Power Electronics

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Lecture - 26

Current Hysteresis Controlled and Basics of space vector PWM

So, in last class we were talking about the switching frequency variation for a hysteresis current controller for a fixed delta I band. So, if you see here, the switching frequency f is equal to f_m into 1 minus m square by 2 plus m square by 2 cos 2 omega t, this m is the modulation index.

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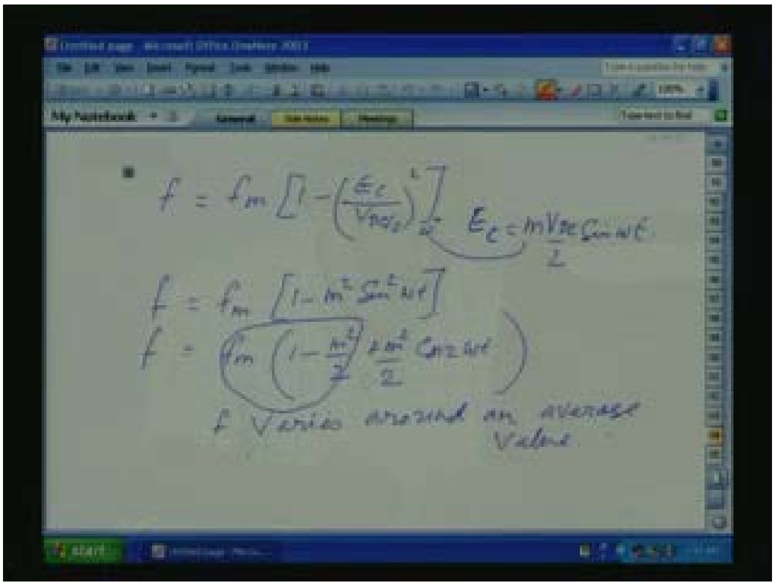

So, the switching frequency varies around a DC volt. So, let us draw how it looks; let us go to the next page.

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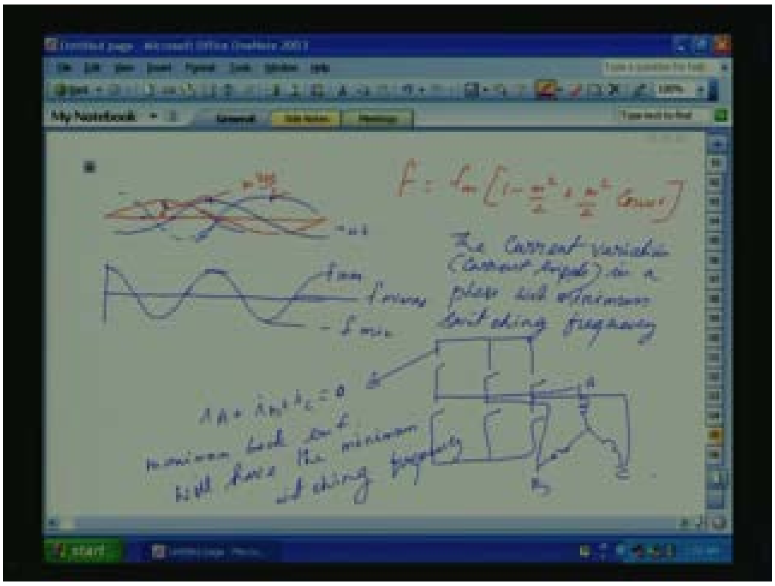

This is our X axis and this is our AC waveform, approximately I am drawing; this is the AC waveform that is the back emf waveform that is here E_c max. Let us say E_c is equal to m into V_{DC} by 2. Now, with respect to this one, how the switching frequency varies? If you see here, when m into V_{DC} by 2 is equal to 0; so let us write down the switching frequency equation that is equal to f is equal to f_m into 1 minus m square by 2 plus m square by 2 cos 2 omega t.

So here, when the back emf is 0, we will have the maximum voltage. So, if you see here, maximum frequency sorry, so if you write down our frequency with respect to this one, it will be like this. Let us draw with a different the colour, I will draw like this; this is our X axis for the switching frequency variation. So here, if you see here, 2 times it varies; switching frequency varies. So, this is our omega t; see, when back emf is 0, you will have the maximum switching frequency and when the back emf is here, you will have the minimum switching frequency. So, it will go like this; this is two times, this is f maximum, this is f minimum and this is f average. So, switching frequency varies. This is for one phase.

Now, to do design the hysteresis controller to avoid the high frequency switching that means if you use a IGBT or a transistor or a thyristor; so depending on that devices, there is a maximum width which we can turn on and turn off the device. So, usually in hysteresis controller, you can decide the hysteresis and hysteresis band based on the maximum switching frequency. Now, this is so far, we have discussed the switching frequency variation with respect to a single phase.

Now, let us take for a three phase. Three phase case if you see here, this will vary, the E_c maximum varies with 120, 120 degree; this is B, B phase, then the C phase will be sorry something like this it will go. So, the maximum point for each phase that is E_c is maximum so that minimum switching frequency happens at various points at each phase happens at different points. So, for a three phase system; this is our A, this is our B and this is our C. i_A plus i_B plus, A let us say B, C; here, i_A plus i_B plus i_C is equal to 0.

