Advance Power Electronics and Control
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Lecture - 26
VSI and CSI

Welcome to our lectures on Advance Power Electronics and Control. Today, we shall discuss about another important entity of the power electronics that is DC-to-AC conversion and we shall discuss about power electronics circuit. So we shall discuss about voltage source converter, voltage source inverter and the current source inverter. Process of converting DC voltage into the desirable repetitive voltage is called the inversion.

It can be of 2 types, 1 is structurally based on the topology and source are may be voltage or current, you want that feeded by the inverter and we shall see that what are the different kind of constraint and the applications of the voltage source converter and the current source inverter.

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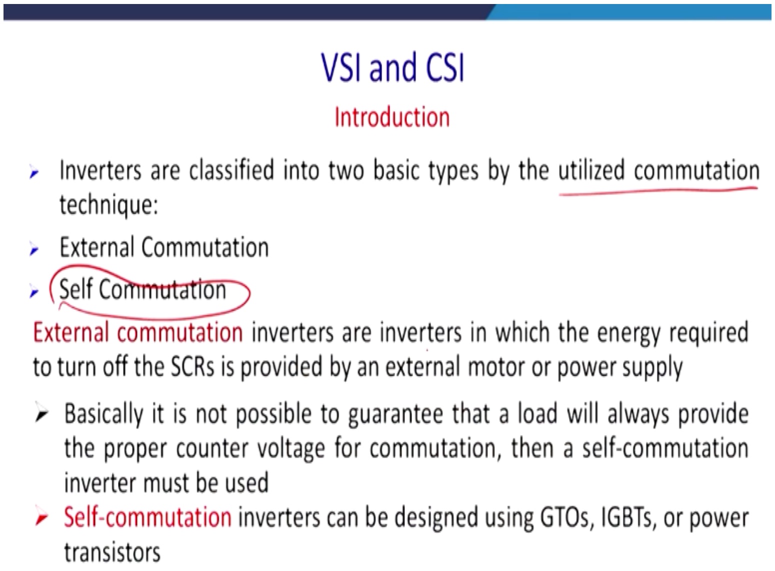

VSI and CSI

Introduction

- Inverters are classified into two basic types by the utilized commutation technique:
- External Commutation
- Self Commutation

External commutation inverters are inverters in which the energy required to turn off the SCRs is provided by an external motor or power supply

- Basically it is not possible to guarantee that a load will always provide the proper counter voltage for commutation, then a self-commutation inverter must be used
- Self-commutation inverters can be designed using GTOs, IGBTs, or power transistors

Inverters are essentially classified into the 2 basic types based on the utilizations of the commutation technique. Previously since power electronics comes into the pictures with invent of the thyristors. So these 1 terms are quite important. So we require whether actually it can be commutated by the external commutation circuits, so you required to have an external commutation circuits to be placed to commutate it.

Or it can ensure that actual commutations like in case of the conversion, DC-to-AC thyristors or line commuted. We will have some kind of thing like that, so that is called the cell commutation and now external commutations, we have actually studied in the different kind of communication technique for the thyristor mostly auxiliary commutation of the thyristors are being employed in case of the thyristor.

Otherwise if you have G2O, you have to have the negative pulses to withdraw the devices. Inverters, in which the energy required to turn AC are provided by the external motor or the power supply. So that is basically the external commutation. Basically it is not possible that load which will provide the proper counter voltage for the commutation, because you know there are different kind of technique for the commutations of the thyristors.

You apply the reverse voltages and you bring the current below basically the below the holding current. If it cannot be done by the load, because for example if you feeding a leading power factor, then what happened current actually goes 0 before voltage goes zero. So it can be naturally commutated. So it does not happen sometime, then we have to see that, we have to externally do it by auxiliary commutation.

Basically, it is not possible to guarantee that the load is always provided, because load is something that actually it is users choice not designers choice. So it will offer you the commutation, then a cell commutation and if it is ensure that the load can provide the process of commutation then we employed the cell commutating inverters and these inverters can be actually used if it is cell commutation type than we actually withdraw by the get pulses.

These are essentially GTOs. It has highest power rating and the lowest switching frequency. IGBT is the middle band in the row, medium power rating of the 10s of kilowatts and 10s of frequencies and power transistor nowadays not used because power distribution is quite high, but you can use the mosfet, which have a higher switching frequency, but lower power rating. So we have a different kind of inverter depending on the source.

