Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 38
Multipulse Converters (Contd.)
Analysis of Multipulse Diode/SCR Rectifiers

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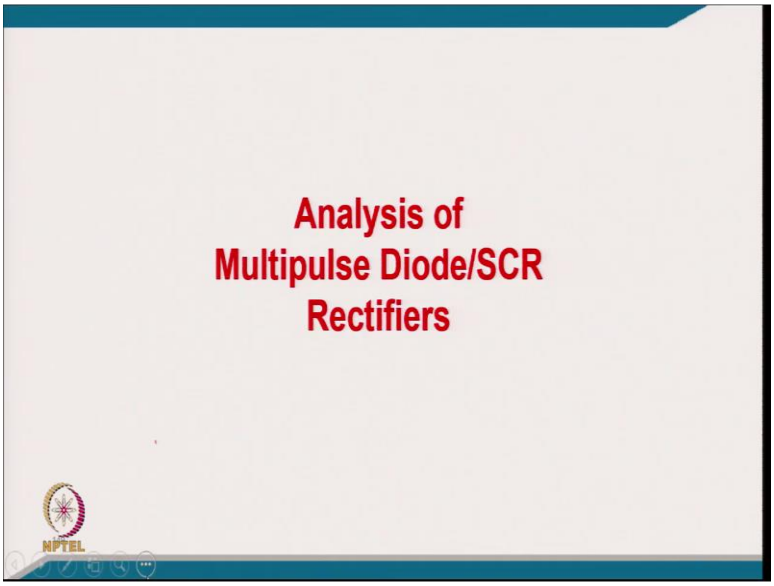

Welcome to the course on Power Quality. We were discussing the improved power quality multipulse AC-DC converter. So, we will discuss today the analysis of multipulse uncontrolled and control converters, which consist of diode and thyristors.

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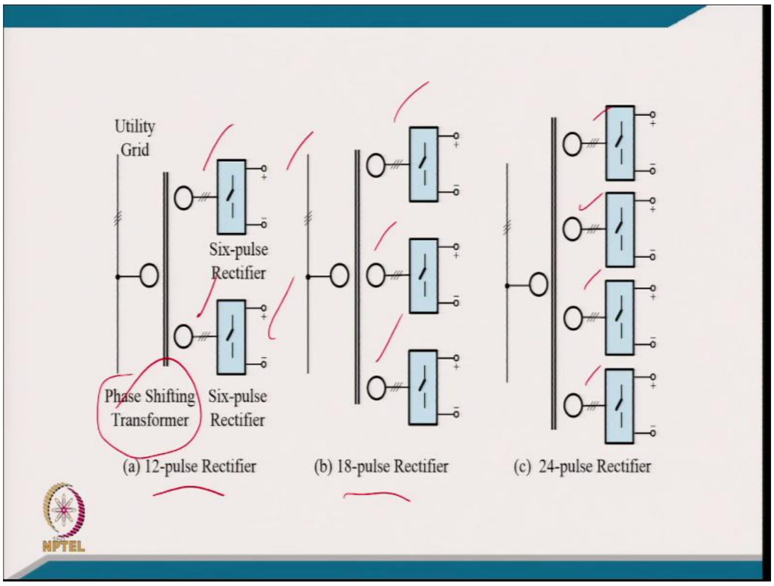

Let us say we have 12-pulse converter with 2 converters, normally it has phase shifting transformer. Many applications we require the isolation, because the utility voltage may be quite different than the application. So, we need 2 converters. As we discussed last time that we require 60 divided by the number of converters like in 12-pulse you have a 2 converters, so it will require 30 degree phase shift between the two sets of winding. And that is the reason we call it a phase shifting transformer. Then, in 18-pulse, of course, we require 3 converters and the required phase shift is 20 degree (60/3). So, you can have a plus minus 20 and 0 degree. And that is the reason you have a 3 converter in 18-pulse. And 24-pulse requires 4 converters, and you can have typically 15 degree phase shift between them.

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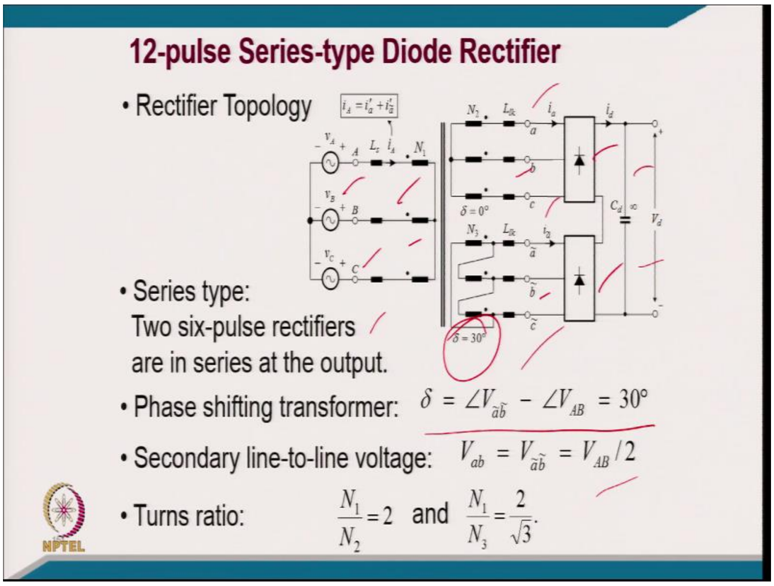

Coming to the first topology. In this, we have 12-pulse series type diode rectifier topology, and 2 converters of 6-pulse, are connected in series. Mostly these converters are used for variable frequency drive, maybe with the induction motor or any other like a synchronous motor or so on. We can have 30-degree phase shift because of your thyristors connection. So, that serve the purpose for phase shifting and you are able to get 12-pulses in the output voltage because of this 30-degrees phase shift. You will also get a quite good current with the reduced harmonics, in which, typically lower than 11^{th} harmonics are eliminated and you have a band of $12n \pm 1$, i.e., 11^{th}, 13^{th}, and that next set will be 23^{rd} and 25^{th}.

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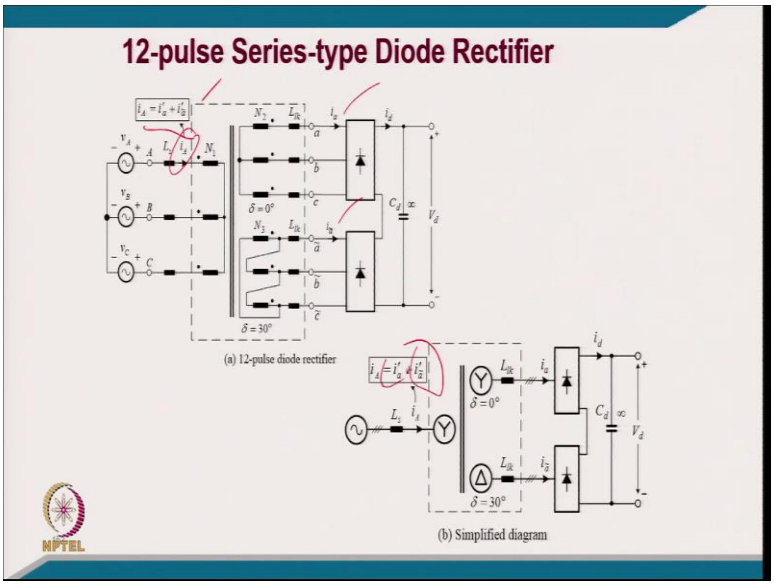

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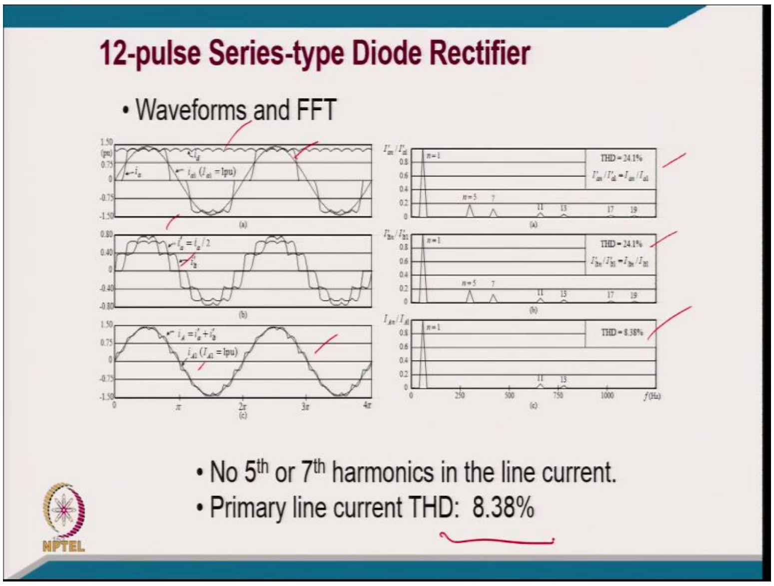

Coming to the waveform and Fast Fourier Transform of it. So, you can see clearly; the load current which is almost like a DC. We have one 6-pulse current, where the fundamental is shown here and another 6-pulse current. I mean you can add both, then you will get this kind of current waveform which is really the current drawn from the supply for particular phase. You can see the THD typically in 6-pulse converter, one 6-pulse converter is 24 percent, another 6-pulse also 24, but that is getting typically get phase shifted. And when you add together, I mean you get 8.38 %. Ideally, you are supposed to get typically order of 15 percent, if the source inductance effect is not there.

So, it is your source impedance in the sense the leakage inductance of the transformer really helps to improve the THD here. I mean in place of 15 percent or 15.5 percent is just going to half like 8.38 percent. So, source impedance makes big difference. Here, there is no 5th and 7th harmonics in the line current and the primary line current THD is 8.38%.

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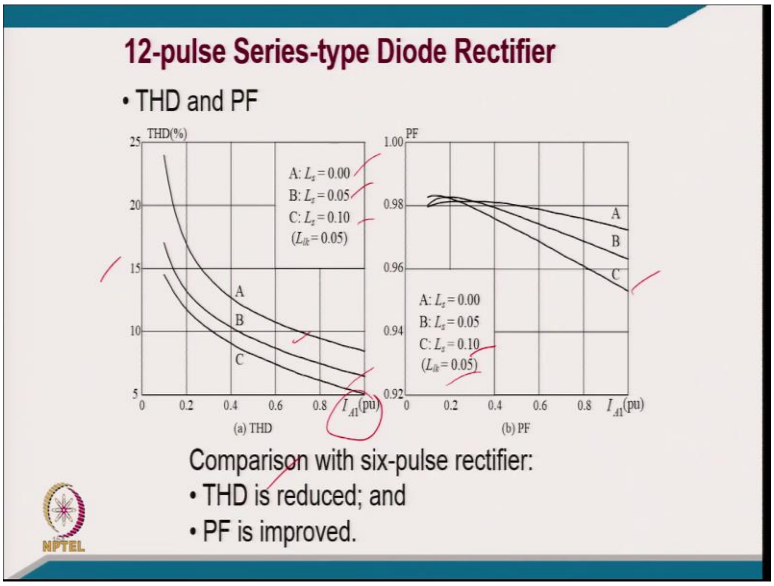

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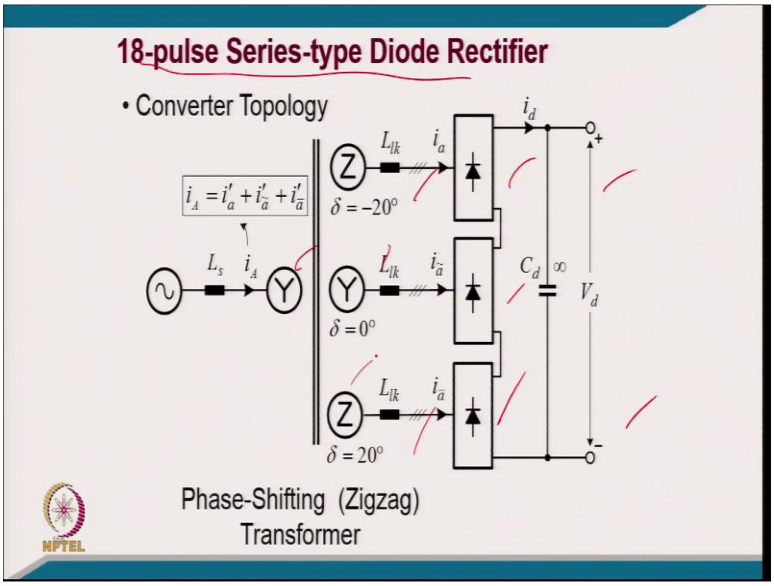

This is typically the you can call it an 18-pulse converter connected in series. You have 18-pulse converter where you require 3 converters, they are connected in series, and the phase shift here, which we have already discussed, is 60 by 3, i.e., 20 degrees, because of 3 converters.

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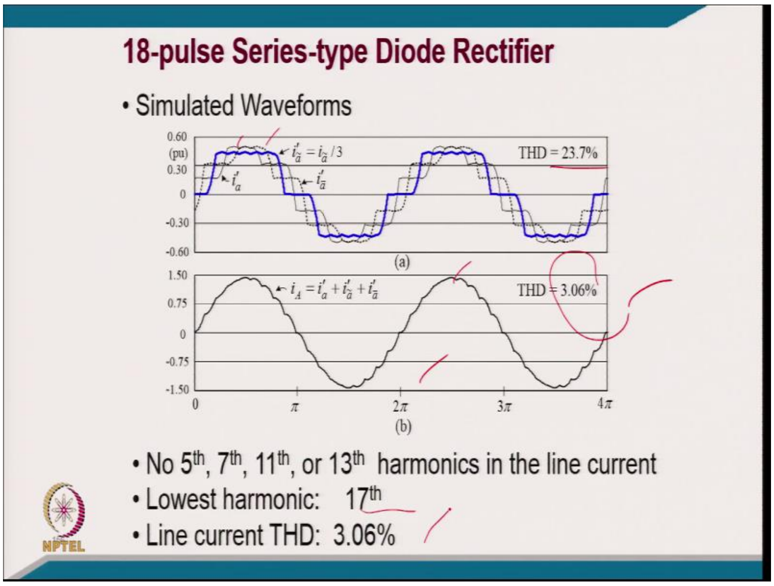

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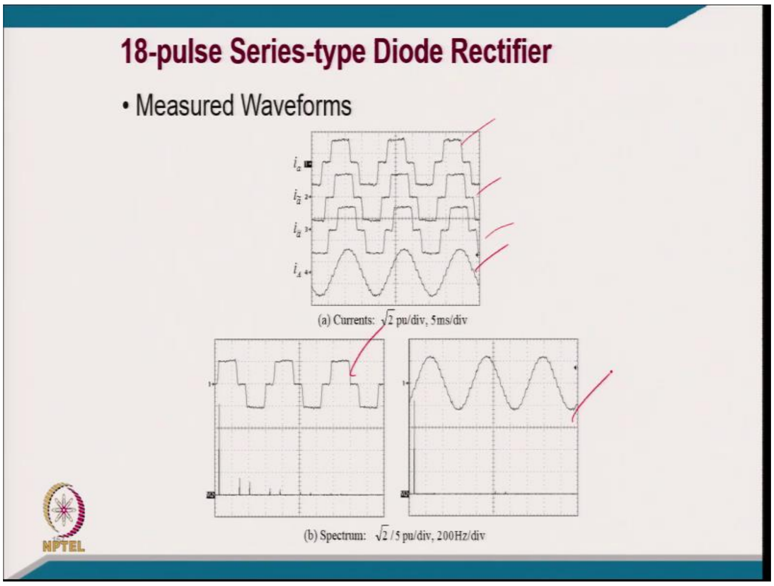

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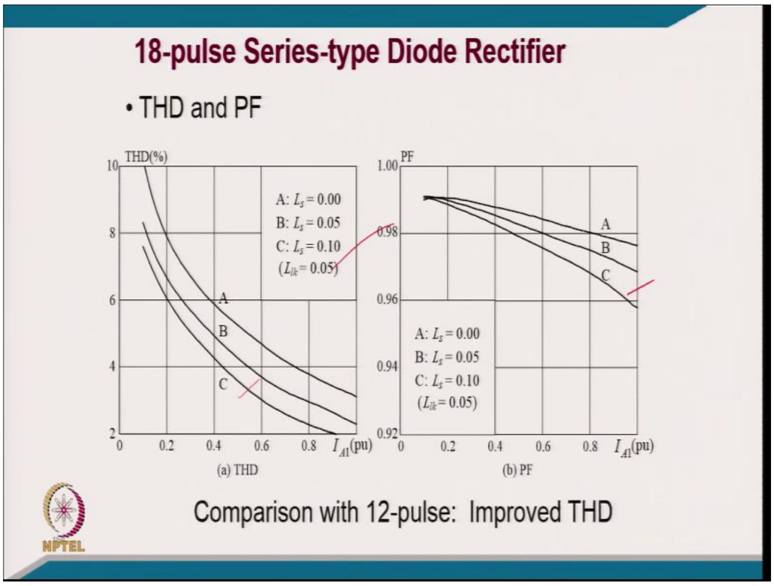

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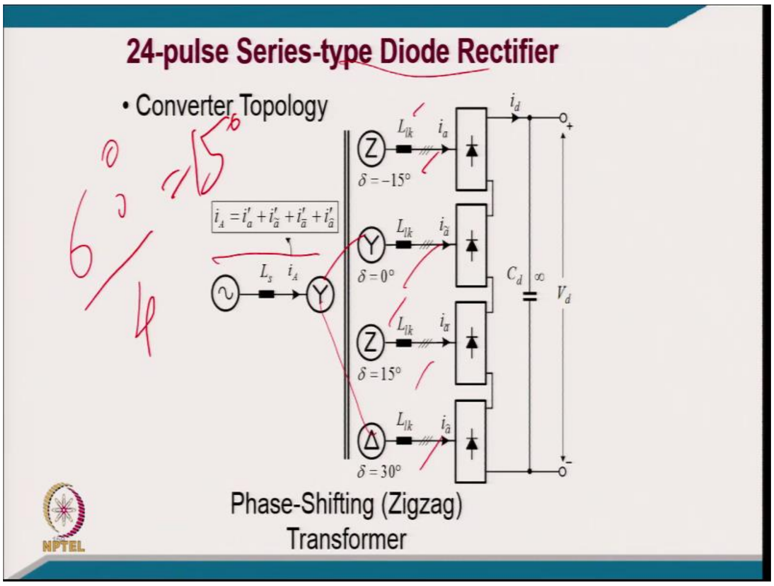

This is typically a 24-pulse series type of diode rectifier. So, here, you can have a 60-degree phase shift divide by number of converter 4, it becomes 15-degrees phase shift. And this 15 degree you can find out here 0, +15, +30, and -15. There may be plenty of way, but that is the way how you can get with the zigzag and typically 30-degree phase shift.

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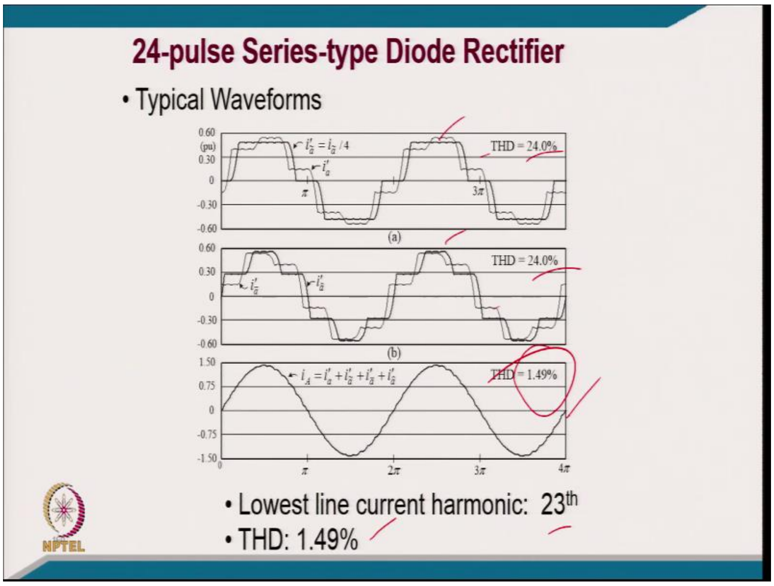

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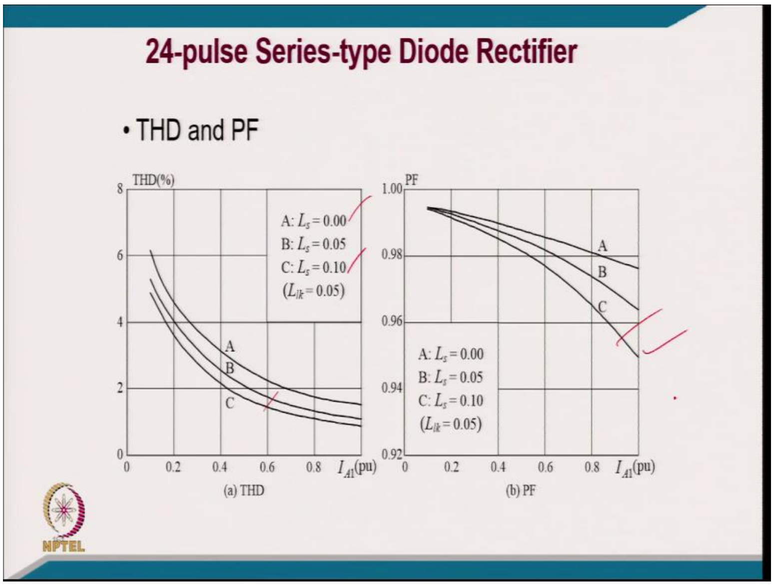

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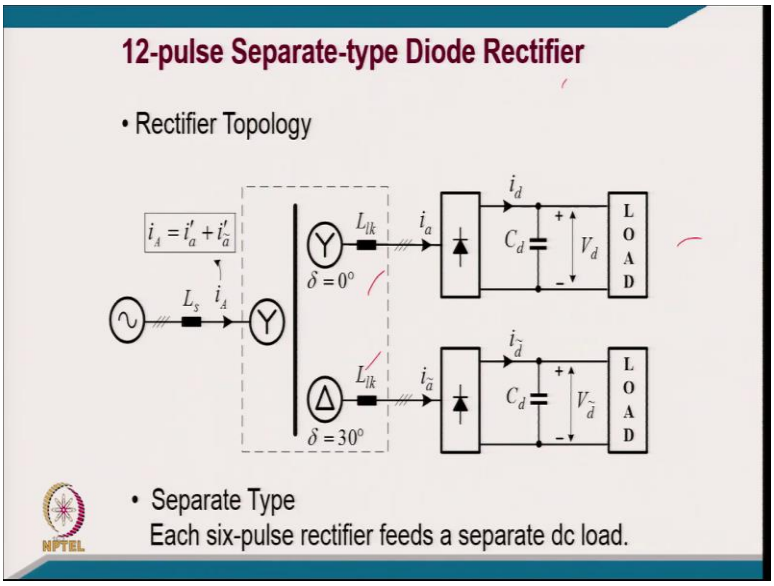

Further, you can have a 12-pulse separate diode bridge rectifier. Many applications we have a such thing. But if you have a phase shift here, then it gets reflected on this side.

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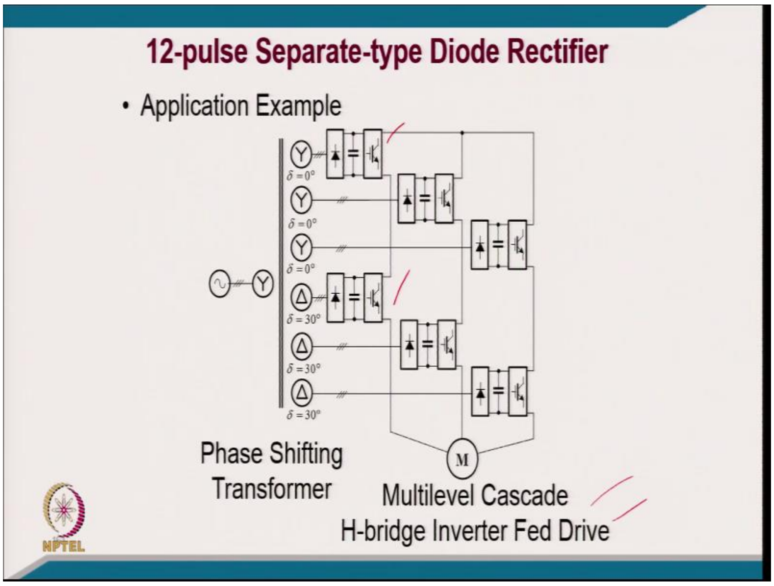

This is an interesting example; you can say multiple multi-level cascaded bridge inverters like Robicon drive system. Here, you can see, it is a kind of a like a 12-pulse connection, so, all these are 0 phase shift and these are 30-degree phase shift. So, for all 3-phases you need the separate secondary. And you can add the voltage there to get the multilevel wave forms. So, these are used normally in medium voltage drive of large rating of order of several megawatt or higher than that.

