Power Electronics

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Lecture - 29

Space Vector PWM Signal Generation

This class we will try to learn a technique; how to implement the space vector based PWM based only on sampled reference space amplitude. So, we will study a simple technique that is SVPWM, SVPWM using only the sampled reference phase amplitudes.

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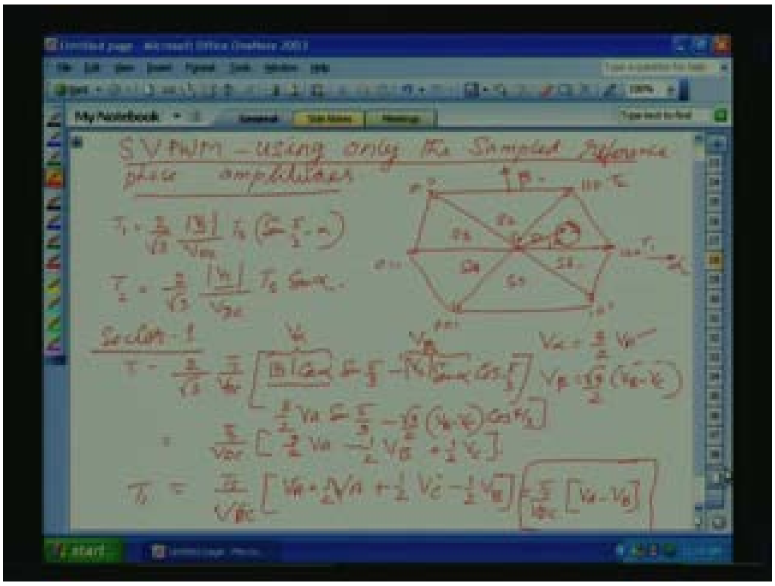

Let us draw our space vector diagram. So, space vector diagram you have, from a three phase system, the periphery is a hexagon. This is our sector one, so this is the hexagonal space vector based structure; this is 100, this is 110, 010, 011, opposite to this one 001, opposite to this one this is 101, this is our sector one - S_1 S_2 S_3 S_4 S_5 S_6. In the previous class we found for any sector when the V_S, the reference voltage space vector in any sector and if the angle is measured from the start of the sector, the period T_1 with which the start of the vector is switched and the T_2 the n vector forming the triangular sector and the zero vector are switched can be found out from this equation; T_1 is equal to 2 by root 3, this way derived our V_S mode of V_S divide by V_{DC} T_S sine pi by 3 minus alpha T_1. T_2 is equal to 2 by root 3 V_S mode divide by V_{DC} into T_S into sine alpha.

See, this one, we know we also know that equation V alpha is equal to 3 by 2 V_A and V beta is equal to from the alpha beta transformation, root 3 by 2 V_B minus V_C; this also we have derived. Now, how we can get this T_1 T_2 in terms of V_A V_B and V_C? Let us say T_1 in sector one, T_1 is equal to 2 by root 3, 2 by root 3 into let us take T_S by V_{DC}, these are constants outside, V_{DC} into V_S, V_S mode into we can or V_S into sine pi by 3 minus alpha, we can expand this one as cos alpha sine pi by 3 minus V_S sine alpha cos pi by 3; this is T_1. What is V_S cos alpha? Here alpha, our alpha is in this direction, beta is in this direction.

For sector one, alpha is along the vector for which the T_1 period, the start of the vector; so V_S cos, this is equal to V_S cos alpha, V_S cos alpha is equal to the corresponding V alpha component of the sampled reference space vector. So, V_S is equal to V alpha. So, substituting this one, this will be equal to 3 by 2 V_A sine pi by 3. V_S sine alpha is equal to the V beta component that is the V beta, V beta is equal to root 3 by 2 into V_B minus V_C that is our three phase amplitude, corresponding three phase amplitude into cos pi by 3. If you substitute these values, finally it will come to T_S by V_{DC}, T_S by V_{DC} into 3 by 2 V_A minus 1 by 2 V_B, after reducing this one simplifying this one, minus 1 by 2 V_B plus 1 by 2 V_C, you will get this way.

So, this again we can simplify is equal to T_S by V_{DC} 3 by 2 V_A, I will put as V_A plus 1 by 2 V_A, V_{DC} this is V_{DC}, V_A plus 1 by 2 V_A, 1 by 2 V_A plus 1 by 2 V_C minus 1 by 2 V_B. So, this V_S is originally, the sampled reference space amplitude is generated with our values along the A B and C axis, ABC axis. So, if you see here, finally it will be equal to T_S by V_{DC} into V_A minus V_B. This we can further simplify, let us see, we can write it like this.

See, what you what I want you to know in this case is the T_1, originally represented or written in terms of V_S and the cos alpha with respect to the sampled reference phase amplitude in sector one is now we are representing in terms of V_A V_B. So, if three phase sampled reference phase amplitude is available; sampling period is known, V_{DC} DC link voltage is known, T_1 is known. So, this again, we can represent in a in a simplified way. Let us go to the next page.

