Power Electronics and Distributed Generation

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Module - 3
Lecture - 38
Examples in power electronic design for DG system continued

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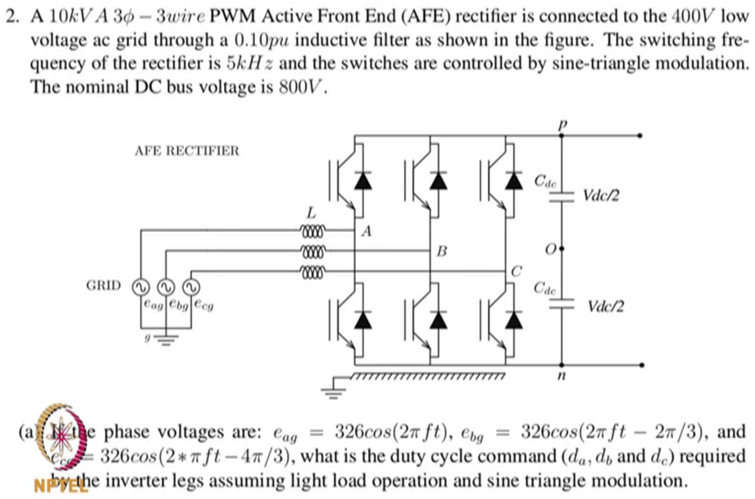

2. A $10kVA$ $3\phi - 3wire$ PWM Active Front End (AFE) rectifier is connected to the $400V$ low voltage ac grid through a $0.10pu$ inductive filter as shown in the figure. The switching frequency of the rectifier is $5kHz$ and the switches are controlled by sine-triangle modulation. The nominal DC bus voltage is $800V$.

(a) If the phase voltages are: $e_{ag} = 326cos(2\pi ft)$, $e_{bg} = 326cos(2\pi ft - 2\pi/3)$, and $e_{cg} = 326cos(2 * \pi ft - 4\pi/3)$, what is the duty cycle command (d_a, d_b and d_c) required by the inverter legs assuming light load operation and sine triangle modulation.

Welcome to class 38 in topics in power electronics and distributed generation. In the last class, we have been looking at an example of a 10 kV A 3 phase inverter and at 400 volts are AC connected to the grid, and through a filter inductance and we are looking at different aspects of the problem. We looked at what duty cycle commands would be required at certain instance of time.

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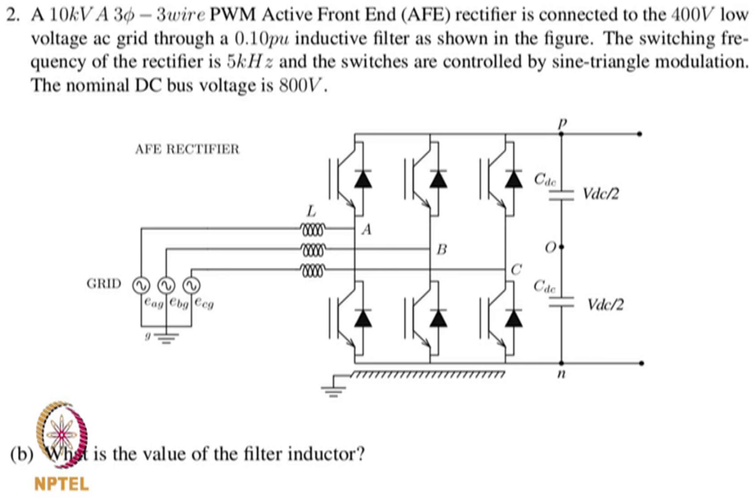
2. A $10kVA\ 3\phi - 3wire$ PWM Active Front End (AFE) rectifier is connected to the $400V$ low voltage ac grid through a $0.10pu$ inductive filter as shown in the figure. The switching frequency of the rectifier is $5kHz$ and the switches are controlled by sine-triangle modulation. The nominal DC bus voltage is $800V$.

(b) What is the value of the filter inductor?

Then we looked at what would be the value of filtered inductor.

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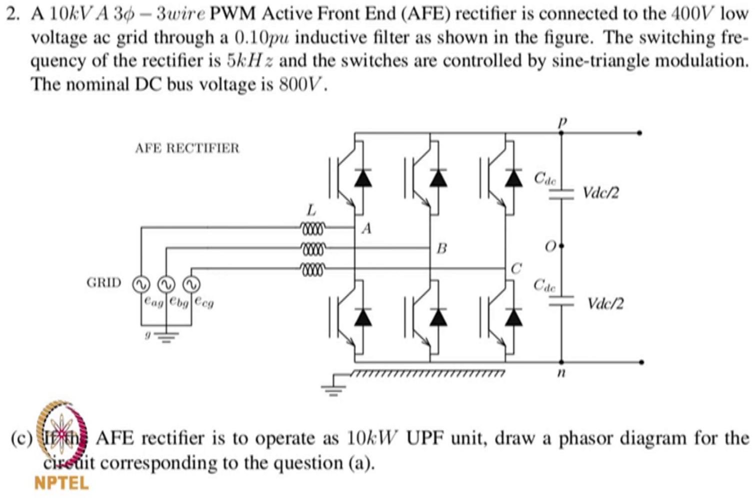
2. A $10kVA\ 3\phi - 3wire$ PWM Active Front End (AFE) rectifier is connected to the $400V$ low voltage ac grid through a $0.10pu$ inductive filter as shown in the figure. The switching frequency of the rectifier is $5kHz$ and the switches are controlled by sine-triangle modulation. The nominal DC bus voltage is $800V$.

(c) If the AFE rectifier is to operate as $10kW$ UPF unit, draw a phasor diagram for the circuit corresponding to the question (a).

We looked at the phasor diagram for operation as a unity power factor active rectifier.

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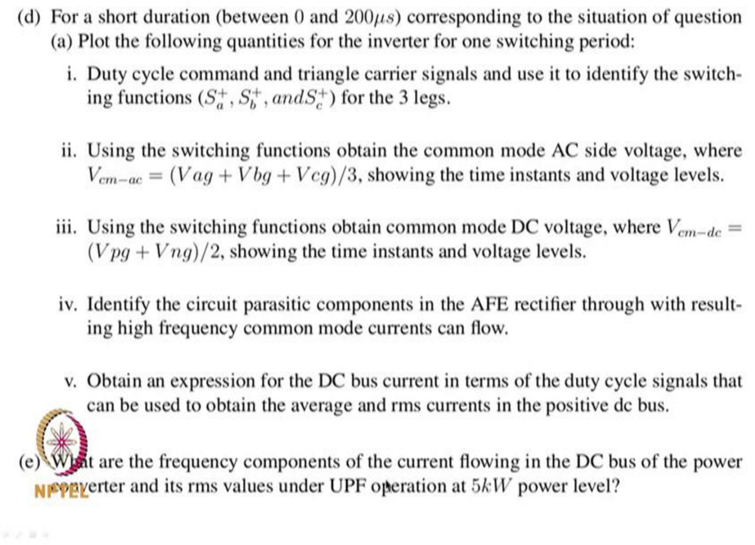

(d) For a short duration (between 0 and $200\mu s$) corresponding to the situation of question (a) Plot the following quantities for the inverter for one switching period:

i. Duty cycle command and triangle carrier signals and use it to identify the switching functions $(S_a^+, S_b^+, andS_c^+)$ for the 3 legs.

ii. Using the switching functions obtain the common mode AC side voltage, where $V_{cm-ac} = (Vag + Vbg + Vcg)/3$, showing the time instants and voltage levels.

iii. Using the switching functions obtain common mode DC voltage, where $V_{cm-dc} = (Vpg + Vng)/2$, showing the time instants and voltage levels.

iv. Identify the circuit parasitic components in the AFE rectifier through with resulting high frequency common mode currents can flow.

v. Obtain an expression for the DC bus current in terms of the duty cycle signals that can be used to obtain the average and rms currents in the positive dc bus.

(e) What are the frequency components of the current flowing in the DC bus of the power converter and its rms values under UPF operation at $5kW$ power level?

And then we looked at for shoot short durations of time, what the switching function would be for the 3 legs. What the common mode voltage would be on the AC side and the DC side? And then we looked at the parasitic components of the power converter through which these common mode currents could potentially flow. Then, we looked at the expression for the DC bus current, and we looked at the different frequency components of the DC bus current, and its rms levels under previous operating conditions.

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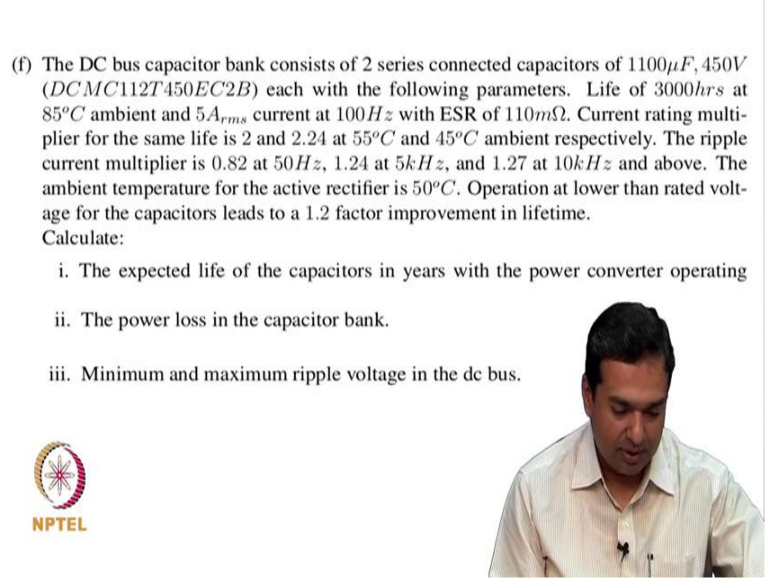

(f) The DC bus capacitor bank consists of 2 series connected capacitors of $1100\mu F, 450V$ $(DCMC112T450EC2B)$ each with the following parameters. Life of $3000hrs$ at 85^oC ambient and $5A_{rms}$ current at $100Hz$ with ESR of $110m\Omega$. Current rating multiplier for the same life is 2 and 2.24 at 55^oC and 45^oC ambient respectively. The ripple current multiplier is 0.82 at $50Hz$, 1.24 at $5kHz$, and 1.27 at $10kHz$ and above. The ambient temperature for the active rectifier is 50^oC. Operation at lower than rated voltage for the capacitors leads to a 1.2 factor improvement in lifetime.

Calculate:

i. The expected life of the capacitors in years with the power converter operating

ii. The power loss in the capacitor bank.

iii. Minimum and maximum ripple voltage in the dc bus.

So, we use that to then, look at what would be the life time of the capacitor, the power loss in the capacitor bank. And the minimum and maximum voltage on the DC bus in terms of looking at the DC bus ripple, and we did that for assuming operation and a balance conditions. We looked at currents at 5 kilo watt power level and at full rated 10 kV A operating conditions.

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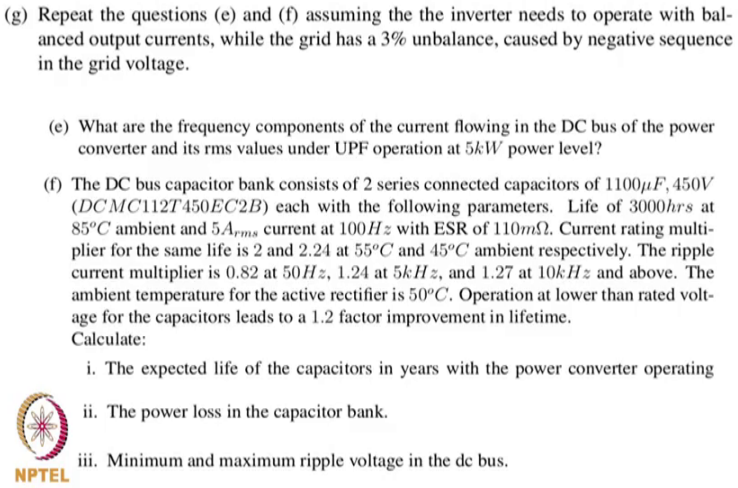

(g) Repeat the questions (e) and (f) assuming the the inverter needs to operate with balanced output currents, while the grid has a 3% unbalance, caused by negative sequence in the grid voltage.