Now in this case, there is a problem; even though individually we have put hysteresis band, the phase which has the maximum back emf, maximum back emf will have the minimum switching frequency. What is meant by this one? So, i_A plus i_B plus i_C is 0, the current in the and the other two phases which have lesser back emf, the current changes will be much faster than the current in the phase where you have the switching frequency is minimum. So, the current variation, so here if you see here, the current variation that is the ripple or the current ripple in a phase with minimum switching frequency, minimum switching frequency will be decided by the other two phases because i_A plus i_B will be 0. So, what is the problem with is one?

So, sometimes in a phase, the current because of the three phase operation and the current in a phase because of this condition, i_A plus i_B plus i_C equal to 0 that means current in a phase, the instantaneous current in a phase depends on the other two phases. So, even though we have designed our hysteresis controller so that the current has to be within the hysteresis band, sometimes overshoot can happen; sometimes in a phase with the minimum switching frequency. That means, I can write it down; the phase which has the minimum switching frequency. This is because instantaneous amplitude of the back emf is maximum here.

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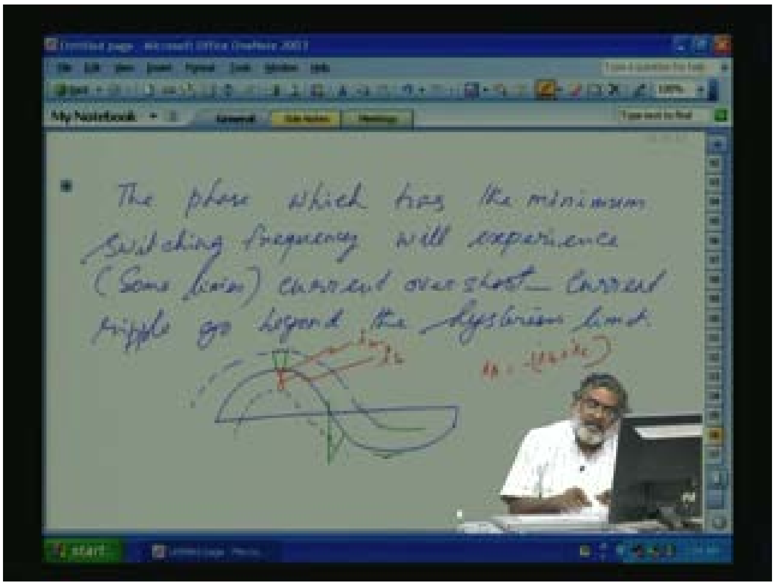

We experience sometimes, not always, sometimes, current overshoot; the peak of which can go a maximum of 2 h. If the hysteresis band is h, it can go up to a maximum of 2 h or we can say the current overshoot that means it can experience down load that means current ripple goes beyond the hysteresis limit. This is maybe we can explain like this, a simple way of explanation like this; let us say this is the phase current we want, I will put the hysteresis band like this, we have enlarged it for clarity.

Now, let us take the fast acting current controllers that means the phase in which the switching frequency is higher or the back emf is lower. Let us say in let us say this is A phase and B phase and C phase, the currents are increasing like this. Let us say, B phase, the current is increasing like this; C phase also, the current is increasing like this. Let us say, this is i_B, this is i_c. In C phase the current will be i_A plus i_B plus i_C, i_A will be equal to minus of i_B plus i_C because i_A plus i_B plus i_c is equal to 0. sorry

So, in C phase, so in A phase, the current will be it must have already reached the let us say, the current has already; suppose if it is here, current must have already reached somewhere here because sum of these two because it is slow acting. Now again, this is going in this direction. So, when it reaches here, i_A plus i_B has to be 0. So, it may go out of this one and they again come back. So, this can happen. This can this is also due to the reason; the inverter's zero states are not properly utilised in the hysteresis controller. What is meant by zero state? Let us see.

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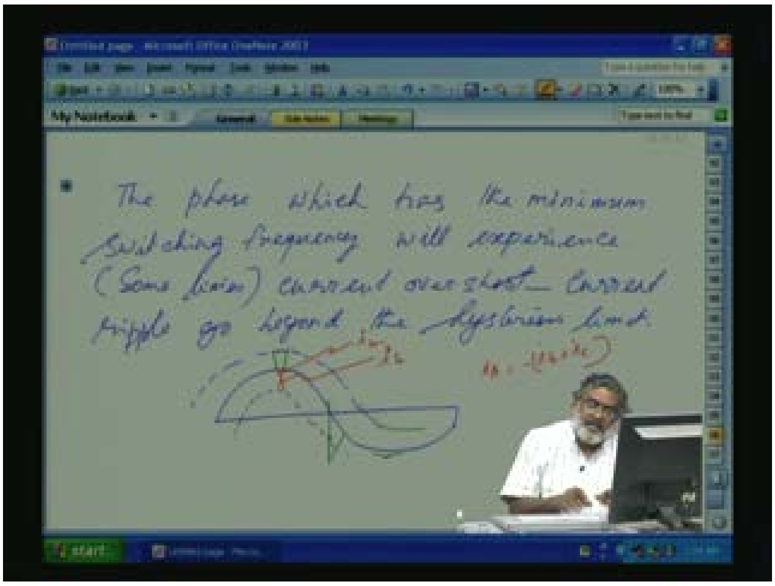

This is our A phase, this is our B phase, this is our C phase; so this is our minus A, minus B, minus C. So here, we are giving the hysteresis limit along the A B C. So, along the A phase let the hysteresis band is here that is the positive unit. So C, it will be here, equal width; B, it will be here. So, if you expand this one, the hysteresis limit for the combined three phase system will be like this; this is the limit, the combined A B C system has to be within this one.