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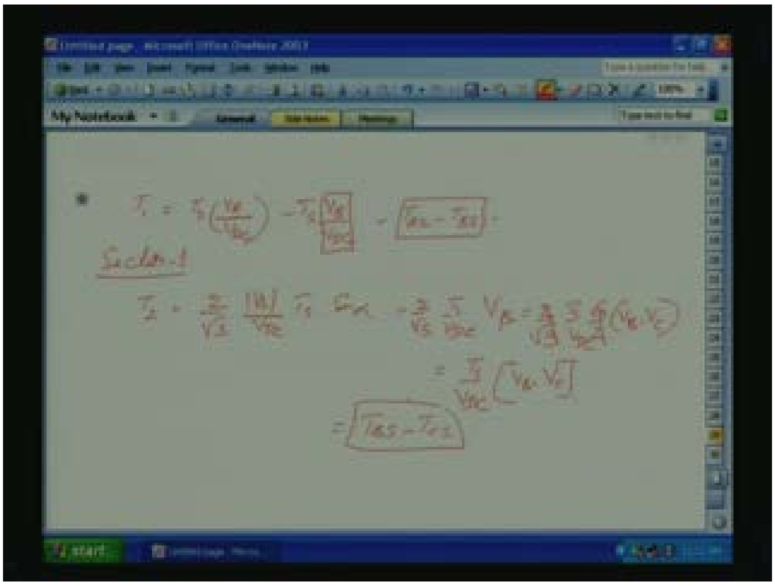

See here, now we can write it T_1 is equal to T_S into V_A by V_{DC} minus T_S into V_B minus V_{DC}, V_{DC} unit is in volts, V_B is also in volts. So, for the DC link voltage, maximum DC link voltage, what is the instantaneous sampled V_A V_B V_C? So, this will become a fraction is a constant. So, T_S this can be represented as T_{AS} minus T_{BS}. So, what we are representing now? The sampled reference phase amplitude, we are representing in terms of in time, in seconds now, a fictitious time that is proportional to T_S divide by V_{DC}. So, V_{AS} V_{BS} sampled reference phase amplitude at that instant is known. In sector one, T_1 is equal to that sampled volume multiplied by T_S by V_{DC} for the A phase minus T_{BS} will give T_1. So, this is very easy, computation is there is not much computation like sine alpha RO 3 by 2; all those things are not there, it is very easy you can find out T_1.

Let us say, what is T_2 in sector one? T_2 is equal to 2 by root 3 V_S mode divide by V_{DC} into T_S into sine alpha. This we can write as 2 by root 3 into T_S by V_{DC} into V_S sine alpha is equal to V beta that is equal to 2 by root 3 into T_S by V_{DC}; what is V beta? V beta is equal to again root 3 by 2 V_B minus V_C. So, this root 3 by 2 and 2 by root 3 goes, this will be equal to T_S by V_{DC} into V_B minus V_C. This is in the fictitious time; we can write it as T_{BS} minus T_{CS}.

So, if you know the sampled reference space amplitude in sector one at any possession sector one, T_1 is equal to T_S into V_M by V_{DC} minus T_S into V_B by V_{DC} or equal to T_{AS} minus T_{BS} and T_2 is equal to V_B minus V_C multiplied by T_S by V_{DC} or T_{BS} minus T_{CS}. So, this is very simple, easily you can find out. So, in digital implementation this is very fast. See, in sector one, T_1 T_2 we have found out in terms of sampled reference space amplitude; is it possible to find out T_2 T_3 T_4 also, in other sectors also? Let us find out. Sector two; so let us draw our or let us draw our hexagon again, once again for our reference.

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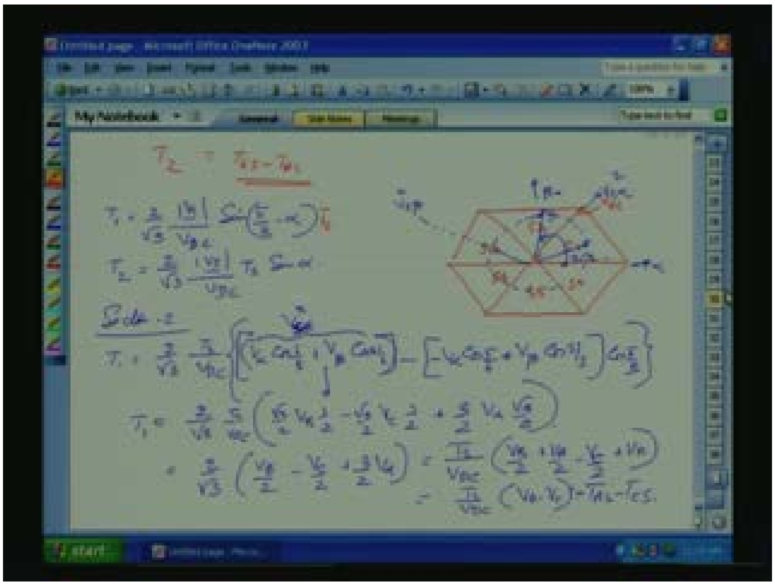