(e) What are the frequency components of the current flowing in the DC bus of the power converter and its rms values under UPF operation at $5kW$ power level?

(f) The DC bus capacitor bank consists of 2 series connected capacitors of $1100\mu F, 450V$ $(DCMC112T450EC2B)$ each with the following parameters. Life of $3000hrs$ at 85^oC ambient and $5A_{rms}$ current at $100Hz$ with ESR of $110m\Omega$. Current rating multiplier for the same life is 2 and 2.24 at 55^oC and 45^oC ambient respectively. The ripple current multiplier is 0.82 at $50Hz$, 1.24 at $5kHz$, and 1.27 at $10kHz$ and above. The ambient temperature for the active rectifier is 50^oC. Operation at lower than rated voltage for the capacitors leads to a 1.2 factor improvement in lifetime.
Calculate:

i. The expected life of the capacitors in years with the power converter operating

ii. The power loss in the capacitor bank.

iii. Minimum and maximum ripple voltage in the dc bus.

So, in the next part of the problem we are looking at when you have a 3 percent unbalance in the grid voltage. And what would be the effect on the frequency components on the currents, and what would be the life time of the, of the capacitors of power loss in the capacitor, and the ripple on the DC bus under a, when you have a 3 percent imbalance? So, under when you had balanced operation, the numbers that we calculated was our power loss, in our power loss in the capacitor was 5.6 watts.

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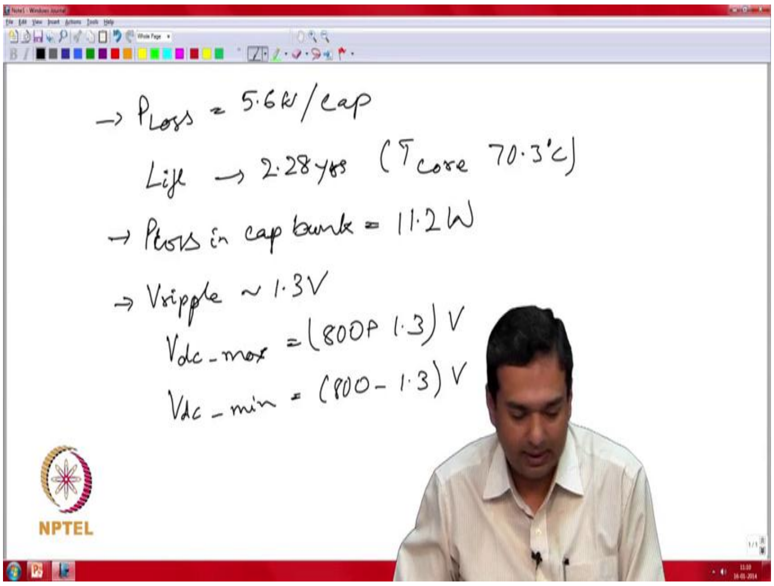

→ $P_{Loss} = 5.6W/cap$

Life → 2.28 yrs (T_{core} 70.3°C)

→ P_{loss} in cap bank = 11.2 W

→ $V_{ripple} \sim 1.3V$

$V_{dc-max} = (800 + 1.3)V$

$V_{dc-min} = (800 - 1.3)V$

And then, we use that to evaluate the temperature of the core of the capacitor. And the temperature we got to be 70.3 degree centigrade, and we got a life of 2.28 years, and our core temperature was 70.3 degree centigrade. And, the power loss in the bank is 11.2 watts because there are 2 capacitors in the bank, upper and the lower capacitor. And then, when we looked at the ripple voltage, we saw that the ripple voltage was dominated by the ESR effect, because the ripple current is at high frequency in this balanced operation. And we saw that the ripple voltage due to the capacitive effect had a amplitude of 3.6 volts, whereas due to the ESR the amplitude was 6.3 volts.

So, the ripple on the capacitor bank, which consists of 2 capacitors, is about 1.3 volts and so we would have V dc max of 800 plus 1.3, and so this appears the high frequency as a band around the nominal 800 volts.

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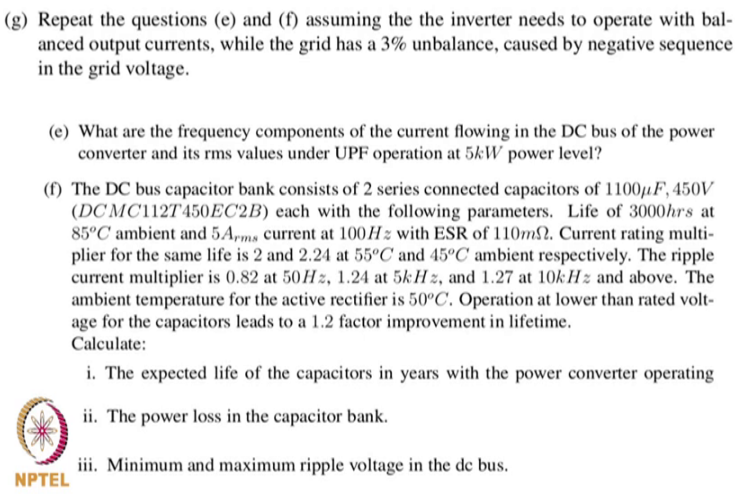

(g) Repeat the questions (e) and (f) assuming the the inverter needs to operate with balanced output currents, while the grid has a 3% unbalance, caused by negative sequence in the grid voltage.

(e) What are the frequency components of the current flowing in the DC bus of the power converter and its rms values under UPF operation at $5kW$ power level?

(f) The DC bus capacitor bank consists of 2 series connected capacitors of $1100\mu F, 450V$ ($DCMC112T450EC2B$) each with the following parameters. Life of $3000hrs$ at 85^oC ambient and $5A_{rms}$ current at $100Hz$ with ESR of $110m\Omega$. Current rating multiplier for the same life is 2 and 2.24 at 55^oC and 45^oC ambient respectively. The ripple current multiplier is 0.82 at $50Hz$, 1.24 at $5kHz$, and 1.27 at $10kHz$ and above. The ambient temperature for the active rectifier is 50^oC. Operation at lower than rated voltage for the capacitors leads to a 1.2 factor improvement in lifetime.
Calculate:

i. The expected life of the capacitors in years with the power converter operating

ii. The power loss in the capacitor bank.

iii. Minimum and maximum ripple voltage in the dc bus.

So, the next part of the problem we are looking at that the 3 percent imbalance, and what would be the resulting quantities that would need to be evaluated on a similar manner.

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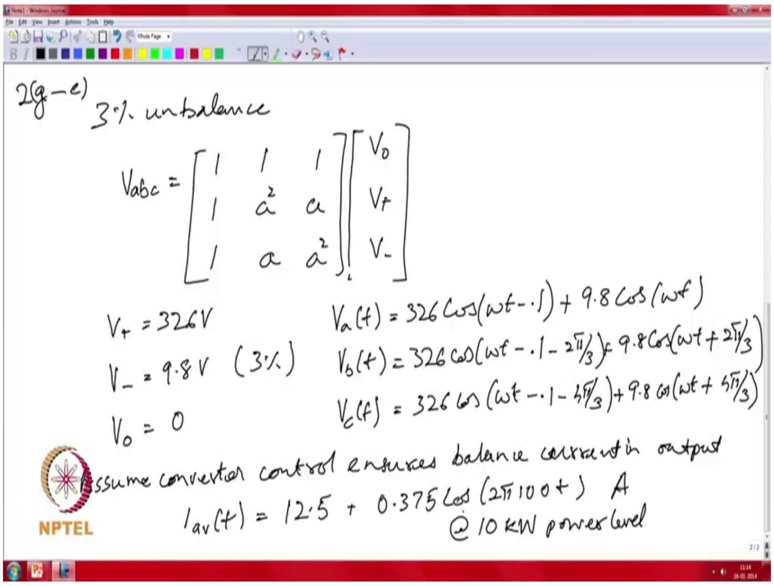

2(g-e) 3% unbalance

$$V_{abc} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix}$$

$V_+ = 326V$

$V_- = 9.8V$ (3%)

$V_0 = 0$

$V_a(t) = 326\cos(\omega t - .1) + 9.8\cos(\omega t)$

$V_b(t) = 326\cos(\omega t - .1 - 2\pi/3) + 9.8\cos(\omega t + 2\pi/3)$

$V_c(t) = 326\cos(\omega t - .1 - 4\pi/3) + 9.8\cos(\omega t + 4\pi/3)$

Assume converter control ensures balance current in output

$I_{av}(t) = 12.5 + 0.375\cos(2\pi 100t)$ A

@ 10 kW power level

So, if you have the 3 percent unbalance, we are talking about in terms of the a, b, c voltages, we are looking at the from a symmetrical component analysis, you would be able to see what the voltages are. So, we can write the symmetrical voltage and transformations, symmetrical confidence transformation V 0, V plus, V minus, and V plus is 326 volts which is our amplitude of the lint neutral voltage when your lint line rms is 400 volts.

And your negative sequence voltage is 9.8 volts, which corresponds to 3 percent of a positive sequence voltage, and as well as sequence voltage is 0. Using this, you can calculate what your V a, V b and V c are, the 0.1 radiant angle difference is from the previous phase power analyses required for power transfer, and V b. So, the signs of 2 pi by 3 is opposite, because this is a negative sequence quantity.

So, we could than make use of the quantities a, b, c voltages and will also assume that the converter still operates with balance currents in its output. You could using the average model come up with your I average would be 12.5 plus 0.375 cos 2 pi 100 t amperes. This is at 10 kilo watt and power level of operation at 400 volts.

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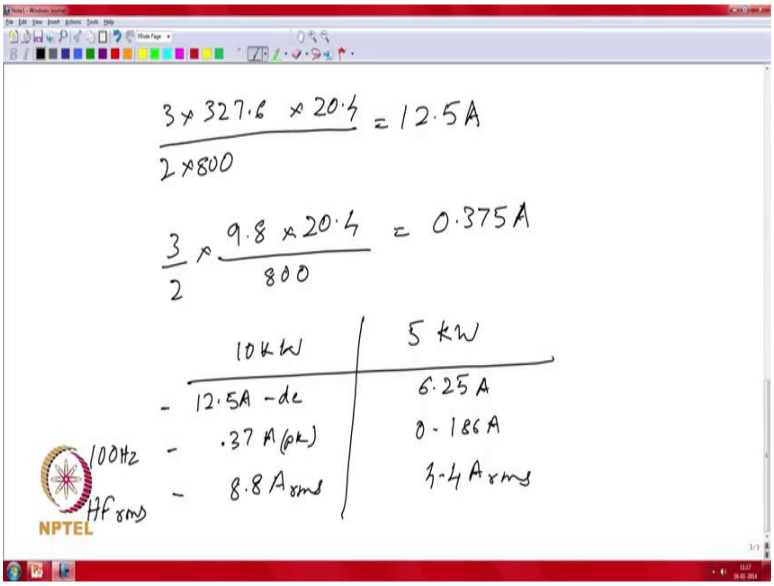

$$\frac{3 \times 327.6 \times 20.4}{2 \times 800} = 12.5A$$

$$\frac{3}{2} \times \frac{9.8 \times 20.4}{800} = 0.375A$$

	10 kW	5 kW
-	12.5A - dc	6.25 A
100Hz -	.37 A (pk)	0.186 A
HF rms -	8.8 A rms	4.4 A rms

So, you could see what this 12.5 and 3.75 numbers correspond to your 12.5 is essentially 3 into 327.6 into 20.4 divided by 800, which is a DC bus voltage 3 by 2 into 800. So, this is the 12.5, 327.6 is the amplitude of your positive sequence voltage. 20.4 is essentially 14.4 amps correspond to 10 kV A operation of a 3 phase power converter at 10 kV A, and the amplitude would be root 2 times 14.4, which is 20.4. So, you get that to be your from your DC power transfer, and your interaction of the positive sequence current and your negative sequence voltage 9.8 volts times your positive sequence current would give your 100 hertz ripple.