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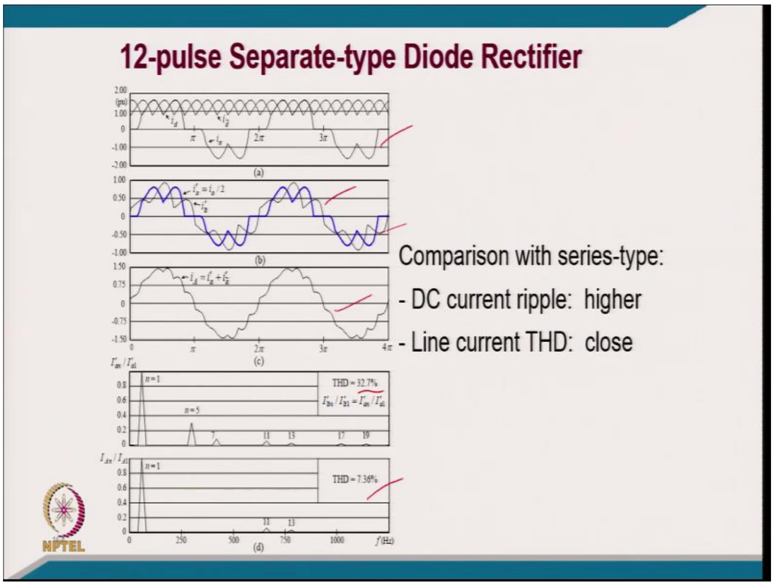

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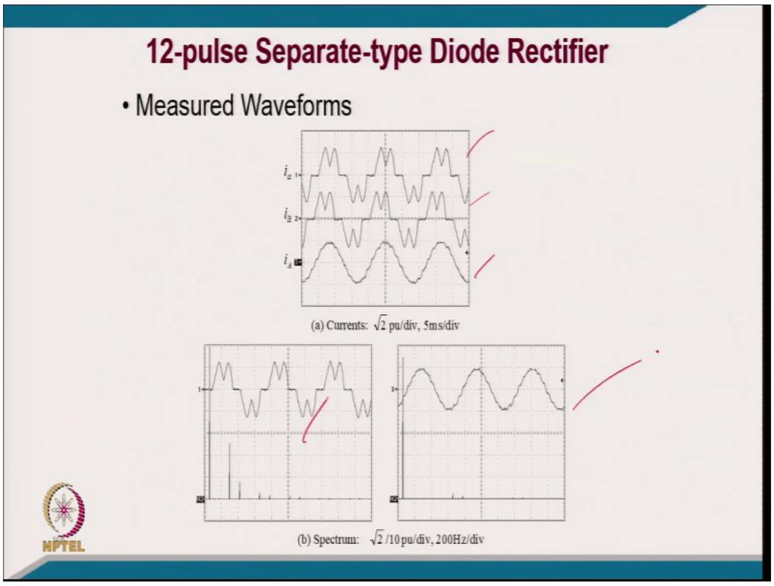

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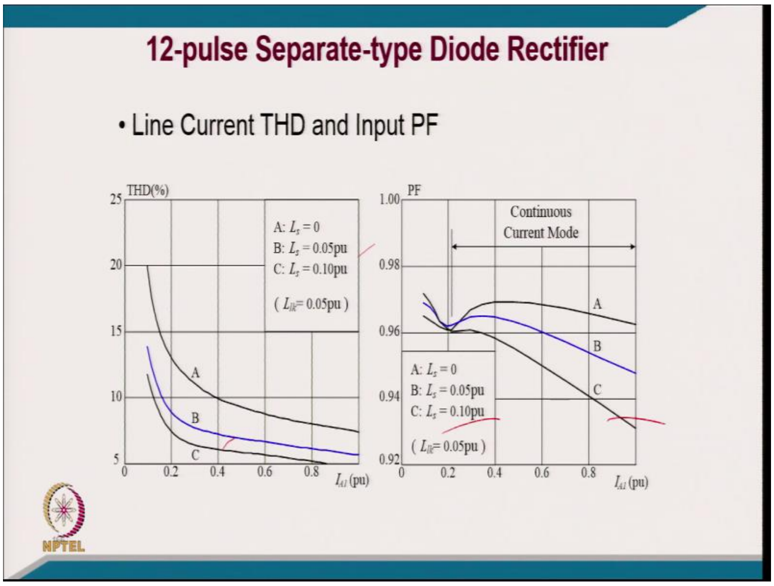

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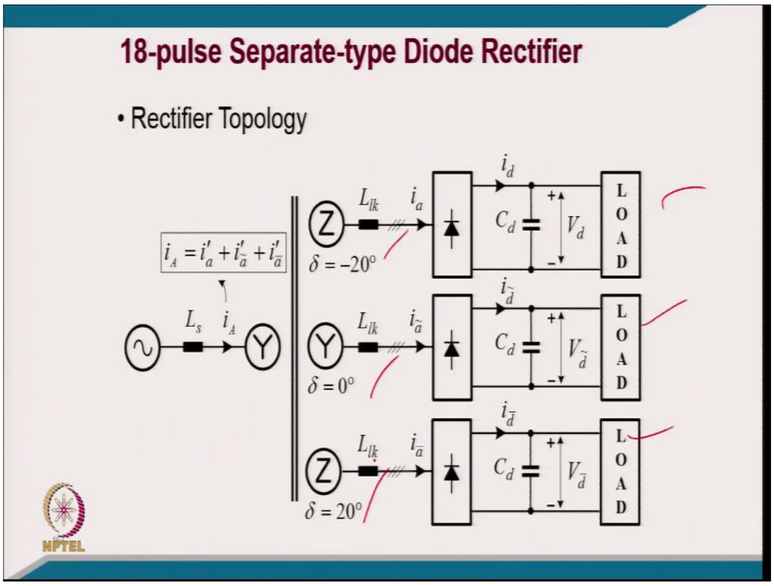

This is typically for 18-pulse. But, you have a separate load for every 6-pulse.

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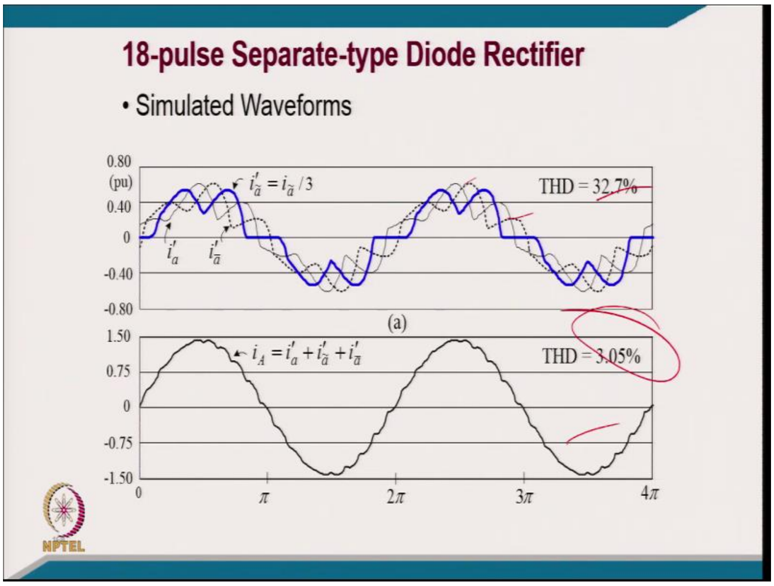

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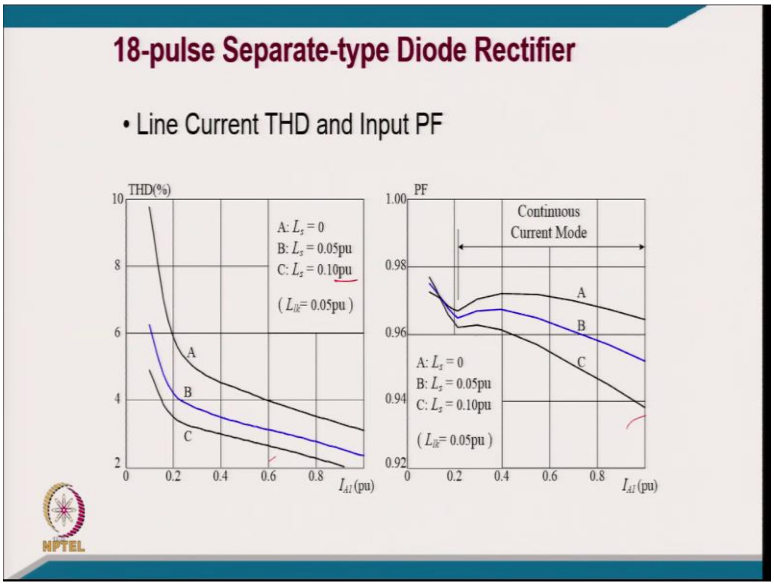

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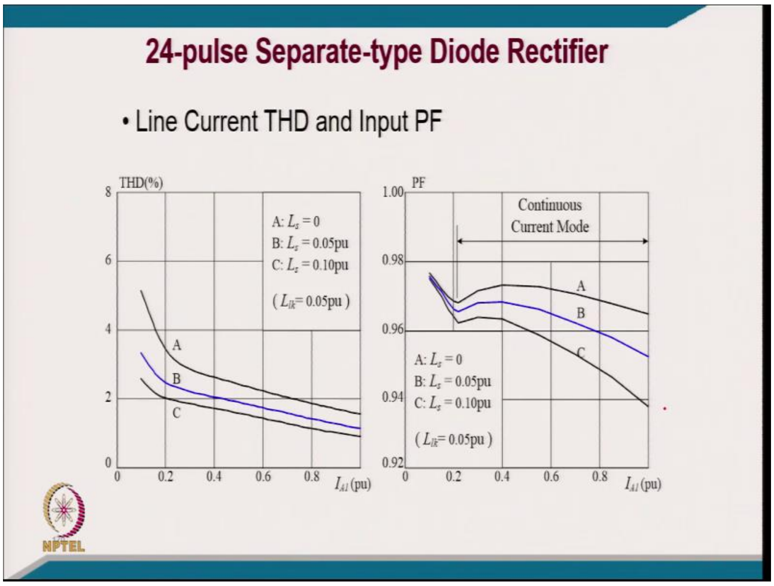

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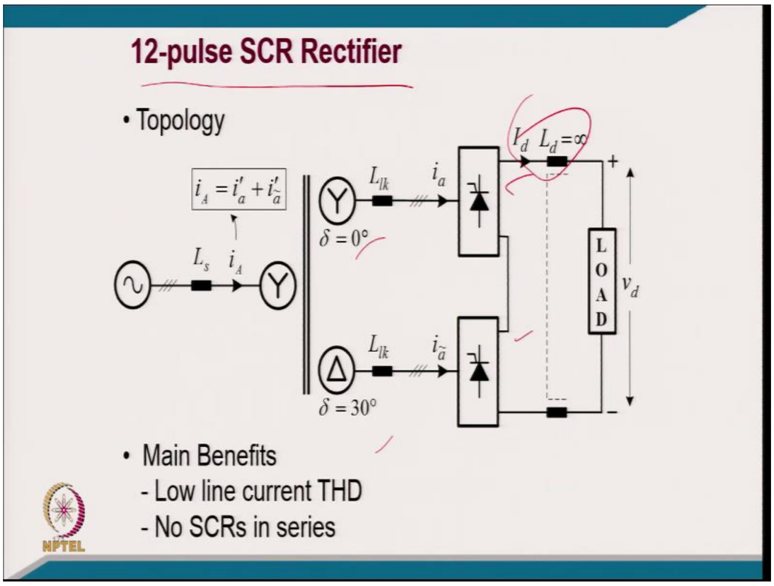

Now, this is the case of control by thyristors control converter or you can call it 12-pulse thyristors control rectifier, where you can control the firing angle for controlling the output power or the let us say if inductance, so, this current will be constant. Here, you will have again typically 30-degree phase shift for 12-pulses.

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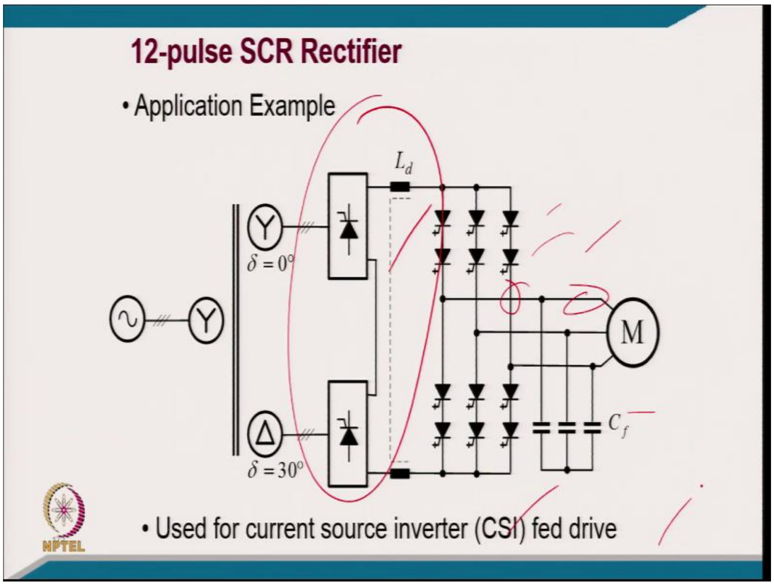

It has a low line current harmonic, and no SCR in series and that is why, it is used for variable frequency drive today. So, virtually, it is a driving a PWM current source inverter, where you are using GTO and you are using the capacitor for making this PWM current continuous.

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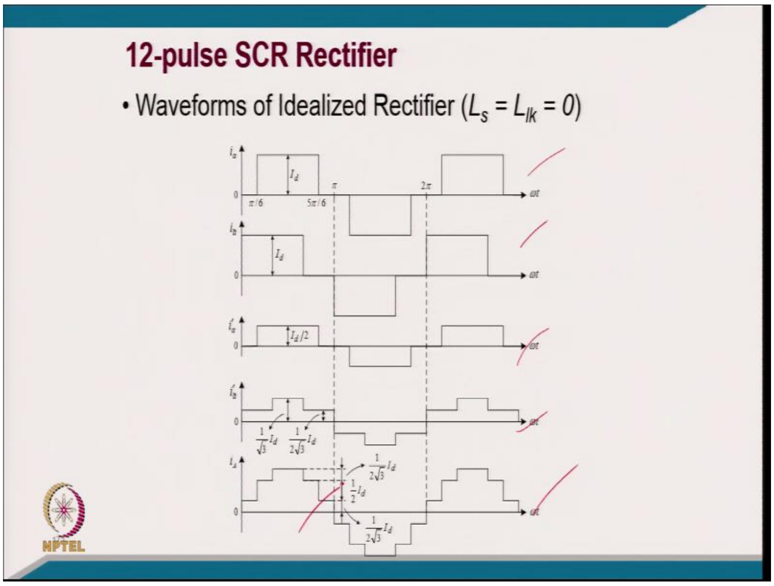

And this is how the current looks like.

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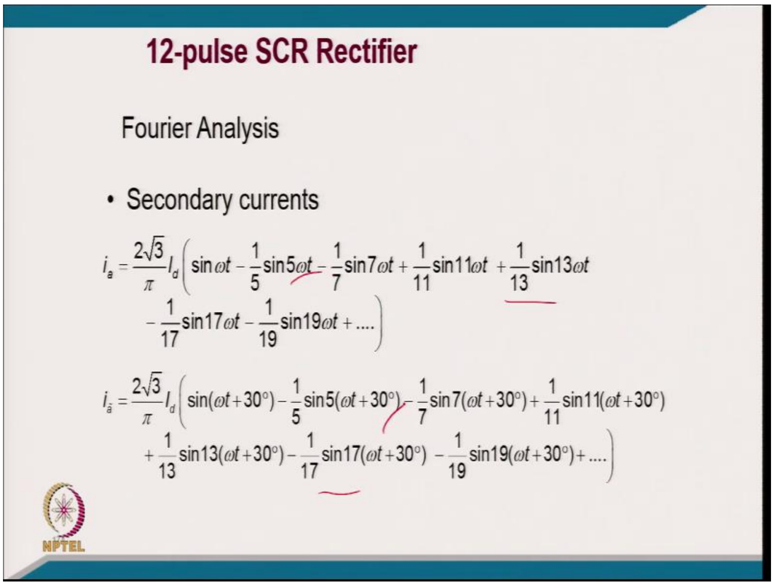

And now you can have a Fourier analysis of this current which you are having in 12-pulse.

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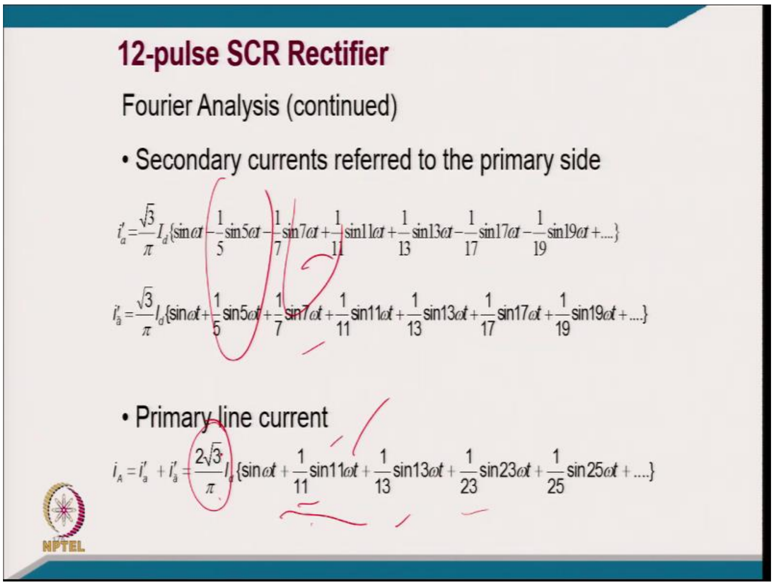

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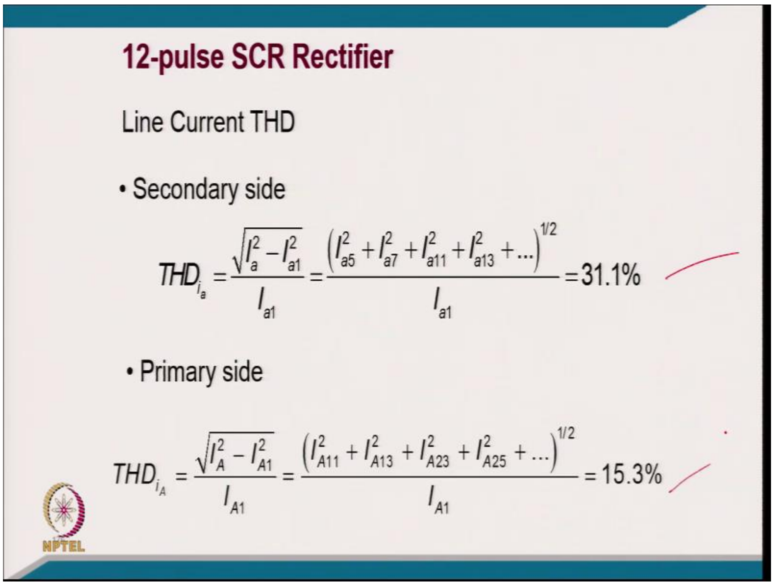

And you will get the THD if you add all four 6-pulses. You will get 31 percent.

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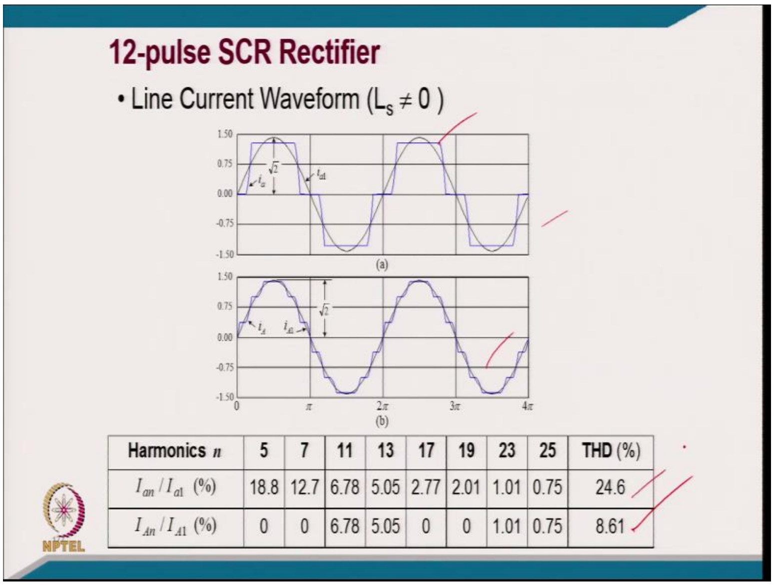

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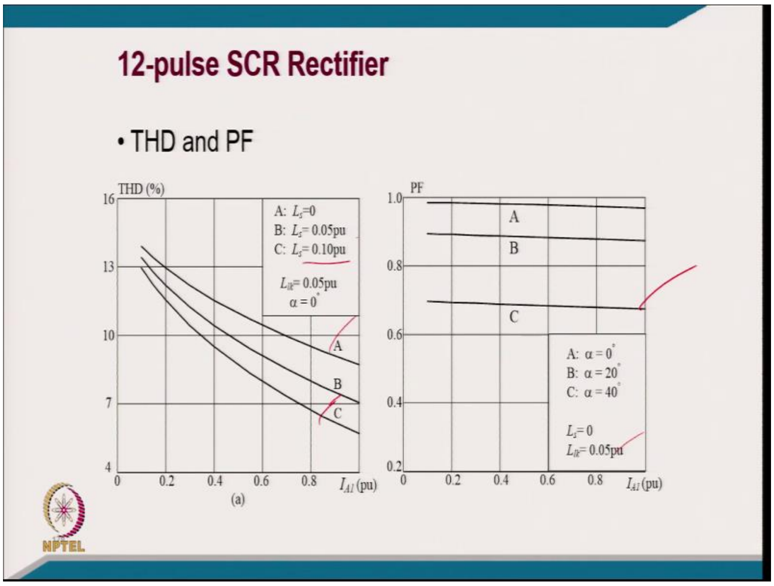

And how the current THD effect with the leakage reactance or the source inductance?

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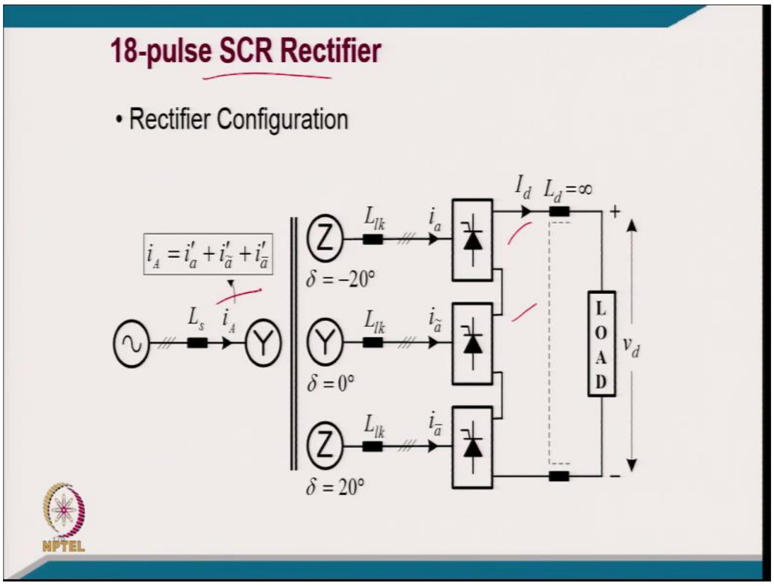

And this is typically like your 18-pulse control rectifier.

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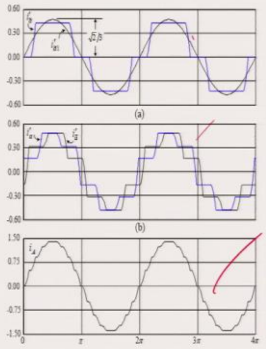
18-pulse SCR Rectifier



Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I'_{an}/I'_{a1} (%)	18.8	12.7	6.78	5.05	2.77	2.01	1.01	0.75	24.6
I_{An}/I_{A1} (%)	0	0	0	0	2.77	2.01	0	0	3.54

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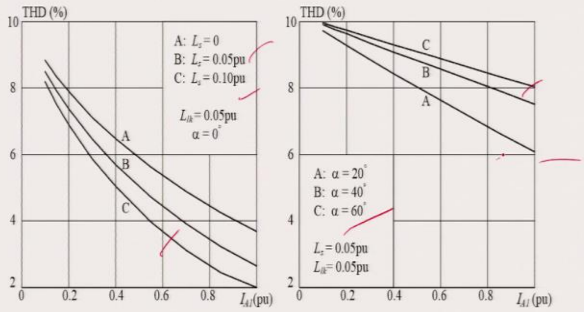
18-pulse SCR Rectifier

- Line Current THD



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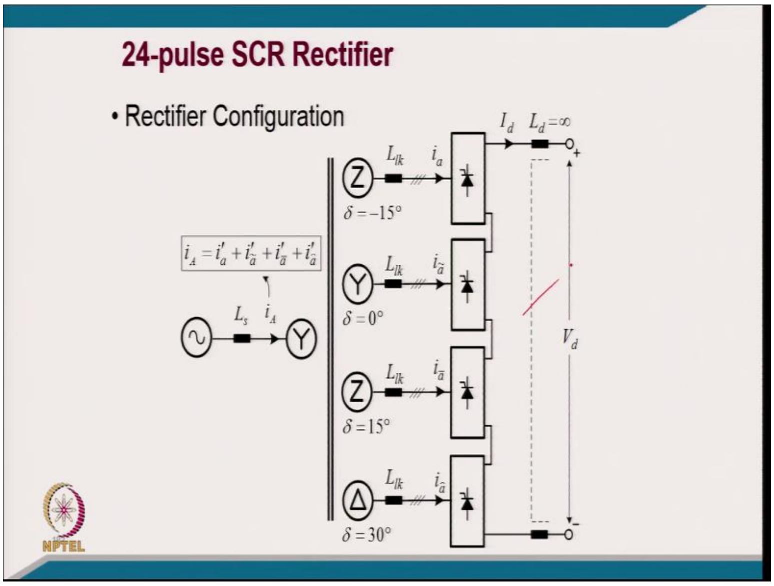

And this is for 24-pulse converter you are using 4 controlled bridges.

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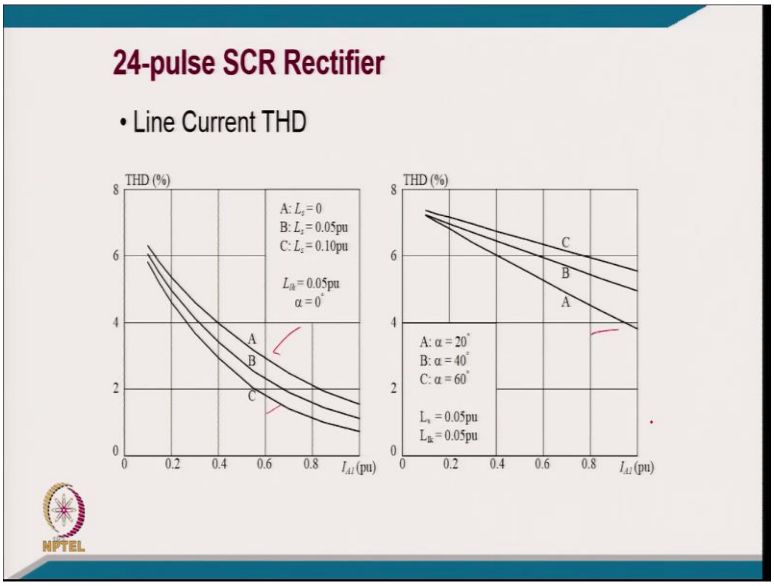

And here also you can see the effect of leakage reactance on THD.

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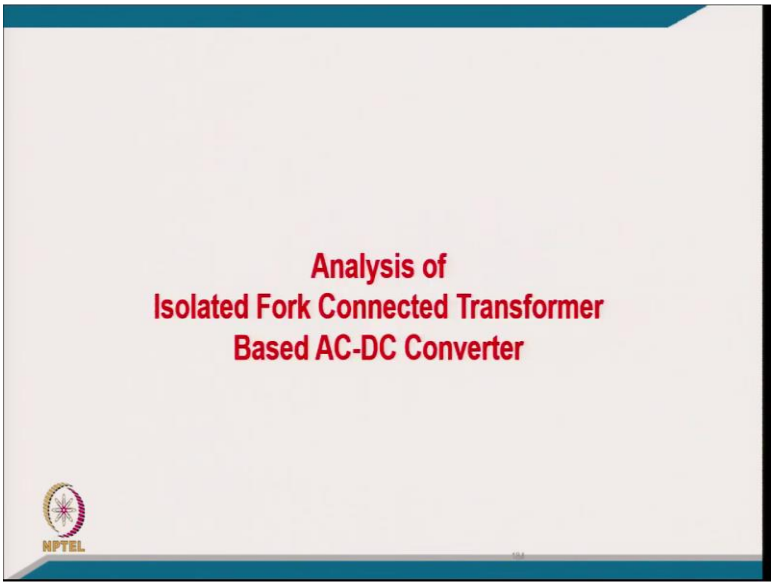

Now, coming to analysis of isolated Fork connected transformer based AC-DC converter.