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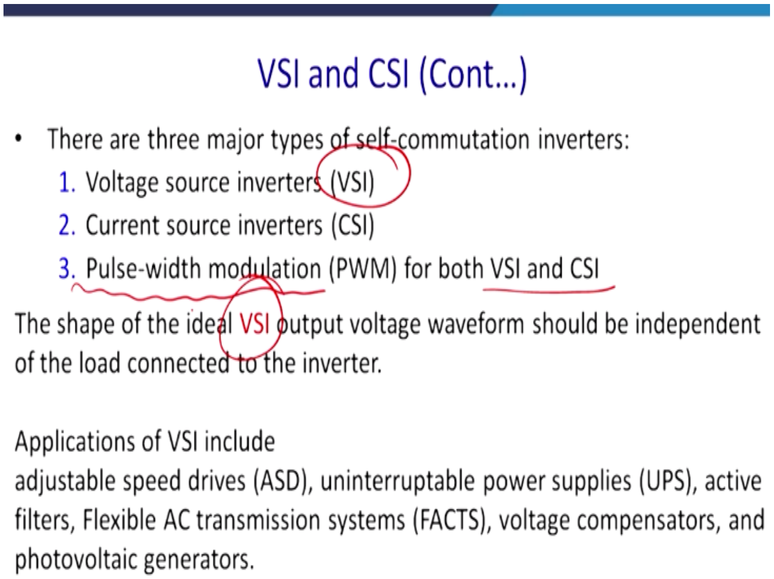

VSI and CSI (Cont…)

- There are three major types of self-commutation inverters:
  1. Voltage source inverters (VSI)
  2. Current source inverters (CSI)
  3. Pulse-width modulation (PWM) for both VSI and CSI

The shape of the ideal VSI output voltage waveform should be independent of the load connected to the inverter.

Applications of VSI include
adjustable speed drives (ASD), uninterruptable power supplies (UPS), active filters, Flexible AC transmission systems (FACTS), voltage compensators, and photovoltaic generators.

Source can be voltage and you are feeding to the load, then it is called voltage source inverter. Similarly, you can have a current source inverter and you will see the different kind of control technique for those inverters and most suitable method is the pulse width modulations, mostly for the VSI you can use it and we shall discuss in details for apply to the both the cases and we will see the advantage of the pulse width modulation over other different kind of converter inversion operation.

Now the shape of the ideal VSI voltage waveform should be independent of the load connected to the inverter. So this is the desirability because it will mimic the characteristics of the rigid grid. So that is the desirability of the VSI, it will actually give you the desired voltage independent of the load connected to it. So this inverter output voltage should not be distorted by adding or withdrawing a different kind of linear or non-linear load.

So application of the VSI includes adjustable speed drive. Why adjustable speed drive, most of this actually motors are induction motors nowadays and thus they run their close to their synchronous speed either near to the 1000 ampere with 64 machine, if it is a 1500 ampere, which is a 44 machine. If we require adjustable speed drive with the wide variation of the range like modern lifts, elevators all those things, then what should you do.

So we required to actually have a power electronic supply that will give us variable voltage and the frequency, so there VSI finds its applications, uninterruptible power supply, it is very common use in case of the basically are desktop kind of applications. So we provide actually power backup, once power is off, then it is called actually offline UPS. You can have a online because if you want to process power.

Then actually once power is there you will take power from the grid and you rectify it through the power factor rectification technique and it is feeded to the inverter to give a process power, so that even this utility provides you the battery power that is get corrected and once power is off that will give the voltage from the battery and if there is a brown mode condition, it will actually give you the compensated voltage or the sag voltage.

So in those application also we use voltage source inverter and thereafter we have acti-filters. Acti-filter essentially what does it do you know due to using these entities, we basically distort the power quality. Power quality is a very big term. Two important entities of the power qualities are power factor and TST. So these are 2 entities that actually affect it because of this adjustable speed type and uninterruptible power supply and other different modern power electronic devices.

Acti-filter essentially a solution provided by the power electronics to this problem where you actively mitigate the harmonic and you improve the power factor that is called active rectifier and thereafter we have a flexible AC transmission system that is fax. So it has a whole gametes of solutions. These are series compensation, shunt and series compensation, angle compensation. So all those things we generally find VSI and the voltage compensator and also photovoltaic inverter is also the type of the VSI.

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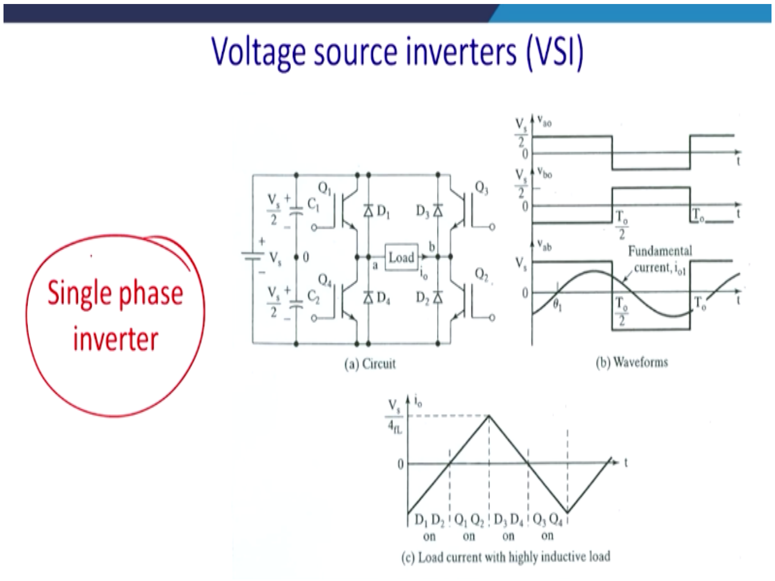