Now, so A B C phases, when the top switch is on, let us say we are taking, we are taking this notation as 1 and bottom switch we are taking as 0. So, there are three switches; so, we can have 8 conditions; either all the top one is one, all the bottom one is on depending on the current or we can also have 001, 010, 011, 100, 101, 110 and this one. When any of these conditions happens, so this demands 111 that is all the top switch is on that means in an inverter all the top switches are on. So, what it mean by that one? All the three terminals are A B C phases are short circuited here, so we loss control.

So here, inverter is in even though 111 is inverter is in a zero state, so current be lose controlled. So, this will make sometimes the current, in this combined three phase boundary. See, we are extending the hysteresis boundary during inverter zero state; zero state not only one, these are zero also, this is also a zero state where inverter terminals are shorted to either to the upper link or to the bottom. This is, so these are called inverter zero states.

So, during this portion, let us take 111; we want the current increase in the all the phases, it could have a hysteresis controller but the links are short circuited, the DC link is inverter is isolated from the motor, so we lose control. So, in such cases, current can exceed the boundary and when again goes out; this is the boundary limit for all the three phases. So, whenever zero state happens, sometimes we lose control and current will go outside the boundary and whenever touches here, when the next switch is turned on or off, then only again it will bring back current inside.

So, this is because of the current in the three phase with the neutralized loads, the current are not independent of each other, current in a phase depends on the current in other two phases. That also means the switching frequency in a phase also depends on the switching frequency in the other two phases or in other words, the current in a phase which has low switching frequency that is maximum back emf will be decided by the current in the other two phases. So, there you will be losing control and current can go outside the boundary and the maximum of two times also it can go. So, this is called sometimes, sometimes that means if you observe the current, if you observe current in a hysteresis controller, depending on where the maximum back emf is there, current will be going like this; sometimes it can go on and come back like this. So double, this can happen.

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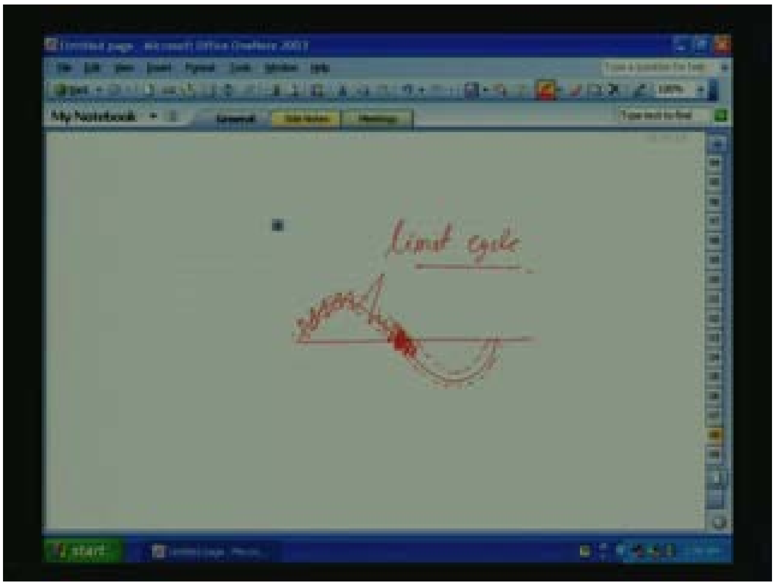

So, we may think we lose control; yes we lose control, not because our fault or our hysteresis controller because of the dependency of the three phase currents. That means any phase current i_A plus i_B plus i_C is equal to 0. So, instantaneous varying of a current in a phase depends on the other two; this is one thing, this is called overshoot. Then current hysteresis controller with a fixed back, this is another problem that is called limits cycle operation.

Sometimes, the band will be switched with very high switching frequency, limit cycle; this is because again let us go back to the ABC diagram, A, B this is C and we told, from the three phases, each limb, either the pole can be connected to the top and the top switch is on, connected to the bottom. So, two states are possible for a limb and there are three phases. So totally, 2 raised to 3; 8 states, combined states are possible.