This is our space vector, voltage space vector domain from our inverter. So, hexagon with equal radii, radii means amplitude of the hexagon, this is equal to V_{DC} depending on the DC link voltage, this amplitude. So the aim, this is equal to, this is sector one, this is sector two, sector three, sector four, sector five, sector six. Now, from the sector one our alpha has moved to sector two now, let us say. Now let us say, this is our new V_S; it is taking it is making a circle for uniform speed.

See, previous it was in sector one, we found out; now it is in sector two. In sector two, alpha has to be measured from the start of the sector but our V alpha is in this direction, V beta is in this direction. So, how do you represent this equation? That is T_1 is equal to we know T_1 is equal to 2 by root 3 V_S mode divide by V_{DC} into sine pi by 3 minus alpha; this is general equation in any sector, T_2 is equal to 2 by root 3 V_S by V_{DC} into T_S into sine alpha. Now, V_S

sine alpha in sector two, it will be along this direction. Now, we have and V_S sine beta will be perpendicular to this one. So, we have to find out now the alpha component along the start of the sector and perpendicular to in S_2, what is the component along our alpha beta where alpha is placed along this axis?

So, if you see here, sector two, T_1 is equal to 2 by root 3 T_S by V_{DC} into the component along this. Suppose, the present V alpha V beta component, the component along this direction is equal to that is along this direction that is V_S cos alpha in sector two, V_S cos alpha in sector two is equal to we are taking in terms of our alpha beta component. That means from ABC to our three phase ABC to when alpha beta when convert; alpha is fixed along this axis, beta is fixed along this axis. So, the component along the start of sector two, component along the start of sector two which will contribute both from alpha beta; so, that will be equal to that is what we are talking about the V_S cos alpha time in the previous time that is equal to V alpha cos phi by 3. This angle is phi by 3, so this will contribute. How much V beta will contribute?

V beta, this is pi by 3 means 60 degree, this will be 30 degree. So, V beta also will contribute towards that one that is V beta into cos pi by 6. This is the new V alpha in sector two, V alpha, V_S alpha, V_S alpha in sector two. So, here V_S alpha means the component along in this direction, start of the sector in terms of V alpha beta this is the one, V_S alpha. Then, same the previous one, expand this equation, then it will be again this will be equal to then what is the V beta component? V beta component in sector two, V_S beta that is V_S beta in sector two, this is the V_S alpha in sector two; V_S beta will be minus of V alpha, minus V alpha, then cos pi by 6, pi by six that is 30 degree. Cos pi by six plus V beta cos pi by 3 that is V beta cos of this component into cos pi by 3; this is our final equation.

So, what we did? The T_1 T_2 in any sector depend on the sampled reference phase voltage V_S along the start of the sector and the perpendicular to that that is V_S alpha V_A beta. But in sector one, V_S alpha is equal to our alpha component, V_S beta is equal to beta component. Now, every sector, the V_S alpha V_S beta has been transferred to our fixed alpha beta component by appropriately taking the component of this one, component of the V_S alpha and V_S beta. Now here, the V_S alpha in sector two and V_S alpha beta in sector two, you have represented with the V alpha and V beta.

Once we know V alpha beta can be represented with our sampled reference phase voltage; so if you simplify this one in sector two, we will get a relation. We can simplify this one, finally T_1 will be equal to 2 by root 3 T_S by V_{DC} into root 3 by 2 V_B into 1 by 2 minus root 3 by 2 V_C 1 by 2 plus 3 by 2 V_A root 3 by 2 that that is we are getting this step from here, substituting for V alpha and V beta that reduce it, you will get this one that is T_1. That will be equal to 2 by root 3 into V_B by 2 minus V_C by 2 plus 3 by 2 V_A is equal to T_S by V_{DC} V_B by 2 plus V_A by 2 minus V_C by 2 plus V_A; this will be finally equal to T_S by V_{DC} into V_A minus V_C that means equal to T_{AS} minus T_{CS} that is our fictitious time.

Fictitious means the V_A V_B V_C amplitudes, as it moves to different sector, it can go both positive and negative because V_A can go positive, negative; so, T_{AS} T_{CS} can also go positive or negative. So, what we want? We want only positive time to find out the switching instants, we will come to that one. Now, what we are dealing? The sampled reference space amplitude from our T_1 T_2 equations using the sampled reference space amplitude, T_1 T_2 we are converting to a fictitious time. That time is proportional to the sampled reference from phase amplitude multiplied by our sampled fixed sampling the period divide by V_{DC}; so, T_{AS} by T_{CS}.