In additions to that, you have the high frequency ripple current. So, you could then evaluate your overall spectrum of the currents, that would be flowing through your DC link. So, at 10 kilo watt power level, also at 5 kilo watt power level, you have 12.5 amps DC at 10 kilo watts or half of that 6.25 amps at 5 kilo watt power level. If you look at here, 100 hertz, you have 0.37 amps peak or 0.186 amps at 5 kilo watt power level and your high frequency rms. This occurs at the switching frequency and its harmonics, this is 8.8 amps rms and 4.4 amps, rms at 5 kilo watt power level. And you could use this numbers to evaluate your temperature losses in the capacitor bank, and the corresponding temperature rise.

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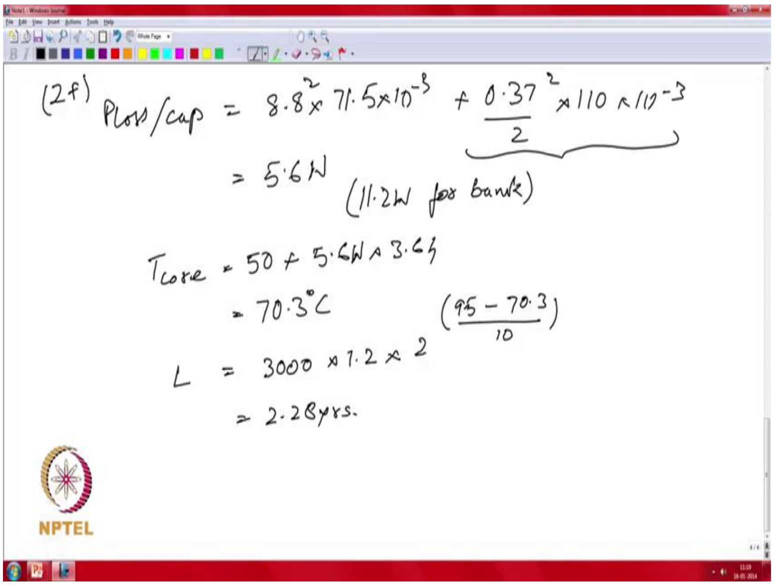

(2f)

$$P_{loss}/cap = 8.8^2 \times 71.5\times10^{-3} + \underbrace{\frac{0.37}{2}^{2} \times 110 \times 10^{-3}}$$

$$= 5.6W \quad (11.2W \text{ for bank})$$

$$T_{core} = 50 + 5.6W \times 3.64$$

$$= 70.3^{\circ}C$$

$$L = 3000 \times 1.2 \times 2^{\left(\frac{95-70.3}{10}\right)}$$

$$= 2.28 \text{yrs.}$$

So, the losses in this particular case, our loss per capacitor is 8.8 square that is the high frequency rms current times 71.5 mini ohms resistance ESR plus 0.37. So, this turns out to be the same 5.6 watts, because the quantity due to the unbalance is quite negligible compare to the quantity 8.8 amps flowing at the high frequencies. So, you have 5.6 watts for the capacitor bank, and 11.2 for the capacitor, and 11.2 watts for the overall bank. And because the power dissipation is not changed, your core temperature stays the same is 50 degree ambient plus 5.6 watts into 3.64, which was a thermal resistance that we calculated.

So, this turns out to be the same temperature 70.3 degree centigrade. So, your life time stays the same, which is 3000 hours into 1.2 factor into 2 to the power of 95 minus 70.3

by 10. So, this turns out to be again 2.28 years, so the 3 percent unbalance did not cause a change in the life time because the power dissipation stayed the same.

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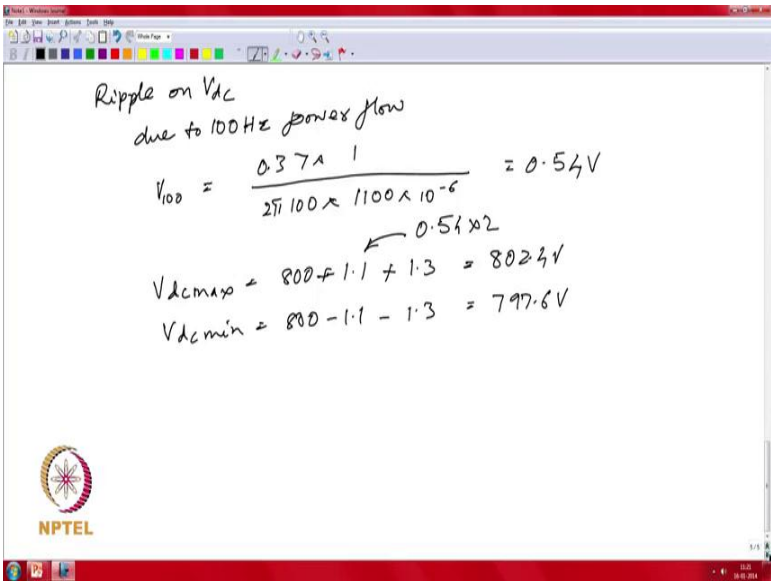

Ripple on V_{dc}

due to 100Hz power flow

$$V_{100} = \frac{0.37 \times 1}{2\pi 100 \times 1100 \times 10^{-6}} = 0.54V$$

$$\underset{\substack{\uparrow \\ 0.54 \times 2}}{}$$

$$V_{dcmax} = 800 + 1.1 + 1.3 = 802.4V$$

$$V_{dcmin} = 800 - 1.1 - 1.3 = 797.6V$$

But if you look at it from the perspective of the DC bus ripple, you have due to 100 hertz, you have V 100, the 100 hertz component is 0.37 into the impedance 1 by 2 pie 100 into 1100 microfarads capacitors.

So, this is 0.54 volts per capacitors so the overall bank would see about 1.1 volt. So, this would be an addition to the high frequency ripple, that shows up and due to the ESR effects, so your V dc max, so this is 0.54 into 2. So, about 2 volts amplitude ripple riding over the, over the DC bus. So, you can see that in terms of the unbalance, there was a effect on the ripple, but not much in terms of participation or life time projection.

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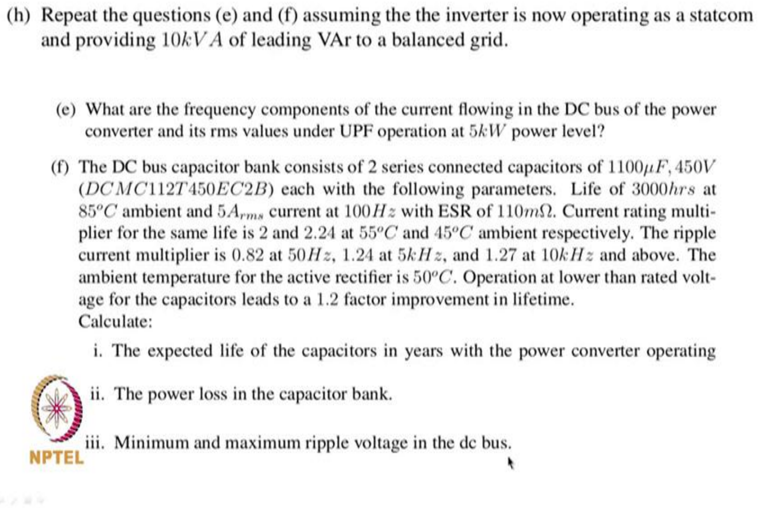

(h) Repeat the questions (e) and (f) assuming the the inverter is now operating as a statcom and providing $10kVA$ of leading VAr to a balanced grid.

(e) What are the frequency components of the current flowing in the DC bus of the power converter and its rms values under UPF operation at $5kW$ power level?

(f) The DC bus capacitor bank consists of 2 series connected capacitors of $1100\mu F, 450V$ ($DCMC112T450EC2B$) each with the following parameters. Life of $3000hrs$ at 85^oC ambient and $5A_{rms}$ current at $100Hz$ with ESR of $110m\Omega$. Current rating multiplier for the same life is 2 and 2.24 at 55^oC and 45^oC ambient respectively. The ripple current multiplier is 0.82 at $50Hz$, 1.24 at $5kHz$, and 1.27 at $10kHz$ and above. The ambient temperature for the active rectifier is 50^oC. Operation at lower than rated voltage for the capacitors leads to a 1.2 factor improvement in lifetime.
Calculate:

i. The expected life of the capacitors in years with the power converter operating

ii. The power loss in the capacitor bank.

iii. Minimum and maximum ripple voltage in the dc bus.

In the, in the last part of the problem, you are asked to repeat the, again this calculation when the inverter is operating as a statcom providing 10 kV A leading VAr to the grid to a balanced grid. So, you could do a similar calculation and identify the frequency components of the current, then use at to calculate the expected life of the capacitor. The power loss in the capacitor bank and the ripple on the DC bus, a similar procedure could be adopted and I will just mention the answers in this particular case.

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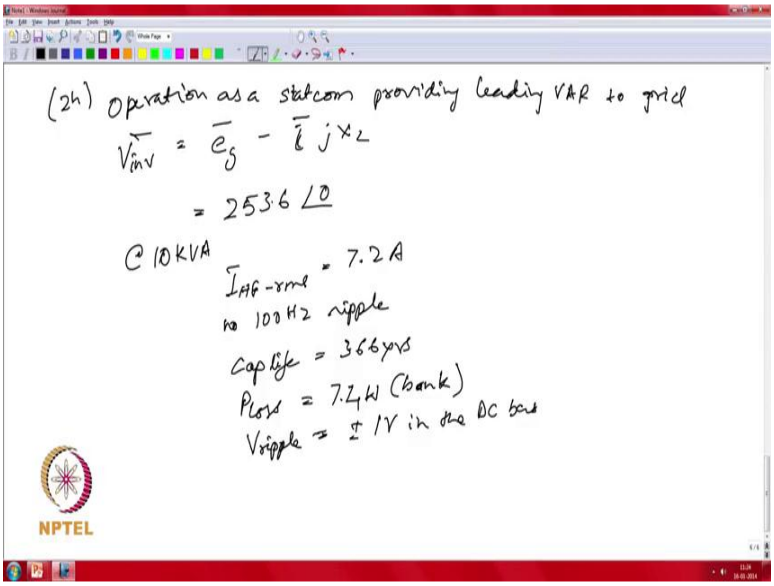

(2h) operation as a statcom providing leading VAR to grid

$\overline{V_{inv}} = \overline{e_g} - \overline{i}\, jX_L$

$= 253.6 \angle 0$

@ 10KVA

$\overline{I_{AF-rms}} = 7.2A$

no 100Hz ripple

Cap life = 366yrs

$P_{loss} = 7.4W$ (bank)

$V_{ripple} = \pm 1V$ in the DC bus

So, in this particular case your inverter voltage, terminal voltage is higher 253.6 at angle 0, and at 10 kV A your high frequency rms current turns out to be lower it is 7.2 amps, and there is a no 100 hertz ripple, because there is no unbalance. And your life time of your capacitance is particular keys works out to be 3.66 years. And your power loss in the capacitor bank is 7.4 watts in the bank. And your ripple is plus or minus 1 volt in the DC bus due to the high frequency ESR of the capacitor. So, you can see that once you have the procedure for evaluating these components, you could apply it for a variety of conditions, and see how your DC bus capacitor would be operating.