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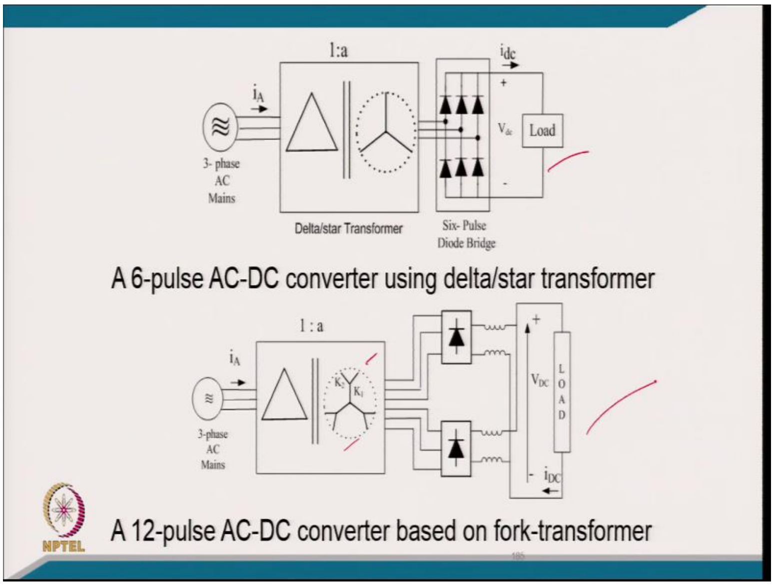

That is the typical example for 6-pulse and 12-pulse.

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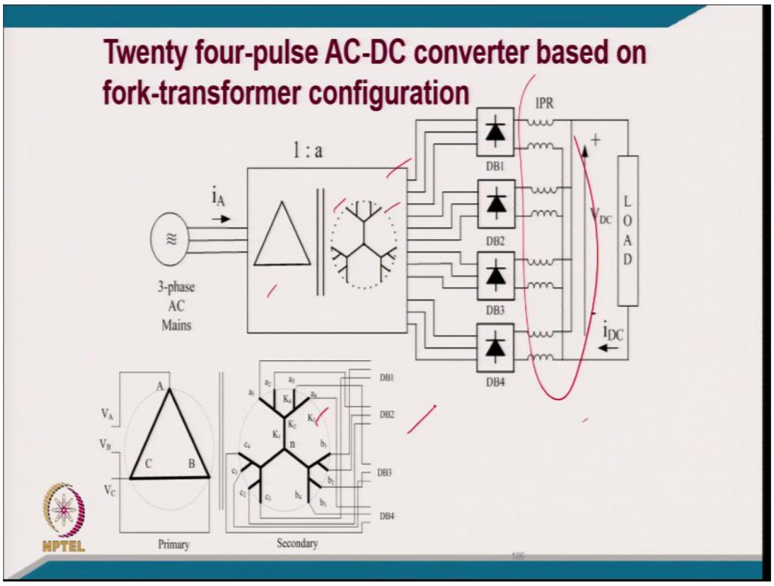

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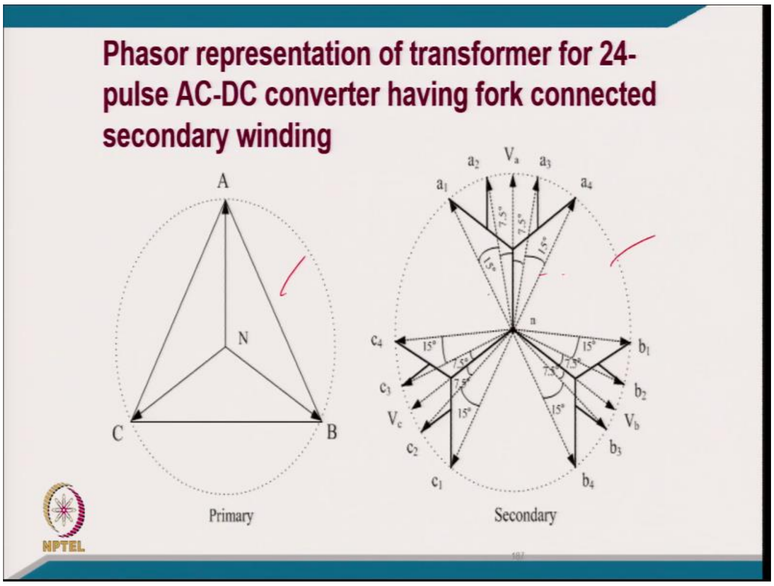

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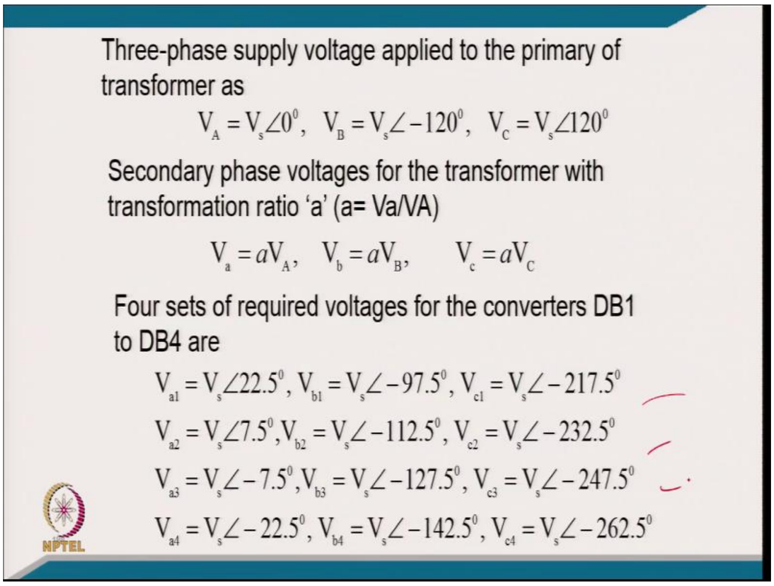

And that is the typically how we are going to have the design of that, I mean these are the voltage requirement.

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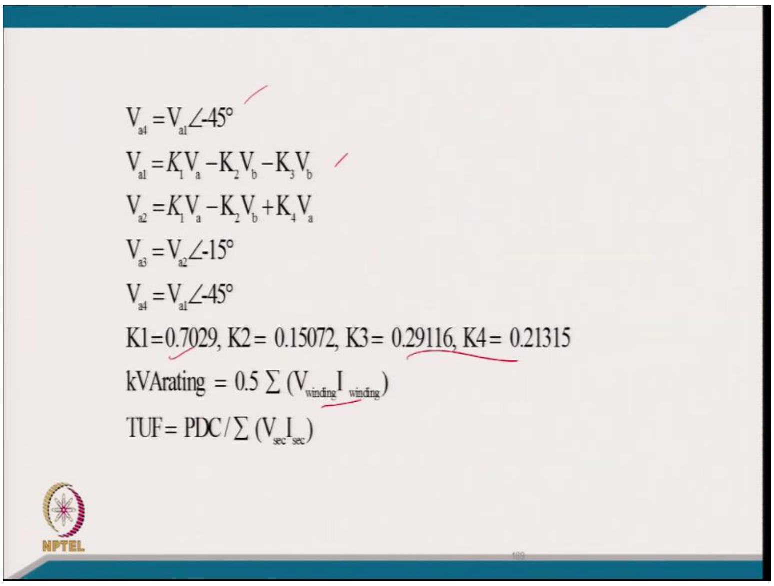

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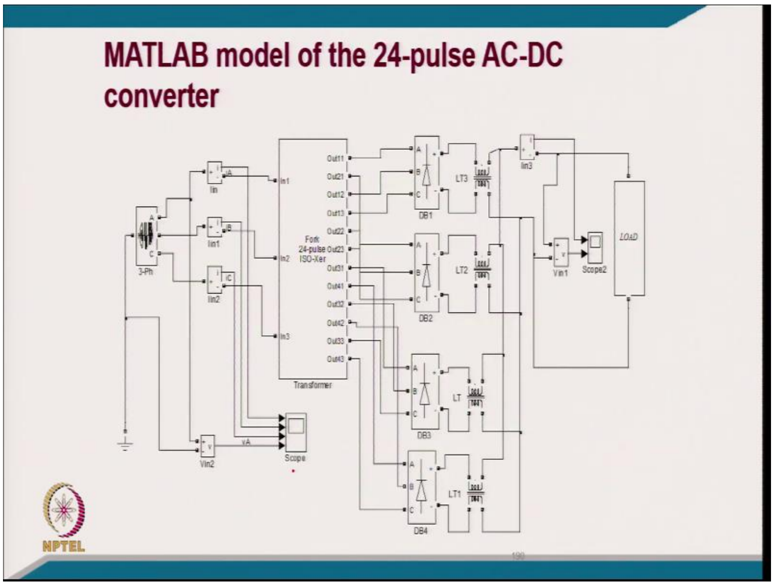

This is typically MATLAB model for the 24-pulse AC-DC converter.

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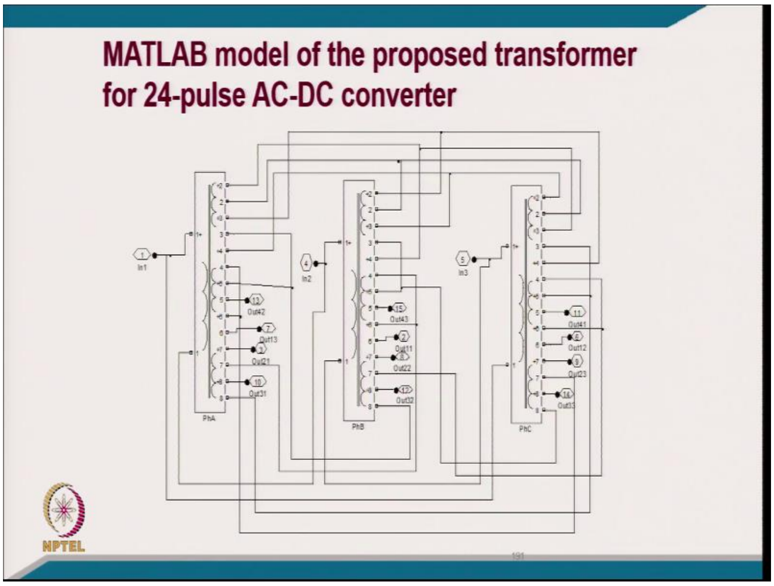

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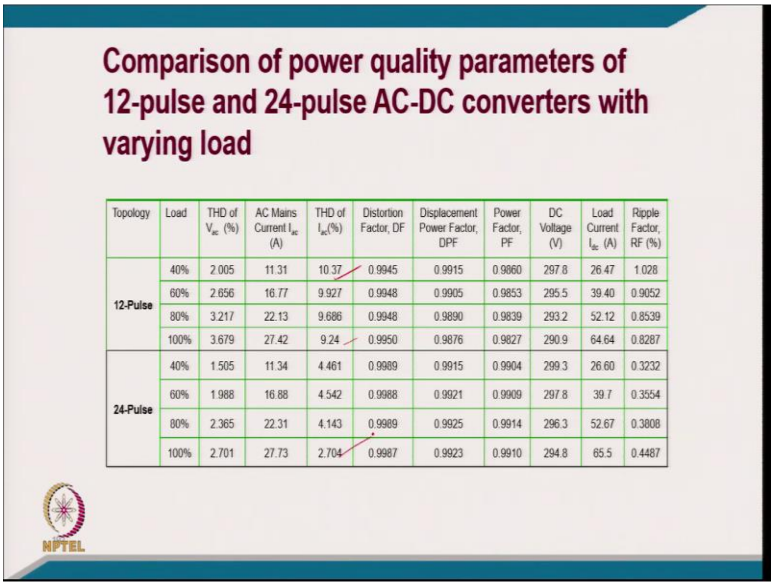

Topology	Load	THD of V_{ac} (%)	AC Mains Current I_{ac} (A)	THD of I_{ac}(%)	Distortion Factor, DF	Displacement Power Factor, DPF	Power Factor, PF	DC Voltage (V)	Load Current I_{dc} (A)	Ripple Factor, RF (%)
12-Pulse	40%	2.005	11.31	10.37	0.9945	0.9915	0.9860	297.8	26.47	1.028
	60%	2.656	16.77	9.927	0.9948	0.9905	0.9853	295.5	39.40	0.9052
	80%	3.217	22.13	9.686	0.9948	0.9890	0.9839	293.2	52.12	0.8539
	100%	3.679	27.42	9.24	0.9950	0.9876	0.9827	290.9	64.64	0.8287
24-Pulse	40%	1.505	11.34	4.461	0.9989	0.9915	0.9904	299.3	26.60	0.3232
	60%	1.988	16.88	4.542	0.9988	0.9921	0.9909	297.8	39.7	0.3554
	80%	2.365	22.31	4.143	0.9989	0.9925	0.9914	296.3	52.67	0.3808
	100%	2.701	27.73	2.704	0.9987	0.9923	0.9910	294.8	65.5	0.4487

And these are the performance for 24, you can see the THD typically of 12-pulse at light load. Ideally, it should be like a 15 percent, if no leakage reactance is there. But it goes even reduced from now 15% to 9.2 percent. And here in 24-pulse we expect 7.5, but because of leakage it at full load it goes 2.7 percent.

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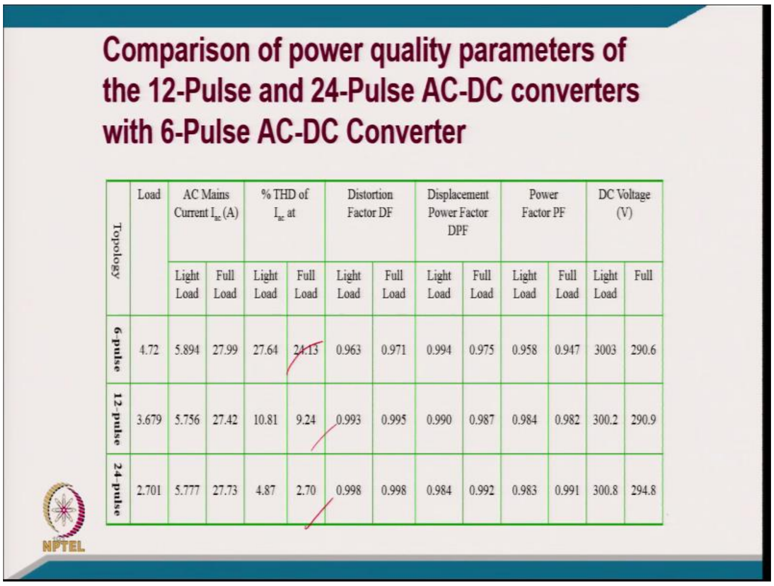

Topology	Load	AC Mains Current I_{ac} (A)		% THD of I_{ac} at		Distortion Factor DF		Displacement Power Factor DPF		Power Factor PF		DC Voltage (V)	
		Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full
6-pulse	4.72	5.894	27.99	27.64	24.13	0.963	0.971	0.994	0.975	0.958	0.947	3003	290.6
12-pulse	3.679	5.756	27.42	10.81	9.24	0.993	0.995	0.990	0.987	0.984	0.982	300.2	290.9
24-pulse	2.701	5.777	27.73	4.87	2.70	0.998	0.998	0.984	0.992	0.983	0.991	300.8	294.8

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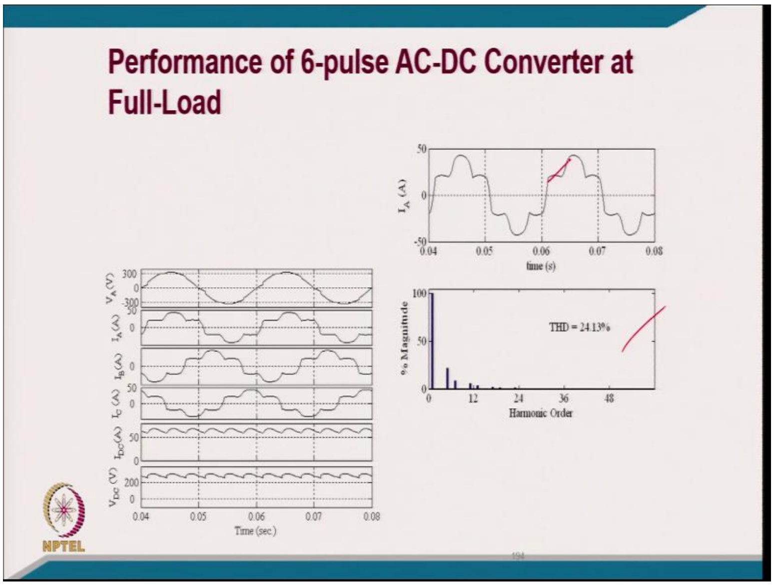

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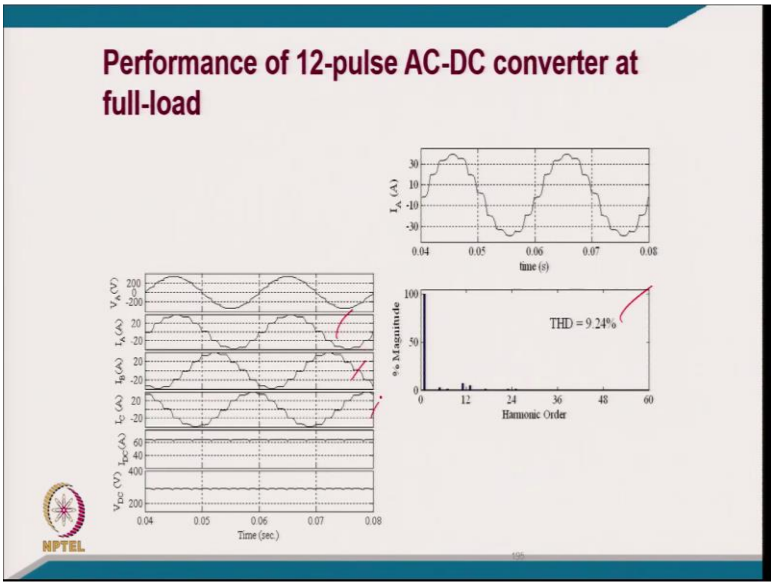

And you have 3-phase line current looks like.

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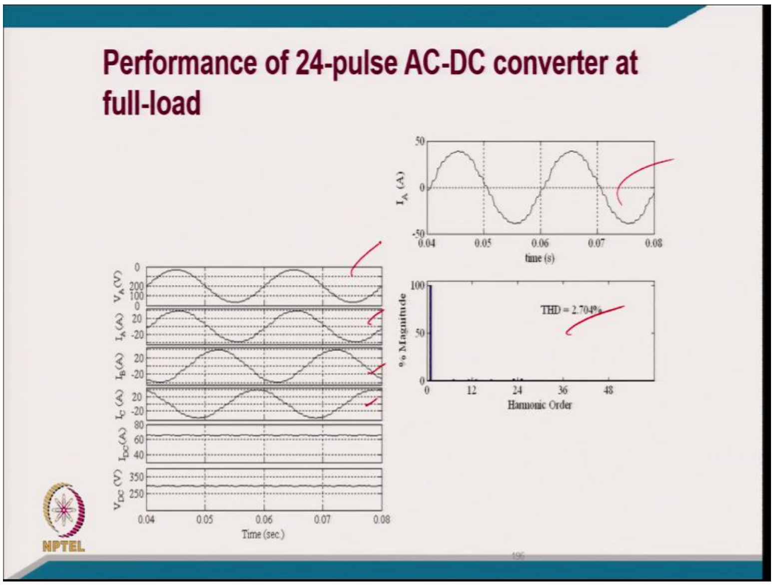

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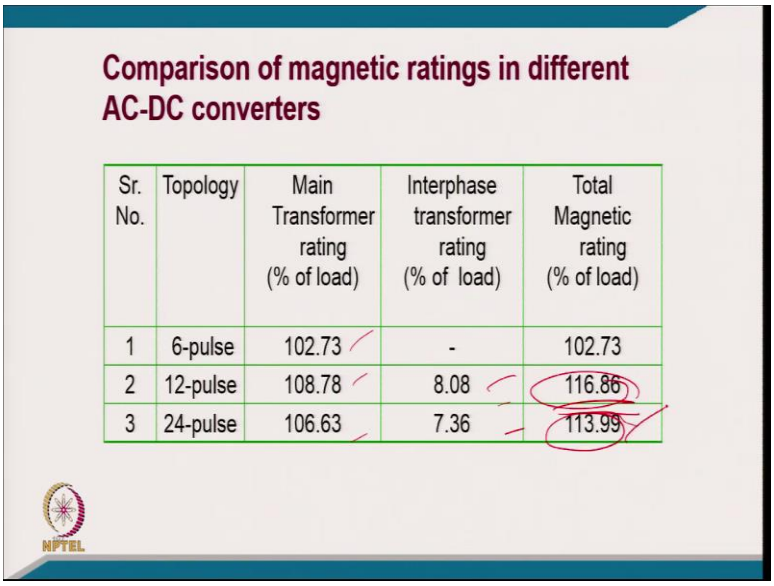

Sr. No.	Topology	Main Transformer rating (% of load)	Interphase transformer rating (% of load)	Total Magnetic rating (% of load)
1	6-pulse	102.73	-	102.73
2	12-pulse	108.78	8.08	116.86
3	24-pulse	106.63	7.36	113.99

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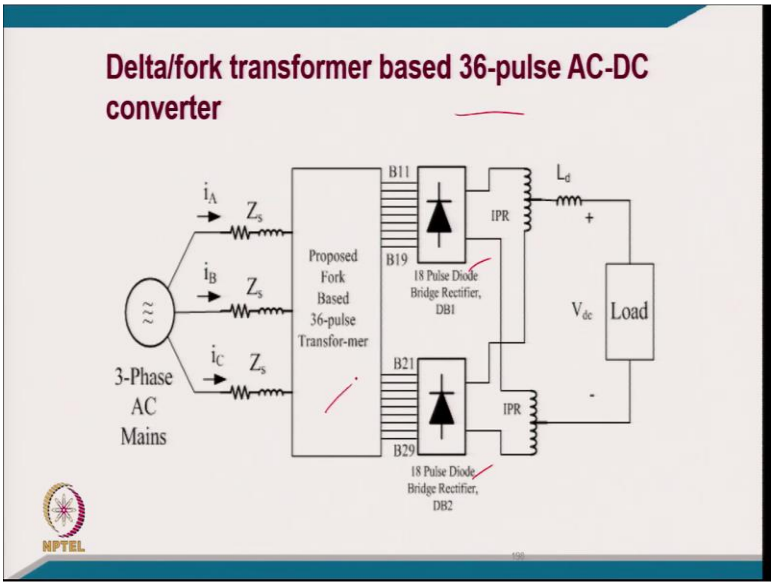

So, this is the power circuit diagram of delta/fork transformer based 36-pulse AC-DC converter.

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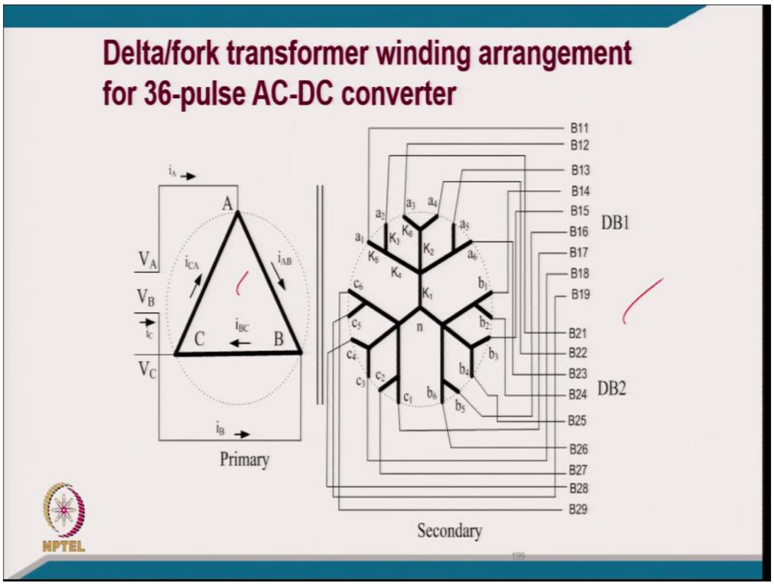
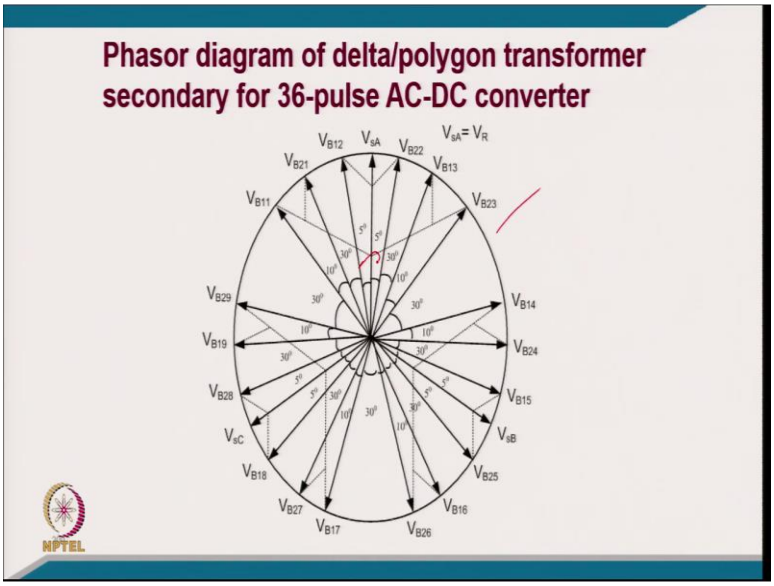


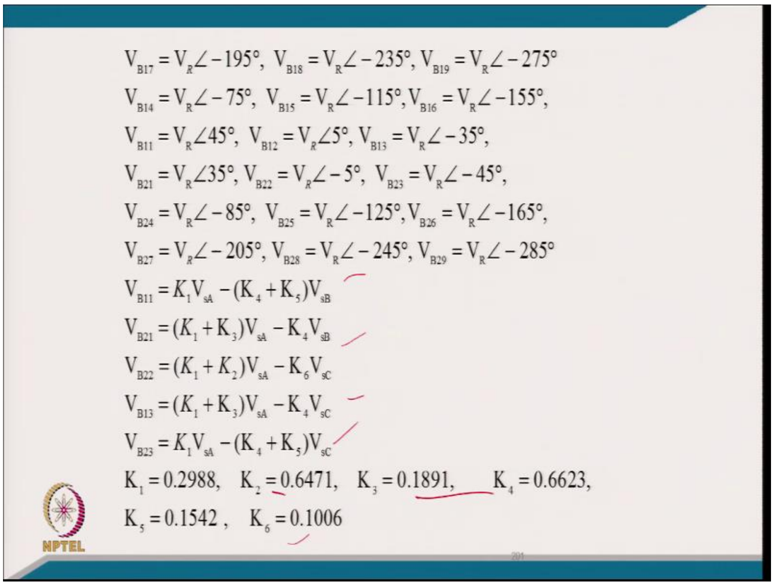
And this is typically how the transformer connection.

