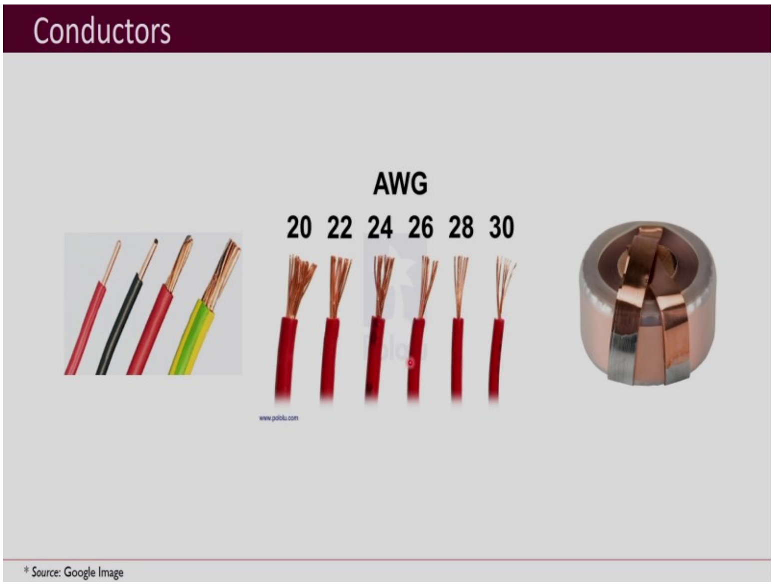
Design of Power Electronic Converters
Professor Shabari Nath
Department Of Electronic And Electrical Engineering
Indian Institute of Technology, Guwahati
Module: Magnetics Design
Lecture: 46
Conductors

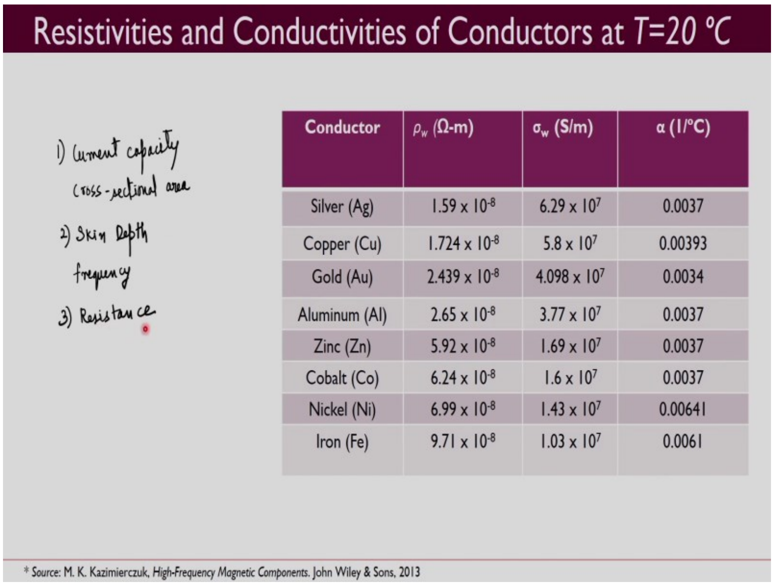
Welcome to the course on Design of Power Electronic Converters. We were discussing magnetics design and we had first reviewed the fundamentals of magnetic circuits. Then now we looked into the losses that takes place in magnetics like inductors and transformers. Now, let us look into the terms associated with conductors. To make an inductor or transformer you mainly need two things, one is the magnetic core and second is conductor. So, let us look into the important terms related to conductors.



So, you all might have seen conductors that means wires. So, wires are of these types. It can be solid, a solid conductor or it can be multi stranded that means, there are multiple wires of small diameters, they are put together and then they are twisted. So, that is called as the litz connection, litz wiring.