Voltage source inverters (VSI)

Single phase inverter

(a) Circuit

(b) Waveforms

(c) Load current with highly inductive load

So let us see that this is the simplest form of the inverter. It is in a breach configuration and you can first, we assume that load is highly inductive. So there is no challenge involved if load is resistive. So voltage and current will be in a phase and thus you do not have much problem, but if it is a lagging kind of aspect is there, voltage is lagging, kind is lagging the voltage by 90 degree then you will find that current is at peak when you require to switch it off.

So that is something the watts case condition and we require to actually take care of those aspects. So this is the VS/2 and this is the voltage applied. Once Q1 and Q2 is on, so voltage AO will be essentially the half of the actually the supply voltage and voltage BO will actually negative. If you combine, then it will be a line voltage AB between these 2 and you will get the full VS and you will see that actually.

This is the square wave is the voltage applied and we assume that current is highly inductive and for this reason will find that current has been phased lagged by angle theta and always the same I said to you diode basically try to decrease the value of the current whether it is a positive cycle or negative cycle. So even if ramp is positive, please see that magnitude of the current is decreasing. So than always you remember that the diodes are conducting.

So it sets a prelude to do actually the switches to the operation. So when you can see that when it is ramping on in a positive direction. So of course that Q1 and Q2 required to actually bring it up, till that time once it is not switched. So D1 and D2 will come into the picture and this will actually try to decrease the current and will try to close to the 0 value. Thereafter Q1 and Q2 has been triggered and that will ramp on this current straight away.

And here at this moment you basically withdraw pulses of Q1 and Q2, but since this current is basically cannot change its direction instantaneously, so current will continue to flow and you will find that so instead of the Q1 and Q2 current will flow through the load through basically D3 and D4. So this will be the path for the current. Now once D3 and D4 has been conducted, so I have always said one start conducts, current falls.

So ultimately current will gradually fall once it is close to 0, you are supposed to turn on your another pair of switches Q3 and Q4 and that will be continued and so on. So this is called square wave operations of the inverter for highly inductive load.

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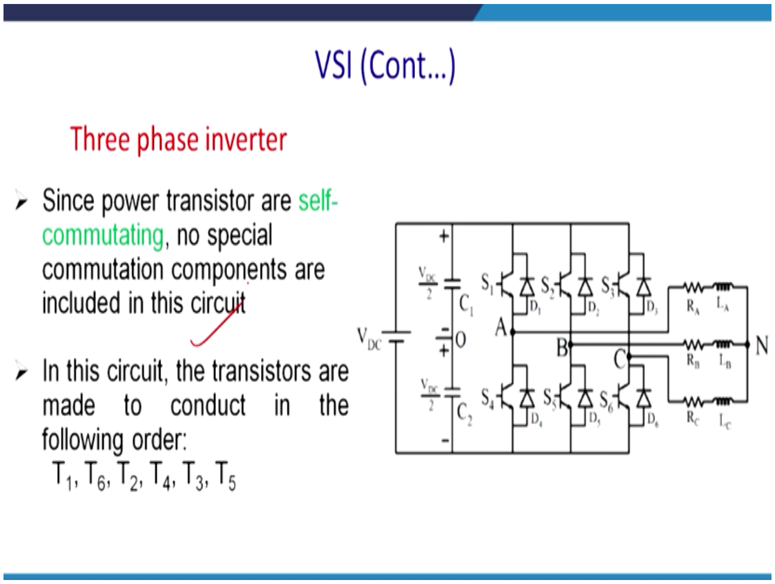

VSI (Cont...)

Three phase inverter

- Since power transistor are self-commutating, no special commutation components are included in this circuit
- In this circuit, the transistors are made to conduct in the following order:
  $T_1, T_6, T_2, T_4, T_3, T_5$

So same thing can be extended for the 3 phase, 3 wire system for 3 phase inverter. Since the power transistors are cell commutating, no special commutation component are included in the circuit. So you will be using GTO, IGBT or power MOSFETs and so if you like to use actually the thyristors, then you will require to incorporate the auxiliary circuit for the commutation. There are different kinds of auxiliary circuit and it has been named by the name of the inverter like McMurray Bedford Inverter.