(Refer Slide Time: 21:18)



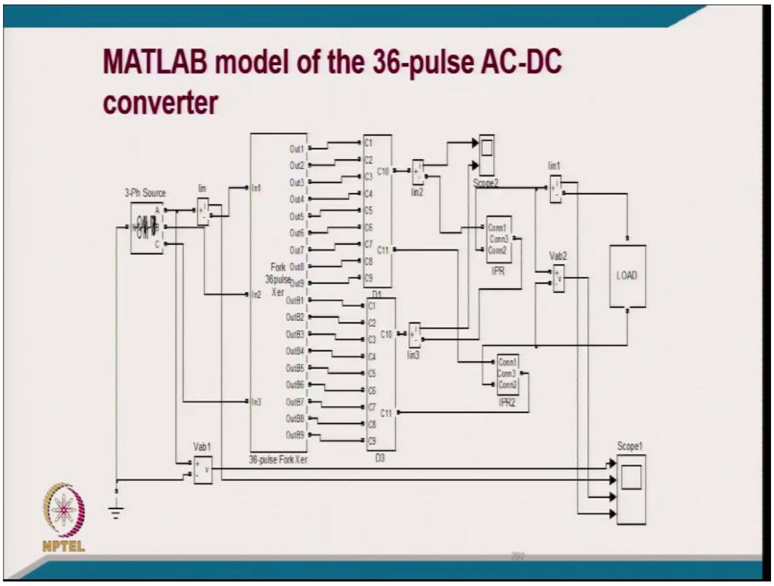
And this is the phasor diagram which all the points should be on same circle to make a same rms voltage on the secondary side.

(Refer Slide Time: 21:47)



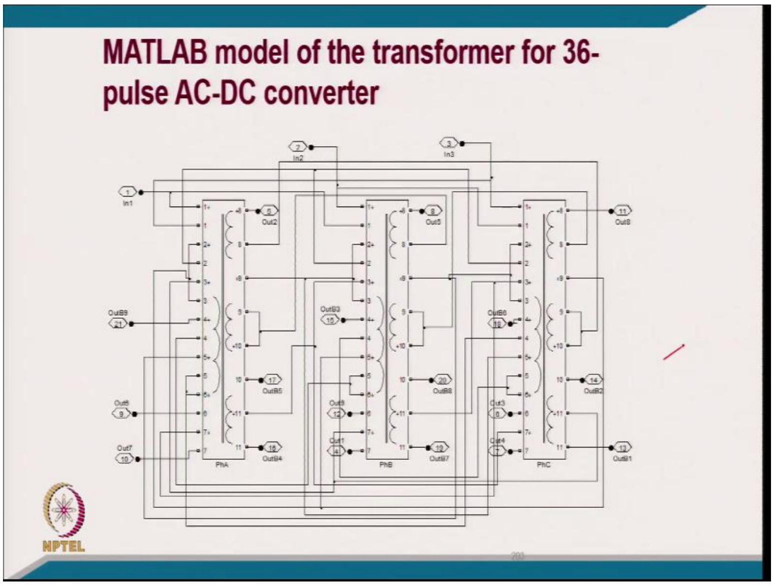
And these are the calculation for the transformer.

(Refer Slide Time: 21:58)



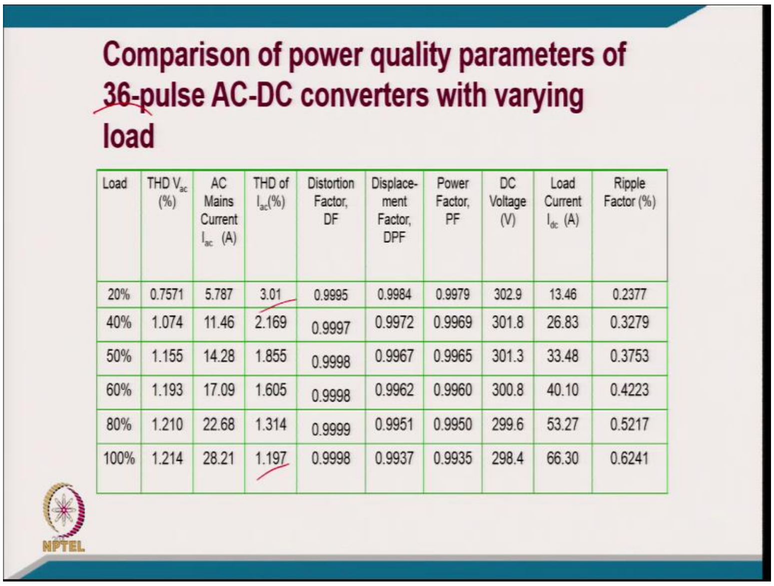
This is the model of the converter along with the transformer.

(Refer Slide Time: 22:03)



And this is the transformer model in MATLAB.

(Refer Slide Time: 22:05)

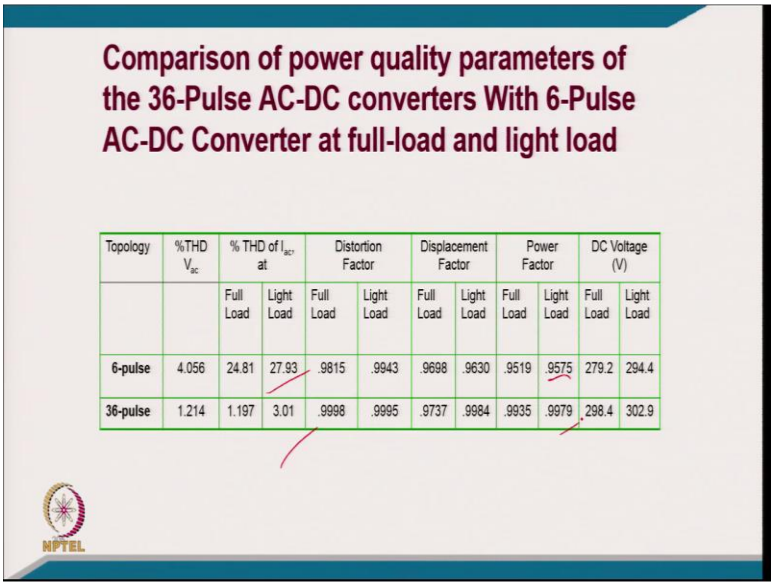


Comparison of power quality parameters of 36-pulse AC-DC converters with varying load

Load	THD V_{ac} (%)	AC Mains Current I_{ac} (A)	THD of I_{ac}(%)	Distortion Factor, DF	Displacement Factor, DPF	Power Factor, PF	DC Voltage (V)	Load Current I_{dc} (A)	Ripple Factor (%)
20%	0.7571	5.787	3.01	0.9995	0.9984	0.9979	302.9	13.46	0.2377
40%	1.074	11.46	2.169	0.9997	0.9972	0.9969	301.8	26.83	0.3279
50%	1.155	14.28	1.855	0.9998	0.9967	0.9965	301.3	33.48	0.3753
60%	1.193	17.09	1.605	0.9998	0.9962	0.9960	300.8	40.10	0.4223
80%	1.210	22.68	1.314	0.9999	0.9951	0.9950	299.6	53.27	0.5217
100%	1.214	28.21	1.197	0.9998	0.9937	0.9935	298.4	66.30	0.6241

And this is the performance during simulation study.

(Refer Slide Time: 22:27)



Comparison of power quality parameters of the 36-Pulse AC-DC converters With 6-Pulse AC-DC Converter at full-load and light load

Topology	%THD V_{ac}	% THD of I_{ac}, at		Distortion Factor		Displacement Factor		Power Factor		DC Voltage (V)	
		Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load
6-pulse	4.056	24.81	27.93	.9815	.9943	.9698	.9630	.9519	.9575	279.2	294.4
36-pulse	1.214	1.197	3.01	.9998	.9995	.9737	.9984	.9935	.9979	298.4	302.9

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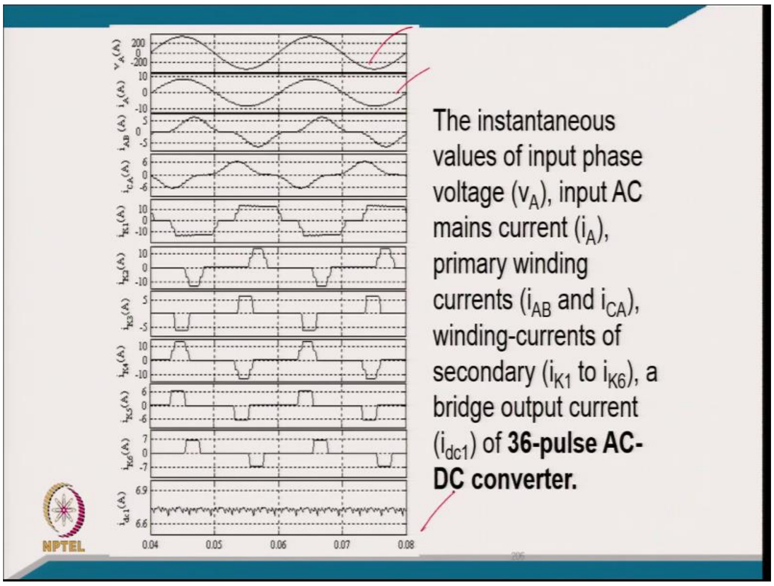
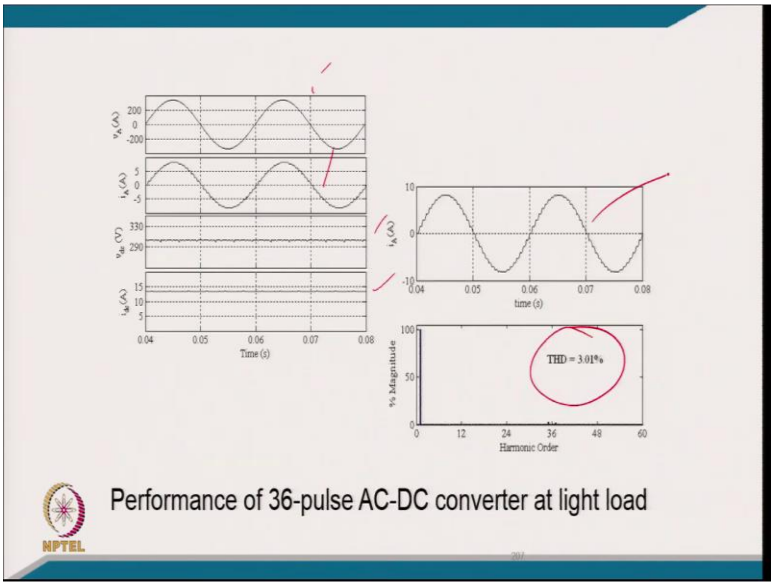


And this is the typically the you can call it current in different winding.

(Refer Slide Time: 22:56)



Current is in phase with the supply voltage and sinusoidal. And this is the harmonic spectrum and the THD around 3 percent of this 36-pulse converter.

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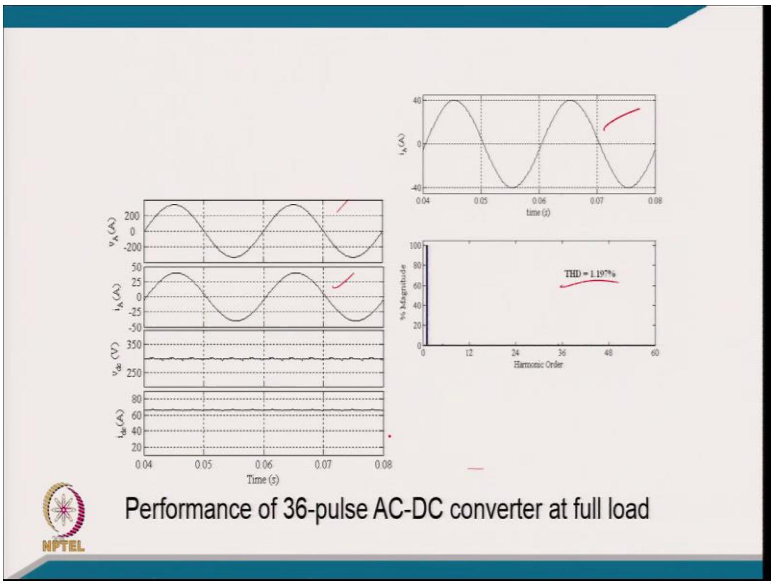
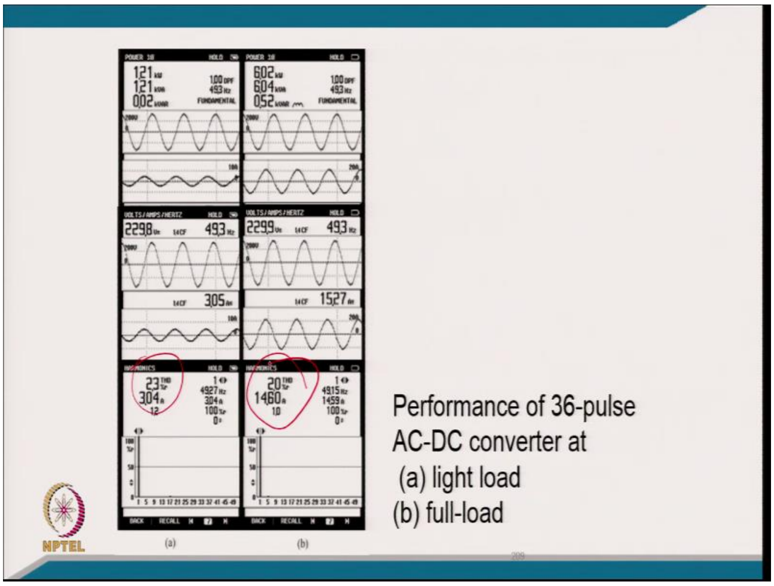


And this is the performance at full load. At full load, the THD is only 1.19 percent. You can see supply voltage supply current, and current waveform with the output voltage output current.

(Refer Slide Time: 23:20)



And these are the experimental results of the 36-pulse AC-DC converter under full load and light load conditions.

(Refer Slide Time: 23:36)

Comparison of magnetic ratings in different AC-DC converters

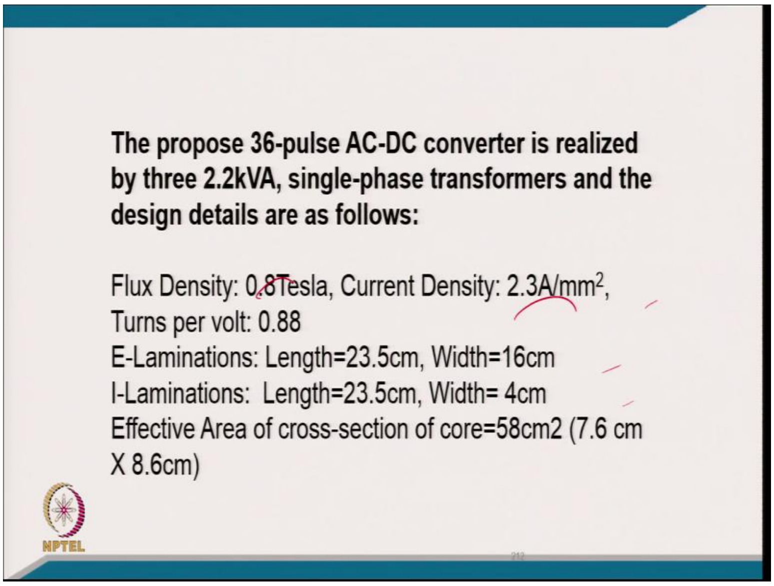
Sr. No.	Topology	Main Transformer rating (% of load)	IPT rating (% of load)	Total rating of magnetics, (% of load)
1	6-pulse	108.0	-	108.0
2	36-pulse	124.2	0.85	125.0

(Refer Slide Time: 23:56)

Test results showing power quality parameters of 36-pulse AC-DC converter

Load (kW)	THD V_{ac} (%)	AC Mains Current I_{ac} (A)	THD of I_{ac} (%)	DPF	PF	V_{dc} (V)	I_{dc} (A)
1.21	1.30	3.05	2.3	1.0	0.999	168.6	7.256
2.16	1.40	5.38	2.5	1.0	0.999	160.9	12.86
3.08	1.30	7.79	2.2	1.0	0.999	151.4	18.40
4.09	1.30	10.28	2.1	1.0	0.998	143.7	24.21
5.29	1.30	13.29	2.1	1.0	0.996	133.7	31.09
6.02	1.20	15.27	2.0	1.0	0.996	127.8	35.37

(Refer Slide Time: 24:06)



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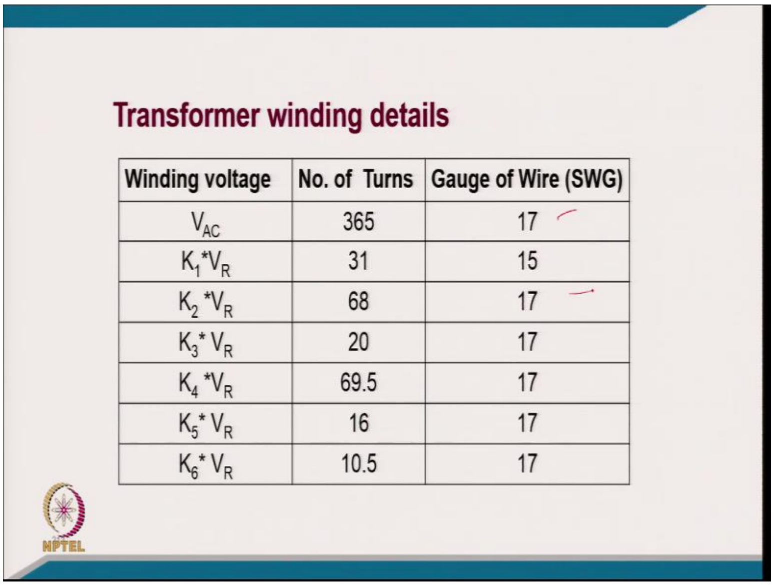

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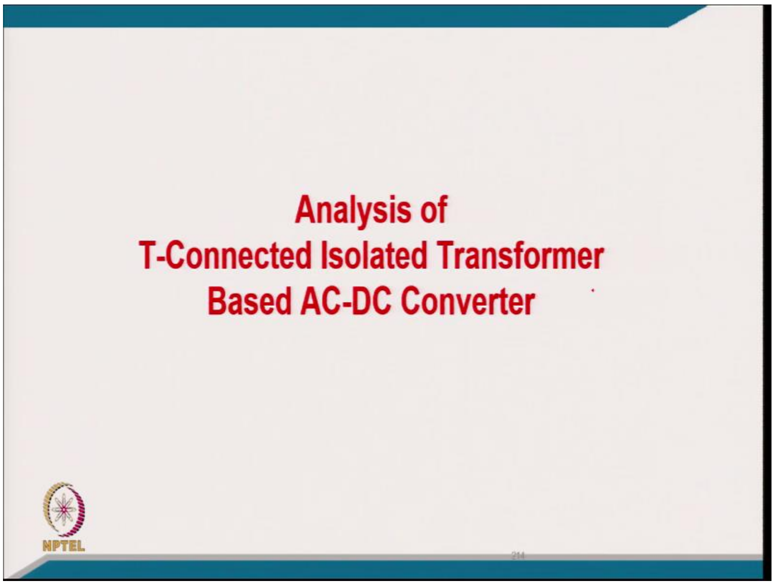
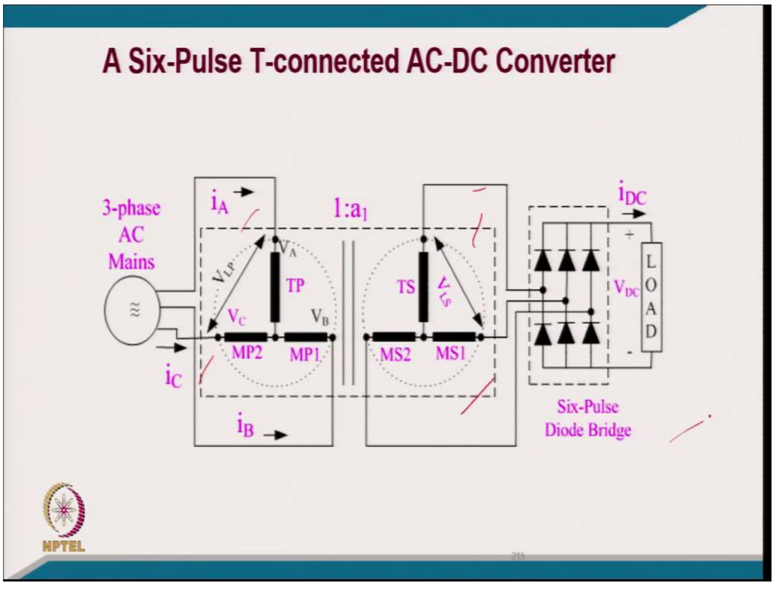


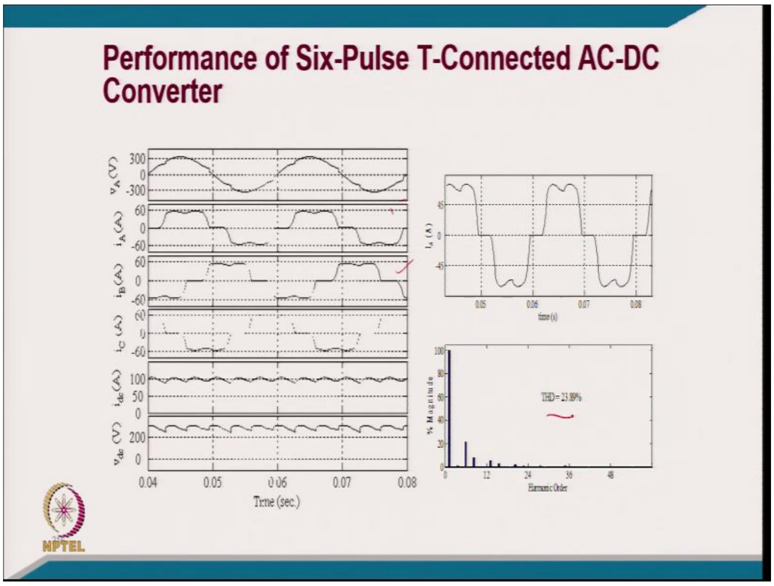
Coming to the analysis of T-connected isolated transformer based AC-DC converters.

(Refer Slide Time: 24:35)



This is the circuit diagram for 6-pulse T-connected AC-DC converter.

(Refer Slide Time: 24:49)



And this is how the current look like because of leakage. The THD in place of 31 percent, it goes 23.89 percent because of the source inductance.

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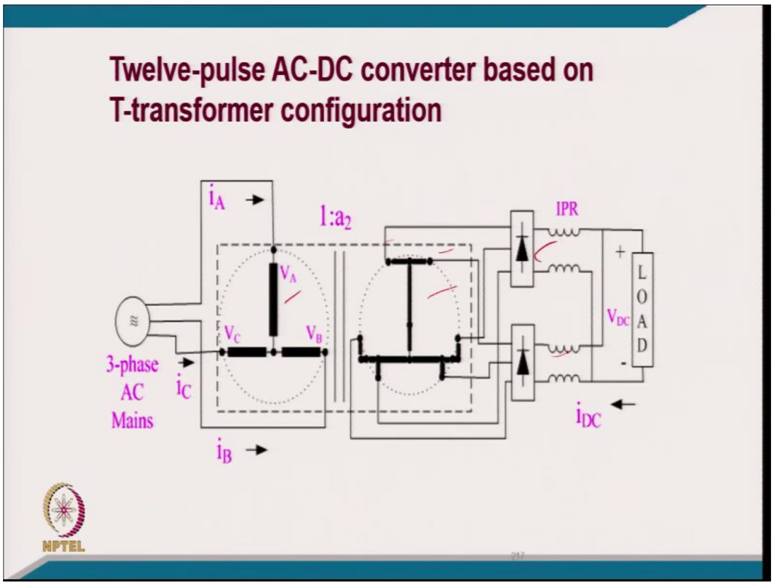

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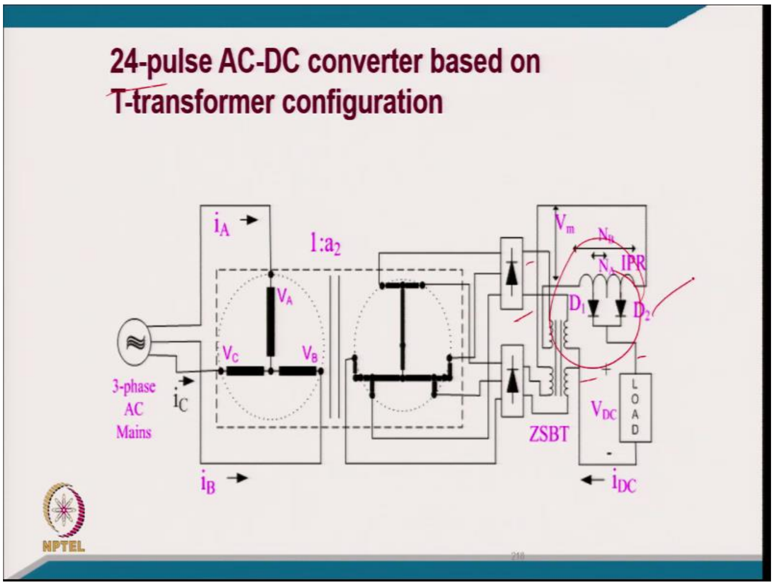

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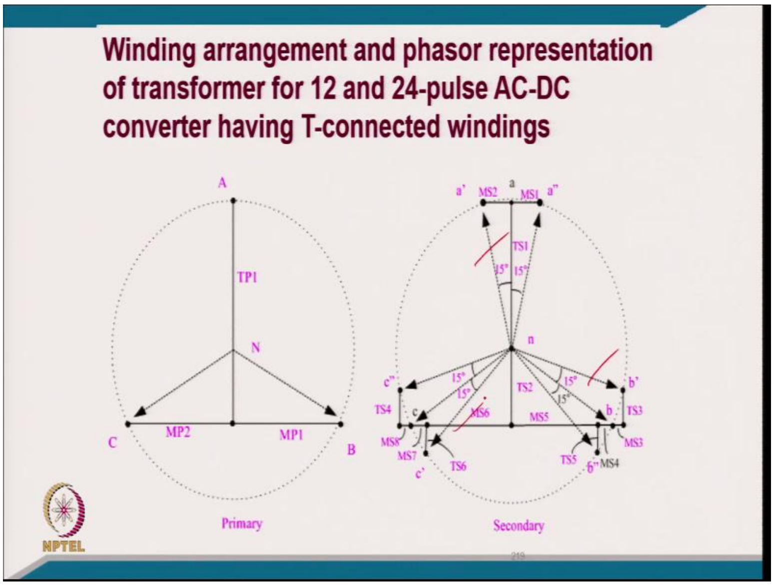
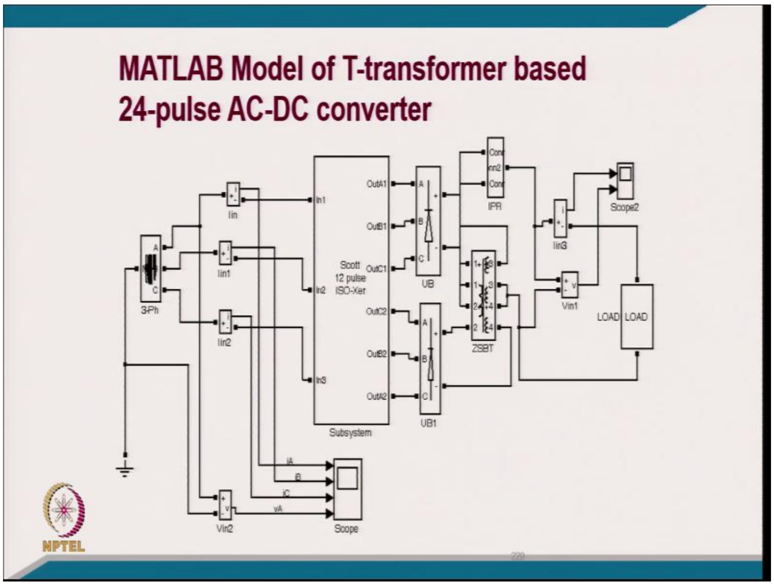


And that is the typically of how the T-connection design is there.