So, that has got some advantages which we will see later in the course. So, this kind of multi stranded arrangement may be there or a solid conductor also may be there and they are available in different sizes. So, you can see that this is a relatively thinner conductor as compared to this one, which is more thicker. There is some number, which is also given over here. About this numbering we will be discussing. This is a standard that is followed for conductor manufacturing. So, these kinds of wires or conductors are used for magnetics design and second type of conductor that may be used, and it is the foils. This is a copper foil.

So, you can see that these are like strips of copper flattened strips or foils, which are also used for the magnetics design. Now, this have certain advantages and we will not go into the details of this copper foils because this is just an introduction to magnetics designs, and we will not go into the details to design using copper foils. But, we will be taking the simpler case which is designed using these kind of wires.



Conductor	ρ_w (Ω-m)	σ_w (S/m)	α (1/°C)
Silver (Ag)	1.59×10^{-8}	6.29×10^{7}	0.0037
Copper (Cu)	1.724×10^{-8}	5.8×10^{7}	0.00393
Gold (Au)	2.439×10^{-8}	4.098×10^{7}	0.0034
Aluminum (Al)	2.65×10^{-8}	3.77×10^{7}	0.0037
Zinc (Zn)	5.92×10^{-8}	1.69×10^{7}	0.0037
Cobalt (Co)	6.24×10^{-8}	1.6×10^{7}	0.0037
Nickel (Ni)	6.99×10^{-8}	1.43×10^{7}	0.00641
Iron (Fe)	9.71×10^{-8}	1.03×10^{7}	0.0061

So, conductors are made of different materials. Now, normally it is copper, but it can be also made of silver or aluminium. It is also something that is used for conductors. Apart from that there are other materials also which can act as conductors. Now, this table shows the resistivity of different conducting materials. Here you can see that lowest resistivity is for silver and then copper has got a higher resistivity than that. So, it is little higher, then gold has higher resistivity. After that aluminium has higher resistivity and then further these have got more high resistivities.

So, now resistivity means that the smaller it is, better it acts as a conductor and so silver would be the best as a conductor. But, since it is expensive, normally people use copper wires. Apart from that people also use aluminum because gold is again very expensive. So, aluminium also is the next over here which is also having reasonable resistivity. So, many times conductors can also be made up of aluminium and the reciprocal of resistivity is the conductivity which is σ_W. So, that inverse of resistivity is conductivity which is again shown here. You can see that the lesser is the resistivity, the higher is the conductivity. Then this shows α, the temperature coefficient. Now, we had discussed the importance before, when we discussed the magnetics losses. So, as temperature increases the resistivity changes or as temperature changes the resistivity changes. So, this resistivity is a function of the temperature and then there is the coefficient (α), which is associated with it that is also given here. So, you can obtain this data easily on Google or from the manufacturers websites. In this way we choose conductors, then the important thing to note down is the current capacity of that conductor and associated with that is the cross-sectional area of the conductor.

Then, next important thing is the skin depth. The skin depth that we had discussed before and it affects the frequency of operation. So, one should look into the frequency till which particular conductor can be used and then of course, one should know the resistance of that conductor. You know that, it is inversely proportional to the cross-sectional area. So, lesser the cross-sectional area, higher is going to be the resistance.

Now, depending on the requirement you may think that this is the cross-sectional area of the conductor which is going to be suitable for you and some other application may require different cross-sectional area of conductor. Now, different people may demand different cross-sectional areas that means different gauge of the wire.

Now, if the manufacturer start making conductors on their own choice, then it will be very difficult for a person to go and buy wires which can be readily used. So, for that, to solve this problem there is a gauging system. It is called as the American wire gauge system. It is a standardized logarithmic system which is used for standardization of the wire gauges and it is pretty old system and is used for quite some time now.