We used to study in when our B.Tech. days, but now gradually it is phasing out with the invent of this actually the modern switching since power transistors are cell commutating, no special switch is required. In this circuit, the transistors are made to conduct and so that you name in such a way that actually the switches, S1, S2, S3, S4 and you can give it because you should have this subtraction and gives you 3.

Then, you can see that consecutive switches will come into the picture. If it is S1, this will be S4. If it is S2, this will be S5. If it is S3, this will be S6 and we shall assume the same thing, we are feeding highly inductive load.

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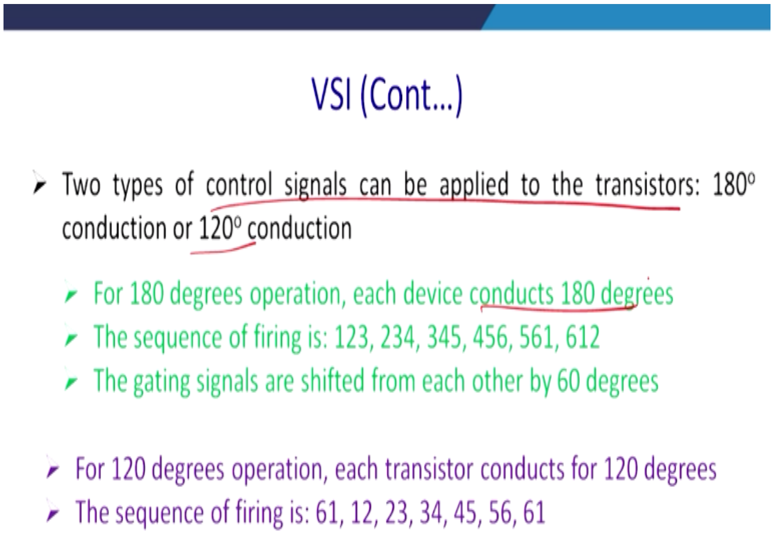

VSI (Cont...)

- Two types of control signals can be applied to the transistors: 180° conduction or 120° conduction
  - For 180 degrees operation, each device conducts 180 degrees
  - The sequence of firing is: 123, 234, 345, 456, 561, 612
  - The gating signals are shifted from each other by 60 degrees
- For 120 degrees operation, each transistor conducts for 120 degrees
- The sequence of firing is: 61, 12, 23, 34, 45, 56, 61

Now we have a different mode of conduction. One switch will conduct 120 degree and we will see that another mode 180 degree. There are 2 types of control signal can be applied to the transistors, 180 degree mode of conduction and 120 degree mode of conductions. In case of the 180 degree mode of operations, each device conducts whole half cycle, that is 180 degree and sequence of firing you will find that actually S1 if it is triggered, you will find the 3 devices will conduct at a time.

So you will find that S1, S2, S3 are 123. 123 will conduct 12 and 3, so ultimately this will conduct initially. Thereafter, next sequence will come that is 234. Thereafter 345, 456, 561 and

612. This has a sequence will gradually follow and we will find that first 2 thyristors 1 and 3 are the switches from the upper legs and 1 in lower leg will conduct. Thereafter, 1 will be the outgoing thyristors after 180 degree. So 234 will conduct incoming thyristors will be 4.

So there will be 2 thyristors from the lower leg and 1 thyristor will be from the upper leg. Similarly, this will follow. Again, there will be 2 thyristors from the upper leg, with odd number are upper and even number are for the lower leg and getting signals are shifted from each other by 60 degree. For this, for 120-degree mode of conductions, each thyristors conducts 120 degree and sequence of firing will find that 61 thereafter 12, 23, 34, 45, 56, 61.

Again it will be repeated thereafter. So first of all 61 and 6, thereafter 12, thereafter 23 and so on consecutively it will carry on. So here you can see at a time 1 thyristor or the switches from the upper leg and another from the lower leg, this is for the lower leg and this is for the upper leg will conduct. So let us see different kind of mode of conductions for 180-degree mode of conduction.

