Power Electronics

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Lecture - 32

High dynamic performance of Induction Motor Drive

Last class we talked about V by F control of induction motor with steady state equivalent circuit. In the study state equivalent circuit, what we found is the rate of change of voltage due to the flux that LDA by dT is or due to the rate of change of current, we found it is only the frequency only have taken into the consideration. But many applications, amplitude as well as frequency we will change. So, in that case, how is the interaction between the fluxes? What is the output power? What is the equivalent model under dynamic conditions; you have to study and then a control under all dynamic conditions for induction motor, how it works need to be studied now. So, this we call high dynamic performance of induction motor drive, high dynamic performance of the induction motor, induction motor I will write an i_m drive.

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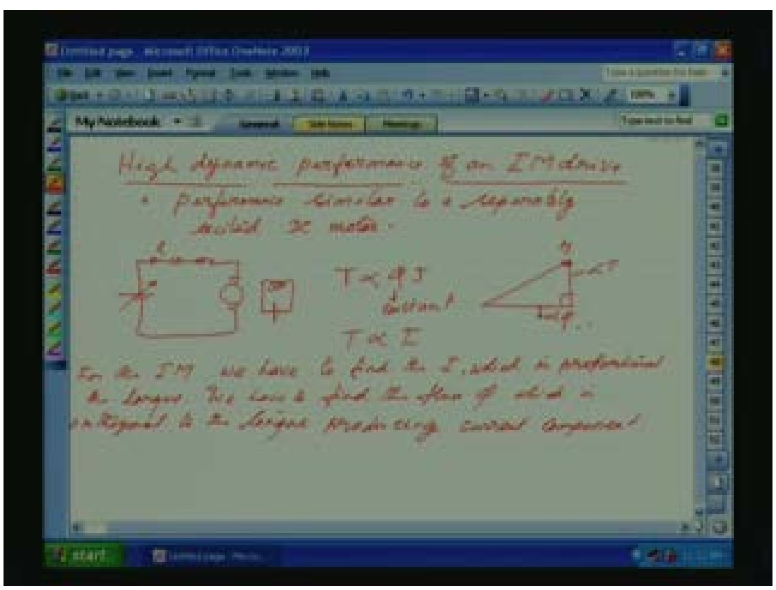

What is meant by high dynamic performance? A performance similar to a, performance similar to a separately excited, this we have studied before, separately excited DC motor. For a DC motor, we will control the voltage; we have the armature resistance and then back emf from the motor but the field, we will control separately, field is kept constant. So, if you see the torque, torque is proportional to phi into I, I is the armature current. So, phi is constant, then T is proportional to I. How we can get a performance similar to this one, induction motor?

So, induction motor we have to found out I; for the induction motor, we have to find the find I which is proportional to torque. Also, in DC machine because of the construction, this flux and i_r orthogonal to each other, armature. So, here also, we have to find out the, find the flux phi which is; so this flux phi also generated by a current I. So, for the induction motor, the current which is coming from the starter is a vector sum of flux producing component and the torque producing component.

Now, we have to find out the flux to be kept constant in vector diagram; this flux which is orthogonal to the torque producing component, torque producing current component. This is as I told before, current in the separately excited machine, the flux and the torque producing components are separately adjusted but in the induction machine, it has to be a vector sum. Vector sum means the i_S. It should be a vector sum of two currents in this direction, orthogonal. Then only, suppose this is the torque producing proportional to the torque, if this should be proportional to phi, then only it changing the torque producing component will not affect the flux because orthogonal. Then only we can say the flux is kept constant.

So, we have to find out the induction machine; from the induction machine model, which is the flux which is orthogonal to the torque producing component. So, let us study the dynamic equivalent circuit model. So before that, briefly we will go to the steady state model.

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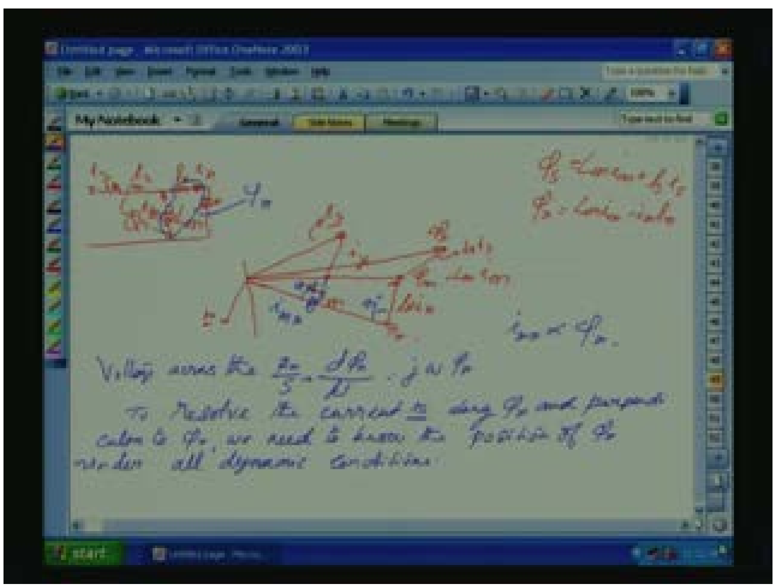