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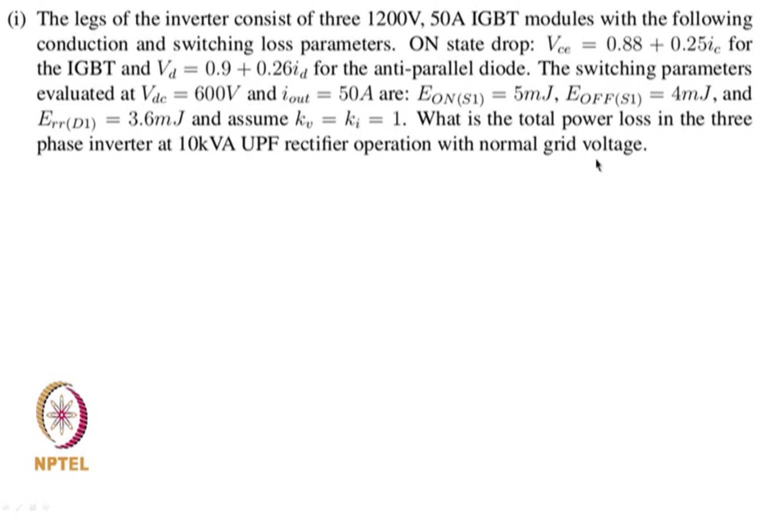

(i) The legs of the inverter consist of three 1200V, 50A IGBT modules with the following conduction and switching loss parameters. ON state drop: $V_{ce} = 0.88 + 0.25i_c$ for the IGBT and $V_d = 0.9 + 0.26i_d$ for the anti-parallel diode. The switching parameters evaluated at $V_{dc} = 600V$ and $i_{out} = 50A$ are: $E_{ON(S1)} = 5mJ$, $E_{OFF(S1)} = 4mJ$, and $E_{rr(D1)} = 3.6mJ$ and assume $k_v = k_i = 1$. What is the total power loss in the three phase inverter at 10kVA UPF rectifier operation with normal grid voltage.

In the last part of the problem, you are told to evaluate asked to evaluate the losses in the semiconductor devices. The 3 legs of the inverter consist of 1200 volt, 50 amp IGBT modules, and the conduction in switching loss parameters are for the IGBT. The collector meter voltage on during on condition is 0.88 volts plus the resistive term of 0.25 times i c. For similarly, for the diode you have a fix on state voltage term of 0.9 volts as a resistive term of 0.26 times your diode current.

The switching parameter for the, for the loss parameter are evaluated at a DC bus voltage of 600 volts and at 50 amps, and the on state loss of the switch is 5 mille joules. Under these conditions, of switching off loss, turn off loss is 4 mille joules for the diode for reverse recovery it is 3.6 mille joules. And we are assuming the scaling factor for voltage and current to be equal to 1. So, you are asked to evaluate the total power loss in the 3 phase inverter, operating as a active rectifier under normal grid voltage.

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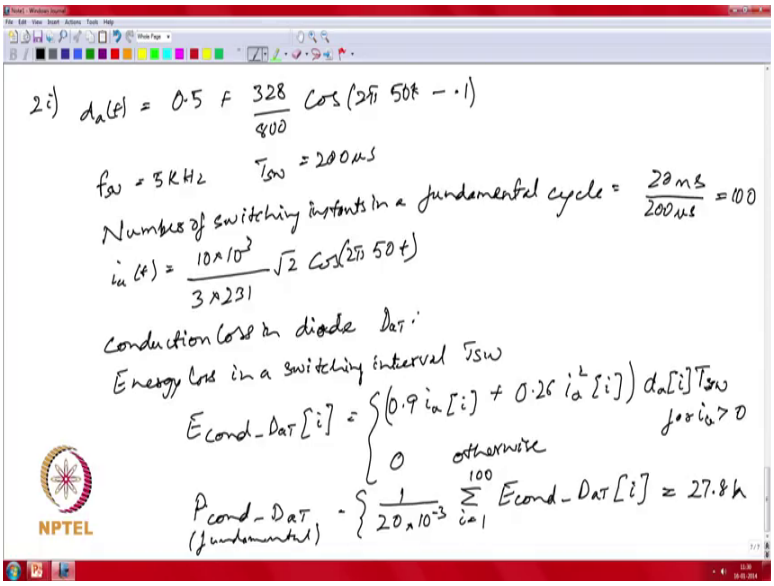

2i) $d_a(t) = 0.5 + \frac{328}{800}\cos(2\pi 50t - .1)$

$f_{sw} = 5\,KHz$ $\quad T_{sw} = 200\,\mu s$

Number of switching instants in a fundamental cycle = $\frac{20\,ms}{200\,\mu s} = 100$

$i_a(t) = \frac{10 \times 10^3}{3 \times 231}\sqrt{2}\cos(2\pi 50t)$

Conduction loss in diode D_{aT}:

Energy loss in a switching interval T_{sw}

$$E_{cond\_D_{aT}}[i] = \begin{cases} (0.9\, i_a[i] + 0.26\, i_a^2[i])\, d_a[i] T_{sw} & \text{for } i_a > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\underset{(\text{fundamental})}{P_{cond\_D_{aT}}} = \frac{1}{20 \times 10^{-3}} \sum_{i=1}^{100} E_{cond\_D_{aT}}[i] = 27.8\,h$$

So, to evaluate this, we will look at the losses in each component, the diodes and the switch. So, the first thing to look at is what your duty cycle of each leg would be your duty cycle will be 0.5 plus 328 by 800 times cos 2 pie 50 t minus 0.1. And these were numbers that we got from the phasor analysis. We have the switching frequency FSW to be 5 kilo hertz, which means that your switching period is 200 microseconds. So, the number of switching instance in a fundamental cycle is 20 milliseconds divided by 200 microseconds.

So, you have 100 switching instance. You also have your phase current i a of t is 10 into 10 to the power of 3 divided by 3 into 231 times square root of 2 to get the peak. So, at 10 kilo watt power level. So, you could use that to then evaluate the conduction laws. So, starting with conduction laws in the diode, so a top diode D a, the energy loss can be evaluated over a switching interval. Your conduction laws is for D a top diode at each switching interval is given by 0.9 times i a at instant i responds to 6 into i a square at instant i for a duration of D a at the i th instant times your switching duration TSW, and for i a which is positive or 0 otherwise.

When i a is negative and then your conduction loss term over a fundamental is given by 1 by 20 milliseconds 20 into 10 power of minus 3 summation of the energy loss terms from i is equal to 1 and there are 100 points over a fundamental. So you have, and this number adds up to be equal to 27.8 watts. Similarly, you could calculate the conduction loss in the, in the IGBT.

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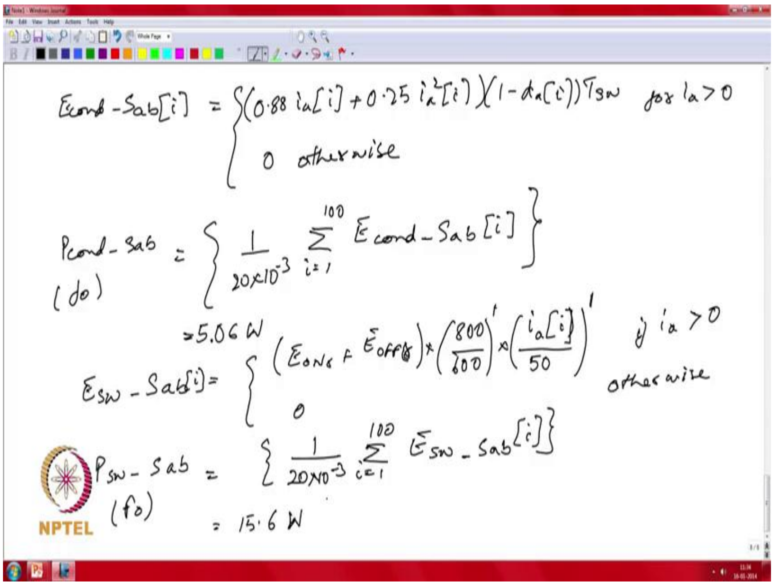

$$E_{cond}-S_{ab}[i] = \begin{cases} (0.88\, i_a[i] + 0.25\, i_a^2[i])(1-d_a(i))T_{sw} & \text{for } i_a > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\underset{(do)}{P_{cond}-S_{ab}} = \left\{ \frac{1}{20\times10^{-3}} \sum_{i=1}^{100} E_{cond}-S_{ab}[i] \right\}$$

$$= 5.06\ W$$

$$E_{sw}-S_{ab}[i] = \begin{cases} (E_{ONR} + E_{offR}) \times \left(\frac{800}{600}\right)^1 \times \left(\frac{i_a[i]}{50}\right)^1 & \text{if } i_a > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\underset{(fo)}{P_{sw}-S_{ab}} = \left\{ \frac{1}{20\times10^{-3}} \sum_{i=1}^{100} E_{sw}-S_{ab}[i] \right\}$$

$$= 15.6\ W$$

So, you have conduction loss and IGBT S a, the bottom IGBT at instant i, it is given by 0.88 times i a of i plus 0.25 i a square of i, and it is operating for a duration of 1 minus D a of i times T sw. When i a is greater than 0, and 0 otherwise and then, to transfer from the conduction to the energy to power over a fundamental cycle, intimated seconds summation i is equal to 1 to 100 of E conduction of S ab of i, and this turns out to be 5.06 watts. Then the remaining term need to be evaluated would be the switching loss term in the IGBT and the switching loss term of the diode.

So, you have for the IGBT S a bottom at instant i is your E on at rated condition plus E off, at rated condition times your actual DC bus voltage is 800 volts, the rated conditions specified is at 600 volts to the power of k v which is 1. And i a at instant i and 50 years the rated condition again to the exponent 1 if i a is positive and 0 otherwise. So, you could then transfer from your energy to your power over the fundamental switching loss, power loss in the IGBT over a fundamental to be equal to 1 by your duration 20 milliseconds, the summation of your loss i 1 to 100 of ESW, S ab of i. And this turns out to be 15.6 watts for this particular operating condition the 10 kilo watt operating condition as active rectifier.

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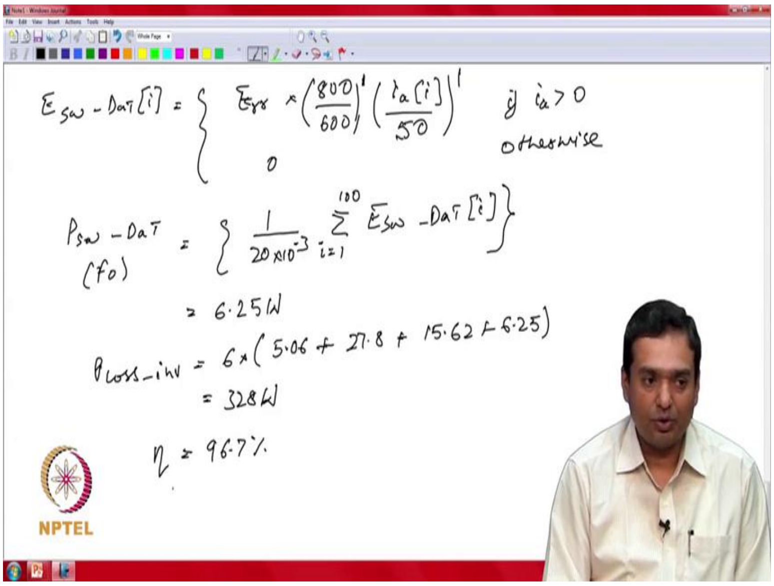

$$E_{sw-DaT}[i] = \begin{cases} E_{rr} \times \left(\frac{800}{600}\right)^1 \left(\frac{i_a[i]}{50}\right)^1 & \text{if } i_a > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\underset{(f_0)}{P_{sw-DaT}} = \left\{ \frac{1}{20 \times 10^{-3}} \sum_{i=1}^{100} E_{sw-DaT}[i] \right\}$$

$$= 6.25\,W$$

$$P_{loss-inv} = 6 \times (5.06 + 27.8 + 15.62 + 6.25)$$

$$= 328\,W$$

$$\eta = 96.7\%$$

If you look at the switching loss in the diode, the anti parallel diode, you have the reverse recovery term under nominal condition, times your 800 by 600 the part of k v. Again, we have taken this as 1, it could be a number less than 1 more commonly, and again i a of i divided by 50. Again, for reverse recovery it is a number typically less than 1, but we have taken it as 1, for i a greater than 0 and 0 otherwise.