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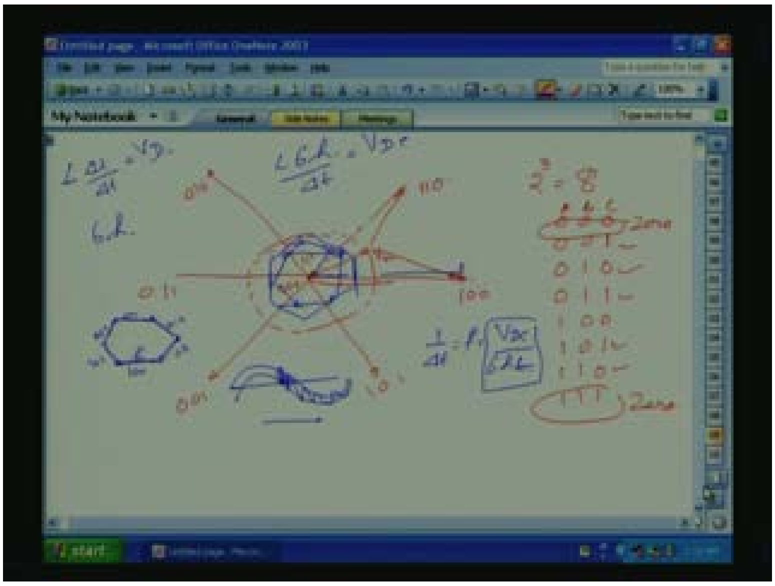

So, depending on the switching states, lets us take 000 all the bottom switches are on, then 001, 010, then 011; this is our A phase B phase C phase, then 100, 101, 110, 111. So, these two are called zero states where during this period, we lose control. That means inverter, all the three all the phases are shorted to either to the top when the 111 is on or to the bottom DC link; so we lose control.

Now see, if you take the combined three; these shows, according to the portion A B C, these are particular vectors. So, let us say 100 that means A phase is 1, B phase are 00 that means this will be there, 100. Then, where will be, this will be B phase 010 that is the voltage vector, the combined three phase, the voltage vector will be along this direction; then this is 001. So, this shows A phase is 1. Now, in that case, this will be, what is this one? That is C phase is negative. So, in all these regions, see the component of A phase along this one, component of this one will be always positive, C phase is negative. So, C phase is negative, so this will be 110.

Now, opposite to this one; this is 010, this will 101. That means in all these direction, the current along the ABC, the vector the voltage vector along the ABC; A and C axis is positive, B will be 0. Now, negative of C will be 011, so we have taken all the 011, 101 we have taken 110 we have taken, 01, so 00. Short circuited means all the three phases are short circuited that means the combined vector is 0. So, these are 111 000.

Now, if you see a combined system, the back emf, back emf is the combined three phase ABC, not the individual, ABC combined system will have for a sinusoidalisation, it will have a magnitude of em and it will be tracing a circle with uniform velocity that is a back emf. Now, for low back emf that means back emf is very small for a motor drive, low speed operation, then V_m is very small, somewhere here; then the current order direction, when the back emf is there, when 111 is 0, the current direction will be difference of these two vector that is either it can be here or when this is here, it can be in this direction.

So, when V_m is 0, if 100 is switched, the current order direction will be in this direction. So, for lower back emf voltages; let us draw the let us draw our hysteresis band with blue. See, this our hysteresis band; A phase - positive and negative, B phase it is here no, the C phase negative it is here, B phase negative it is here, then C phase, this is this one, so this is hexagon; this way it goes.

So, when back emf is 0, the current order direction whenever all these; these we call, all these six are called active vectors, these two are zero vectors. Whenever the active vectors are switched, current order direction will be along the axis V_m is 0. So, when it happens, see when 110 is switched, it will go like this. So, that means it will go from here to here, the moment it is touched here one, so it will go to 110, 110 means again it will go like this, then it will go like this, it will come like this. So, it will make 6, the 6; from here it will go like this, then there is another one, 6 will be there.

So, in a cycle of operation, it will make for it will make 6 jumps equal to our hysteresis band because back emf is 0. So, when 110 is there, it will be like this; the moment when we touch it; 110 is there, we are touching here, so 110 it will go like this, then 010 it will go like this, then 011 it will come along this direction, then 001, 001 in this direction, then 101 it will come like this. So, the current order direction for this one, it will be 100, current order this will be 001. Whenever our back emf is 0, then this will be 010, then 011 in this direction, then 001, then 101.

So, current ripple, the combined system current ripple will go like this in all the three phases together. So, it will make 6 passes and come to the starting point. So, this distance depend on our hysteresis band, this is equal to h. So, we will make total distance is 6 h and if you this length, it is our DC link voltage. So, 100 we are taking.

So, let us say when the 1 is switched on, it is plus V_{DC} by 2; when the 00 are minus V_{DC} by 2. So, this length is V_{DC}. So, you have L into delta I by dt is equal to V_{DC}. What is the delta I distance travelled? Distance travelled is equal to 6 h, current ripple. So, L into 6 h by delta t is equal to V_{DC}. So, from this one, 1 by delta t is equal to frequency of it is equal to V_{DC} by 6 h into L. So, L is the leakage inductance of the surface machine.