In steady state model, see let us take the current; this is our i_m, this i_m plus i_r is equal to our i_s based on our equivalent circuit model. Here, everything is based on the air gap flux; this is i_m, this is our i_r, this is our i_s. Now, we know, the air gap flux is proportional to IF. So, let the air gap flux is somewhere here; this is equal to L_m into i_m, phi m is equal to L_m i_m. Now, from this equivalent circuit, the starter flux is equal to that is starter flux that is this one, it is coupled here by these two inductors; the phi s equal to L_m i_m plus l_S into i_s. So, i_s is proportional to this one, so along this direction somewhere. Let us say, this is equal to l_S i_s, our phi m phi s is here.

Now, i_r is going in this direction, so if you say the notation; current entering is positive here and current leaving is negative, the phi r rotor flux is equal to L_m i_m minus i_r L_r, L_r is the leakage inductors, this one. So, that means, how it will be? So, phi m is equal to, so minus i_r; so this is l_S i_r, so actual our i_r is this one. So this is, this direction is minus i_r; so, it will be like this, parallel to the i_r, L_m i_m minus l_r i_r. So, our si r will be here. See, if you see here, from the equivalent circuit, si r is the one which couples the rotor that is flux here coupling this inductance, this is the si r.

After the si r we get, we have only seeing the resistance; so voltage across the resistance R_r by S, R_r by S is equal to d si r by dt. These si r by dt assuming flux is kept constant sinusoidal; so d si r by dt is equal to si r is equal to sine omega t, it will be j omega si r into cos omega t. So, this voltage is proportional to si r and the voltage and current through R_r as using proportional. So, this si r and this one will be 90 degree.

So, if you locate i_s; previously we have with respect to air gap flux, we had defined i_s as a vector sum of i_m plus si r. Also we can, i_s we can define with a another component which is let say magnetizing component, rotor flux producing component imr that is this one and the perpendicular component, this is also 90 degree. So, i_s originally defined with i_m plus i_r vector sum of imr can also be defined with the current imr which is responsible for si r because all these flux are produced by the components of i_s where the air gap flux or the air gap flux the starter leakage that is si s or si r. So, flux is proportional to the current.

So, a current component which is proportional to the flux is already availably i_s. So, if you take the flux si r and the current component which is responsible for si r that is we are taking as IMR, imr is proportional to si r, then there is an orthogonal component that is perpendicular to imr which is the torque producing component. So, this imr plus i_r equal to i_s.

So, if we find an equivalent circuit based on this one, then there is an equivalent circuit that is required for the high dynamic performance drive applications. That means we have to keep this i_r which is proportional to imr or which is perpendicular i_r, we have to keep varying during the torque portion and this imr we have to keep constant so that si r is also constant. So, there is a decoupled control possible in the same way as in separately excited DC motor. But if you see here, this is based on steady state equivalent circuit; under dynamic conditions, this magnitude of i_s can vary, so this si r with respect to si m, position with respect to i_s can vary. So, what we want? To find out, to resolve the current, to resolve the current i_s along phi r and perpendicular to it, to Phi r; we need to know the position, position of si r and all dynamic conditions. So, this is the problem here.

So, we need an equivalent circuit which is valid under all dynamic condition that means whenever the i_s varies or the flux amplitude varies, si m amplitude varies, si s varies; how is the relative position of all these vectors? From that, find out the si r and resolve si r, resolve i_s along si r and perpendicular to it and keep the component along si r constant, the current component; so si r will be kept constant. So, same like separately excited machine the flux is kept constant and we are controlling the orthogonal component for the torque variation.

So, let us study the dynamic equivalent circuit for the induction machine. Let us go to that one and from there, we will divide the control; resolve the current i_s along si r and i_r, this is called the field oriented control, the famous or vector control. For the dynamic equivalent circuit, here also, here we will use the space vector notation. So, we studied the space vector in the context of space vector PWM. So again, we will just remember some of the basis here.