In a similar way, we can substitute for T_2 also. If you substitute for T_2, it will be, we can simplify that one, T_2 will be in sector two, T_2 in sector two will be equal to T_{BS} minus T_{AS}, it will come like this. So, this way, in all sectors, we can find out what is the sampled reference phase amplitude gives? How, from the sampled reference phase amplitude, how we can convert or how we can find out T_1 T_2 based on our fictitious time multiplied by T_S by V_{DC}? So, if you derive that one, the final chart will be, let us draw the table; this table can be used.

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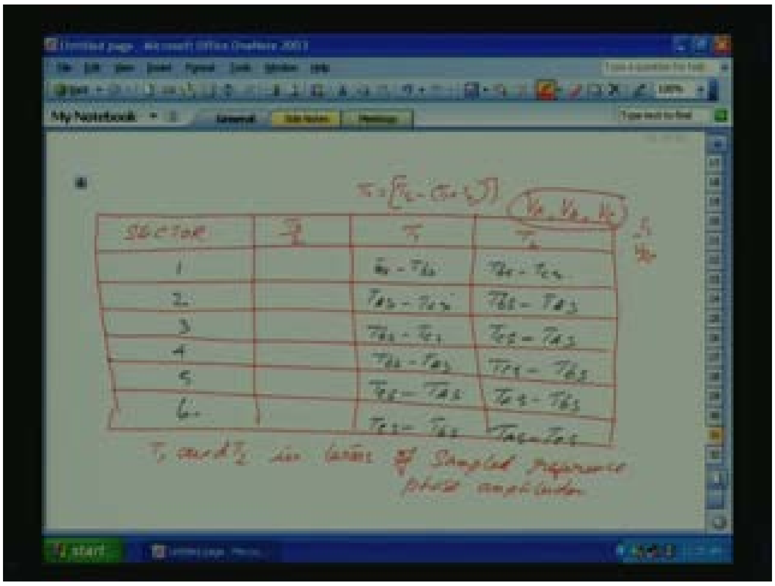

This is the sector information, then T_0 by 2, then T_1 and T_2. So, this is the sector, T_0 by 2 t; once the T_1 T_2 is found out, T_0 is equal to T_S minus T_1 plus T_2. From there we can find out T_0. Why T_0 by 2 is required? We are splitting the T_0 by 2, start and end with equal duration and the active vector is placed at the middle; so, T_1 and T_2. So, the T_1, this table gives the sampled reference phase, the T_1 T_2, T_1 and T_2 in terms of sampled reference phase amplitude. Let us say, we will divide this one into 6, 6 sectors are there; 1, 2, 3, 4, 5 and 6.

So, let us in sector one; T_1 is equal to T_{AS} minus T_{BS}, T_2 is equal to T_{BS} minus T_{CS} and sector two is equal to see, what is T_0 by 2? Whether we have to do this one or is are anyway simple way to find out; that we will come later. So, T_{AS} minus T_{BS}, T_{BS} minus T_{CS}, then this is equal to T_{AS} minus T_{CS} T_1, T_{BS} minus T_{CS}, here T_{BS} minus T_{AS}, then T_{CS} minus T_{AS}, here also T_{CS} minus T_{BS} T_1. Here it will be equal to T_{BS} minus T_{AS}, then T_{CS} minus T_{AS}, here also T_{CS} minus T_{BS}, T_{AS} minus T_{BS}, T_{AS} minus T_{CS}; 2, 3, 4, 5, 6. What is the advantage now?

If the sampled reference phase amplitude that is our V_A V_B V_C is known, multiply each one with T_S by V_{DC}, we will get the corresponding fictitious timing in each sector and simple subtraction; we will get the T_1 T_2 in each sector. So, this is very easy to find out. Let us say, what is the meaning of this one? Let us find out, T_{AS} minus sampled reference phase angle and how to do the thing. Let us go to the next sector. If you see here, let us draw our reference phase amplitude.