So, again you calculate your power from your energy over a fundamental cycle, the time is 20 milliseconds for a fundamental, and this turns out to be 6.25 watts, and for this is per IGBT device or per diode. So, if you have a 3 phase inverter, you have 6 IGBT switches and 6 anti parallel diodes, so for the inverter would be 6 times.

So, this would be 328 watts, so if you are looking at the efficiency of such a converter your efficiency considering just the losses, and your semi conductor would be 96.7 percent. So, if you are considering losses in the other components like your DC bus capacitor in your filter inductors, the efficiency would come further down. So, this is the maximum achievable efficiency due to the losses in the semi conductor itself.

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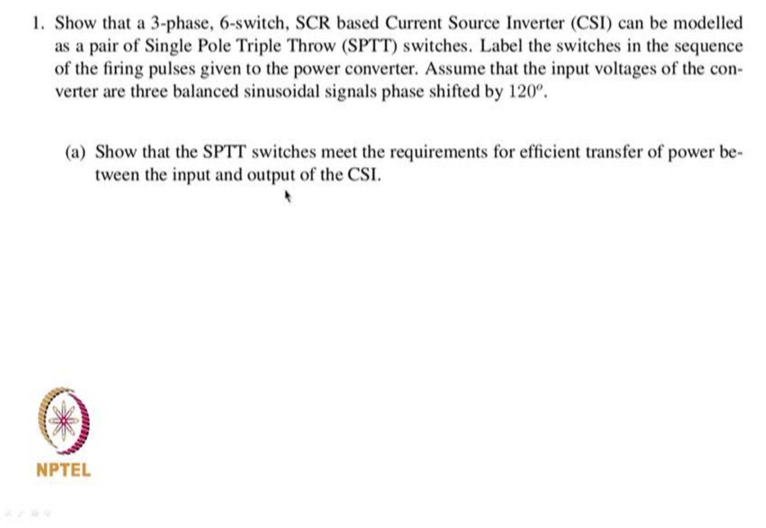

1. Show that a 3-phase, 6-switch, SCR based Current Source Inverter (CSI) can be modelled as a pair of Single Pole Triple Throw (SPTT) switches. Label the switches in the sequence of the firing pulses given to the power converter. Assume that the input voltages of the converter are three balanced sinusoidal signals phase shifted by 120^o.

   (a) Show that the SPTT switches meet the requirements for efficient transfer of power between the input and output of the CSI.

So, in the next problem, we are looking at a 3 phase 6 switch SCR current source inverter, and like to show that it can be modeled as a pair of single pole triple throw switches. And label the switches in the sequence of the firing pulse typically given to a current source inverter, and will assume that the input voltages are balanced and sinusoidal each phase shifted by 120 degrees. And first part of the problem is to show that this single pole triple throw switch needs the requirement for efficient transfer of power between the input and output of the current source inverter.

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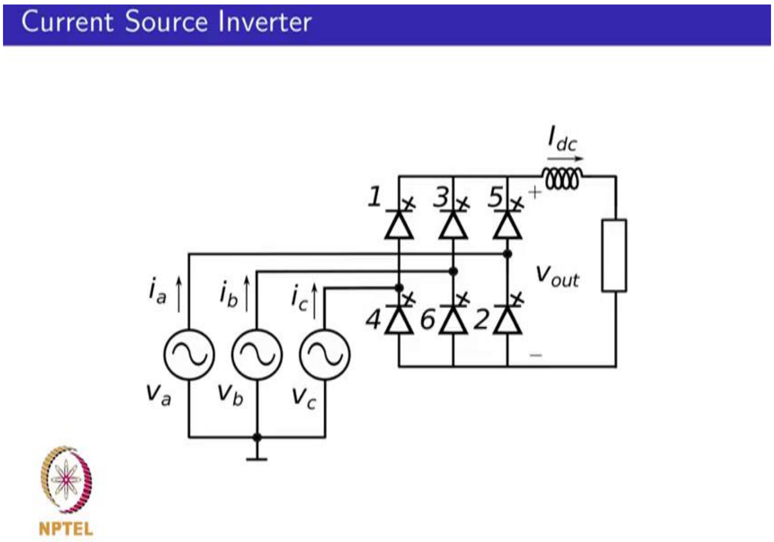

Current Source Inverter

So, if you look at typical current source inverter, you have thyristors or GTOs connected. So, you need reverse blocking devices 3 phase, so you have voltage V a, V b, V c, current i a, i b, i c. Your DC link has a large inductor which emulates a current source, and the output can be a load or it can be a source when you need regeneration or breaking and you could then, write down the expression for the voltages.

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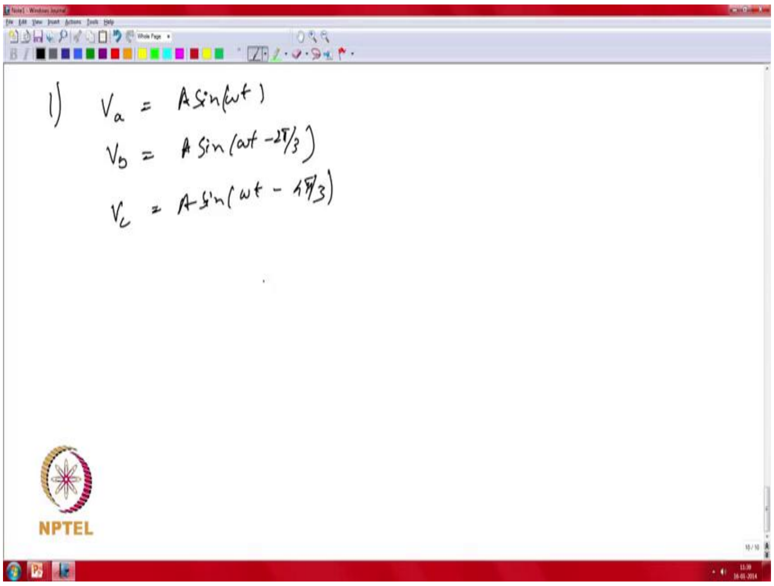

1) $V_a = A\sin(\omega t)$

$V_b = A\sin(\omega t - 2\pi/3)$

$V_c = A\sin(\omega t - 4\pi/3)$

This we have a balance set of voltages V a, V b is a sin omega t minus 2 pi by 3, and to model it, we could show.

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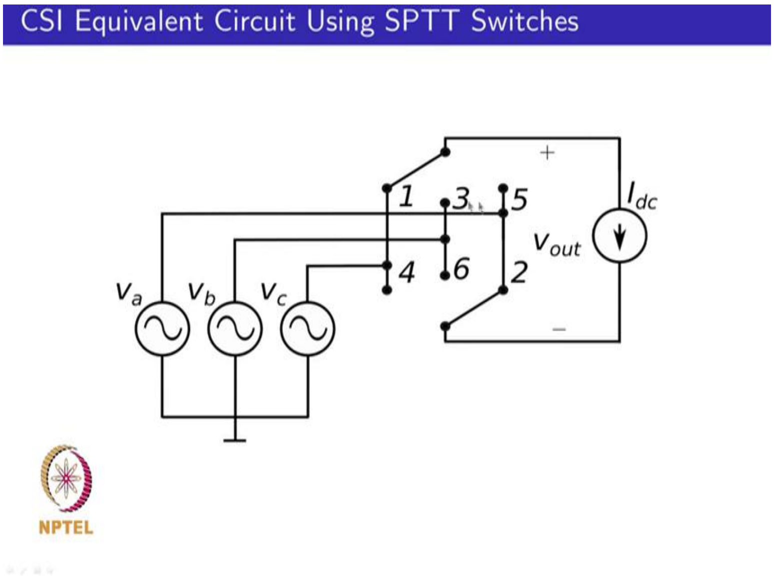

CSI Equivalent Circuit Using SPTT Switches

To show that you could model it as a pair of single pole triple throw switches.

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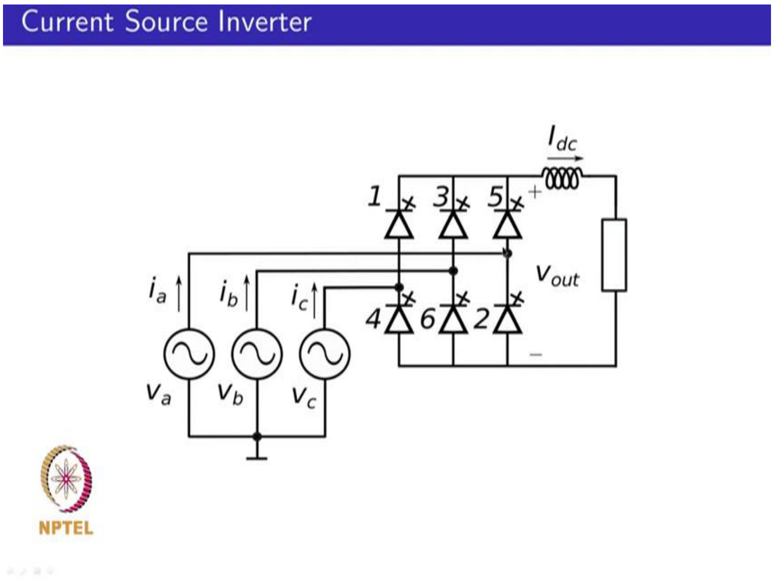

Current Source Inverter

So, the previous power converter can be modeled as a pole connected to 3 throws on the top, and similarly a pole connected to 3 throws on the bottom.

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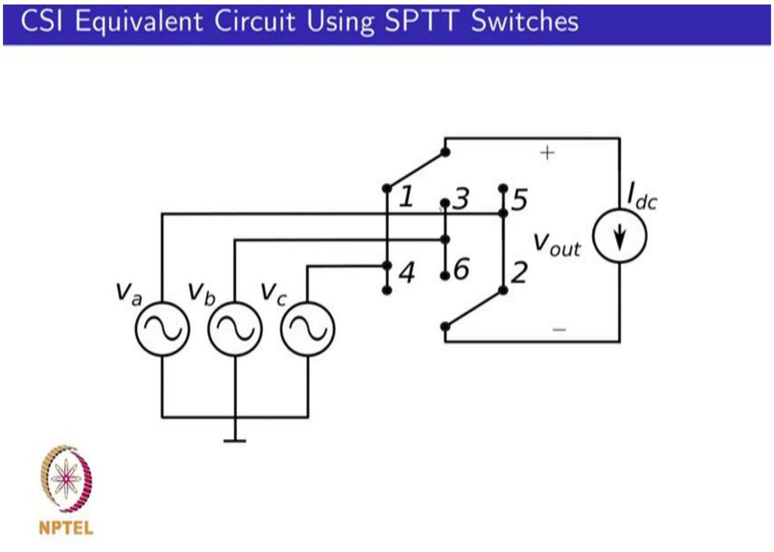

CSI Equivalent Circuit Using SPTT Switches

So, you have essentially a switch which could link 0.1 to the top or 0.3 to the top or 0.5 to the top or you could link say 4 to the bottom or 6 to the bottom or 2 to the bottom.