(Refer Slide Time: 26:23)



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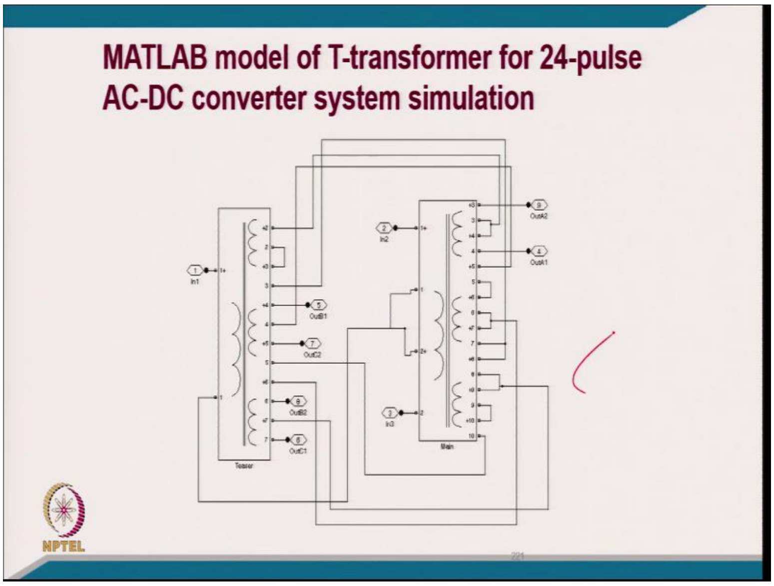
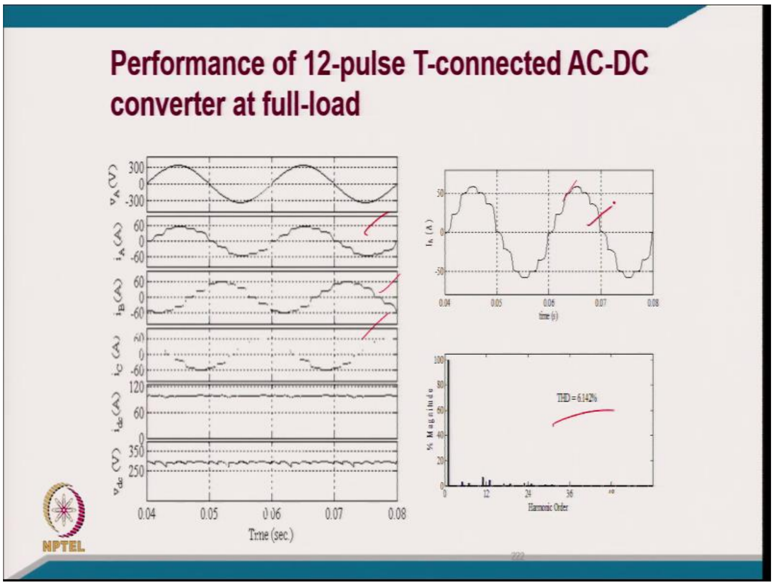


And this is the typically model of overall system and this is the transformer connection model.

(Refer Slide Time: 26:27)



And these are the currents like typically in case of the your 12-pulse 3-phase currents drawn from the supply. And the THD of this, is in the order of 6.14% in place of 15 percent because of the effect of leakage reactance of the transformer.

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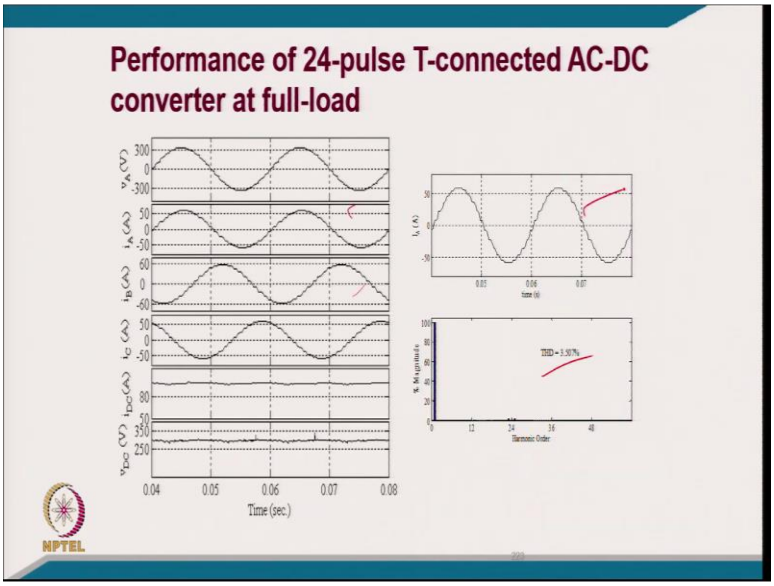

And these are of course, for 24-pulse with the pulse doubling, the THD reduces to order of 3.5 percent in place of 7.5 because again effect of the leakage reactance and the current goes very close to the sinusoidal.

(Refer Slide Time: 26:52)

Comparison of Power Quality Parameters of 12-Pulse and 24-Pulse AC-DC Converters

Topology	Load	THD of V_{AC} (%)	AC Current I_A (A)	THD of I_A(%)	Distortion Factor, DF	Displacement Factor, DPF	Power Factor PF	DC Voltage (V)	Load Current I_{dc} (A)	Ripple Factor %
12-Pulse	20	0.814	8.820	9.633	0.9953	0.9853	0.9807	300.2	20.09	1.955
	40	1.281	17.03	7.612	0.9971	0.9729	0.9701	298.4	40.16	1.823
	50	1.681	21.19	7.400	0.9971	0.9682	0.9654	297.0	49.88	1.759
	60	1.913	25.47	6.939	0.9974	0.9704	0.9679	296.7	59.74	1.696
	80	2.307	33.87	6.348	0.9977	0.9731	0.9709	296.2	79.47	1.725
	100	2.804	41.85	6.142	0.9977	0.9738	0.9716	295.8	98.78	1.757
24-Pulse	20	1.032	8.583	5.469	0.9985	0.9980	0.9965	301.5	20.10	0.5062
	40	1.604	16.99	4.759	0.9988	0.9969	0.9957	300.4	40.04	0.3273
	50	1.834	21.17	4.452	0.9989	0.9965	0.9954	299.9	49.98	0.7368
	60	2.022	25.33	4.218	0.9989	0.9961	0.9950	299.3	59.85	0.8025
	80	2.337	33.57	3.814	0.9990	0.9952	0.9942	298.2	79.53	0.9586
	100	2.582	41.77	3.507	0.9991	0.9945	0.9936	297.2	99.09	1.1390

(Refer Slide Time: 27:05)

Comparison of power quality parameters of 12-pulse and 24-pulse AC-DC converters with varying load

Topology	% THD of V_{ac}	AC Mains Current I_s (A)		% THD of I_s		Distortion Factor		Displacement Factor		Power Factor		DC Voltage (V)	
		Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load
6-pulse	4.848	8.899	42.37	27.56	23.89	0.9640	0.9716	0.9945	0.9777	0.9587	0.9499	300.7	292.7
12-pulse	2.804	8.820	41.85	9.633	6.142	0.9953	0.9977	0.9853	0.9738	0.9807	0.9716	300.2	295.8
24-pulse	2.582	8.583	41.77	5.469	3.507	0.9985	0.9991	0.9980	0.9945	0.9965	0.9936	301.5	297.2

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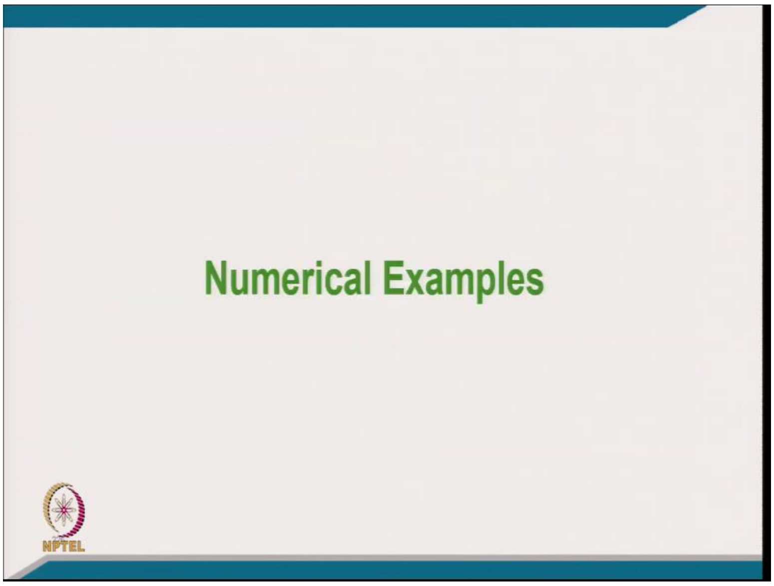

Well, coming to now the numerical examples of the multi-pulse converter.

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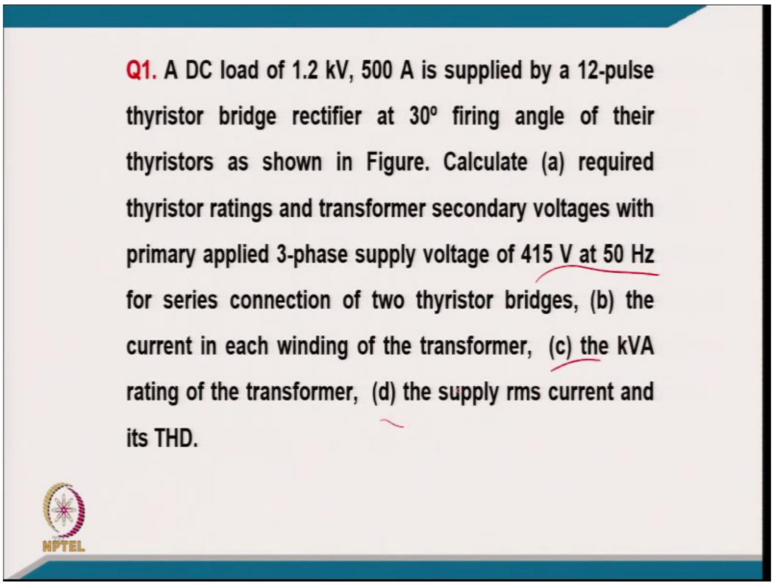
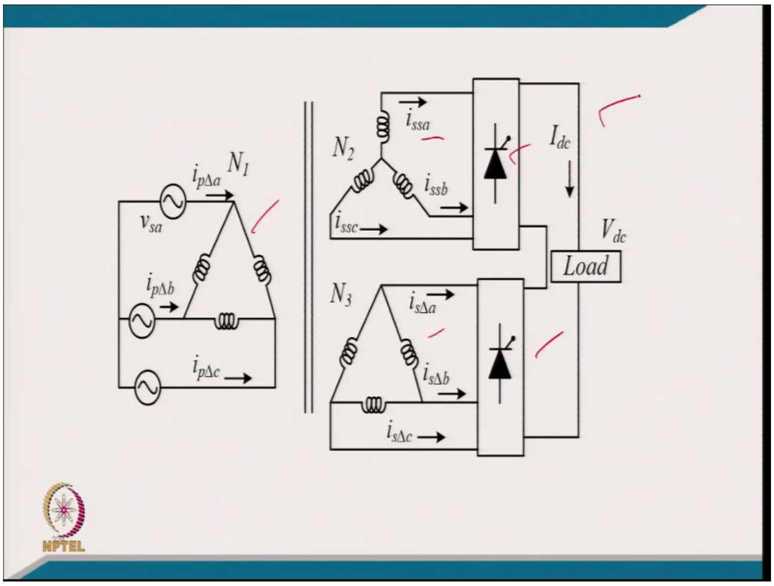


Starting with 1st example. A DC load of 1.2 kV, 500 A is supplied by a 12-pulse thyristors bridge rectifier at 30° fire angle of their thyristors, as shown in the figure. Calculate, required thyristors ratings and the transformer secondary voltages with a primary applied 3-phase supply voltage of 415 V/50 Hz for series connection of two thyristors bridge, the current in each winding of the transformer, the kVA rating of the transformer, the supply RMS current, and its THD.

(Refer Slide Time: 27:59)



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Solution Given supply voltage V_{LL} =415V, frequency of supply (f) =50Hz, DC Load current (I_{dc}) = 500 A and DC load voltage (V_{dc}) = 1.2kV

The total DC voltage across series connected thyristor bridge rectifier is (V_{dc}) 1.2kV So, DC voltage across single thyristor bridge rectifier = (V_{dc1}) =1.2kV/2 = .6kV

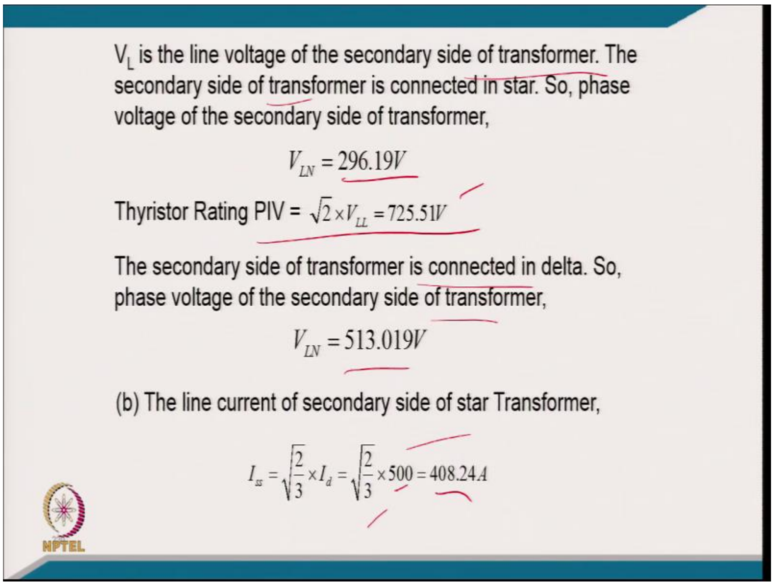
(a) Average output voltage of one thyristor bridge rectifier,

$$V_{dc1} = \frac{3\times\sqrt{2}}{\pi} V_L \cos\alpha$$

$$.6\times10^3 = \frac{3\times\sqrt{2}}{\pi} V_L \cos\alpha$$

$$V_L = \frac{\pi\times.6\times10^3}{3\times\sqrt{2}\times\cos 30^\circ} = 513.019V$$

(Refer Slide Time: 28:53)



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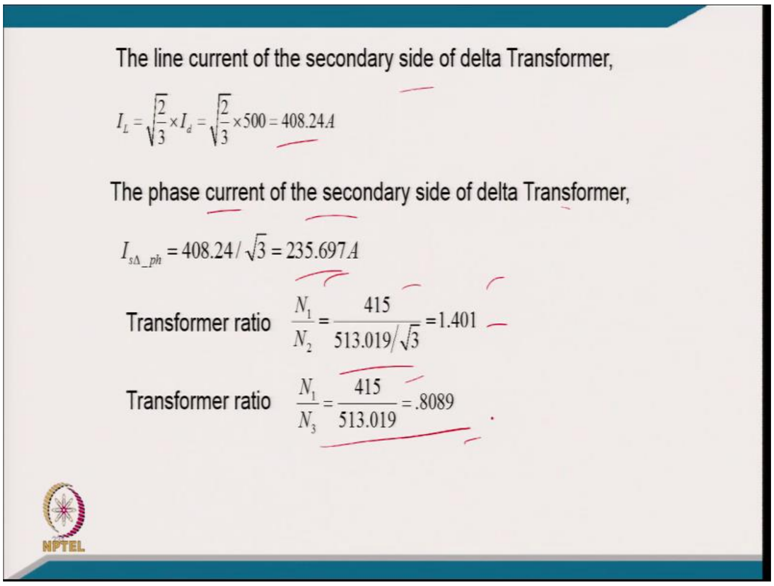

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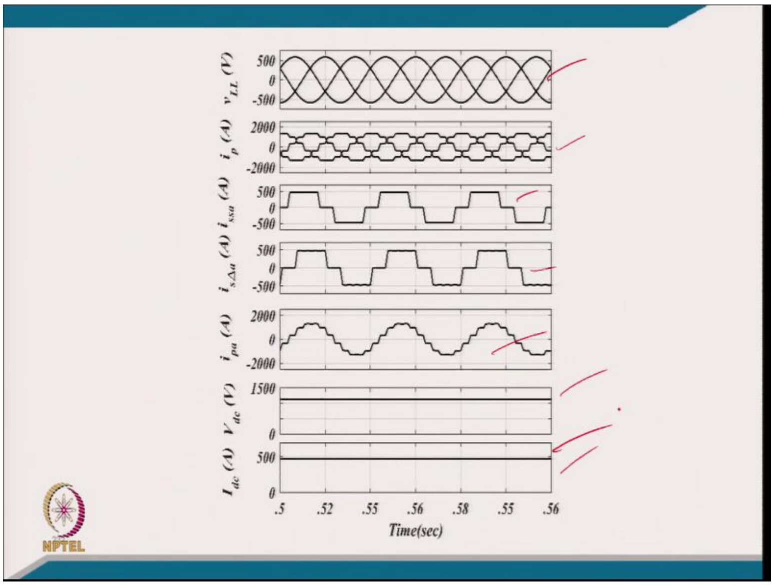

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The supply RMS current of the primary side of transformer,

$$I_{p\_ph} = \frac{N_2}{N_1} I_{sstar} + \frac{N_3}{N_1} I_{sdelta\_phase}$$

$$= (0.714 \times 408.2\angle -30^0 + 1.24 \times 235.697\angle 0^0) = 563.83\angle -15^0 A$$

$$I_{p\_L} = 976.58A$$

(c) KVA rating of Transformer = $.5\sum(3 \times V_{LN} \times I_{ph})$

$$= 0.5 \times 3\{(V_{\Delta S} \times I_{\Delta S}) + (V_{YS} \times I_{YS}) + (V_{\Delta P} \times I_{\Delta P})\}$$

$$= 0.5 \times 3\{(513.019 \times 235.697) + (296.19 \times 408.24) + (415 * 563.83)\} KVA$$

$$= 713.726KVA$$

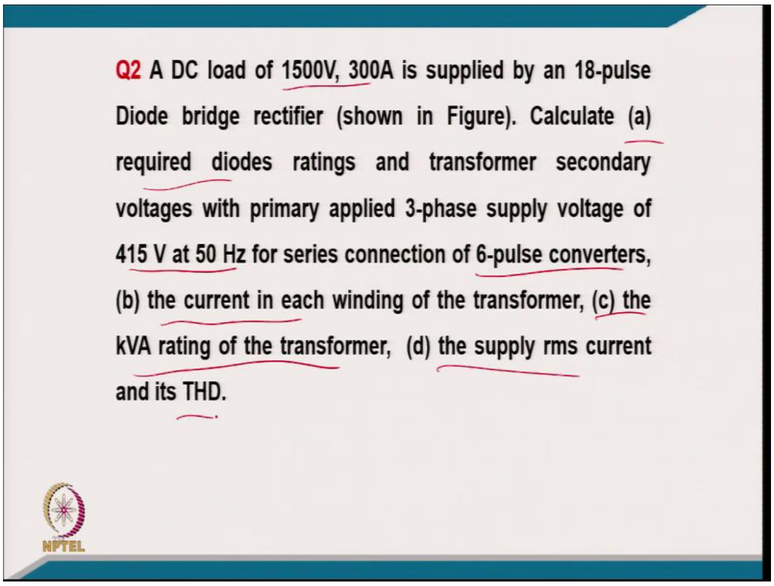
The THD (Total Harmonic Distortion) of primary side of transformer,

$$THD = \sqrt{\frac{I_{11}^2 + I_{13}^2 + I_{23}^2 + I_{25}^2 + I_{35}^2 + I_{37}^2 + I_{47}^2 + I_{49}^2}{I_1^2}} \times 100 = 15.23\%$$

233

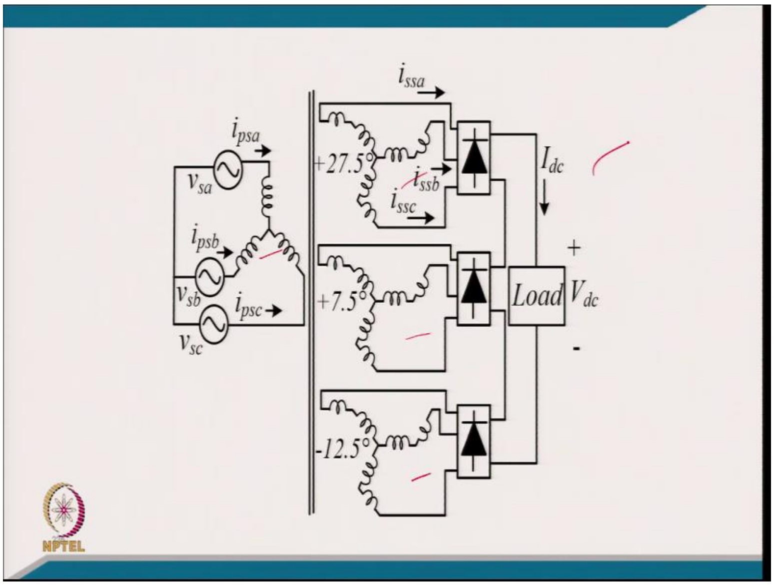
The solution of this problem is given in the abovemention slides.

(Refer Slide Time: 30:54)



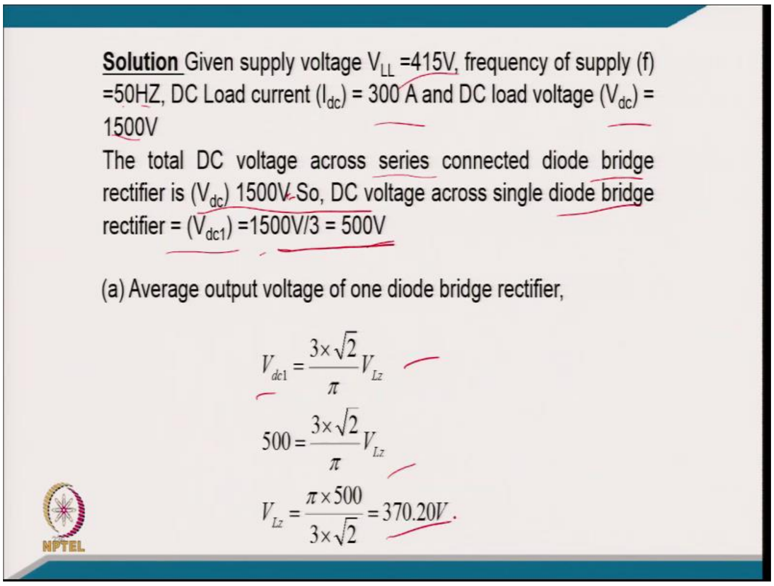
Coming to 2nd example, a DC load of 1500 V, 300 A is supplied by an 18-pulse diode bridge rectifier, as shown in figure. Calculate, the required diodes rating and transformer secondary voltages with primary applied 3-phase supply voltage of 415 V/50 Hz for series connection of 6-pulse converter, the current in each winding of the transformer, the kVA rating of the transformer, the supply RMS current and its THD.

(Refer Slide Time: 31:23)



This is the typical connection. Because of zigzag connection, you are getting 18-pulses.