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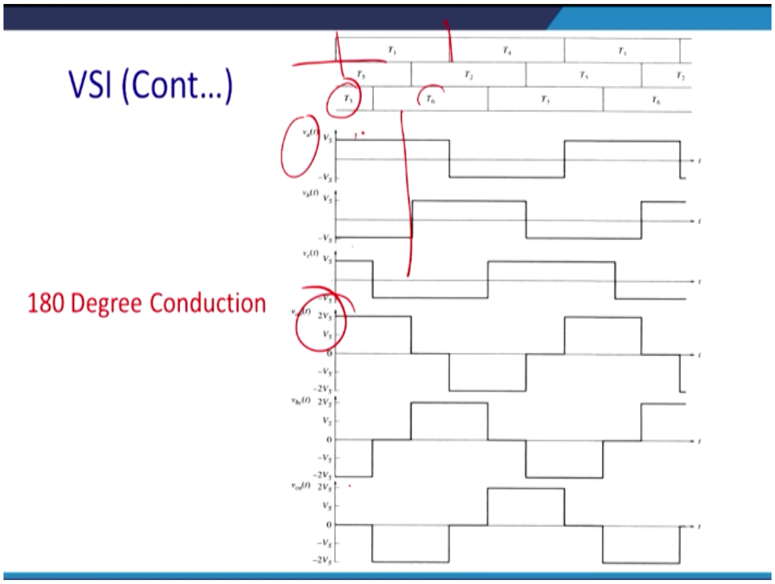

VSI (Cont...)

180 Degree Conduction

So each thyristors individually will conduct for 180 degree. So this will start at the at stop time of switch T1 and this will be T4 and this will be again T1. So after actually we can see that. Before that, T5 was conducting and when T1 comes into the picture and T3 was conducting. So you can see that at the interval what are the devices are conducting. So you can see that is T1, T2, T3, thereafter you can see that T6 comes into the picture, then T1, T2, T6 and subsequently those series will come.

So VS will be actually the VA, will have this kind of pattern and thereafter you will get PB that will be a 120 degree phase shifted and similarly you will have VC so that will be 240 degree phase shifted or 60 degree leading. Now if you subtract this, you essentially will get the line voltages PAB that is 2PS and this will be this kind of nature and so it will be steps and similarly it will be actually for CA and similarly it will be for BC and it will be for the CA.

Both will have the same relations of the same phase shift. So these are 3 line voltages and these are 3 phase voltages.

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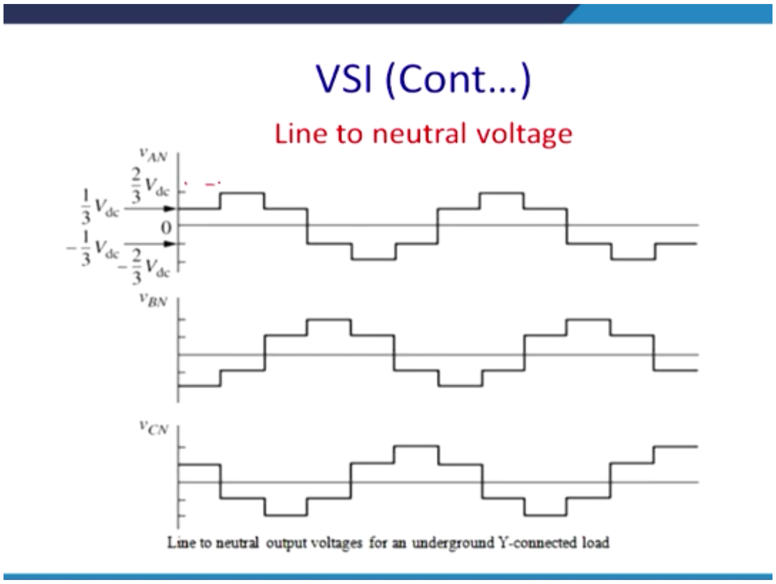

VSI (Cont...)

Line to neutral voltage

Line to neutral output voltages for an underground Y-connected load

Now you can see 1 thing. So if you can see that, so this voltage is essentially the 2/3rd of the deceivers voltage and this is basically the neutral voltage, line to neutral voltage. So you will find that a staircase voltage line to neutral in case of this 180 degree mode of conduction. Similarly, this voltage will be actually BDC/3, thereafter 2BDC/3 and so on and same staircase kind of profile will be followed.

If it is actually line to neutral output voltage for unground stair connected load, this will be the profile, you will get it in case of the phase voltages.

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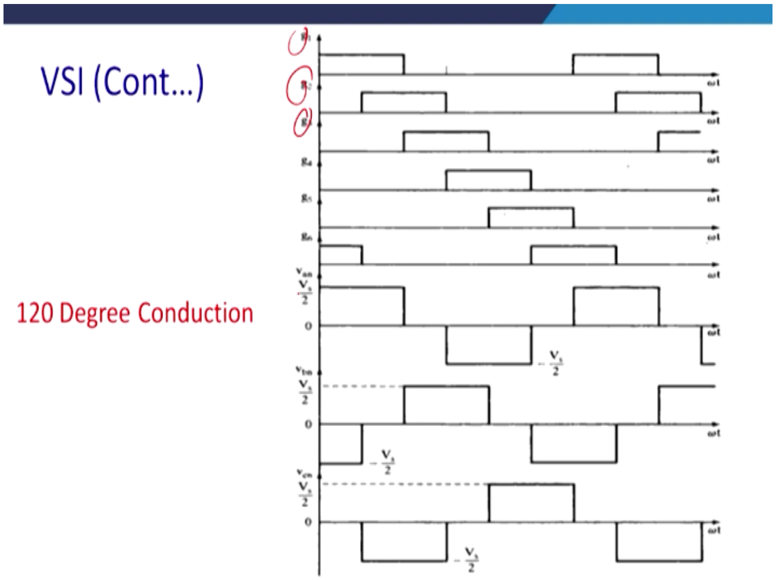

