turn square. So, this is the value of the permeance.

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$$\Lambda = \frac{\mu_0 \mu_r A_c}{l_m + \mu_r l_g} = 4.717 \times 10^{-7} \text{ H/turns}^2$$

Turns:  $N = \sqrt{\frac{L}{\Lambda}} = 22.13$  Choose  $N = 23$  turns

Wire gauge:  $A_{wcalc} = \frac{I_{rms}}{J} = \frac{I_0}{J} = \frac{5}{3 \times 10^6} = 1.67 \times 10^{-6} \text{ m}^2 = 1.67 \text{ mm}^2$

So, once we have obtained the permeance, next it is easy for us to obtain the turns; number of turns that are needed to be bound on the inductor core. This is given by the relation N is equal to root of L by permeance square root of that. So, this is 23.13, choose round it off to the upper next upper integer 23 turns and this is N. Next we have to find the wire gauge, the area of cross section of the wire be calculated I rms by J which is I naught by J. This case which is 5 amps by 3 into 10 to the power 6 which comes turns out 1.67 10 to the power of minus 6 meters square or 1.67 mm square.

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Wire Size Table				
BWG	Diameter with enamel (mm)	Area of bare conductor (mm <sup>2</sup> )	Area (DPCU)	Weight (g/km)
43	0.886	0.60173	4.36	0.910
44	0.907	0.65181	4.53	0.949
45	0.929	0.69827	4.69	0.987
46	0.952	0.74125	4.87	1.025
47	0.976	0.78176	5.04	1.062
48	1.001	0.81989	5.21	1.099
49	1.027	0.85564	5.38	1.135
50	1.054	0.88901	5.55	1.171
51	1.082	0.92000	5.72	1.207
52	1.111	0.94861	5.89	1.242
53	1.141	0.97484	6.05	1.277
54	1.172	0.99869	6.21	1.312
55	1.204	0.99900	6.37	1.347
56	1.237	0.99781	6.53	1.382
57	1.271	0.99512	6.68	1.417
58	1.306	0.99093	6.83	1.452
59	1.342	0.98524	6.98	1.487
60	1.379	0.97805	7.13	1.522
61	1.417	0.96936	7.28	1.557
62	1.456	0.95917	7.43	1.592
63	1.496	0.94748	7.58	1.627
64	1.537	0.93429	7.73	1.662
65	1.579	0.91960	7.88	1.697
66	1.622	0.90341	8.03	1.732
67	1.666	0.88572	8.18	1.767
68	1.711	0.86653	8.33	1.802
69	1.757	0.84584	8.48	1.837
70	1.804	0.82365	8.63	1.872
71	1.852	0.80006	8.78	1.907
72	1.901	0.77507	8.93	1.942
73	1.951	0.74868	9.08	1.977
74	2.002	0.72089	9.23	2.012
75	2.054	0.69170	9.38	2.047
76	2.107	0.66121	9.53	2.082
77	2.161	0.62942	9.68	2.117
78	2.216	0.59633	9.83	2.152
79	2.272	0.56204	9.98	2.187
80	2.329	0.52655	10.13	2.222

$201 \times 10^{-6} = 4.717 \times 10^{-7} \text{ H/turns}^2$

$5 \times 10^{-3}$

Choose  $N = 23$  turns

$= \frac{5}{3 \times 10^6} = 1.67 \times 10^{-6} \text{ m}^2 = 1.67 \text{ mm}^2$

Now, look into the wire table. So, look into the wire table; we need to look at a wire bare conductor area having greater than 1.67 mm square.

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SWG	Diameter with enamel (mm)	Area of bare conductor (mm <sup>2</sup> )	Area (20°C/L)	Weight (kg/km)
14	1.270	1.6174	34.8	16.107
17	1.000	1.0000	20.8	10.210
16	1.270	2.0750	44.3	18.679
15	1.625	2.6700	56.4	25.444
14	2.000	4.0000	75.3	35.111
13	2.500	6.2500	111.4	52.766
12	3.150	9.9225	168.5	80.222
11	4.000	16.0000	233.4	111.444
10	5.000	25.0000	318.3	152.777
9	6.300	39.6900	444.2	211.111
8	8.000	64.0000	616.8	288.888

$201 \times 10^{-6} = 4.717 \times 10^{-7} \text{ H/turns}^2$   
 $5 \times 10^{-3}$   
 Choose  $N = 23$  turns  
 $= \frac{5}{3 \times 10^6} = 1.67 \times 10^{-6} \text{ m}^2 = 1.67 \text{ mm}^2$

Let us go down this and you see that here SWG 16. Now, here in this row we will find SWG 16 which has bare conductor area of 2.075 mm square greater than this. So, pick that value.

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$N = \sqrt{\frac{L}{\mu}} = 22.13$  Choose  $N = 23$  turns

Wire gauge:  $a_{Wcalc} = \frac{I_{rms}}{J} = \frac{I_0}{J} = \frac{5}{3 \times 10^6} = 1.67 \times 10^{-6} \text{ m}^2 = 1.67 \text{ mm}^2$

SELECT **SWG 16** ( $a_w = 2.075 \text{ mm}^2$ )

Window area cross check:  $A_{Wk} = 101 \times 0.6 = 60.60 \text{ mm}^2$   
 $N \cdot a_w = 23 \times 2.075 = 47.725 \text{ mm}^2$   
 **$A_{Wk} > N \cdot a_w$**

So, now let us write down select SWG 16 which has a wire cross section area of 2.075 mm square. SWG 16 is selected and this has to be bound on to the inductor core which we have chosen P 36 power 22. There is a last check that we need to do what is known as the window area check, to see if the windings will fit into the available window area.

$A_w K_w$  is 101 mm square into 0.6 which 60.60 and  $N$  into a  $w$  that is wire cross section as we have read from the read out from the wire table is 23 into 2.075 which is 47.75. And, you see that  $A_w K_w$  is greater than  $N$  into a  $w$  and therefore, the inequalities satisfied. And, you know that this number of turns or this gauge will fit into the available window area. And therefore, the design is successfully completed.