American Wire Gauge (AWG) Size Table

AWG	Diameter [mm]	Area [mm²]	Resistance [Ω/km]	Max Current [A]	Max Frequency for 100% skin depth
0000 (4/0)	11.684	107	0.16072	302	125 kHz
000 (3/0)	10.40384	85	0.202704	239	160 kHz
00 (2/0)	9.26592	67.4	0.255512	190	200 kHz
0 (1/0)	8.25246	53.5	0.322424	150	250 kHz
1	7.34822	42.4	0.406392	119	325 kHz
2	6.54304	33.6	0.512664	94	410 kHz
3	5.82676	26.7	0.64616	75	500 kHz
4	5.18922	21.2	0.81508	60	650 kHz
5	4.62026	16.8	1.027624	47	810 kHz
6	4.1148	13.3	1.295928	37	1100 kHz
7	3.66522	10.5	1.634096	30	1300 kHz
8	3.2639	8.37	2.060496	24	1650 kHz
9	2.90576	6.63	2.598088	19	2050 kHz
10	2.58826	5.26	3.276392	15	2600 kHz
11	2.30378	4.17	4.1328	12	3200 kHz
12	2.05232	3.31	5.20864	9.3	4150 kHz

* Source: https://www.solaris-shop.com/content/American%20Wire%20Gauge%20Conductor%20Size%20Table.pdf

American Wire Gauge (AWG) Size Table (cont..)

AWG	Diameter [mm]	Area [mm²]	Resistance [Ω/km]	Max Current [A]	Max Frequency for 100% skin depth
13	1.8288	2.62	6.56984	7.4	5300 kHz
14	1.62814	2.08	8.282	5.9	6700 kHz
15	1.45034	1.65	10.44352	4.7	8250 kHz
16	1.29032	1.31	13.17248	3.7	11 kHz
17	1.15062	1.04	16.60992	2.9	13 kHz
18	1.02362	0.823	20.9428	2.3	17 kHz
19	0.91186	0.653	20.40728	1.8	21 kHz
20	0.8128	0.518	33.292	1.5	27 kHz
21	0.7239	0.41	41.984	1.2	33 kHz
22	0.64516	0.326	52.9392	0.92	42 kHz
23	0.57404	0.258	66.7808	0.729	53 kHz
24	0.51054	0.205	84.1976	0.577	68 kHz
25	0.45466	0.162	106.1736	0.457	85 kHz
26	0.40386	0.129	133.8568	0.361	107 kHz
27	0.36068	0.102	168.8216	0.288	130 kHz
28	0.32004	0.081	212.872	0.226	170 kHz

* Source: https://www.solaris-shop.com/content/American%20Wire%20Gauge%20Conductor%20Size%20Table.pdf

American Wire Gauge (AWG) Size Table (cont..)

AWG	Diameter [mm]	Area [mm²]	Resistance [Ω/km]	Max Current [A]	Max Frequency for 100% skin depth
29	0.287202	0.0642	268.4024	0.182	210 kHz
30	0.254	0.0509	338.496	0.142	270 kHz
31	0.22606	0.0404	426.728	0.113	340 kHz
32	0.2032	0.032	538.248	0.091	430 kHz
33	0.18034	0.0254	678.632	0.072	540 kHz
34	0.16002	0.0201	855.752	0.056	690 kHz
35	0.14224	0.016	1079.12	0.044	870 kHz
36	0.127	0.0127	1360	0.035	1100 kHz
37	0.1143	0.01	1715	0.0289	1350 kHz
38	0.1016	0.00797	2163	0.0228	1750 kHz
39	0.0889	0.00632	2728	0.0175	2250 kHz
40	0.07874	0.00501	3440	0.0137	2900 kHz

* Source: https://www.solaris-shop.com/content/American%20Wire%20Gauge%20Conductor%20Size%20Table.pdf

So, this table shows that there is a number that is given for different diameters of wires. So, manufacturers usually make the wires based on this gauging system, in short this is called AWG. So, here the way for the numbers are given. It is like that the lower is the number, the higher is the diameter of that conductor. For example, here you can see that this is AWG1 and the diameter is *7.348* and this is a gauge *5* and the diameter here is *4.6*.