VSI (Cont...)

120 Degree Conduction

Now let us see that the conductions for 120 degrees, mode of conduction, this is G1, G2, G3, G4 and all the pulses and switches will conduct for the period of 120 degree and then we have phase shifted all these pulses will have a 60 degree phase shifted. G1 and G2 will have 60 degree phase shifted and these are the gate pulses and corresponding switches will be actually T1 or S1 as you have seen.

So this is T2 and T3 and so on. We assume that this will conduct for the same duration of their respective gate pulses. So this is basically the neutral voltage and ultimately you will see that, you know, when it is on upper thyristors was conducting 1 and lower thyristors 6 was conducting and thus you will get this voltage at 120 degree time. After that, once T1 is off, then you would not get any voltage across the BAN.

Then again after an interval of pi/6, the lower thyristors T4 is triggered and you will get –VS/2. Similarly, in this case, you know the lower thyristors was conducting for the phase B, that is basically the 2, thereafter it will be off for the period of actually 60 degree, then at this moment actually T3 will be actually switched on and will conduct till the time of another 120 degree. Similarly, this will be basically the case of first. T6 has been switched on.

Thereafter actually T2 is actually switched on, thereafter this is the case of T4 being switched on.

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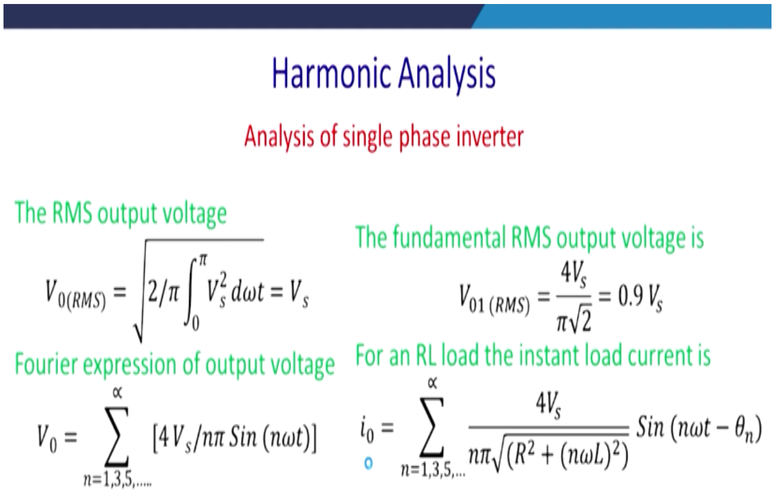

Harmonic Analysis

Analysis of single phase inverter

The RMS output voltage

$$V_{0(RMS)} = \sqrt{2/\pi \int_0^{\pi} V_s^2 \, d\omega t} = V_s$$

The fundamental RMS output voltage is

$$V_{01\,(RMS)} = \frac{4V_s}{\pi\sqrt{2}} = 0.9\,V_s$$

Fourier expression of output voltage

$$V_0 = \sum_{n=1,3,5,\ldots\ldots}^{\propto} [4\,V_s/n\pi \, Sin\,(n\omega t)]$$

For an RL load the instant load current is

$$i_0 = \sum_{n=1,3,5,\ldots}^{\propto} \frac{4V_s}{n\pi\sqrt{(R^2 + (n\omega L)^2)}} Sin\,(n\omega t - \theta_n)$$

Now harmonic analysis of it. So what should be the RMS value of the output voltage since it is an AC. We are interested to find it out this RMS value. So we require to integrate over it 2/pi 0 to pi V square ddt and you will get essentially the value=PS and now we require to find it out the individual components. So you can find it out since there is symmetry involved, so only odd harmonics will be present. So we have harmonics that is 1, 3, 5 so on to infinity.

So the fundamental RMS output voltage is V01(RMS) 4VS/pi root 2=0.9VS. For unload the instant load current is, so you can actually integrate over it 1, 3, 5 to infinity for VSn pi under root R square n omega L square sin n omega T-theta n. So this is the basically essentially you divide it by the load, you get the load current. So basically this inductive component will change and offer a different kind of impedance or different kind of different frequencies.