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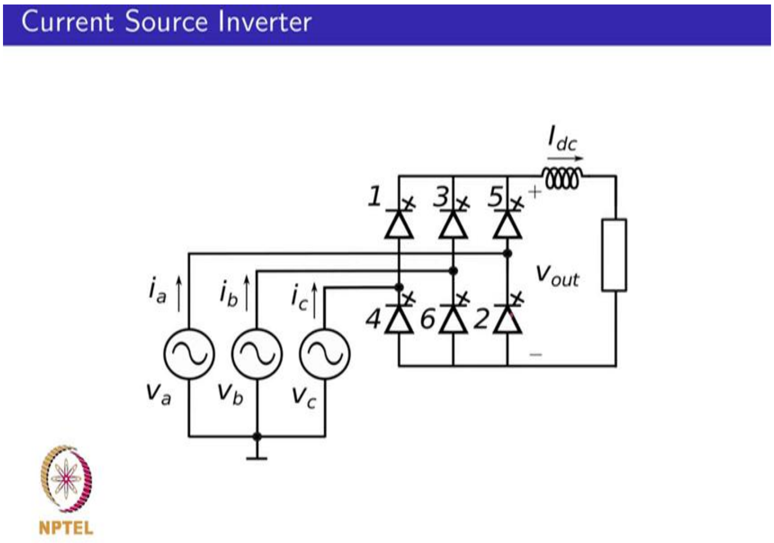

Current Source Inverter

Again 4, 6, 2, 1, 2, 3, are essentially the switches, which is, which could be the thyristor or GTOs which would be fired, and typical firing sequence would be 1, 2, 3, 4, 5 and 6. So hence the labeling 1, 3, 5, 4, 6, 2 for the, for the switching devices.

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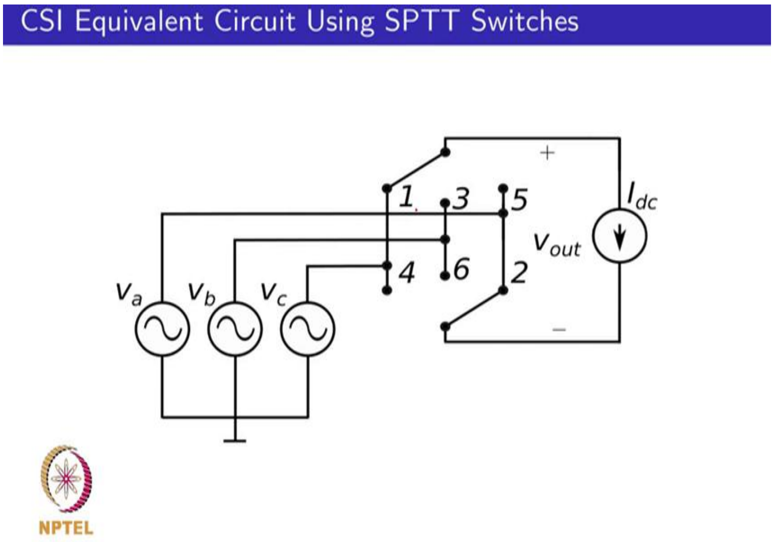

CSI Equivalent Circuit Using SPTT Switches

So, you could see that in this particular configuration your top single pole triple throw switch would be either in position 1, 3 or 5, which means that 1 and 3 is never shorted together because the pole would be only at one of this three points. So, which means that your voltage source would never get short circuited. Similarly, your top throw would be either on 1, 3 or 5, and your bottom would be either on 4, 6 or 2, which means that your current source has always a path for the current you will never be open circuiting the current source. So for example, when in this particular configuration, your 1 is connected to phase c which means that i c would be equal to i dc, and 2 is connected to V a, which means that i a would be equal to minus i dc.

So, you always have a path for current and you will never short out any of the voltage source. And you can efficiently meet the requirements of the voltage sources on the AC side or the current source on the DC side. And hence power can be transferred without any shorting of voltage source or opening of the current source, and you always provide a path for the source conditions to be met.

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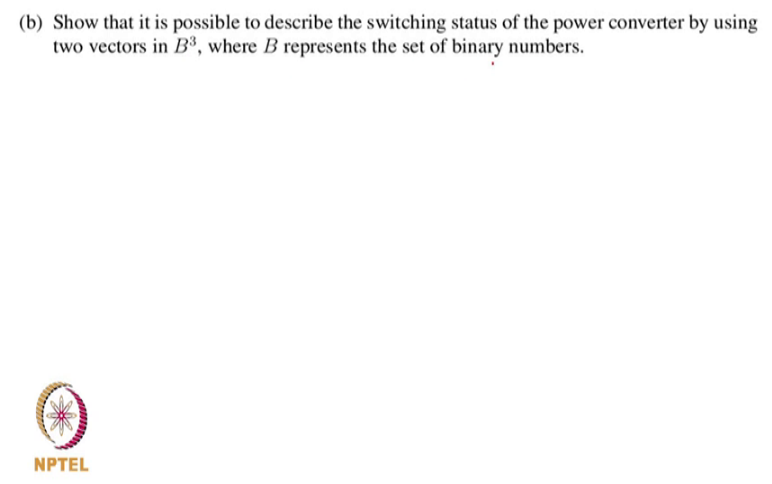

(b) Show that it is possible to describe the switching status of the power converter by using two vectors in B^3, where B represents the set of binary numbers.

So, in the next problem we would like to show that the switching states of this particular CSI converter can be shown as by two pair of vectors with three binary values. So B 3, so the each vector would have a binary value of 0 or 1, and there would be three terms for that particular vector, so we represents the set of binary numbers.

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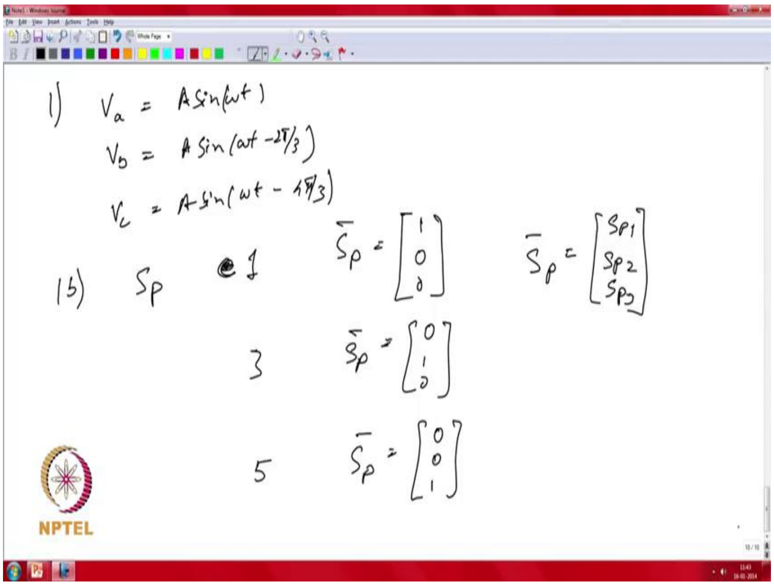

1) $V_a = A\sin(\omega t)$

$V_b = A\sin(\omega t - 2\pi/3)$

$V_c = A\sin(\omega t - 4\pi/3)$

1b) S_p @ 1 $\bar{S}_p = \begin{bmatrix}1\\0\\0\end{bmatrix}$ $\bar{S}_p = \begin{bmatrix}S_{p1}\\S_{p2}\\S_{p3}\end{bmatrix}$

3 $\bar{S}_p = \begin{bmatrix}0\\1\\0\end{bmatrix}$

5 $\bar{S}_p = \begin{bmatrix}0\\0\\1\end{bmatrix}$

So, if you look at your switching positions, your top switch could be considered as a switching vector S p, and when S p is device 1 is fired at switch 1, your S p vector could be shown to be 1 0 0. Similarly, when it is at position 3, your S p vector could be 0 1 0 and when it is at position 5 your S p vector could be 0 0 1. So, you could think of S p as a vector with three components S p 1, S p 2 and S p 3 and each S p 1, S p 2, S p 3 taking components values of either 0 or 1. And depending on whether it is at position 1, 3 or 5, it would take the corresponding values.

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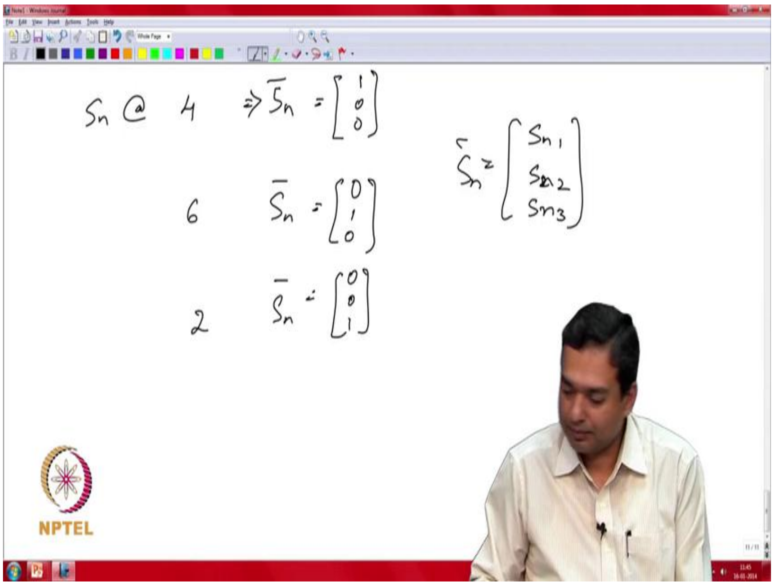

S_n @ 4 $\Rightarrow \bar{S}_n = \begin{bmatrix}1\\0\\0\end{bmatrix}$ $\bar{S}_n = \begin{bmatrix}S_{n1}\\S_{n2}\\S_{n3}\end{bmatrix}$

6 $\bar{S}_n = \begin{bmatrix}0\\1\\0\end{bmatrix}$

2 $\bar{S}_n = \begin{bmatrix}0\\0\\1\end{bmatrix}$

Similarly, for your vector S n so, for the switch S n at position 4, we would have S n, would be 1, 0, 0, and similarly at 6 your S n would be 0, 1, 0, and 2 your S n would be 0, 0, 1. Similarly, S n vector can be thought of as three components S n 1, S n 2 and S n 3, each having a value of either 0 or 1. And the switch provides information about the status of the, which switch in the power converter is on at a given duration of time. So, either of the three components of S n can be 1. So, no two of those S n values, components S n 1 and S n 2 cannot be simultaneously 1. Any one of the three can be 1 at a given point. Similarly, any one of the S p components can have a value of 1.

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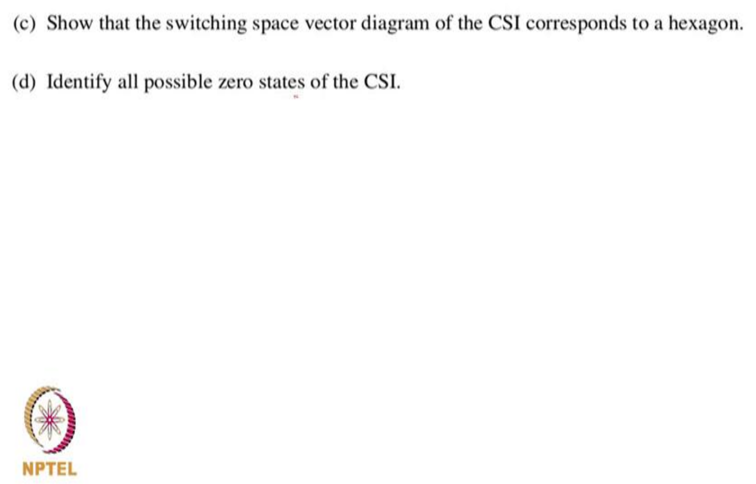

(c) Show that the switching space vector diagram of the CSI corresponds to a hexagon.