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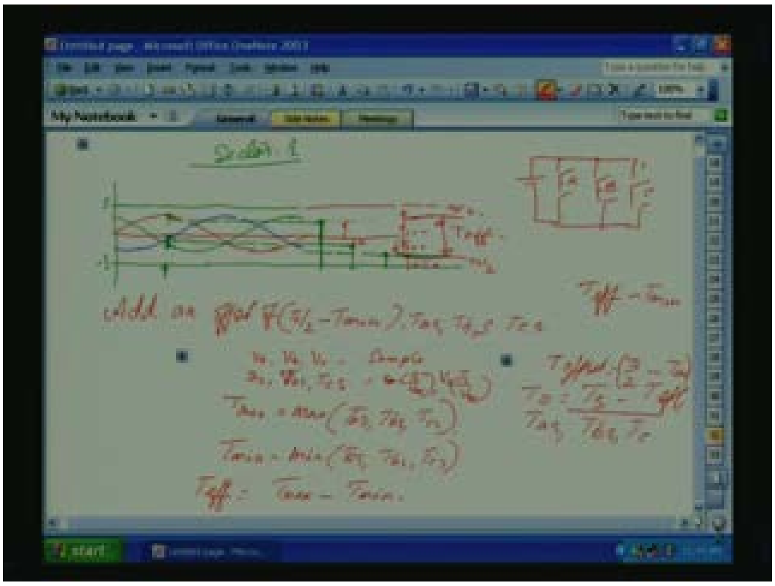

Let us say this is our A phase, this our zero line, now our B phase, we will go with a different colour. Now, let us have our C phase; as the speed varies, we want to generate different circle with different radii. So, with different radii we have different amplitudes of the sine waves. So the maximum, maximum inscribed circle happens let us see at this point. Then the amplitude reaches here, plus 1 and minus 1, this is the one, so plus one and minus one. That time, this sine amplitude reaches maximum, the circle inscribed circle will have the maximum radii. Now, this ABC is for a particular circle with a reference, with the radii equal to V_S.

Now, let us take in sector one; in sector one, this is in sector one, we are sampling the V_A V_B V_C at one point. See, sector one, the sampling will be somewhere here, this is here we are sampling. When we sample, these are the amplitude; for the C phase it is here, B phase it is here, A phase it is here. When you sample it and let us take, if you take the minus point to this point, let us say for a triangle waveform, as it moves from here to here, high frequency sine wave; high frequency triangle wave, as it moves from here to here, till this point, sine is greater than the triangle for A phase. So, you will get high signal here, after that it will be zero.

Now, if you see here, the amplitude till that point, it will be here; this is the amplitude, A phase. Now, B phase, where it will be? That is here, amplitude if you take, B phase it will be here, the sampled amplitude is here if you measure from the bottom side. But the sampled amplitude if you see here; this is the amplitude, always it will start from the zero, the sample it sampled amplitude for the A phase will be from here to here. For the C phase if you take, this is the amplitude.

Now, if you see here, as we go from here to here, if you say the sine triangle period till this portion till C is switched; what is the output? Sine is greater than the triangle; so till this period till this period, it will be minus, minus, minus. So, the amplitude if you measure, we will get only the positive amplitude from here to here. Here you will get the B negative amplitude, C you will get this one, this is the amplitude you will get and this is for the B. But if you or if you compare with the sine triangle, till this period, as the triangle waveform increase; we are sampling from here, so as it goes moves from here, sine is greater than the triangle. So, till this period it will be plus, plus, plus. After that, this will go negative. So, this will be, C phase will be from here to here; plus plus minus. Then from here to here, it will be plus minus minus. Then from if you extend this one, then from here to here, it is minus, minus, minus.

Now, we want to know the effective period. Effective period is from here to here, effective period is see this is the zero period, start of this; so the effective period is only this much that is the active vector period that is called T effective. Now, this is the T_0 by 2, first T_0 by 2, this is the last T_0 by 2; so we have to equally divide and place it. So, how do you find out the T effective period? You sample, first you sample the V_A V_B V_C, V_A V_B V_C sample, then convert it to T_{AS} sorry T_{BS} and T_{CS}. How? That is V_A multiplied by T_S by V_{DC}, V_B multiplied by T_S by V_{DC}, similarly.

Now, if you see here, the T effective period is between the maximum of the sampled value and minimum of the sampled value. See minimum, here it is negative; maximum is positive. So, you find out T maximum, T maximum is equal to maximum of our T_{AS} T_{BS} and T_{CS}. Then you find out T_B that is minimum of T_{AS} T_{BS} T_{CS}. Then what is the T effective in sector one? T effective is equal to T maximum minus T minimum; T effective we have found out, now how you will find out the T_0? Very easy, T_0 is equal to t s minus T effective.

Now, we want the time period in positive that is during which we have to see if you see here, from here to here, for the leg if you say, take the inverter, if you take the inverter like this; A B C, this is our V_{DC}. For the A phase, let us say this is A, this is B, this is C. So, till this portion, till this period, we want the top switch is on. But if you see here, we are starting from here, A phase is only this much; this much period is negative. So, what we want? Shift the whole thing to the positive side. So, how do you do it?

First, find out the T effective, T effective and we also note that we also know the T minimum, T effective want to the positive side, everything, T effective minus T minimum will be always negative. The T effective minus T minimum T_S minus T effective minus T minimum will shift the whole thing to this positive side. Then again you add T_0 by 2; so the offset to be added so that everything go to the positive side is equal to T offset is equal to T_0 by 2 minus T minimum.