So it will be actually this nature. Now what should be the line voltage. Generally, what happens, this is the average value. It should be 0. So we assume that there is exact symmetry involved and we do not have any DC value and from the symmetry, we know that actually, the cos component will be 0, we are left with only the sin component and so we can see 1 thing.

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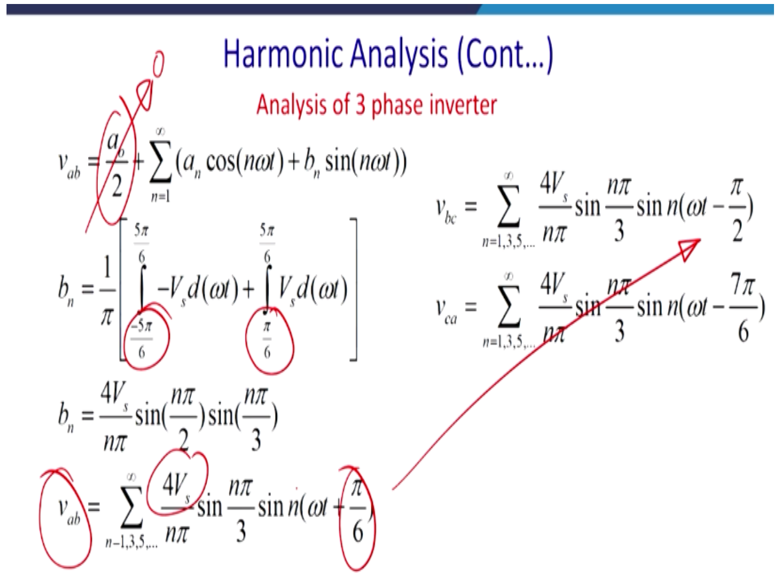

Harmonic Analysis (Cont...)

Analysis of 3 phase inverter

$$v_{ab} = \overset{0}{\cancel{\frac{a_0}{2}}} + \sum_{n=1}^{\infty}\left(a_n\cos(n\omega t) + b_n\sin(n\omega t)\right)$$

$$b_n = \frac{1}{\pi}\left[\int_{\frac{-5\pi}{6}}^{\frac{5\pi}{6}} -V_s\,d(\omega t) + \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_s\,d(\omega t)\right]$$

$$b_n = \frac{4V_s}{n\pi}\sin\left(\frac{n\pi}{2}\right)\sin\left(\frac{n\pi}{3}\right)$$

$$v_{ab} = \sum_{n=1,3,5,\ldots}^{\infty}\frac{4V_s}{n\pi}\sin\frac{n\pi}{3}\sin n\left(\omega t + \frac{\pi}{6}\right)$$

$$v_{bc} = \sum_{n=1,3,5,\ldots}^{\infty}\frac{4V_s}{n\pi}\sin\frac{n\pi}{3}\sin n\left(\omega t - \frac{\pi}{2}\right)$$

$$v_{ca} = \sum_{n=1,3,5,\ldots}^{\infty}\frac{4V_s}{n\pi}\sin\frac{n\pi}{3}\sin n\left(\omega t - \frac{7\pi}{6}\right)$$

That you know till -5pi/6 to +5pi/6 a voltage actually for the phase A is –VS. Thereafter, till this value, it is positive. So you can calculate and while by integration, the value of BAn will come out to be 4VS/nPi where n can be any integer sin n pi/2sin n pi/3. So this will be the basically the BM. So what should be the value of AB, AB will be essentially you subtract. So you will get 1, 3, 5 0 to infinity 4VS/n pi/sin n pi/3 sin n omega T+pi/6.

So similarly you will get these values R 120 degree phase shifted. So these values will lead the phase value by 30 degree, so it is +pi/6, here it is instead of -120 degrees pi/2 and here it is another phase shifted by 120 degrees that is 7pi/6. So this will be the expressions of the 3 voltages.

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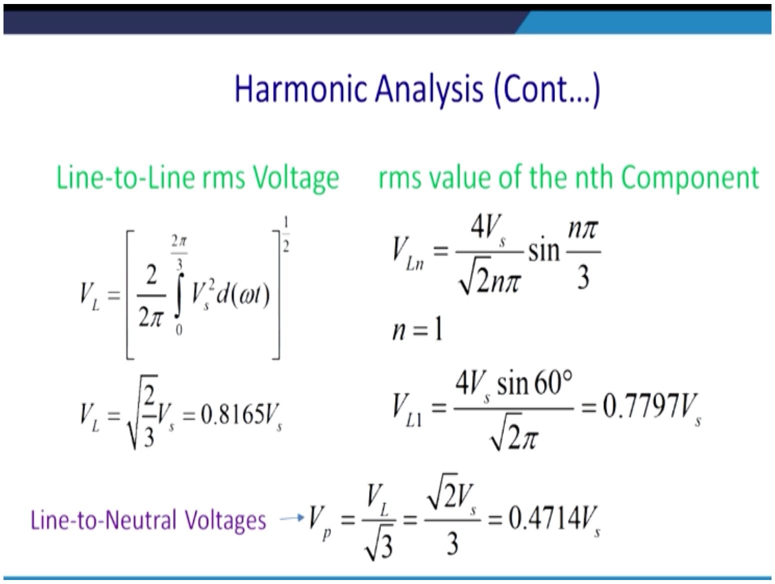