(d) Identify all possible zero states of the CSI.

NPTEL

And in the next problem, you are told to show the switching space vector diagram for the current source inverter. And show that it corresponds to a hexagon, and to identify all possible 0 states of the current source inverter.

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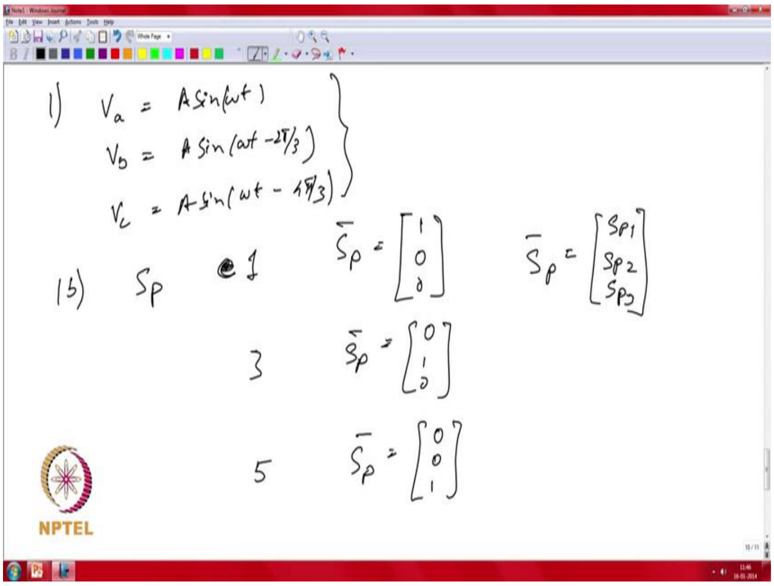

1) $V_a = A\sin(\omega t)$

$V_b = A\sin(\omega t - 2\pi/3)$

$V_c = A\sin(\omega t - 4\pi/3)$

1b) S_p 1 $\bar{S}_p = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ $\bar{S}_p = \begin{bmatrix} S_{p1} \\ S_{p2} \\ S_{p3} \end{bmatrix}$

3 $\bar{S}_p = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$

5 $\bar{S}_p = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

So, we have seen that the voltages V a, V b, V c are given by this quantity, and then we can look at, at what duration of angle alpha, where alpha would be equal to your omega t would each of the switch S p and S n be on for what durations corresponding say for a diode bridge operation where you firing delay is close to 0. So, under such a condition what would be the values that S p and S n takes.

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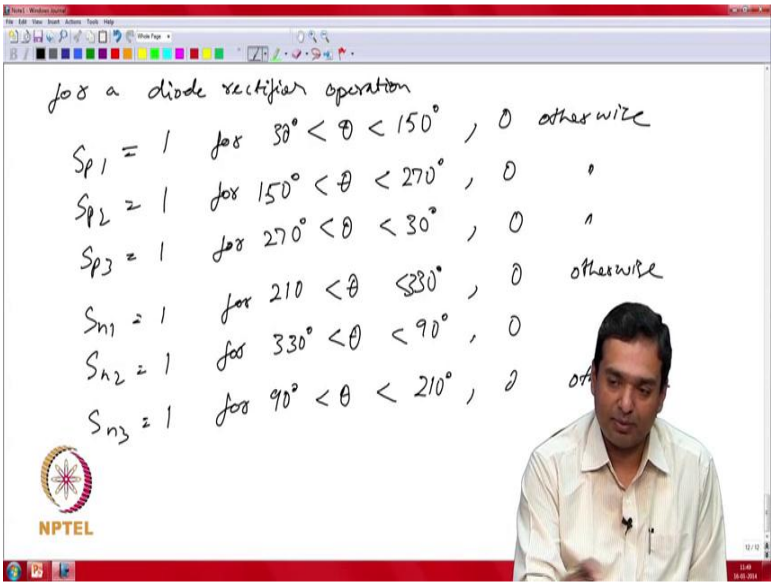

for a diode rectifier operation

$S_{p1} = 1$ for $30° < \theta < 150°$, 0 otherwise

$S_{p2} = 1$ for $150° < \theta < 270°$, 0 "

$S_{p3} = 1$ for $270° < \theta < 30°$, 0 "

$S_{n1} = 1$ for $210 < \theta < 330°$, 0 otherwise

$S_{n2} = 1$ for $330° < \theta < 90°$, 0

$S_{n3} = 1$ for $90° < \theta < 210°$, 0 ot

So for when it is operating without any delays, firing delays, etcetera for the thyristor, your S p would be on, S p 1 would be on for 30 degrees less than theta, less than 150 degrees and 0 otherwise. Similarly, S p 2 would be on when that particular phase is having, carrying the highest voltage. So, this would be your normal conduction duration would be between 150 and 270 and 0 otherwise.

Similarly, S p 3 would be 1 for 270, and similarly you could write the durations when the bottom switches would be naturally on, S n 1 would be 1 for 210. Similarly, S n 2 and S n 3 would be 1 for 90 degrees less than theta, less than 210 and 0 otherwise. So, this is when your diode rectifier is essentially operating as a 6 step, in 6 step operation assuming constant DC link current. So, if you are operating at higher frequencies in p w m will be upward, using stage, which are adjacent in this shorter durations of this particular angles. So, you could then look at your transformation from your abc reference to your alpha beta reference, because your state vector diagram is drawn in your alpha beta plain.

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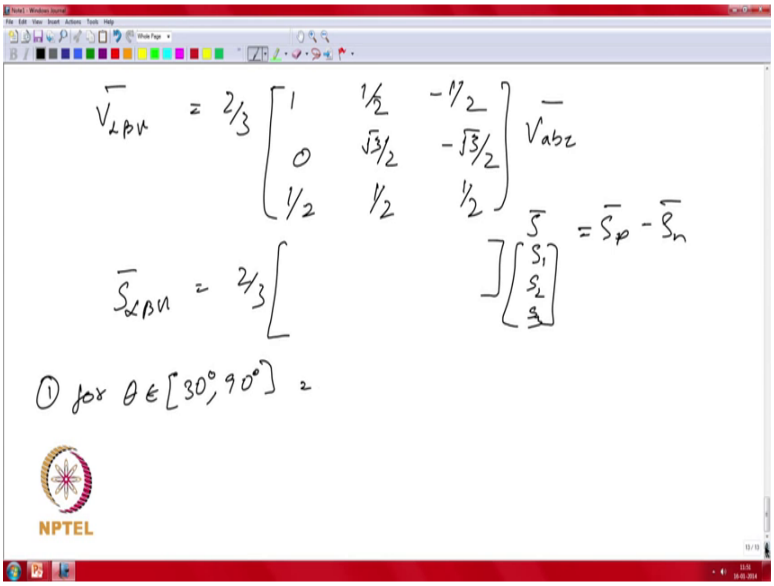

$$\bar{V}_{\alpha\beta\gamma} = 2/3 \begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \bar{V}_{abc}$$

$$\bar{S} = \bar{S}_p - \bar{S}_n$$

$$\bar{S}_{\alpha\beta\gamma} = 2/3 \begin{bmatrix} & & \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

① for $\theta \in [30°, 90°] =$

So, you have your V alpha beta gamma is two-thirds half minus half times V abc vector. And similarly you could take your switching vectors S alpha beta gamma to be two-thirds of this same matrix, times your switching vector S, where S corresponds to S 1, S 2, S 3. And this in turn, corresponds to your S p vector minus your S n vector, where you are taking your S p to be your 1 0 0, 0 1 0, etcetera, and adding them as real numbers to get your switching vector S. So, then you could look at the durations say for duration between, say for theta belonging to say 30 degrees to 90 degrees.

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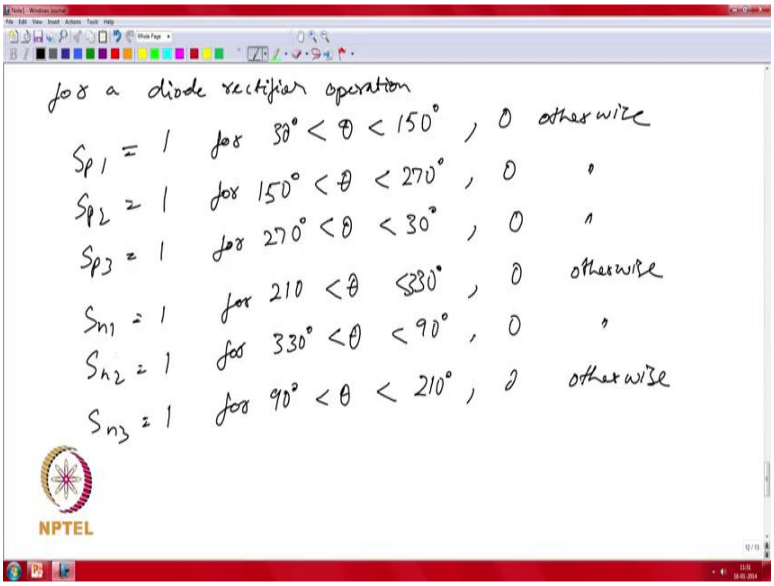

for a diode rectifier operation

$S_{p1} = 1$ for $30° < \theta < 150°$, 0 otherwise

$S_{p2} = 1$ for $150° < \theta < 270°$, 0 〃

$S_{p3} = 1$ for $270° < \theta < 30°$, 0 〃

$S_{n1} = 1$ for $210 < \theta < 330°$, 0 otherwise

$S_{n2} = 1$ for $330° < \theta < 90°$, 0 〃

$S_{n3} = 1$ for $90° < \theta < 210°$, 0 otherwise

If you look at this particular duration then, we could see that S p 1 would be having a value of 1 with the others being 0, and similarly your S n 2 would be having a value between 30 degrees and 90 degrees. This would be S n 1 would be having a value of 1 and the S n 1 and S n 3 would be 0, and S n 2 would be having a value of 1.

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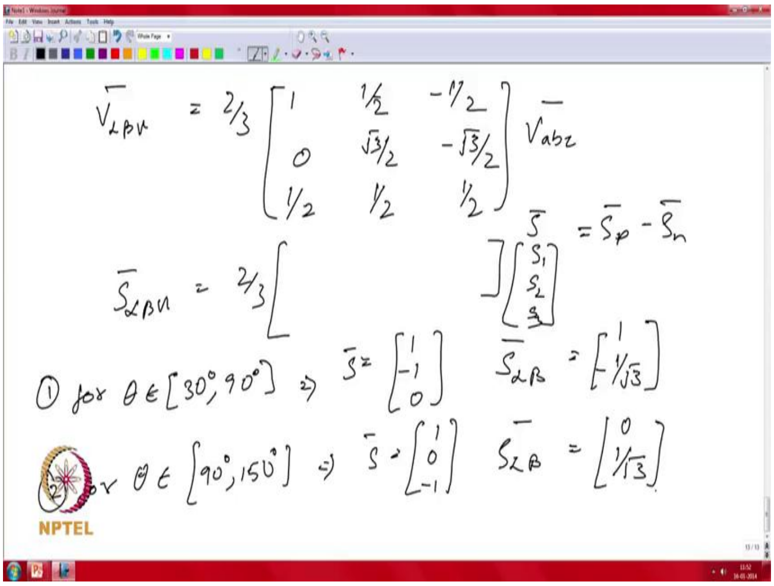

$$\bar{V}_{\alpha\beta\gamma} = \frac{2}{3}\begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \bar{V}_{abc}$$

$$\bar{S} = \bar{S}_p - \bar{S}_n$$

$$\bar{S}_{\alpha\beta\gamma} = \frac{2}{3}\begin{bmatrix} & & \\ & & \\ & & \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

① for $\theta \in [30°, 90°] \Rightarrow \bar{S} = \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} 1 \\ -1/\sqrt{3} \end{bmatrix}$

② for $\theta \in [90°, 150°] \Rightarrow \bar{S} = \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} 0 \\ 1/\sqrt{3} \end{bmatrix}$

So, you could write your S vector to be equal to 1 minus 1 0, and you could use this transformation to look at your S alpha beta to be equal to 1 minus 1 by root 3. Similarly, you could look at your other switching positions from 90 degrees to 150 degrees, your switching vector is 1, 0 minus 1, and your S alpha beta would be equal to 0, 1 by root 3.