So, you have got the T_{AS} T_{BS} T_{CS}, T_{AS} T_{BS} T_{CS}; this depend on the sampled reference space amplitude can be positive or negative. So, everything you want to shift to the positive side and the zeroes you want to shift it to the start and end with the T_0 by 2, you add to this T_{AS} T_{BS} T_{CS} and offset. So, we will write it here add an offset of T_0 by 2 minus T minimum; T minimum will be always negative, so minus of minus it will be positive to add to the T_{AS} T_{BS} and T_{CS}. You will get the corresponding gate signal for the top switch in a sampling period. So, rest of the period, bottom switch you have to turn out. So, this is the algorithms we want.

So, let us go to the sector two now, how it works. So, let us find out the sampling instants for the T_0 by 2 period. So, this is our zero line, this is our A phase, this is our B phase, this is our C phase that is A B C.

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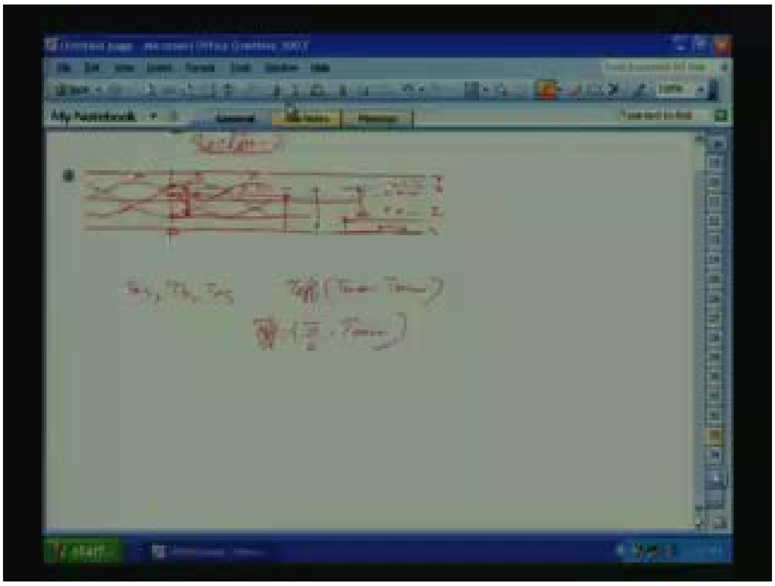

Now, we are sampling, so this is our maximum limit, maximum positive limit for the V_S with the maximum radii inscribed the hexagon for the maximum modulation index. So here, if you see here, for the sector two, we are sampling at this point. So, when you sample at this point, V_B has the maximum amplitude at this point, this is V_B.

Now, let us say the sampling, we are sampling at this point and V_B has the amplitude here, this is V_B; now V_C has the amplitude here, negative. So, this is what is, this one is for V_A. So, here the maximum amplitude for V_B and the minimum is for V_C. So, if you see here, till this point, for a sine triangle, till this point, A phase top switch is on; B phase top switch is on till this point from here if you take that is from here, starting from here, A phase is from here to here and C phase it is here. We are sampling it here, so C phase will have here, upto this point.

Now, if you see here, this is our maximum range here, the T effective is always T maximum and T minimum that is this one, from here to here. This is the T effective period. If you see here, till this point, it is plus, plus, plus. Then till this point, it is C is negative, so plus, plus, negative. Then from here onwards upto this point, this is B phase. So, it is minus, plus, minus. Then from here to here it is minus, minus, minus; this is in sector two. If you see here, this is 7, plus, plus, minus is equal to vector location two, this is three, then this is the eight zero in our space vector diagram.

So, here also the same we can use it T_{AS} T_{BS} T, we can find out, T_{AS} T_{BS} T_{CS} we can find out, then T effective is equal to T maximum and T minimum, T maximum minimum of this phase. Then T offset is equal to T_0 by 2 minus T minimum. This offset you add to this one, everything will go to the positive side and we will get the corresponding gate signal porter four switches of any land and the remaining period in a sampling period, we have to switch on the bottom switch. So, this algorithm will be very simple. So, let us write down the algorithms for digital implementation, very simple algorithm. So, our algorithms for the space vector PWM, we will write now.