So, depending on this L, during back emf is 0, high frequency switching will be there; you can observe in the current hysteresis band. So, this is called limit size. This is during only the back emf at three zero. So, sometime we can see this type of high frequency switching, then we will go. So, what it shows for a three phase machine with not independently controlled? Because for ABC system with neutralize disconnected, the currents are, the current in a phase is depending on the current in other two phases. So, this can create sometimes the variation in one phase, the current variation can depend on the current variation in other two phases where the switching frequency is higher. So, this can lead to overshoots that means current can sometimes come out of the hysteresis band. Also, when the back emf is zero because of the combined effect, current will make a high frequency circulation like this combined current effect. So, this will result in high frequency switching in individual phase, this is called limit cycle operation.

Now, but current hysteresis controller is very easy to implement; it sends the current, you have a reference current, so current hysteresis controller, how the controller will be, it is very easy to implement.

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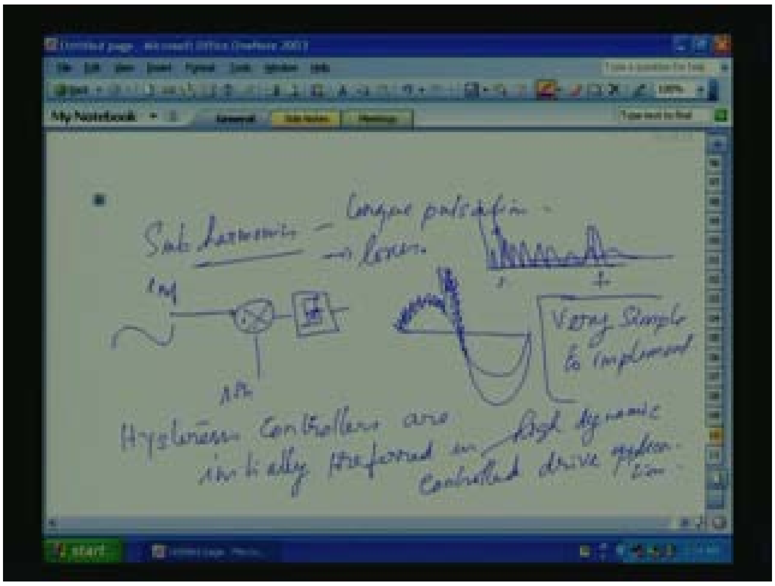

So, you have reference current i reference, these are sinusoidal current; this you compare with our feedback current i feedback, this you give to our hysteresis comparator, this is our h. And, whenever the hysteresis comparator touches the top band, you switch the bottom devices; whenever touches the lower band, switch on the top phase for each phase. So, it is very easy to implement, it has fast dynamics. Fast dynamics means let us see our curve reference is like this, it is going study state operation, so current is within the hysteresis band, it goes there.

Now, at this point due to some control action, let us see frequencies are same; the current reference has gone here. So, what happens? Along with our current reference, our hysteresis also moves. Now, according to this one now, our current reference is below the hysteresis band. So now, the top switch will be immediately on and current will quickly rise. Then there onwards, again it will go to the hysteresis band. So, this has fast dynamics. So, it is initially used in hyper performance drive such as vector controlled drive application; we will talk about the vector control drive application later.

So, hysteresis controllers; so, initially preferred in high dynamic controlled applications, control drive applications this is used. But the problem is there is a wide switching frequency variation is there. So, the hysteresis spectrum, the current harmonics spectrum not like our sin triangle PWM with harmonics shifted at the high order harmonics setted at f_c and f_m. Since, the switching frequency variation is there, we can have all sort of spectrum; the distributor spectrum will be there. Sometimes you can see, for various operations, some harmonic source. That means frequency below the, so other switching frequency come slower; the side bands can be shifted to the lower side of the fundamental. So, it can also create sub harmonics.

So, the moment some harmonics means motor drives, it can create torque pulsations, also losses, harmonic losses. So, these are some of the problem. But it is very easy to implement that means hysteresis controller is very easy to implement, very simple to implement that is very important. So, there are many marks related to switching frequency variation control of hysteresis controller. So, we will not be talking about that one now, we will go another popular very popular PWM controller that is called the space vector PWM control.

See, so far we talked about the PWM control based on the individual phases. Now, at the end of current hysteresis controller, we talked about the combined effect and we call the combined vector from all the three phases. So now, hereafter we will talk about not as individual, as a combined effect of three phases that is as one vector; that one vector which is which is the combination from all the three phases and based on that one, combined effect, how you do the PWM control, this is called space vector PWM control.

So, before coming to the space vector PWM control, let us study, what is meant by space vector? What is in literature? What is meant by space vector? How the concept has raised? So, in many of the latest literature, PWM control literature, people always talk about space vector PWM control. They do not talk about the individual phases but instead, the combined effects space vector PWM control. This is very important, very interesting.