(Refer Slide Time: 31:44)



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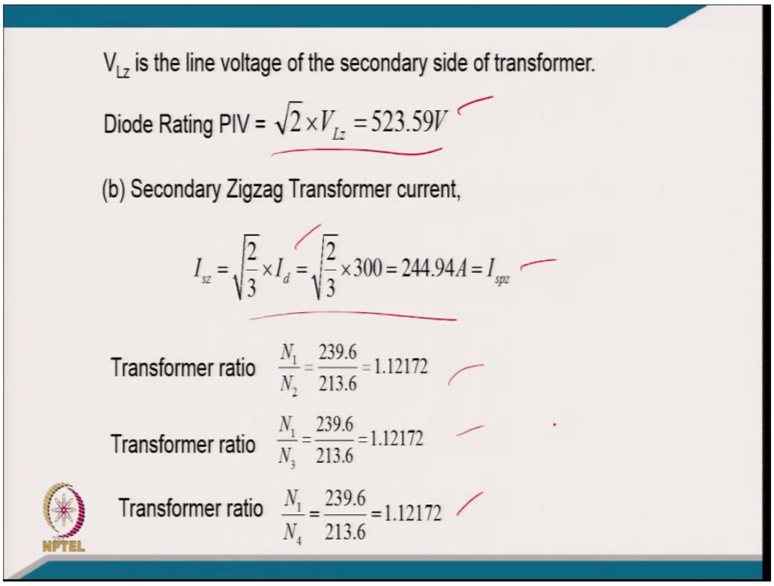
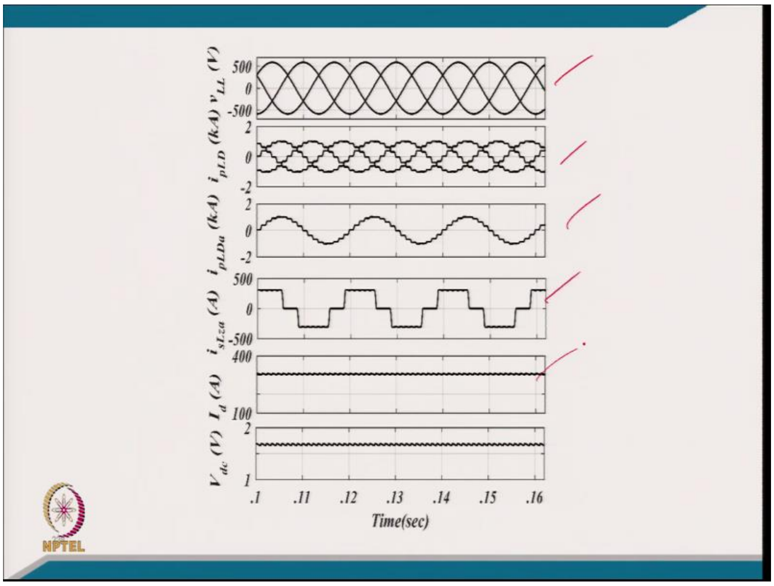


(Refer Slide Time: 32:30)



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$$I_{ppY} = \frac{N_2}{N_1} I_{spz} + \frac{N_3}{N_1} I_{spz} + \frac{N_4}{N_1} I_{spz}$$

$$= (244.94\angle +27.5^0 + 244.94\angle +7.5^0 + 244.94\angle -12.5^0) \times \frac{1}{1.12172}$$

$$= 628.746\angle 7.5^0\ A$$

$$I_{pLY} = 628.746 A$$

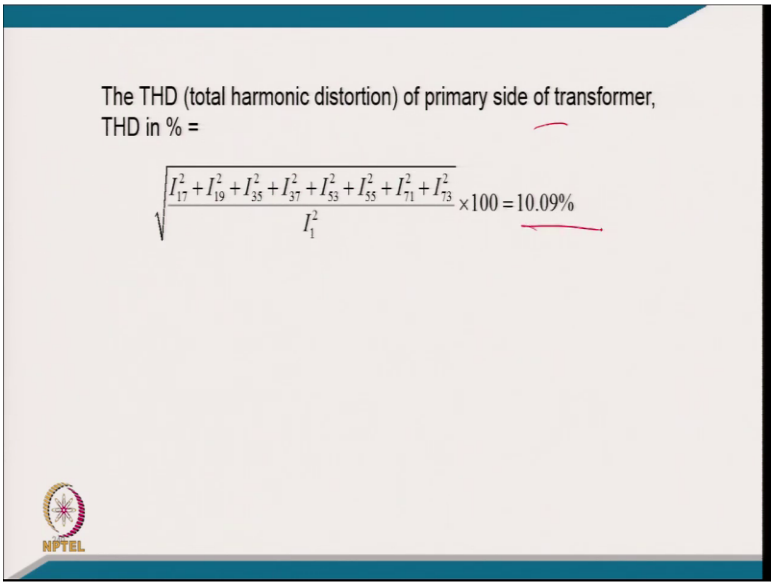
(c) KVA rating of Transformer

$$.5\sum(3 \times V_{LNm} \times I_{npm})$$

$$= .5((3 \times V_{LNz} \times I_{spz}) + (3 \times V_{LNz} \times I_{spz}) + (3 \times V_{LNz} \times I_{spz}) + (3 \times V_{LNY} \times I_{ppY}))$$

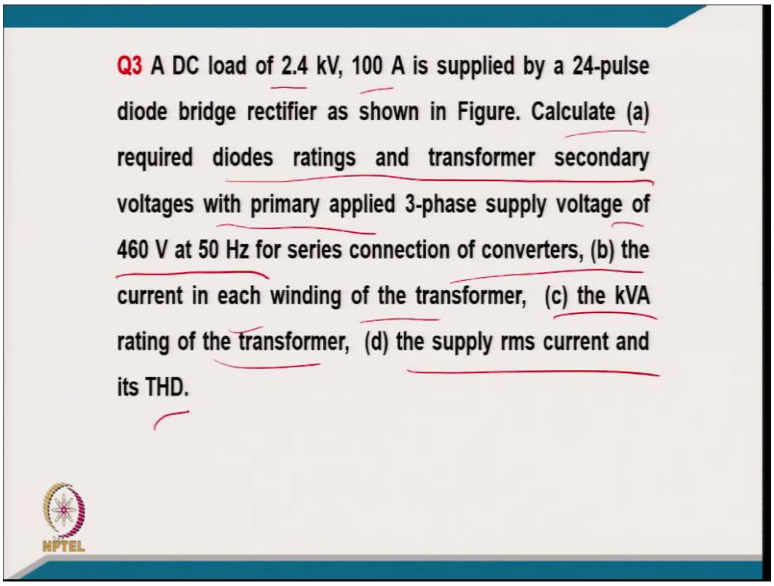
$$= 461.5\text{kVA}$$

(Refer Slide Time: 33:06)



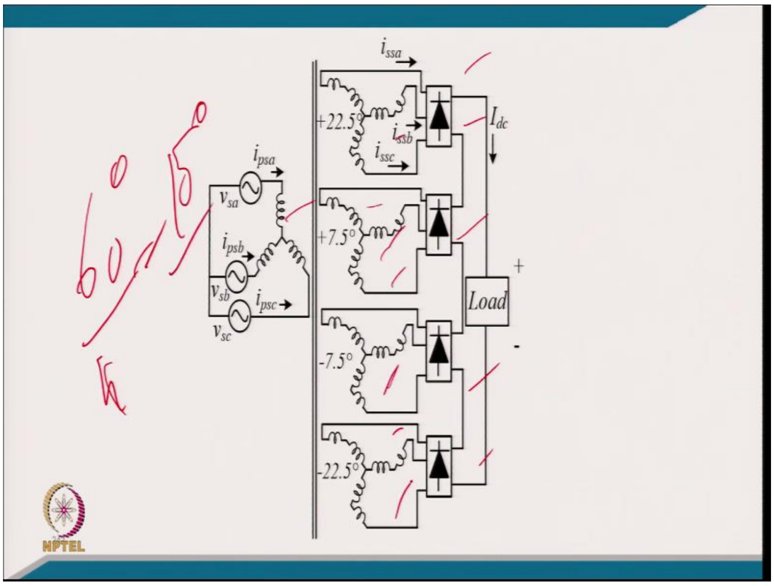
The solution of this problem is given in the abovemention slides.

(Refer Slide Time: 33:14)



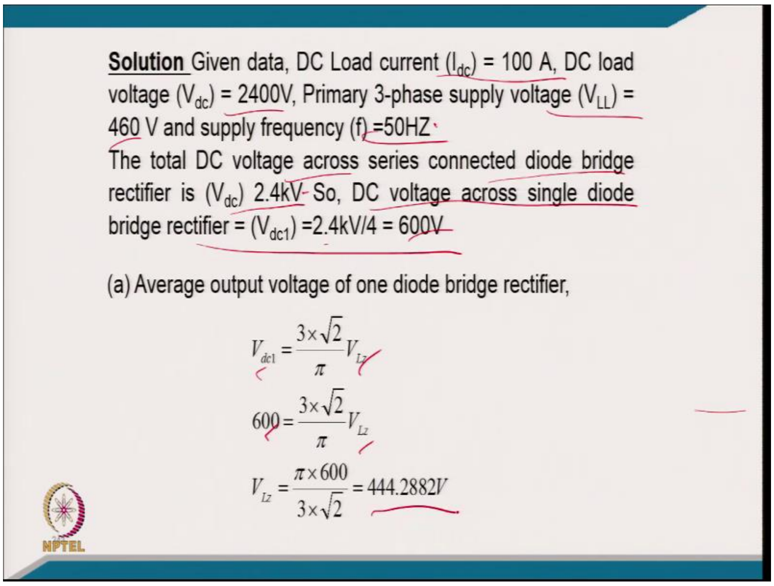
Coming to 3rd example. A DC load of 2.4 kV, 100 A is supplied by a 24-pulse diode bridge rectifier as shown in figure. Calculate, the required diodes rating and transformer secondary voltages with primary applied to 3-phase supply of 460 V/50 Hz for series connection of the converters, the current in each winding of the transformer, the kVA rating of the transformer, the supply current, and its total harmonic distortion.

(Refer Slide Time: 33:45)



This is the 24-pulse converter, in this, the 4 bridges are connected in series. The phase shift should be like a 15 degree, i.e., ± 7.5°, so, it is a 15° between two bridges. Because of 4 bridges, 60 by 4, it become your 15°.

(Refer Slide Time: 34:13)



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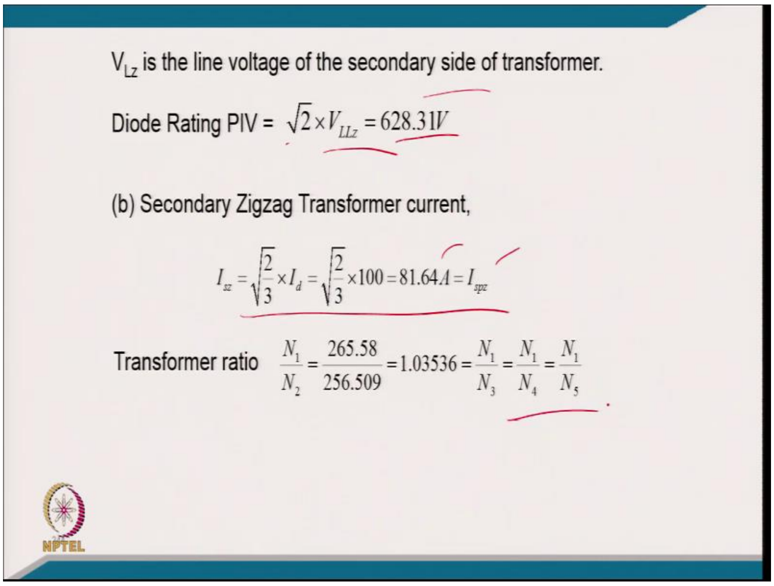

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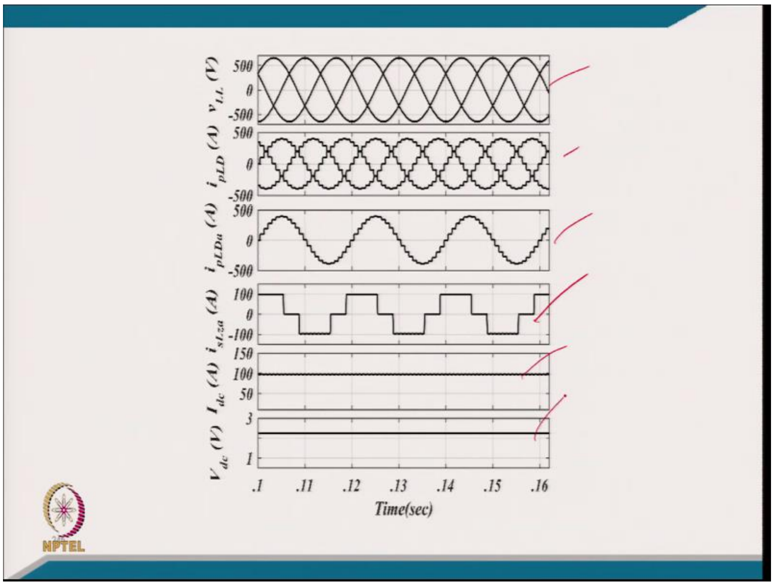

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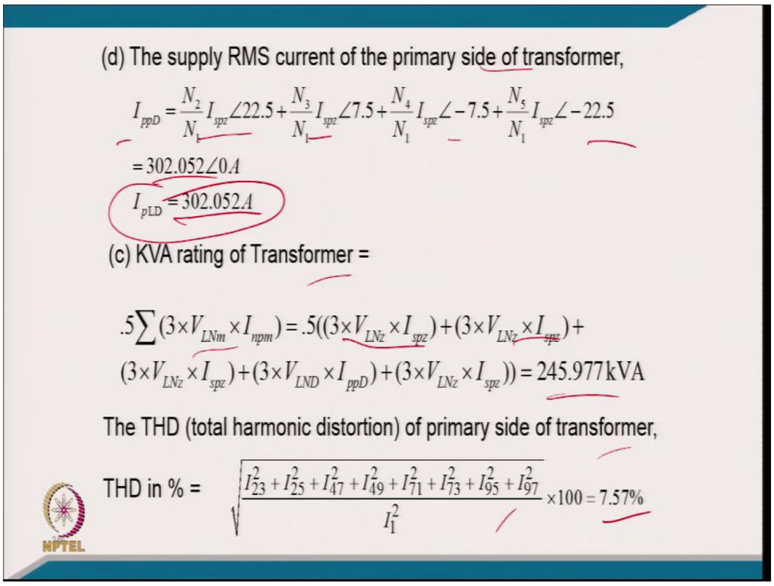
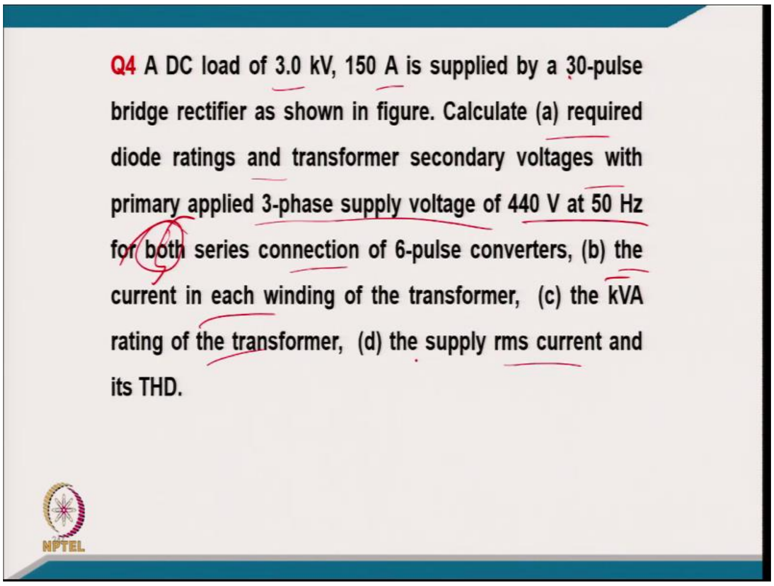


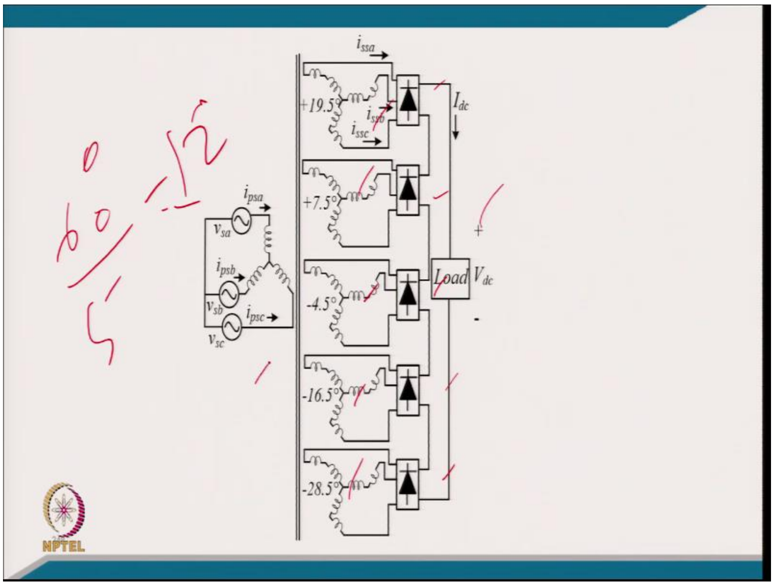
The solution of this problem is given in the abovemention slides.

(Refer Slide Time: 35:59)



Coming to 4th example. A DC load of 3 kV, 150 A is supplied by a 30 pulse bridge rectifier, as shown in the figure. Calculate, required diode ratings and transformer secondary voltages with the primary applied 3-phase voltage of 440 V at 50 Hz for series connected 6-pulse converter, the current rating in each winding of the transformer, kVA rating of the transformer, supply current RMS current and the THD.

(Refer Slide Time: 36:34)



This is the system for 30 pulse. For 30-pulse, you have 5 converters each of 6-pulse.

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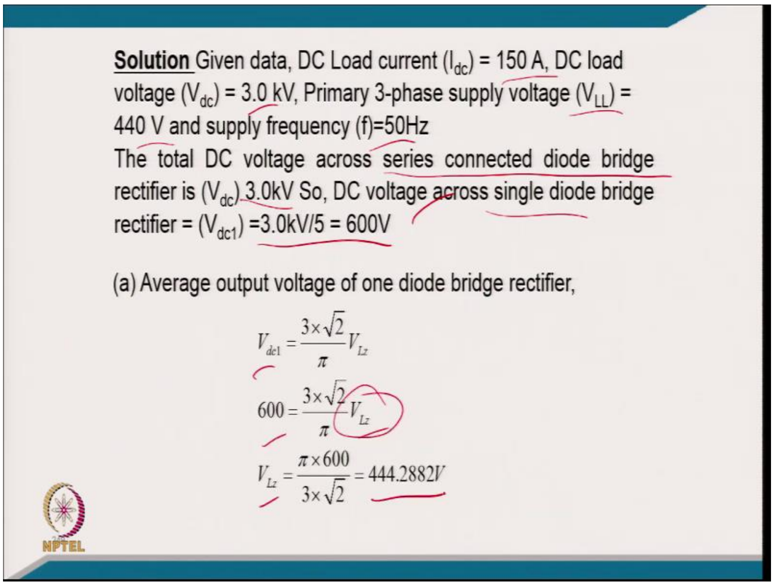

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V_{Lz} is the line voltage of the secondary side of transformer,

Diode Rating PIV = $\sqrt{2} \times V_{Lz} = 628.31V$

(b) Secondary Zigzag Transformer current,

$$I_{sz} = \sqrt{\frac{2}{3}} \times I_d = \sqrt{\frac{2}{3}} \times 150 = 122.47A = I_{spz}$$

Transformer ratio

$$\frac{N_1}{N_2} = \frac{254.03}{256.509} = .99035 = \frac{N_1}{N_3} = \frac{N_1}{N_4} = \frac{N_1}{N5} = \frac{N_1}{N6}$$

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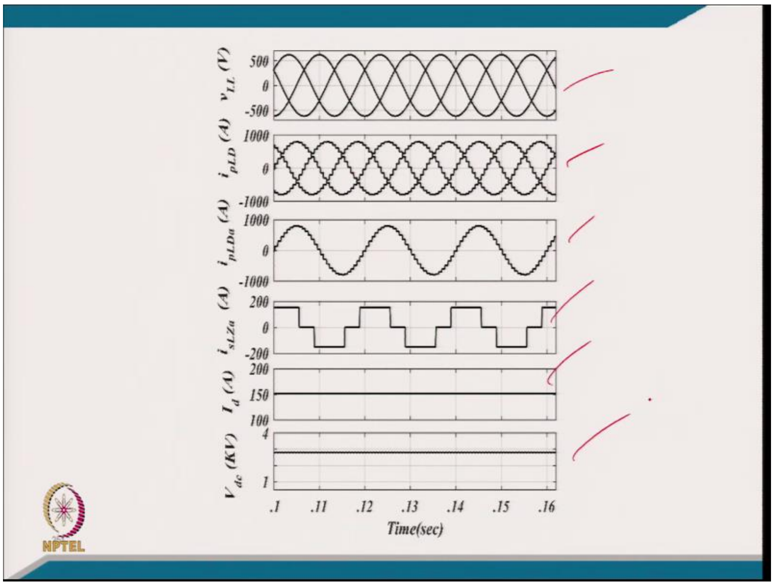

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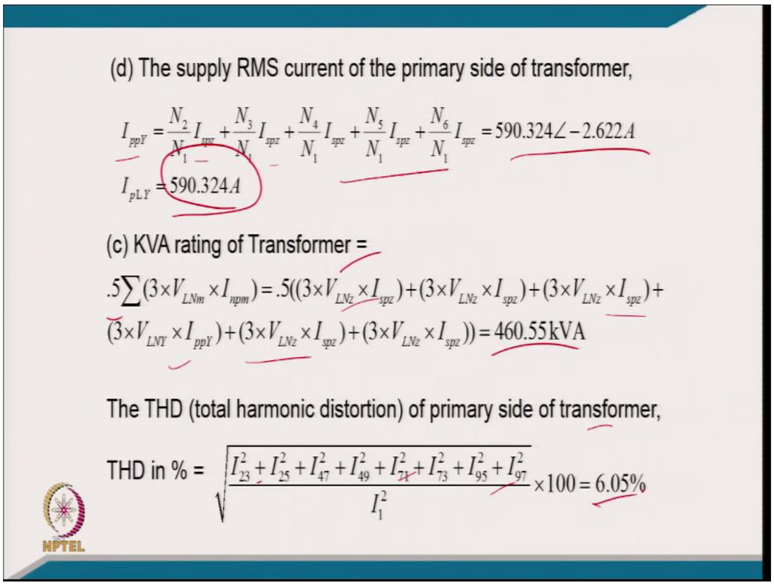

The solution of this problem is given in the abovemention slides.

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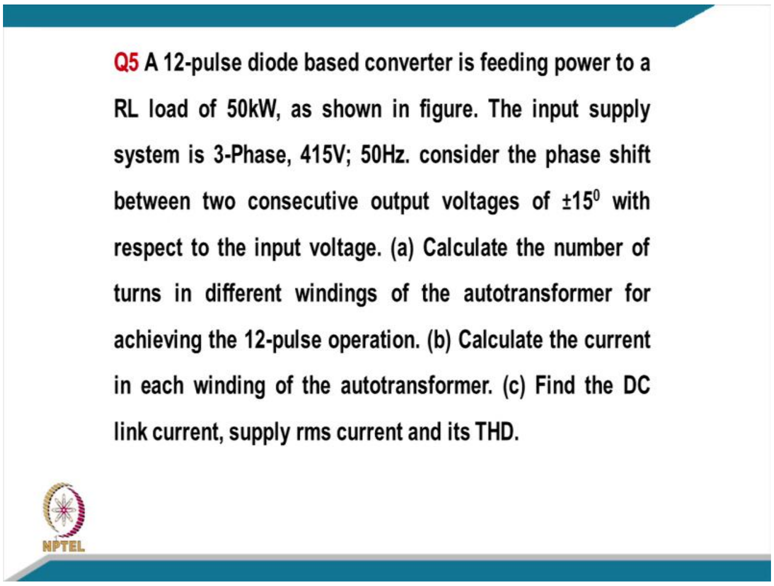

Coming to 5th example. A 12-pulse diode bridge converter feeding to a RL load of 50 kW, as shown in figure. The input supply is 3-phase, 415 V, 50 Hz. Consider the phase shift between two consecutive output voltages of ±15^o with respect to the input voltage. Calculate the number of turns in different winding of the auto transformer for achieving 12-pulse operation, calculate the current in each winding of auto transformer. Find the DC link current, supply RMS current and its total harmonics distortion.

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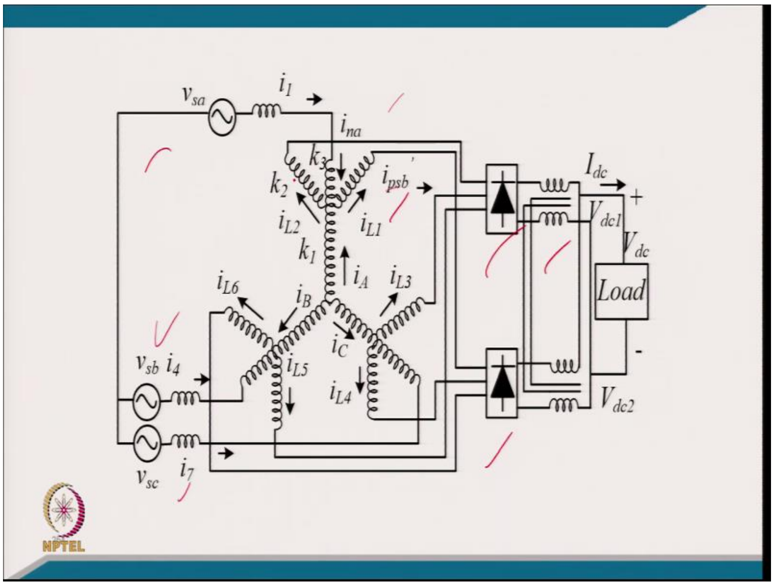

This is typically the connection for getting 12-pulse from 3-phase supply, with 2-phase shifted converter with the inter phase transformer, we are able to get phase shift like a ±15°.

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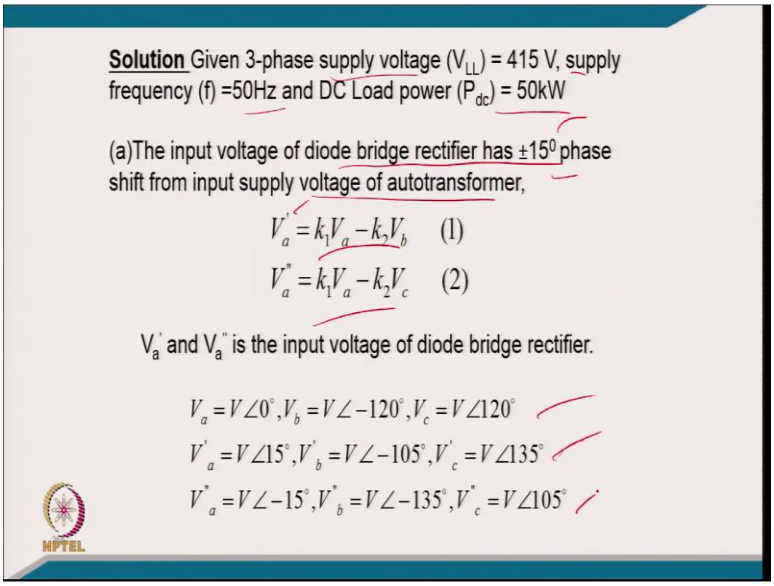

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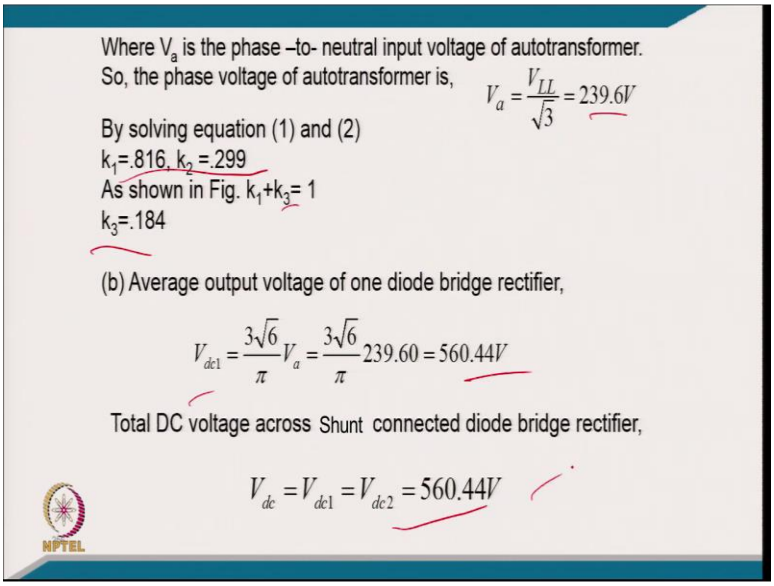

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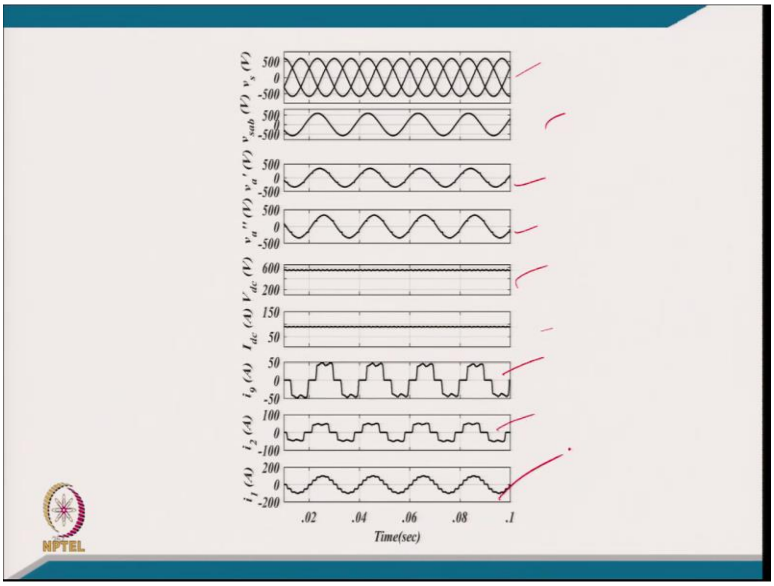

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(c)The output DC current of RL load, $I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{50 \times 10^3}{560.44} = 89.21A$

The input current of diode bridge rectifier is,

$$i_{L1} = i_{L2} = i_{L3} = i_{L4} = i_{L5} = i_{L6} = 0.5\left(\sqrt{\frac{2}{3}} I_{dc}\right) = 0.5\left(\sqrt{\frac{2}{3}} \times 89.21\right) = 36.42A$$

As considering the input power of autotransformer is equal to the output power auto transformer,

$$P_{in} = P_o$$

$$P_{in} = \sqrt{3} V_{LL} I_L$$

$$I_L = \frac{P_{in}}{\sqrt{3} V_{LL}} = \frac{50 \times 10^3}{\sqrt{3} \times 415} = 69.56A = i_1 = i_4 = i_7$$

i_1,i_4 and i_7 is the input current of autotransformer,

(Refer Slide Time: 41:00)

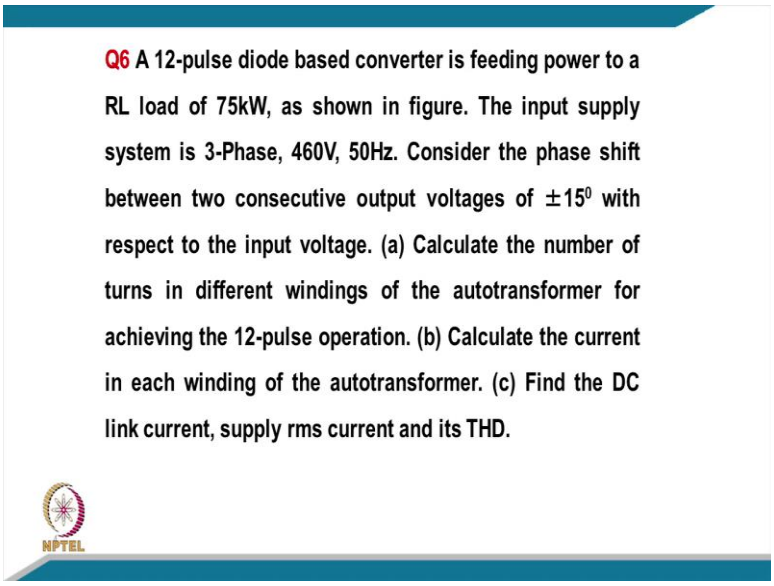
$$i_{na} = i_1 = 69.56A$$

The THD (total harmonic distortion) of input side current of auto transformer,

$$\text{THD in \%} = \sqrt{\frac{I_{11}^2 + I_{13}^2 + I_{23}^2 + I_{25}^2 + I_{35}^2 + I_{37}^2}{I_1^2}} \times 100 = 15.23\%$$

The solution of this problem is given in the abovemention slides.