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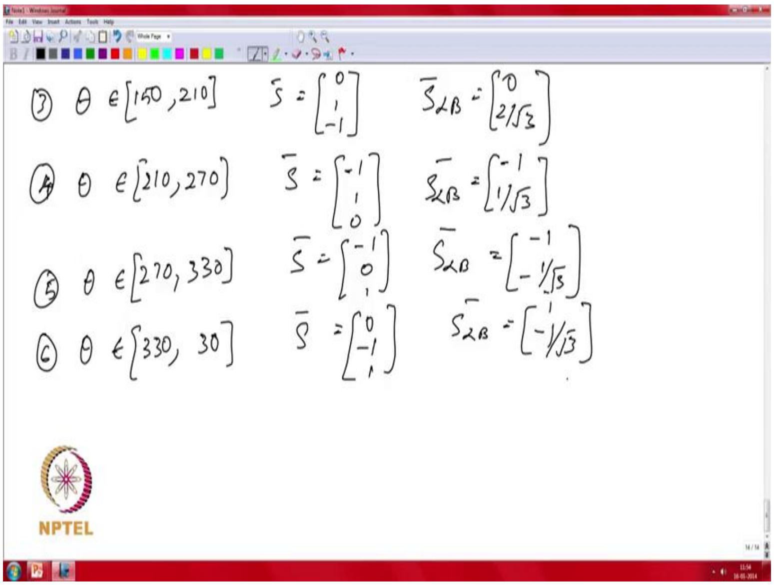

③ $\theta \in [150, 210]$ $\quad \bar{S} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} 0 \\ 2/\sqrt{3} \end{bmatrix}$

④ $\theta \in [210, 270]$ $\quad \bar{S} = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} -1 \\ 1/\sqrt{3} \end{bmatrix}$

⑤ $\theta \in [270, 330]$ $\quad \bar{S} = \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} -1 \\ -1/\sqrt{5} \end{bmatrix}$

⑥ $\theta \in [330, 30]$ $\quad \bar{S} = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}$ $\quad \bar{S}_{\alpha\beta} = \begin{bmatrix} 1 \\ -1/\sqrt{3} \end{bmatrix}$

Your third position would be for theta belonging to the range 150 to 210, your S vector would correspond to 0, 1 minus 1. And your S and your alpha beta plain would correspond to 0, 2 by root 3. And your vector 4 would be for the duration 210 to 270, your S would be minus 1, 1, 0, and your S alpha beta would be minus 1, 1 by root 3. Between 270 and 330 degrees, your switching vector would be minus 1, 0, 1, S alpha beta equal to minus 1, minus 1 by root 3, and your 6 th vector would be theta during the duration 330 to 30 degrees .

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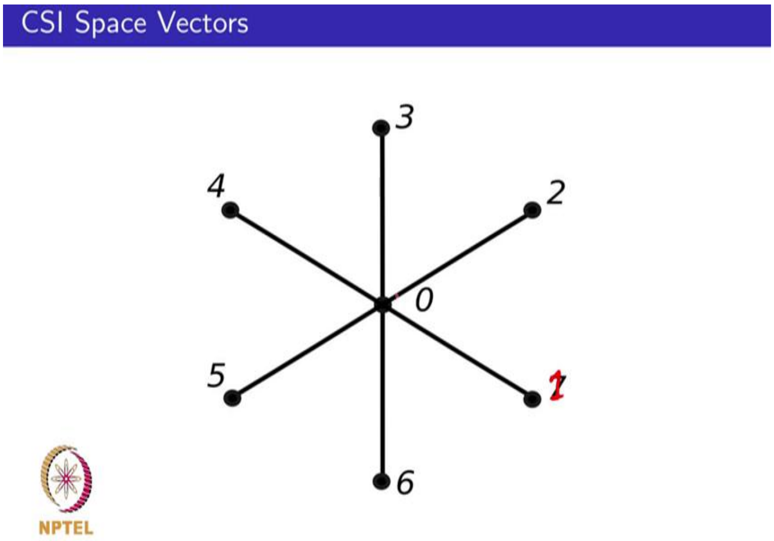

CSI Space Vectors

So, if you plot these vectors, you will see that, the 6 vectors you would have the corresponding positions of 1, 2, 3, 4, 5, 6. There are, there are 6 points around a hexagon. So you would get a similar space vector diagram and 0 vector corresponds to the center, unlike the voltage source space vector diagram this is actually rotated by 30 degrees.

So, this is very similar to what you would experience in for a voltage source inverter, you could make use of the modulating states, and show that for a current source inverter also you have a hexagon corresponding to the state vector diagram. The 0 state would correspond to the condition when say for example.

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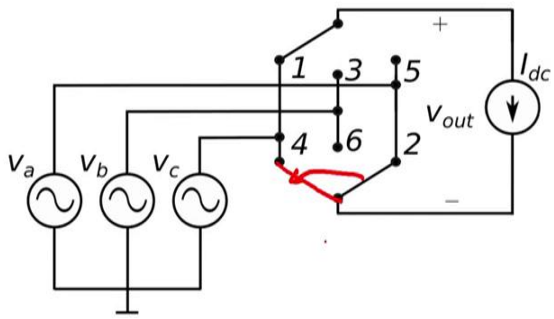
CSI Equivalent Circuit Using SPTT Switches



If both the throws are at the same point, then essentially the voltage seen by your DC source would be 0, because two switches would be connected to the, both the throws would be connected to the same pole. And your voltage sources would all be open circuit at which means that your i a, i b and i c would be equal to 0. So, there is no energy transfer during the 0 states. And there are three possible 0 states it could either be connected to 1 and 4 or you be connected to 3 and 6 or 4 and 2. So, you have three 0 states. So, you could write down the three 0 states as…

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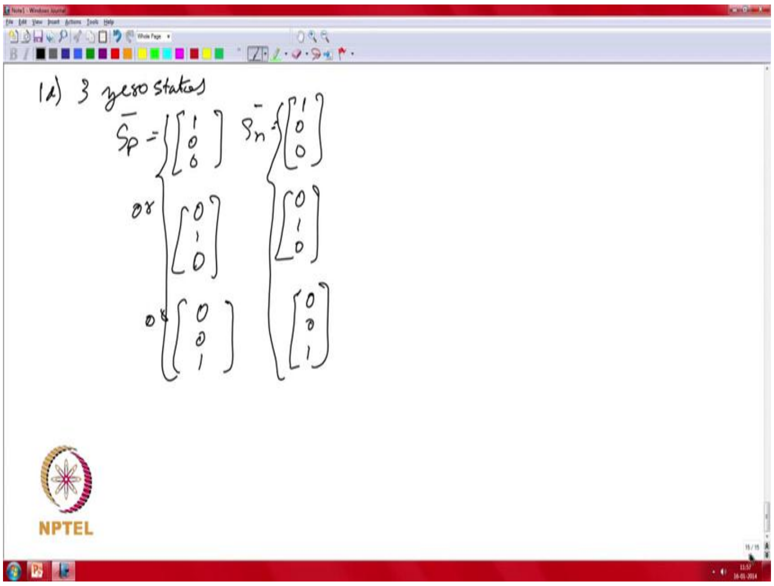

1(a) 3 zero states

$$\bar{S}_p = \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \text{ or } \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \text{ or } \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right. \qquad \bar{S}_n = \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right.$$

So, there are three possible 0 states, and unlike in a voltage source inverter where there are two 0 states in a current source inverter. There are three 0s possible 0 states, to look at the input output relationship between your AC and AC voltage. And the output DC voltage and also the DC current and the input AC current, you could write down the relationship.

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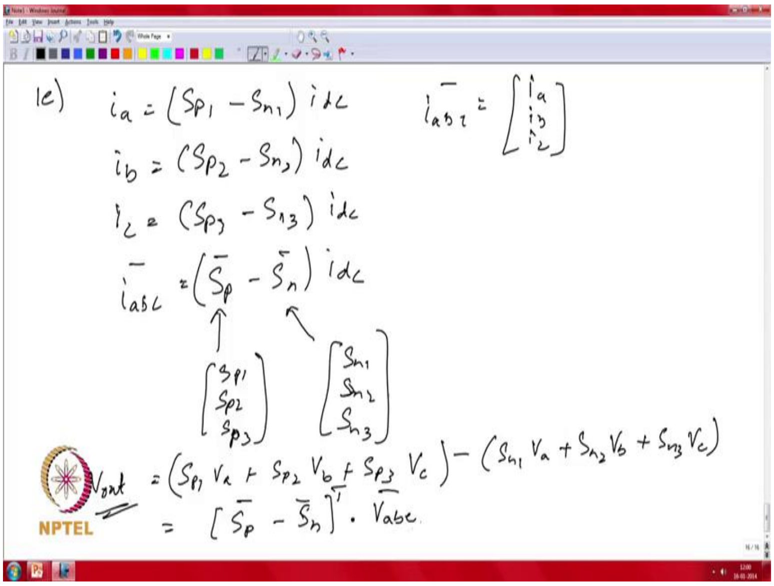

1c)

$$i_a = (S_{p1} - S_{n1})\, i_{dc} \qquad \bar{i}_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$i_b = (S_{p2} - S_{n2})\, i_{dc}$$

$$i_c = (S_{p3} - S_{n3})\, i_{dc}$$

$$\bar{i}_{abc} = (\underset{\begin{bmatrix} S_{p1} \\ S_{p2} \\ S_{p3} \end{bmatrix}}{\bar{S}_p} - \underset{\begin{bmatrix} S_{n1} \\ S_{n2} \\ S_{n3} \end{bmatrix}}{\bar{S}_n})\, i_{dc}$$

$$V_{out} = (S_{p1} V_a + S_{p2} V_b + S_{p3} V_c) - (S_{n1} V_a + S_{n2} V_b + S_{n3} V_c)$$

$$= [\bar{S}_p - \bar{S}_n]^T \cdot \bar{V}_{abc}$$

So, you have your i a is equal to S p 1 minus S n 1 times i dc. Similarly, your i b is S p 2 minus S n 2 times i dc. Your i c is S p 3 minus S n 3 times i dc. You could also write it as in a more compact form, we have i abc vector to be i a, i b, i c, and S p 1, S p is equal to S p 1, S p 2, S p 3. So, you could write it as i abc vector is equal to S p minus S n times i dc. So, this relates your AC side currents to your DC current of your CSI. Similarly, you could write your where essentially your S p vector is S p 3 and S n vector is.

Similarly, you could write your output voltage V out, which is the voltage across your positive and negative poles of the, of the switch is S p 1 V a plus S p 2 V b plus S p 3 V c minus S n 1 V a plus S n 2 V b plus S n 3 V c. So, this could be written as essentially S p vector minus S n vector, transpose, take the dot product times V abc vector would give you output voltage vector. So, you could make use of your switching state vectors to actually obtain your input output relationship.

So, here you get the output voltage in terms of your input voltages, and then you get your input currents i abc in terms of your DC current. So, this gives you your input output relationship of this particular power converter. So, we have looked at now the example problems and the next class, we will continue with where we had left off for the filter design, we had looked at LCL filter, and looked at how to determine the values of L and C. We will start with looking at how to determine what would be the damping components required to damp out the oscillations in such a LCL filter in the next class.

Thank you.