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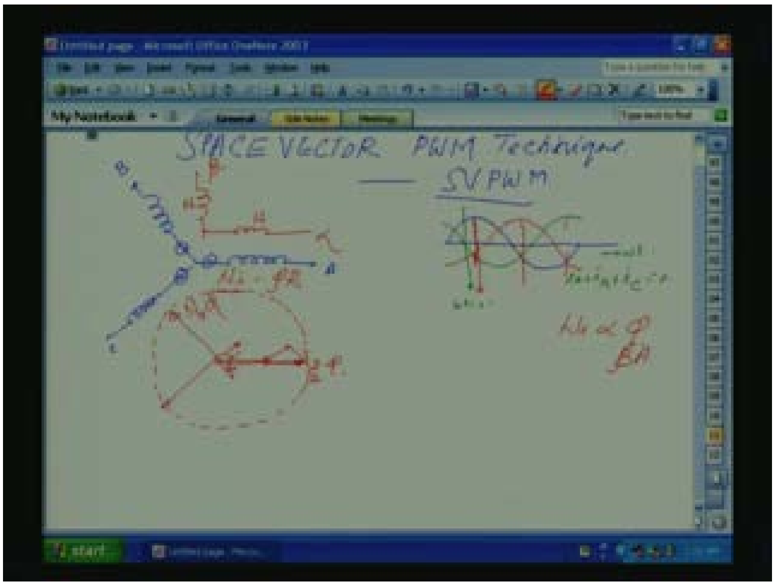

Let us call space vector, space vector based PWM control, PWM technique where in literature it is called SVPWM. What is meant by space vector? Let us see. Now, we are going to consult the voltage and current variation in a machine. Let us take a three phase system, let us take a machine like induction machine as not as individual FEC, combined effect of all the three. See, what is meant by combined effect of all the three? Let us take schematic representation of this is our A phase, B phase, the B phase winding what I am seeing in a machine, this is B phase and the C phase, this is C phase, this is the assuming resistance is negligible. So, this is the basic three phase representation of a machine with back emf load is also there, back emf is there, we can put this one.

Now, in all our PWM controller; what we want? We are using PWM technique for voltage control but what is the final thing we want? The final target is sinusoidal nearly sinusoidal variation of the current that is what we want. Let us say, let us study; when the machine is excited with three sinusoidal currents, so this is our A phase, now B phase I will draw with a different colour 120 degree, this is our B phase, approximate then and let us draw our C phase, this is our ABC current, this is our omega t.

Let us see, when the machine is excited with three sinusoidal currents, let us take what happened the mmf or the flux generated in the inside the machine? Let us take our omega t is equal to 0 here when A phase is maximum. So here, when A phase is maximum, we know that i_A plus i_B plus i_C is equal to 0. When A phase is maximum, the flux along the A phase or the mmf, mmf flux along the A phase is equal to that is N into i is equal to flux into reluctance of that. So, this is called the mmf. So mmf, N_i is proportional to the flux, reluctance of the machine is uniform, it is not varying. So, the N_i is proportional to the flux generated or the flux density you can say, f_c is equal to B flux density into area. So, mmf N_i is proportional to our flux density. Let us say flux density that is the number of lines per unit area. So, as the current is maximum, the flux density, the number of lines per unit area will increase.

Let us say, so if you see, the flux density is proportional to i; now when A is maximum, the flux density let us say N_i is in this direction. This is for the A phase. What will happen here, omega t is equal to 0? When omega t is equal to 0 that is this point sorry I have taken this is the omega t is equal to 0, at this point, B and C are equal and negative and half the value. Then only we can i_A plus i_B plus i_C equal to 0. So, the flux or the flux density, the flux is along in this direction; D is minus, C is also minus, so B will be in this way, half the value. So, if this is take the amplitude as one, this will have half the value but the C will be minus, so it will be in this direction. So, where we will have the peak flux density where in the machine?

See, we will take the component along in this direction, component along in this direction it will cancel. So, the component along in this direction will be parallel to this one, then this also parallel to this one. So, it will go like this. So, this one, this is 60 degree, this is 60 degree. So, if you see here, this is if this is phi, these two will be together will constitute phi by 2. So, total it will be 3 by 2 phi in this direction plus already this is phi by 2 and cos 60 half, so half into half, one fourth. Here also, half into one fourth, one fourth plus half, so 3 by 2 phi. So, maximum flux density direction that will be along the A phase axis.

Now, let us take a case where at this point here, when B is maximum sorry when B is maximum that is at this point, not this point. So, let us draw when B is maximum that is at this point. At this point if you see, current through B phase is maximum and C and A is negative and half the value. So, if you see, according to the same explanation here, now the max 3 by 2 phi will be along in this direction, 3 by 2 phi.

Now again, when C is maximum, the 3 by 2 phi; here A and B are negative, C is maximum, the 3 by 2 phi will be in this direction. Now, if you try to plot the maximum, the direction along the maximum flux density axis starting from here, taking various points in this curve; so the maximum flux density wave will raises up. What it shows? For sinusoidal excitation, when the machine is excited with the sinusoidal current, the maximum flux density wave in sinusoidal distribution of the flux is possible inside the machine and the peak value of the flux as the speed moves depends on and it will trace a circle inside the machine. That is what we want during. So, this will trace a circle, the resultant flux density wave.

So, if you see here for the analysis, this is generated from our three phase system. So, this circle is generated can also be generated by an equivalent two phase systems. Let us say our equivalent two phase system, you do not work a three phase, the same circle here it represents the flux distributions, sinusoidal flux distribution and it raises as the frequency varies, the peak value traces a circle. This is generated by a three phase, it can also generated by a two phase system.