So, the diameter is lesser here and the diameter is greater here. So, in the AWG system, higher is the gauging number, the thinner the wire is going to be. Then we need the cross-sectional area of the wire. So, when we know the diameter, we can find out the cross-sectional area. So, cross sectional area is just this cross-sectional area of the wire where this will be diameter d. Further you need to find out the resistance. So, those resistances in Ω/km and those are also given for these wires.

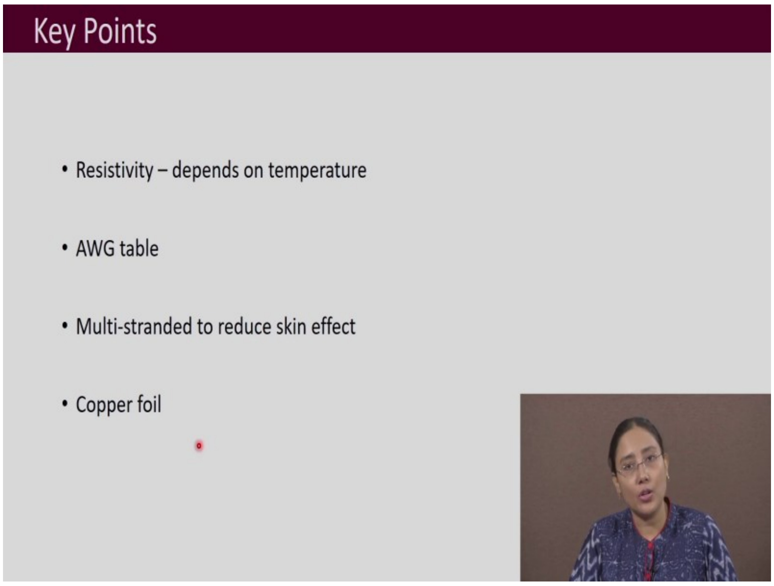
Now, this data is for copper wires. So, if you know the cross-sectional area and the length is taken as *1 km*, and the resistance of these conductors is also given. Now, as the resistance is inversely proportional to the cross-sectional area, you can see here that this cross-sectional area is greater. So, here the resistance is less as compared to over here. Where the cross sectional area is smaller and the resistance is relatively greater.

So, as you go down or as AWG gauging number increases, the resistance also increases and the cross-sectional area decreases and the diameter also decreases. Now, we should also be knowing the maximum current for that you are choosing this conductor, and it is able to carry. Because then you can decide for the particular application based on the current rating, which is the gauge that you should choose. So, here you can see that those maximum current capacity is also given here and this is also going to decrease because higher is the resistance lesser will be the current carrying capacity.

So, that's what we see here. Further about the skin depth I told you. It is something which increases the resistance for AC application and it depends on the frequency. So, higher the frequency lesser is going to be the skin depth. Now, for 100 percent skin depth the frequency is also given over here.

So, 100 percent skin depth means that this is the cross-sectional area of the wire. So, then over this entire diameter or this skin depth current should be flowing and the maximum limit of the frequency is given over here.

So, that data is given and obviously, this will be like that, as cross-sectional area reduces, the frequency is going to increase because the lesser the diameter, higher will be the frequency for 100 percent skin depth achievement. So, like that this is shown on this slide up to gauge 12, there it is up to gauge 40. You can obtain these kind of tables that is also shown here. This is till AWG 28. The data is given and then till AWG 40 also this data is provided here. So, these kind of tables and charts are very readily available on the internet. You can download them and you can select the conductor or the gauge which is going to be suitable for the particular design.



So, the key points of this lecture are the resistivity. It depends on temperature and different materials have different resistivity. Usually, copper and aluminium are the materials which are used for conductors. Further, there is a gauging system which is the AWG system, standardized system from which you can select the conductor that is going to be suitable for the gauge of the wire.

Multi-stranded wires are used to reduce the skin effect problem. Because if the wires become more thinner, then for higher frequencies also 100 percent skin depth can be achieved. So, for that purpose also multi stranded wires are used. Otherwise sometimes solid wires also may be used but multi stranded are preferred for higher frequencies. Apart from that copper foils are also used for magnetics design. Thank you.