(Refer Slide Time: 41:13)



Coming to 6th example. A 12-pulse diode based converter is feeding power to a RL load of 75 kW, as shown in figure. The input supply system is 3-phase 460 V, 50 Hz. Consider the phase shift between two consecutive output voltages ±15^{o} with respect to the input voltage. Calculate the number of turns in different winding of the auto transformer for achieving 12-pulse operation. Calculate the current in each winding of the auto transformer. Find the DC link current, supply RMS current and its THD.

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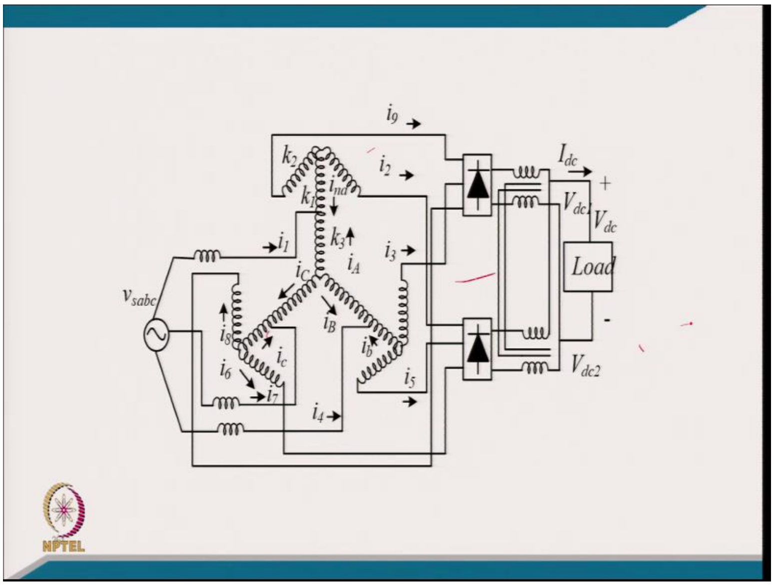
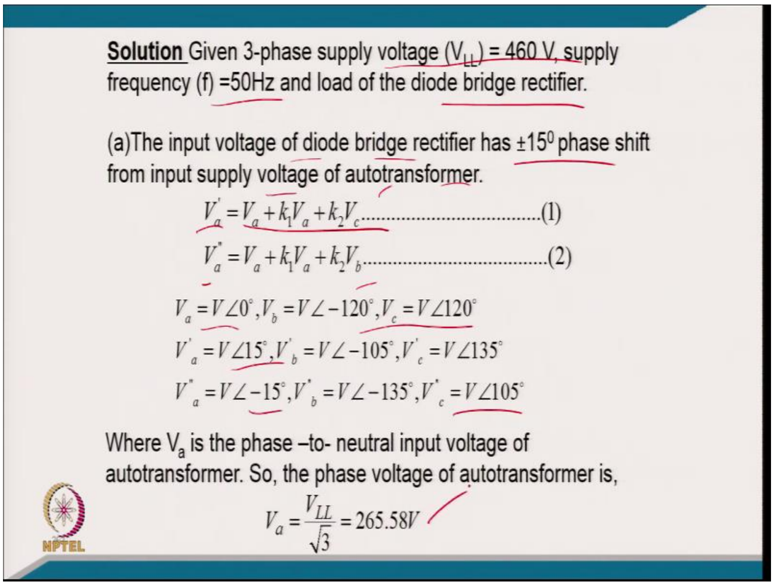


This is the typical connections, you can call it as an umbrella kind of connection, you are making like a tapping for giving input supply and then you are rising the voltage and then you are having a ±15 degree phase shift for getting 12-pulse converter.

(Refer Slide Time: 42:05)



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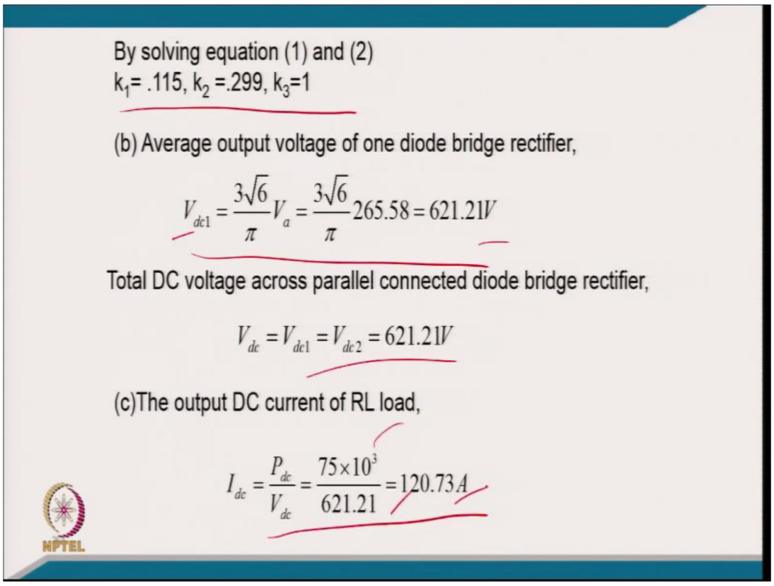

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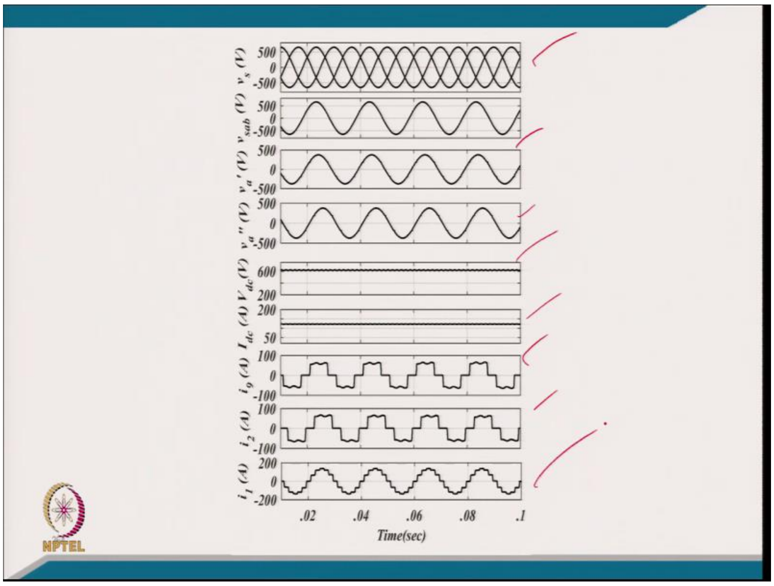

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The input current of diode bridge rectifier is,

$$i_9 = i_2 = i_3 = i_5 = i_8 = i_6 = 0.5\sqrt{\frac{2}{3}}I_{dc} = 0.5\times\sqrt{\frac{2}{3}}\times 120.73 = 49.29A$$

As considering the input power of autotransformer is equal to the output power auto transformer,

$$P_{in} = P_o$$

$$P_{in} = \sqrt{3}V_{LL}I_L$$

$$I_L = \frac{P_{in}}{\sqrt{3}V_{LL}} = \frac{75\times 10^3}{\sqrt{3}\times 460} = 94.133 = i_1 = i_4 = i_7$$

i_1, i_4 and i_7 is the input current of autotransformer,

$$i_{na} = -(i_9 + i_2) = -(49.29\angle -15^0 + 49.29\angle +15^0) = -95.22A$$

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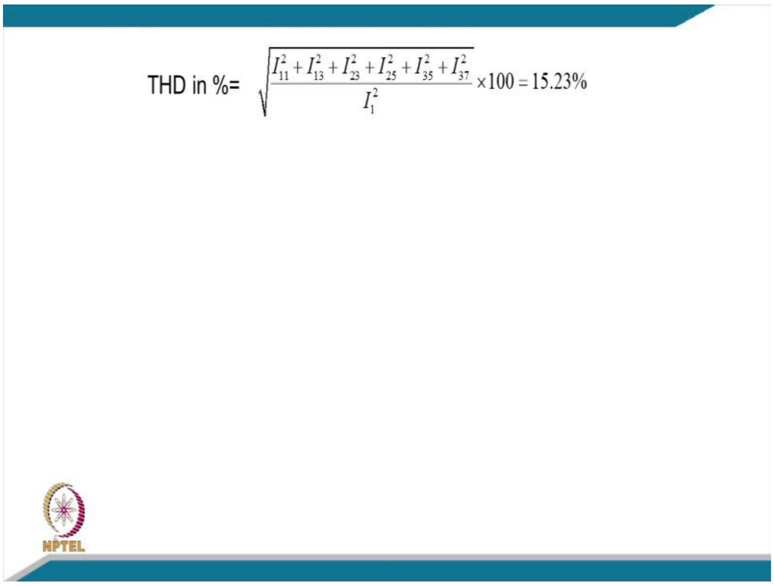

The solution of this problem is given in the abovemention slides.

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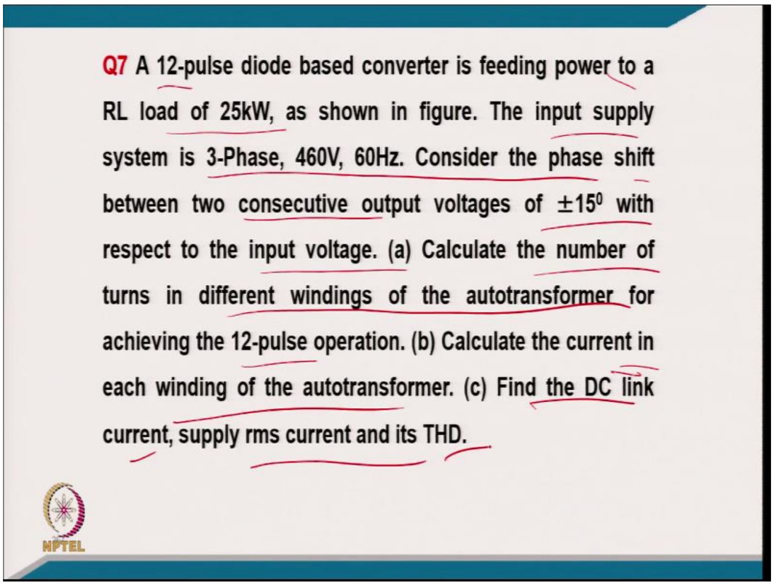
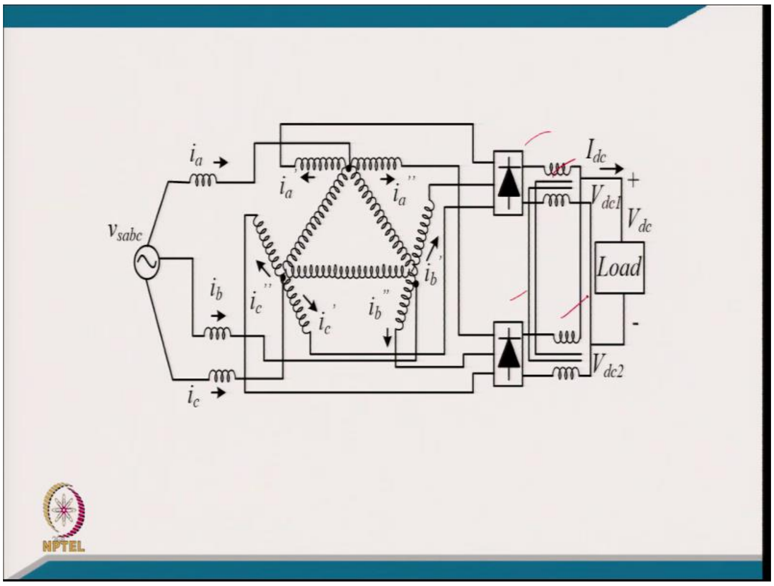


Coming to 7th example. A 12-pulse diode bridge converter is feeding power to a RL load of 25 kW, as shown in figure. The input supply system is 3-phase, 460 V, 60Hz. Consider the phase shift between two consecutive output voltages of $\pm 15^o$ with respect to the input voltage. Calculate the number of turns in different windings of autotransformer for achieving 12-pulse operation. Calculate the current in each winding of auto transformer, the DC link current, supply RMS current, and its THD.

(Refer Slide Time: 44:03)



And this is the another connection for getting a 12-pulse of ±15° which is called as extended delta.

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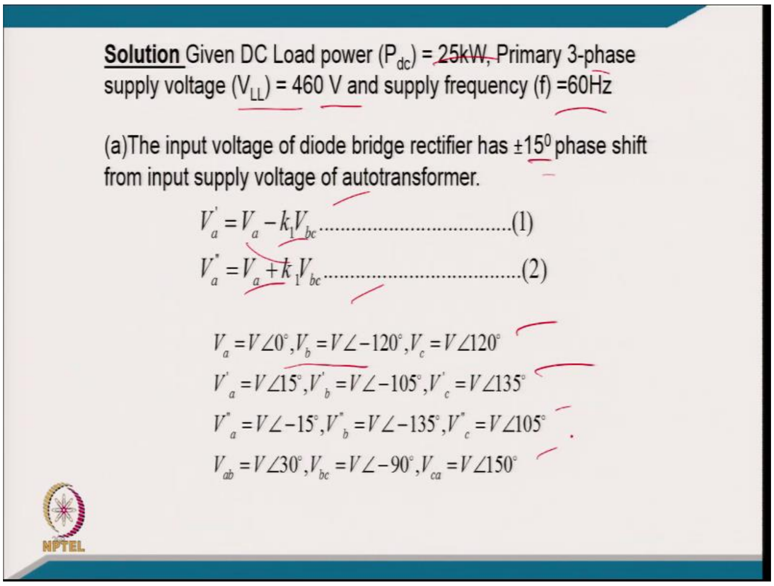

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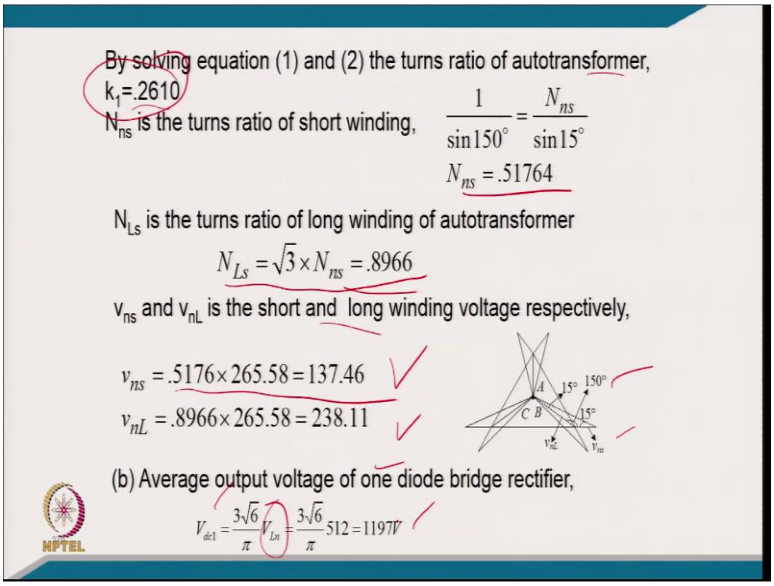

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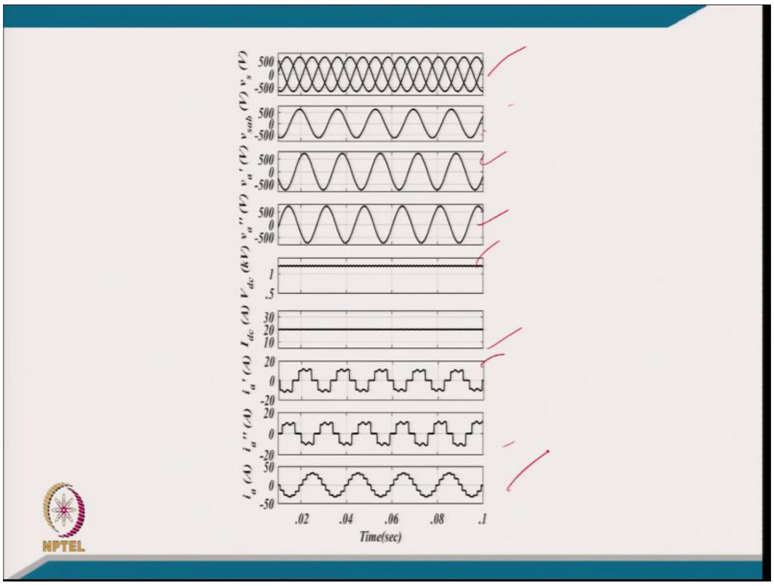

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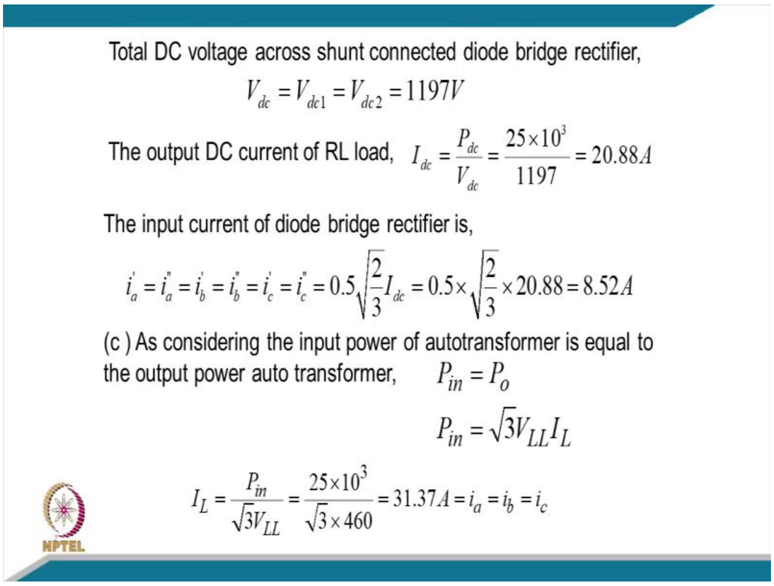

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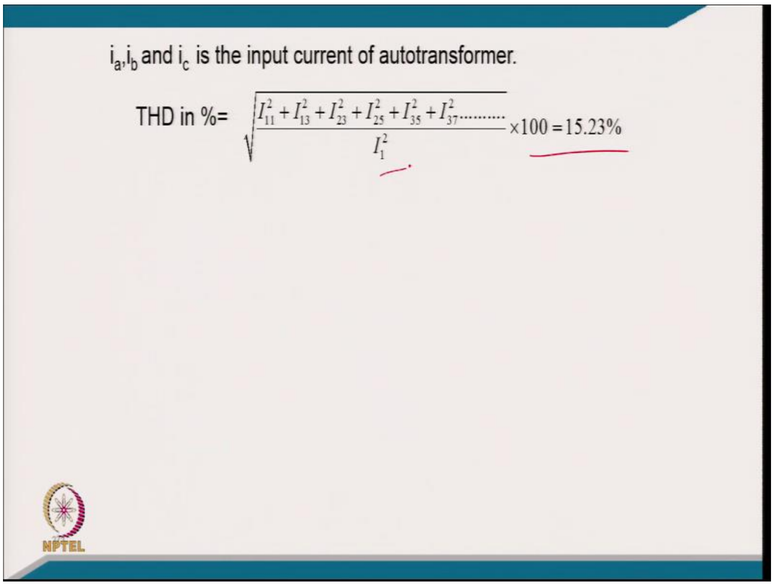

The solution of this problem is given in the abovemention slides.

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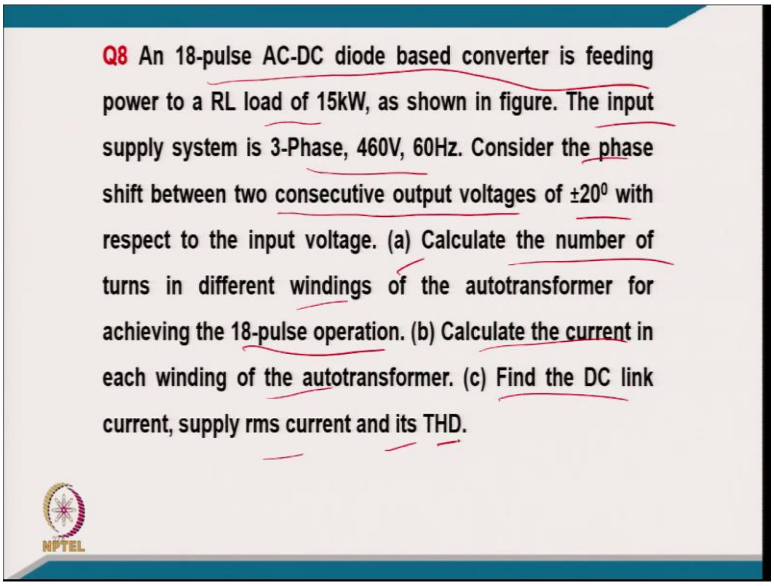
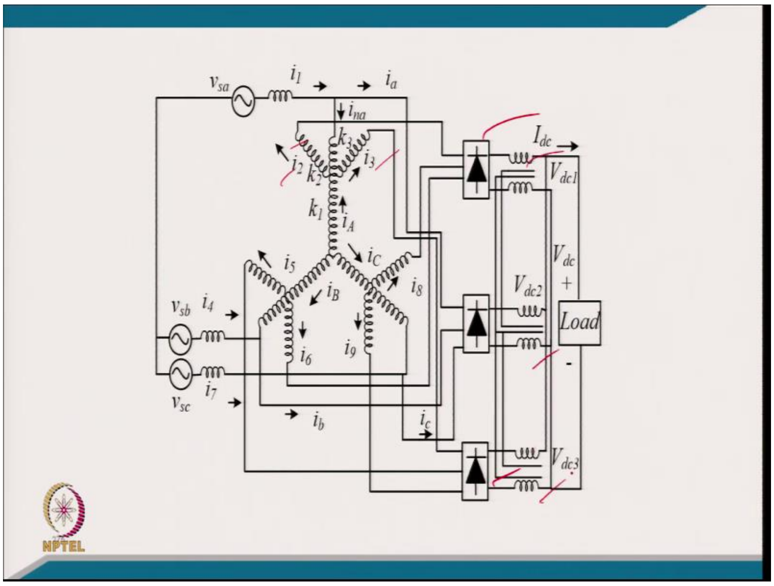


Coming to 8th example. An 18-pulse AC-DC diode based converter is feeding power to a RL load of 15 kW, as shown in figure. The input supply system is 3-phase 460 V, 60 Hz. Consider the phase shift between the two consecutive of ±20^{o} with respect to the input voltage. Calculate the number of turns in different windings of the autotransformer for achieving 18-pulse operation, calculate the current in each winding of the auto transformer, find the DC link current, supply RMS current, and its THD.

(Refer Slide Time: 46:24)



The aforesaid system is presented as follows.