Let us see, this is 2 phase system alpha and beta. Let us say this is N, this is also N, same number of times. Then let us see what is this component? The current component along this i alpha and b beta such that it will also generate a flux distribution like this, circular flux distribution as the fundamental frequency variation that is this is simple that three phase to two phase transformation. So, let us derive that one.

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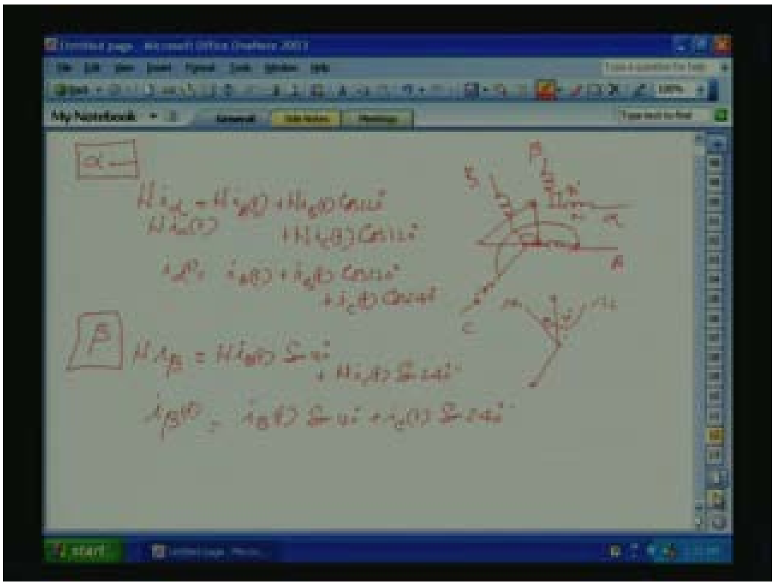

See, the real and imaginary part, let us take N into i alpha that is mmf along the alpha axis that means again for clarity we will make it like this this is A, 120 degree you have B, this is C, ABC. Now, you have alpha, beta. So number of transits, what is N_i alpha? N_i alpha is component of the mmf along the ABC axis; see, the component of the early ABC axis along the alpha axis. So, the component along, these are in along the same phase, direction is the same that is they are collinear. So, the component along the A phase which contribute to alpha axis is equal same as N into i_A (t). See, i_A is sinusoidally varying, so that is the function of type.

Now, what is the mmf produced by the B which contribute to the alpha axis? So, this will be 120 degree, cos 120 degree. So, N into i beta t into cos 120 degree whatever the component along the C will be cos 240 that is this one, 240 degree, this is 120 degree. So, this we can and number of times is the same and the mmf or the flux density wave depends on the instantaneous value of current and the component along the alpha axis is equal to cos 120. So, from this one, we can see; the equivalent current i alpha is equal to i_A (t) plus i_B (t) cos 120 degree plus i_C (t) into cos 240 degree. So, i_C (t) is 240, this is the alpha component, alpha.

Now, let us take the beta axis. Beta axis is this is 90 degree, so i_A will not contribute along to the beta axis only i_B and i_C. So, i_B and i_C if you see here, this is the beta axis, i_B is along this one and i_C is along this one, this is 90, so this has to be 30 degree. So i_C, this is minus i_C, i_B this also will make 30 degree.

So, the beta axis the component mmf will be i_B, N into i beta; the mmf which is proportional to the flux density where or the peak value of the flux depending on the i_B, flux density wave i_B N into i beta will be i_A, the flux along A axis will not contribute. So, this will be N into i $_B$ (t) into i beta; how much it will come? We can either write from here to here, cos 30 we can write it but from this 120 240, same thing if you use it, this is also can be i beta into sin 120, it will be sin 120 degree and plus N into i_C (t) into sin 240 degree, this will be like this. Here, i beta, from this one, i beta is equal to this i beta is also functional type, it is varying; as the i_A i_B varies i beta (t) also varies. This will be equal to i beta t into sin 120 degree plus i_C (t) into sin 240 degree.

So, at any instant, the resultant peak value of the flux that is the maximum flux density wave will be will apply to find out where in the machine it will be there, we have to vector some the flux density wave or mmf along the alpha and beta. So, let us take N into i alpha t, beta is along the i alpha plus t beta; so here, this way. So this amplitude; let us go to the next page.

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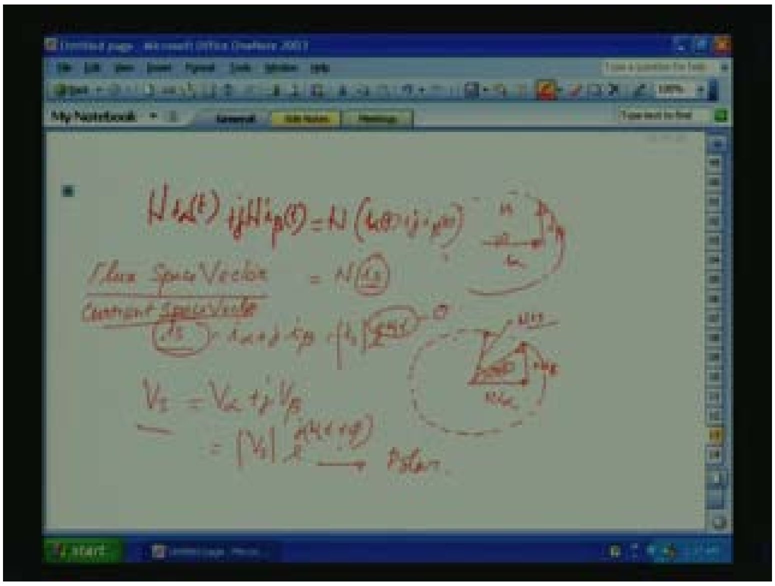