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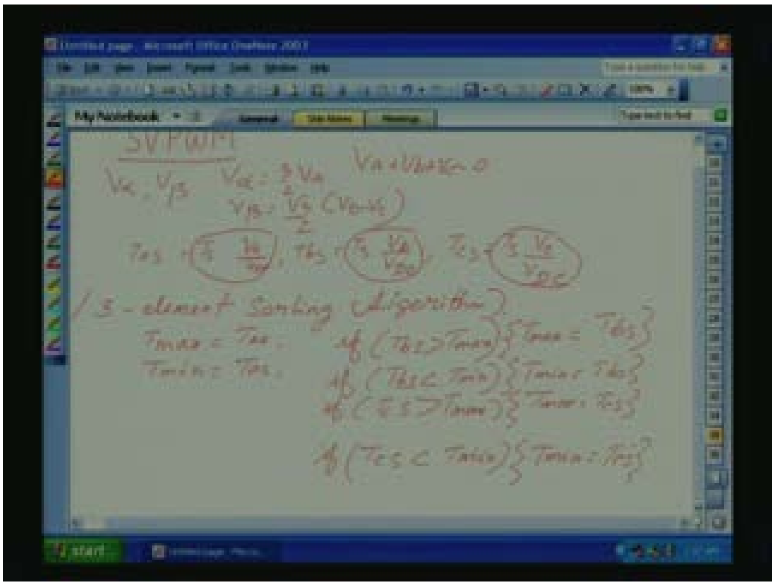

First we will get from the control, V alpha and V beta. From there, we can find out V_{AS}; V alpha is equal to 3 by 2 V_A and V beta is equal to root 3 by 2 V_B minus V_C. Also we know, for space vector, V_A plus V_B plus V_C has to be zero. Now, V_A V_B V_C is known, go on, then we will find out T_{AS} is equal to T_S into the sampled value of V_A divide by V_{DC}.

Similarly, T_{BS} is also equal to T_S into V_B by V_{DC} and T_{CS} is equal to T_S into V_C divide by V_{DC}. T_{AS} is equal to T_S into V_A by V_{DC}, T_{BS} also is equal to T_S into V_B by V_{DC}, T_{SC} is equal to T_S into V_C by V_{DC}. Then we have to find out the maximum and minimum; that we will use three element sorting algorithm. Let us take T maximum is equal to T_{AS}, T minimum also we will take as T_{AS}.

Now, if T_{BS} greater than T maximum, then T maximum is equal to T_{BS}. If T_{BS} less than T minimum, then T minimum is equal to T_{BS}. Then one more, if T_{CS} greater than T maximum, then T maximum is equal to T_{CS} or if T_{CS} less than T minimum, then T minimum is equal to T_{CS}. So, by this sorting algorithms, we can find out or at end of this command, we can find out which is maximum, which is minimum and which is the middle one. Now, we can find out the effective time calculation.

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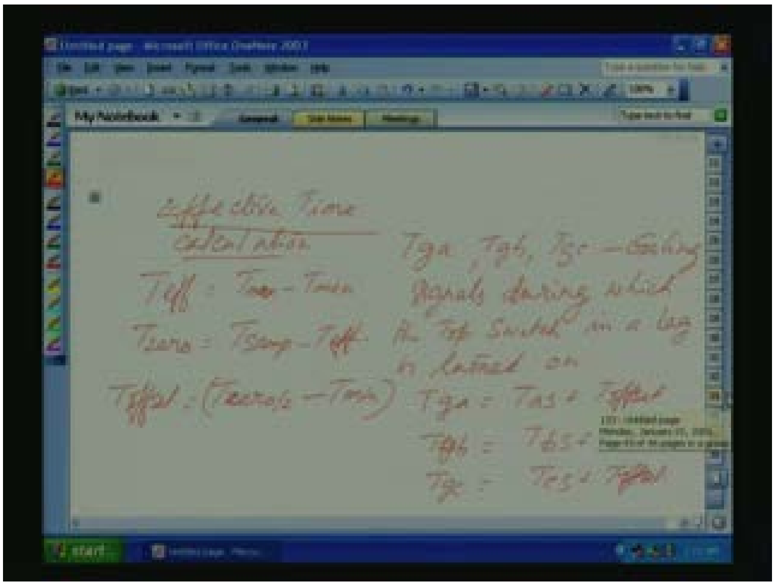

The effective time calculation, effective time calculation that is T effective, this is very easy is equal to T maximum minus T minimum. From the previous sorting algorithm, we have find out what is T maximum and what is T minimum, T effective we find out. Now, T_0 is equal to T sampled minus T effective. Now, we want the offset because all these, till now period, our T_{AS} T_{BS} T_{CS} will have maximum value and one will be minimum value. Minimum, depending on the sector, it will have minimum or maximum. Now, for the gate signal, we have to get the positive value. So, we have to add the offset. The T offset to be added to all the T_{AS}, T offset is equal to T_0 sorry T_0 by 2 minus T minimum.

Now, our gate signal that means the gate in a sampling period, gating signals during which the top switch in a leg is turned on, this is equal to adding the offset. So, Tga will be T_{AS} plus T offset Tgb is equal to T_{BS} plus T offset, Tgc is equal to T_{CS} plus T offset. So, rest of the period in a sampling period corresponding motor switch, you turned on. So, this algorithm is very simple.