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Solution Given 3-phase supply voltage (V_{LL}) = 460 V, DC Load power (P_{dc}) = 15kW, and supply frequency (f) =60Hz

(a)The input voltage of diode bridge rectifier has $\pm 20^0$ phase shift from input supply voltage of autotransformer.

$$V_a' = k_1 V_a - k_2 V_b \text{..................................(1)}$$

$$V_a'' = k_1 V_a - k_2 V_c \text{..................................(2)}$$

$$V_a = V\angle 0^\circ, V_b = V\angle -120^\circ, V_c = V\angle 120^\circ$$

$$V'_a = V\angle 20^\circ, V'_b = V\angle -100^\circ, V'_c = V\angle 140^\circ$$

$$V''_a = V\angle -20^\circ, V''_b = V\angle -140^\circ, V''_c = V\angle 100^\circ$$

Where V_a is the phase –to- neutral input voltage of autotransformer. So, the phase voltage of autotransformer is,

$$V_a = \frac{V_{LL}}{\sqrt{3}} = 265.58V$$

(Refer Slide Time: 47:11)

By solving equation (1) and (2) turns ratio of autotransformer,

k_1=.742, k_2=.395

As shown in Fig. k_1+k_3= 1

k_3=0.258

(b) Average output voltage of one diode bridge rectifier,

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} V_a = \frac{3\sqrt{6}}{\pi} 265.58 = 621.22V$$

Total DC voltage across series connected diode bridge rectifier,

$$V_{dc} = V_{dc1} = V_{dc2} = V_{dc3} = 621.22V$$

The output DC current of RL load,

$$I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{15\times 10^3}{621.22} = 24.15A$$

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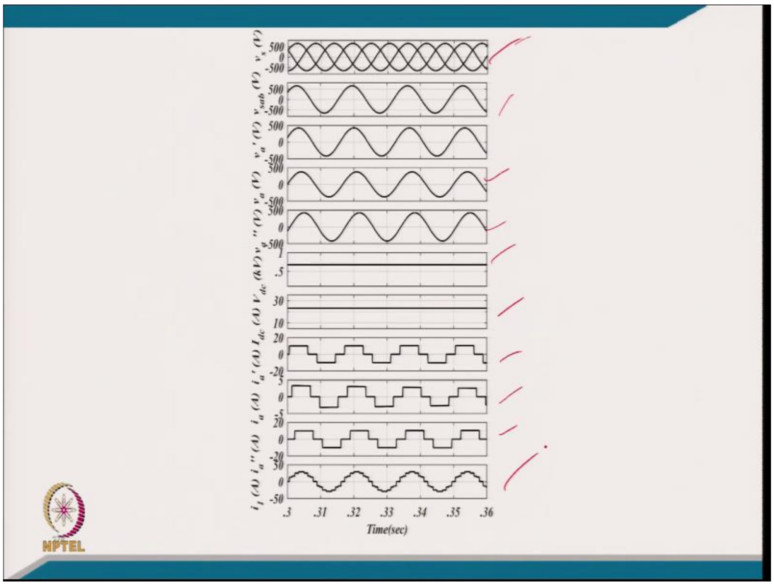

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The input current of diode bridge rectifier is,

$$i_2 = i_3 = i_5 = i_6 = i_8 = i_9 = i_a = i_b = i_c = 0.33\sqrt{\frac{2}{3}}I_{dc} = 0.33\times\sqrt{\frac{2}{3}}\times 24.15 = 6.51A$$

(c)As considering the input power of autotransformer is equal to the output power auto transformer,

$$P_{in} = P_o$$

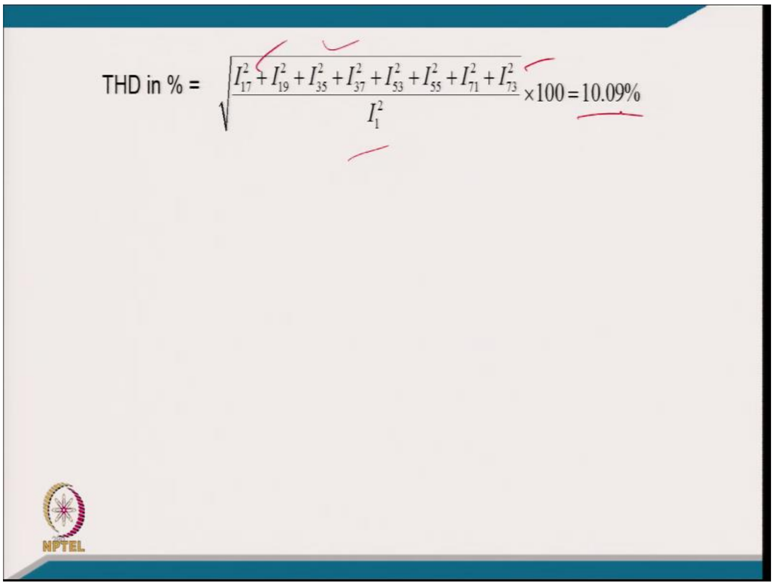
$$P_{in} = \sqrt{3}V_{LL}I_L$$

$$I_L = \frac{P_{in}}{\sqrt{3}V_{LL}} = \frac{15\times10^3}{\sqrt{3}\times 460} = 18.83A = i_1 = i_4 = i_7$$

$$i_{na} + i_a = i_1$$

$$i_{na} = i_1 - i_a = 18.83 - 6.51 = 12.32A$$

(Refer Slide Time: 48:09)



The solution of this problem is given in the abovemention slides.

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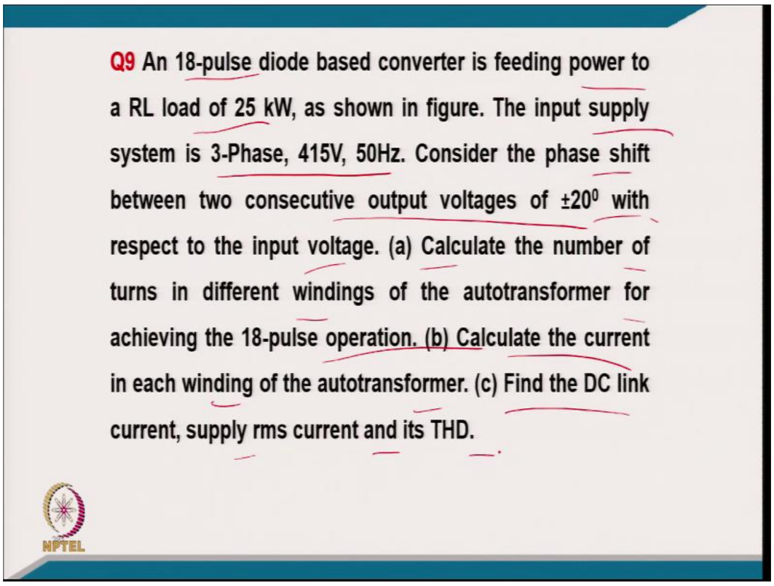
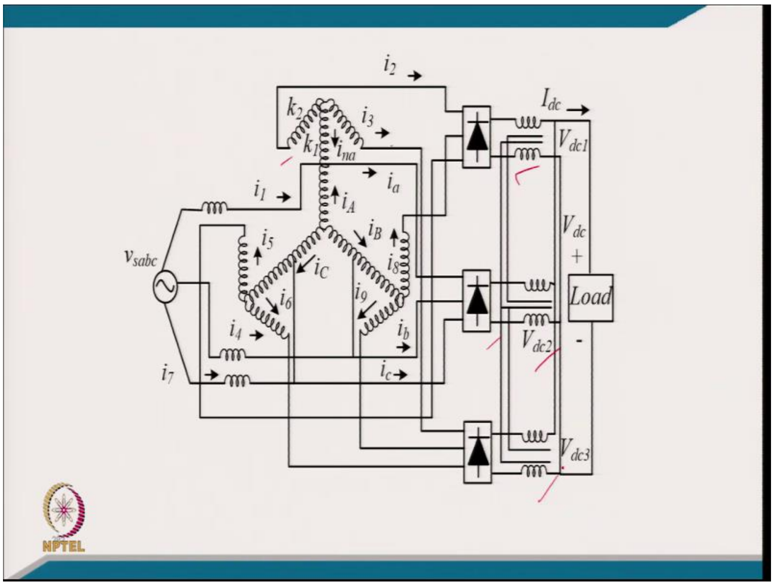


Coming to 9th example. A 18-pulse diode bridge converter feeding power to RL load of 25 kW, as shown in the figure. The input supply is 3-phase, 415 V/50 Hz. Consider the phase shift of two consecutive output voltages of ±20° with respect to the input voltage. Calculate, the number of turns in different windings of the autotransformer for achieving 18-pulse operation, calculate the current in each winding of the autotransformer, find the DC link current, supply RMS current, and its total harmonics distortion.

(Refer Slide Time: 48:51)



So, this is typically the connection for 18-pulse configuration with ±20º phase shift with this fork kind or the umbrella kind of connections.

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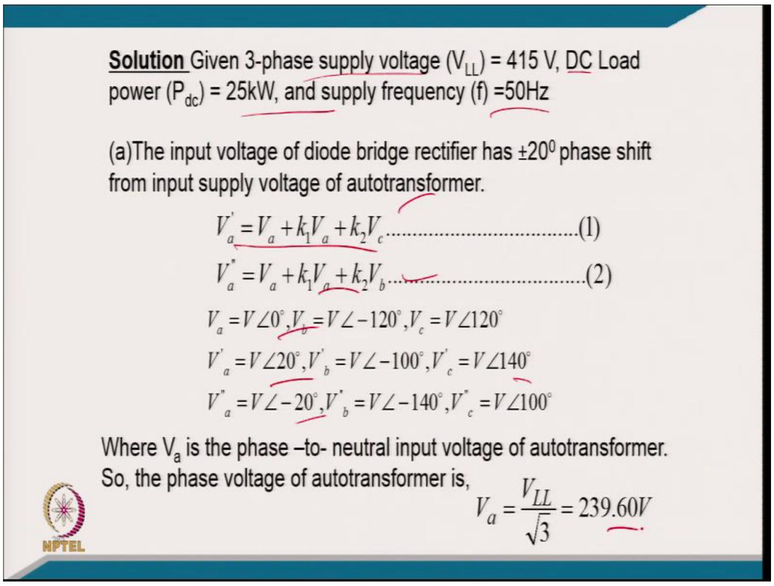

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By solving equation (1) and (2) turns ratio of autotransformer, k_1=0.137, k_2 =0.395

(b) Average output voltage of one diode bridge rectifier,

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} V_a = \frac{3\sqrt{6}}{\pi} 239.60 = 560.44V$$

Total DC voltage across series connected diode bridge rectifier,

$$V_{dc} = V_{dc1} = V_{dc2} = V_{dc3} = 560.44V$$

The output DC current of RL load,

$$I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{25 \times 10^3}{560.44} = 44.60A$$

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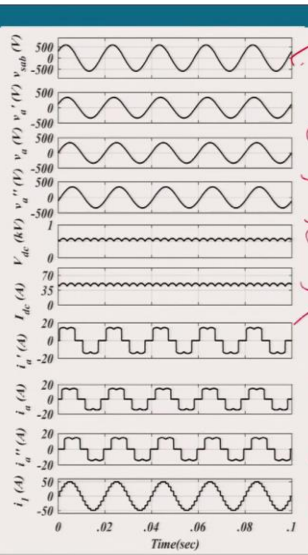

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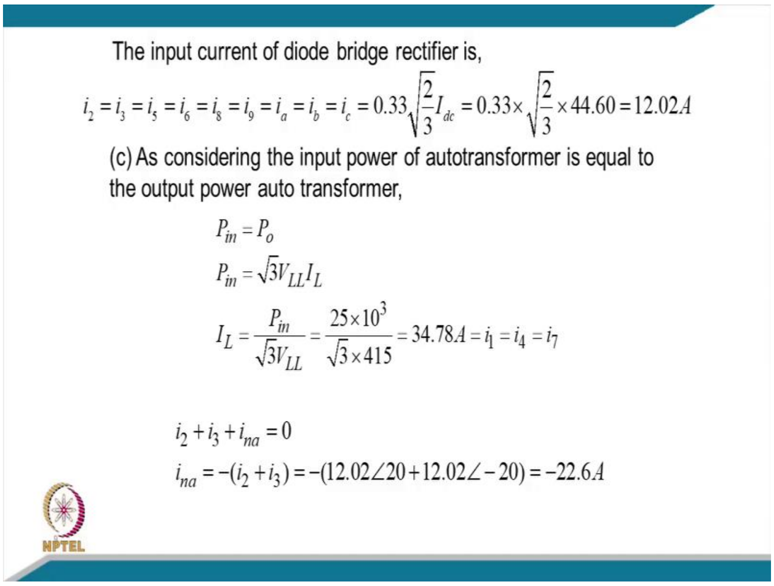

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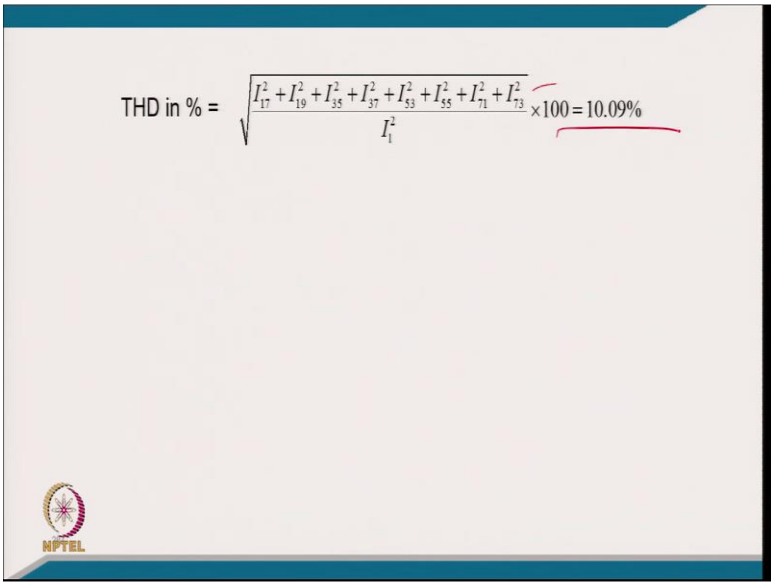

The solution of this problem is given in the abovemention slides.

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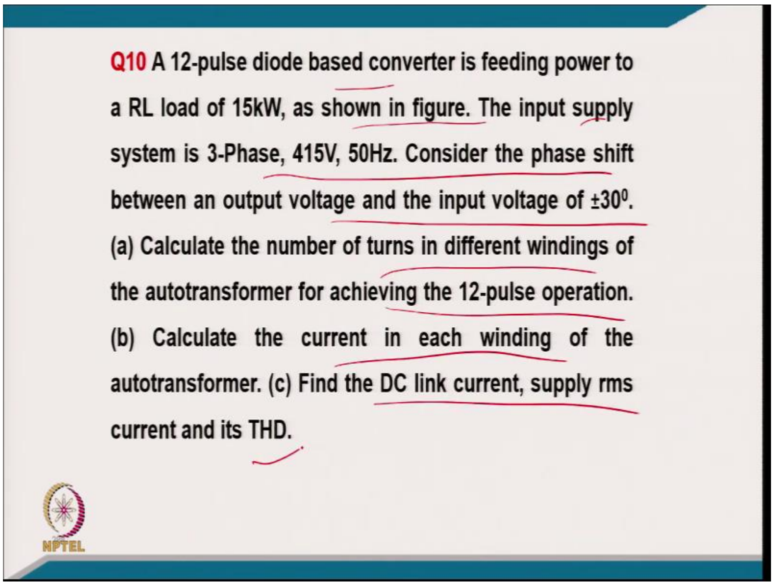
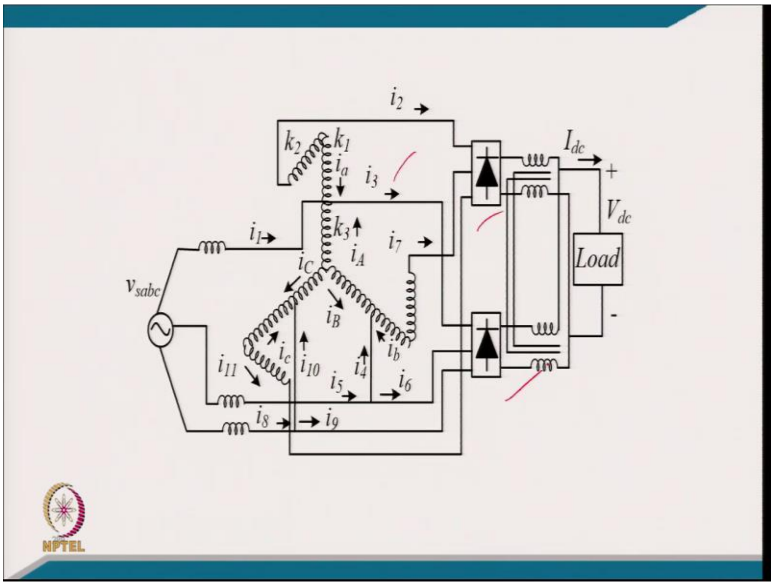


Coming to 10th example. A 12-pulse diode bridge converter is feeding the RL load of 15 kW, as shown in figure. The input supply system is 3-phase, 415 V, 50 Hz. Consider the phase shift of ±30°. Calculate the number of turns in different winding of autotransformer for achieving the 12-pulse operation. Calculate the current in each winding, DC link current and supply RMS current, and its THD.

(Refer Slide Time: 50:55)



The aforesaid system is presented as follows.

(Refer Slide Time: 51:02)

Solution Given 3-phase supply voltage (V_{LL}) = 415 V, DC Load power (P_{dc}) = 15kW and supply frequency (f) =50Hz

(a)The input voltage of diode bridge rectifier has ±30^0 phase shift from input supply voltage of autotransformer.

$$V_a' = V_a + k_1 V_a + k_2 V_c \text{.............................(1)}$$

$$V_b' = V_b + k_1 V_b + k_2 V_a \text{.............................(2)}$$

$$V_c' = V_c + k_1 V_c + k_2 V_b \text{.............................(3)}$$

$$V_a = V\angle 0^\circ, V_b = V\angle -120^\circ, V_c = V\angle 120^\circ$$

$$V'_a = V\angle 30^\circ, V'_b = V\angle -90^\circ, V'_c = V\angle 150^\circ$$

Where V_a is the phase –to- neutral input voltage of autotransformer.

So, the phase voltage of autotransformer is, $V_a = \frac{V_{LL}}{\sqrt{3}} = 239.60V$

(Refer Slide Time: 51:16)

Solving equation (1), (2) and (3) the no. of turns ratio autotransformer, k_1=0.155 k_2=0.577 k_3=1

(b) Average output voltage of one diode bridge rectifier,

$$V_{dc} = \frac{3\sqrt{6}}{\pi} V_a$$

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} 239.60$$

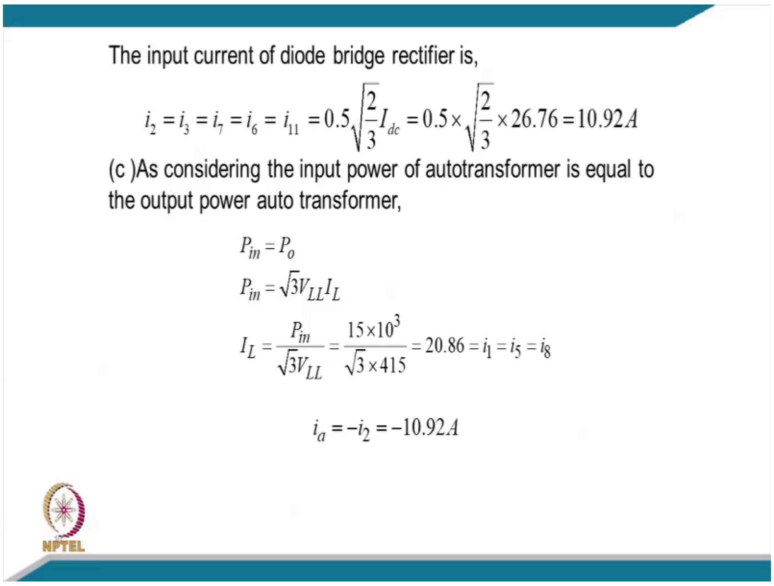
$$V_{dc1} = 560.44V$$

Total DC voltage across Shunt connected diode bridge rectifier,

$$V_{dc} = V_{dc1} = V_{dc2} = 560.44V$$

The output DC current of RL load, $I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{15\times 10^3}{560.44} = 26.76A$

(Refer Slide Time: 51:29)



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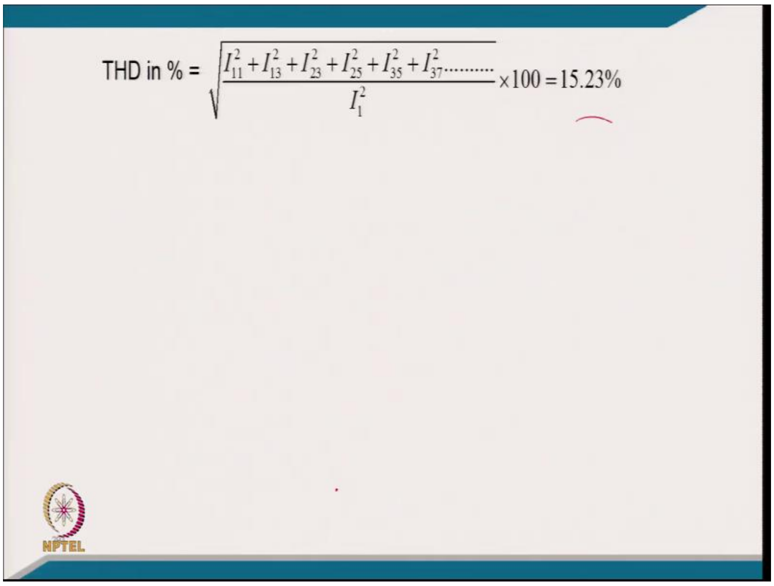

The solution of this problem is given in the abovemention slides.

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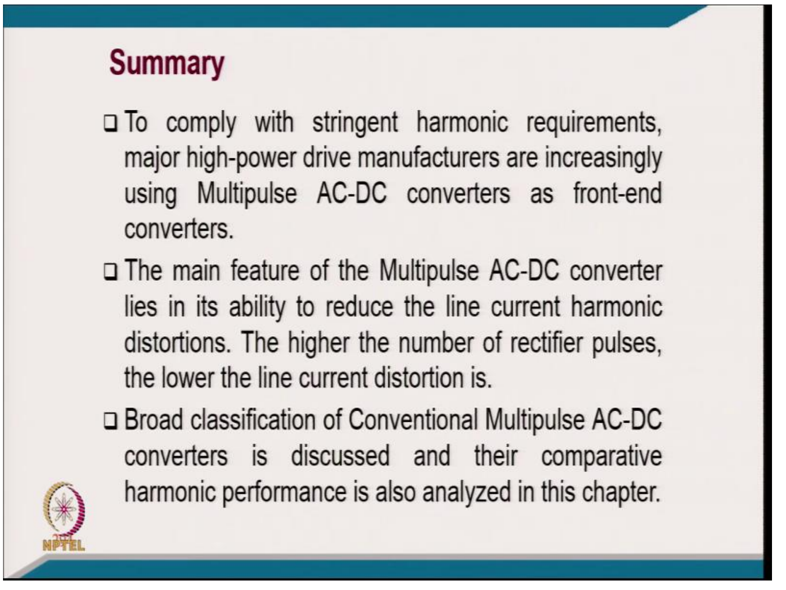

Now, coming to summary of multi-pulse improved power quality converter. To complied with stringent harmonics requirement, major higher-power drive manufacturers are increasingly using multi-pulse AC-DC converters as front end converters. The main feature of multi-pulse AC-DC converter lies in its ability to reduce with the line current harmonics distortion. The higher the number of rectifier pulses, the lower will the line current distortion. Broad classification of conventional multi-pulse AC-DC converter is discussed and their comparative harmonic performance is analyzed.

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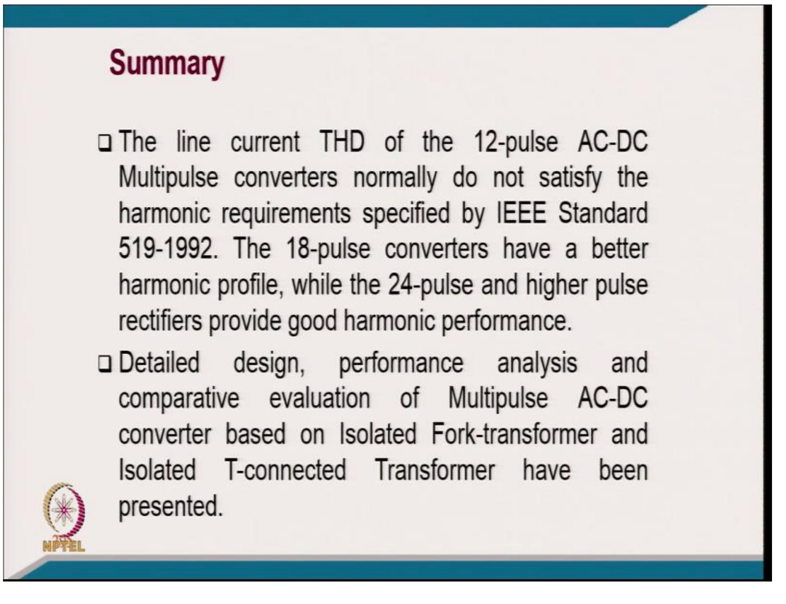

The line current THD of the 12-pulse converter, normally do not satisfy the harmonic requirement as specified by IEEE 519 standard, whereas, the 18-pulse converters have better harmonic. Further, the 24-pulse and higher number of pulses provide a good harmonic profile. Detailed design, performance analysis, and comparative evaluation of multi-pulse AC-DC converter based on isolated fork-transformer, and isolated T-connected transformer have been presented.

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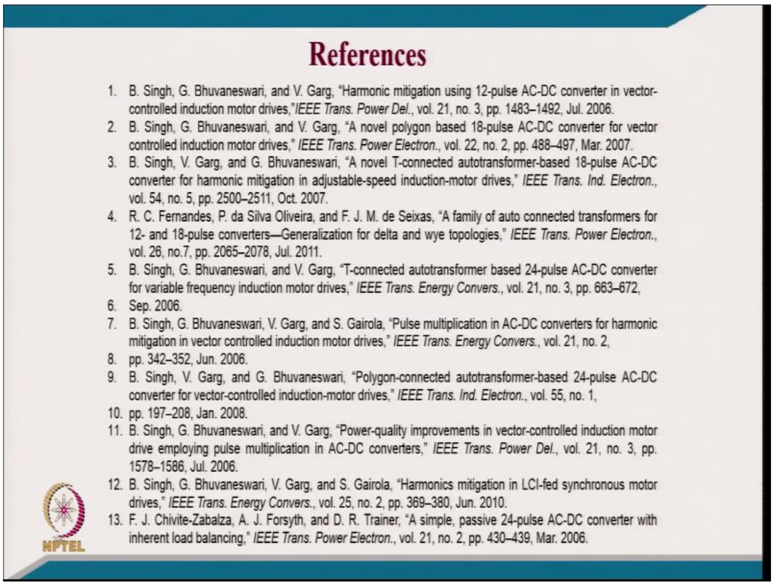

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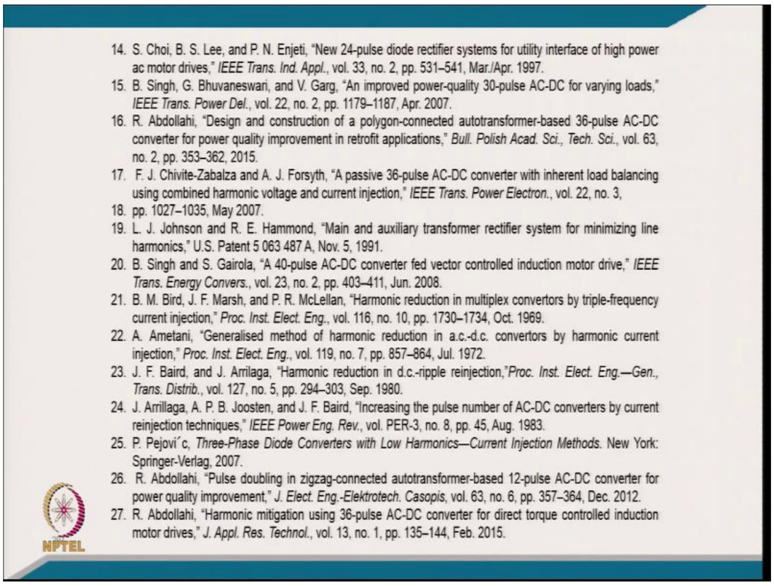

And these are the references.

Thank you like.