The N_i alpha t plus this N_i alpha along this direction and beta t in this direction; so, this amplitude will vary as the beta varies not as the i_A i_B i_C amplitude varies. So, at any instant, this component is the vector sum of these two orthogonal components. That means it can compress N into plus N into plus j into N j. So, j is introduced, it is a vector sum. This also we can write as N into i alpha t plus ji beta t. So, this i alpha plus if i alpha is here, i beta is here; let us take this as i_S. So, this will be equal to N into i_S.

So, to show that this is the vector, I will put an underscore that means it has a magnitude as well as an angle, the theta that depends on the instantaneous amplitude of i alpha and beta. So, i alpha i beta varies as I have told, this one; trace a circle or our N i_S if it our N_i alpha N_i beta, N_i beta depending on this value, this will trace a circle. What we will trace circle? Our N into i_S that is the resultant flux. So, we know that in the machine, the peak value of the flux, the maximum flux in instantaneous wave will trace a circle with constant amplitude when you excite with sinusoidal current. So, this we can call as flux space phasor or space vector, flux space vector because it exists inside the machine and it has an angle. It is not like our conventional vector with a fixed angle, this is a function of angle theta t.

Now, this flux space phasor if you say, it is produced by the current space phasor i_S, so if you remove this constant; what is our current space vector equivalent that mathematical expression? Current space phasor, current space vector but this is vector exists in the space but this is if you remove the constant, we can also also have an equivalent current space vector definition is equal to i alpha plus ji beta. If you see here, this i_S this is one quantity, it is the sum of real and imaginary which in turn are produced by the individual ABC currents. So, this can also be represent as an i_S magnitude or some here i is to j, the speed is theta t as the frequency is the omega s, omega s into t; this is the angle, theta is this angle. So, this is called the current space vector.

Now, if you see here, the current space vector is generated, current is generated by sinusoidal current means it is by sinusoidal voltage individual phases with a phase angle phi for an induction machine, for a current will be always lagging. So, we can also have an equivalent, we can also have an equivalent voltage space vector representation that is V_s is equal to V alpha plus jV beta is equal to V_s magnitude into V raised to j omega st plus some phi with respect to current. So, what is the advantage here? All the three variations, we represent it with two quantities; one is the magnitude and the other one is the angle. This is called the polar representation.

So, what it indicates? For a sinusoidal flux variation, we should have a sinusoidal current variation. Now, in PWM operation, you see, when you have the PW operation, the average variation is circular. So, that means average variation of the current is circular or in turn, we should have a PWM scheme such that the combined effect of all the three with respect to volt, the voltage space vector, the tip of the voltage space vector should an average variation tracing a circle with uniform velocity.

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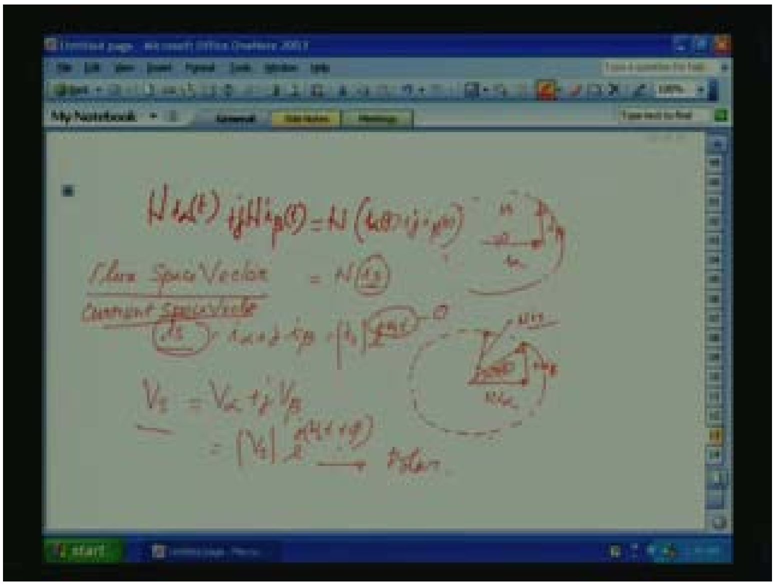

So, the space vector PWM aims at having a voltage space vector, the average variation of the space vector, the tip of the vector should trace a circle with a uniform velocity equal to the input excitation frequency. So, how to generate this space vector, voltage space vector PWM so that the resultant voltage space vector or the average variation of the space vector will trace a circle; we will study in the next class.