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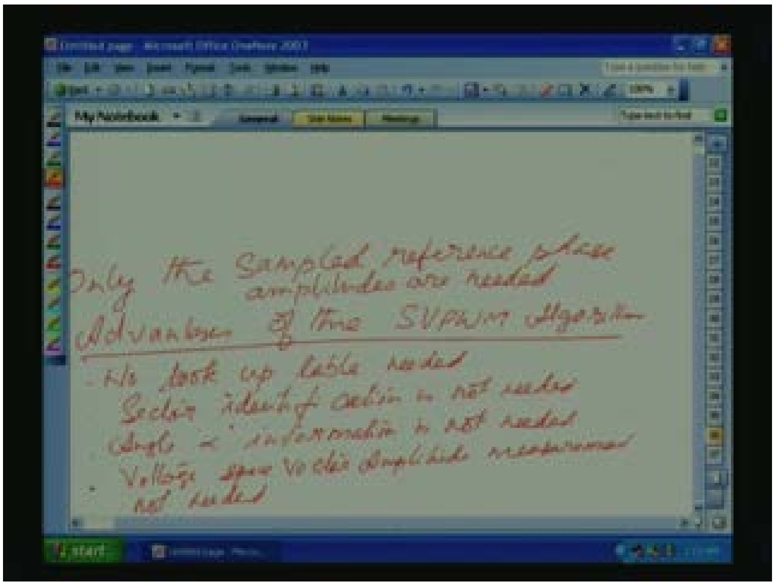

The advantages of this algorithm of the SVPWM algorithm; now look up table is needed, sector identification is not required, is not needed. The angle, alpha with which the reference space vector makes with the start of the sector, the alpha angle information is not needed. Voltage space vector amplitude, measurement is not required, not needed. Then what is needed? If you see here, we require only the sampled reference phase amplitude in a sampling period are needed. So, it is very easy, it is a simple sorting algorithm; there is no multiplication, there is no square rooting, there is no sine and cosine function is needed.

So, we can easily from the controller if you know alpha beta, we can easily find out transform the alpha beta into ABC and once you fix the T_S for a particular inverter switching; let us take one kilo hertz, one kilo hertz sampling, it will be one millisecond.

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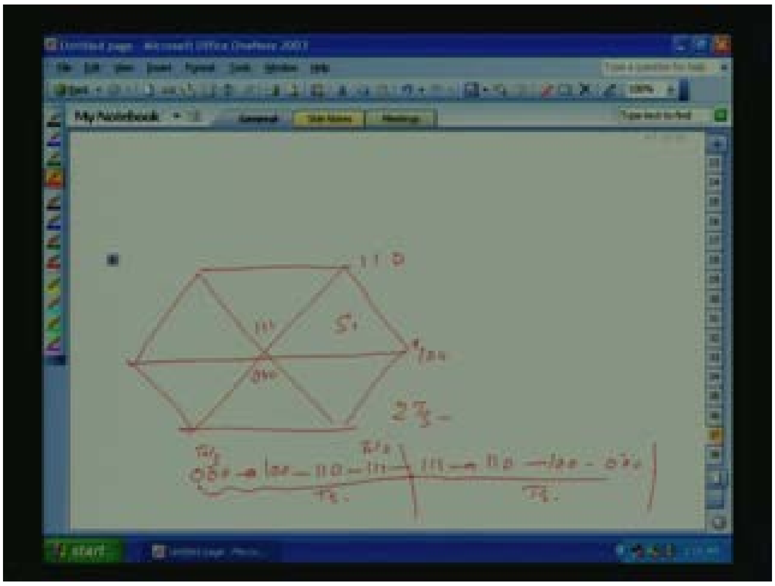

But if you see here, in a sector, this is our hexagon. Let us say S_1, it goes from plus sorry 100 to 110, then 111 000. So, in a sampling period, we will go, we will start from 000 if you start, next it will go to 100, then will go to 110, then the start T_0 but int T_0 by 2 will be 111 T_0 by 2; this is one sampling period. In the next sampling period, in the next sampling period, you will start with 111. So, that will ensure minimum switching. Then we will go to 110, then 100, then 000. So, if you see here, this is the next sampling period.

So, inverters started with a 00 state and ended with 00 within two sampling intervals that means in two T_S, inverter has come to original state. So, inverter switching period is equal to two times the T_S. So, for a one kilo hertz sampling period is required, so our T_S has to be 5 microsecond. Then appropriately, we have to toggle a count down for the zero and positive and switch between that and sequence has to be changed. So, this way, very easily we can implement the space vector PWM in the linear modulation.

In the R modulation that means when we have to go to extra modulation range where the zero period will not be or there zero period will be zero. So correspondingly, whenever the zero period become negative, we correspondingly adjust the gain such that T_1 plus T_2 is equal to T_S, then you get the R modulation. So, with this basic introduction from DC to AC converter, now we will use this one for a motor control, for typical induction motor drive applications; we will study this one in the next class.