Harmonic Analysis (Cont...)

Line-to-Line rms Voltage

$$V_L = \left[\frac{2}{2\pi}\int_0^{\frac{2\pi}{3}} V_s^2\, d(\omega t)\right]^{\frac{1}{2}}$$

$$V_L = \sqrt{\frac{2}{3}}V_s = 0.8165V_s$$

rms value of the nth Component

$$V_{Ln} = \frac{4V_s}{\sqrt{2}n\pi}\sin\frac{n\pi}{3}$$

$$n = 1$$

$$V_{L1} = \frac{4V_s \sin 60^\circ}{\sqrt{2}\pi} = 0.7797V_s$$

Line-to-Neutral Voltages $\rightarrow V_p = \frac{V_L}{\sqrt{3}} = \frac{\sqrt{2}V_s}{3} = 0.4714V_s$

Now harmonic analysis, so what is the amount of the harmonic present into the system. So line to line voltage, RMS value of the component. So VL of course this voltage across the inductor you can integrate over it. So 2/2pi, actually you will know that it will conduct for a period of 2pi/3, so V square S ddt1/2. So this value will be root 2/root 3*VS that is 0.8165 something like that.

So similarly RMS values for the n-th component you will have to actually find the n-th value and you will get 4VS/under root 2n pi sin n pi/3 for n=1, you will get P1=this value. So line neutral voltage will be essentially VL/root 3 is basically root 2VS/3 that is 0.471. So this will be the values for the line to neutral voltage.

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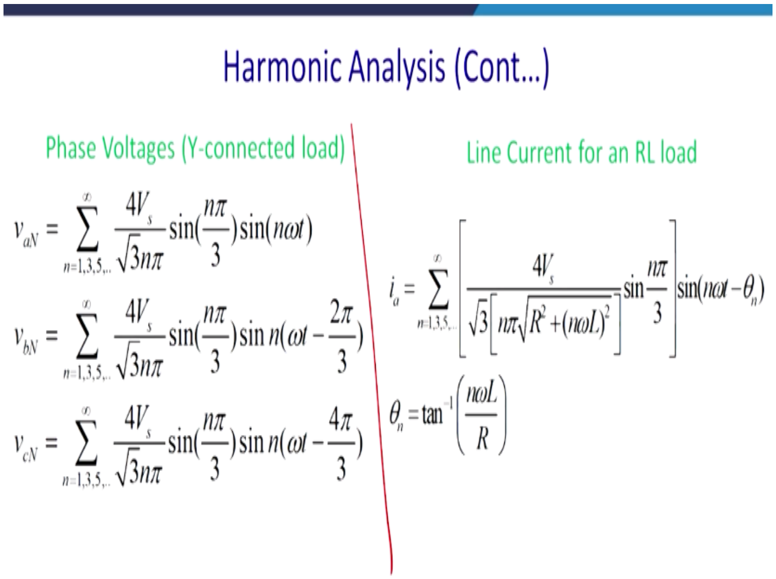

Harmonic Analysis (Cont...)

Phase Voltages (Y-connected load)

$$v_{aN} = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi}\sin(\frac{n\pi}{3})\sin(n\omega t)$$

$$v_{bN} = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi}\sin(\frac{n\pi}{3})\sin n(\omega t-\frac{2\pi}{3})$$

$$v_{cN} = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi}\sin(\frac{n\pi}{3})\sin n(\omega t-\frac{4\pi}{3})$$

Line Current for an RL load

$$i_a = \sum_{n=1,3,5,..}^{\infty}\left[\frac{4V_s}{\sqrt{3}\left[n\pi\sqrt{R^2+(n\omega L)^2}\right]}\sin\frac{n\pi}{3}\right]\sin(n\omega t-\theta_n)$$

$$\theta_n = \tan^{-1}\left(\frac{n\omega L}{R}\right)$$

Similarly, we can connect the value for the Y connected load and so you can calculate, you can substitute the previous values. So these will be values for the actually the different phase voltages. Thank you for your attention. We shall continue our discussion from this point from your next class. Thank you.