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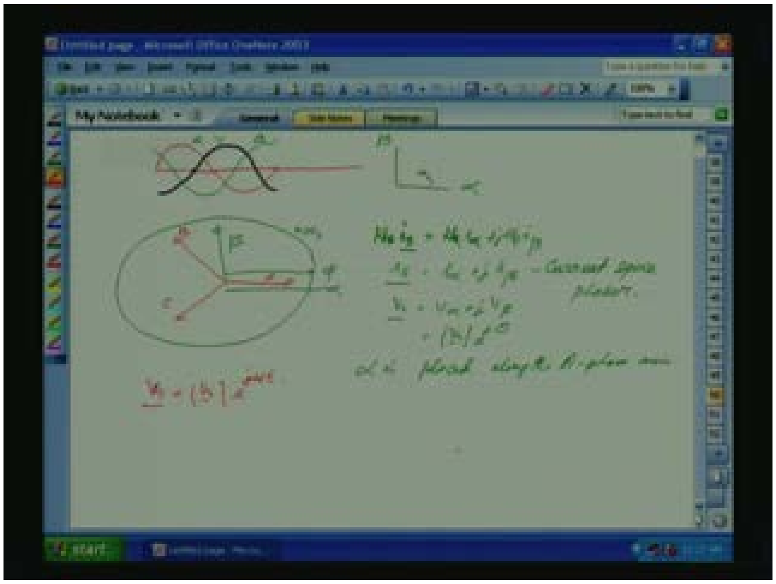

So, when the machine is excited with a three sinusoidal currents and the machine is excited with three sinusoidal currents, let us say this is RYB or ABC; we know that there will be a flux, air gap flux which is tracing a circle and the speed is omega s, the synchronous frequency of this one and this flux freeze spacer is we have put as N_s into i_s is the mm, this is equal to N_s i alpha plus N_s plus j N_s i beta. So even though, this flux, the rotating flux is produced by three phase quantities, we can also have an equivalent two phase quantity; alpha, beta. So, this is the flux which is already there in the air gap.

Now, this flux is proportional to current. If you remove this N_s is a constant, then we can have a definition for current space phasor, this is also equal to N alpha plus j i beta. This is called the current space phasor, space phasor or vector anything is okay, both are same. Move this current, this current is produced by the three currents i_A i_B i_C or also, this current space phasor, this current is sinusoidal current is flowing into the machine is due to the excitation with sinusoidal voltages. That voltages and current will have a phase angle of phi. So, we can also have a definition, equivalent voltage space vector definition; V alpha plus j V beta.

So Vs, what is Vs? Vs is equal to there is a mod plus there is an angle, this angle will measure with respect to alpha, axis, this is the angle alpha and this alpha, we will always place, alpha is placed along the A phase axis; so, this is alpha, this is beta. Now, our ABC quantities are; A is along this direction, B is 120 degree, C is also 120 degree. So Vs, let us take our Vs is equal to Vs mod e raise to j omega t because all these flux space phasor, the flux and current and voltage space vector which rotates, the tip of the vector rotates with the angular frequency omega t that is an excited frequency. But there is only, but there is always a fixed phase difference between the voltage and current during steady state. In dynamic conditions, angle as well as the magnitude varies. So, this is our Vs.

Now, let us write down the phasor quantity for the induction machine. Let us take the induction machine is a squirrel cage induction machine where there is no voltage excitation from the rotor side, rotor is short circuited.

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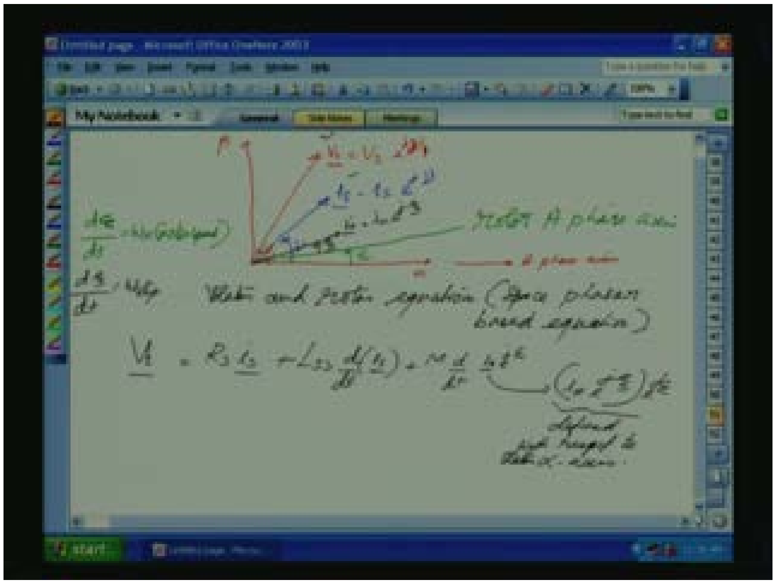

So first, we draw our alpha axis; this is the beta, this is the alpha axis and alpha axis is placed along our A phase axis, this is the alpha and this is the beta and we are measuring the angle with respect to alpha axis. So, let us take a general position of Vs, voltage space vector. Let us take, Vs is equal to e raise to j gamma one. Which is gamma one? Gamma one is this angle, this is the function of time as Vs varies. So, general position, this Vs e raise to j gamma one; see Vs is equal to sorry Vs is our space vector which we have as a magnitude. So, we will at an angle, so we will write that way; Vs is equal to, Vs this is the amplitude into e raised to j sorry e raised to j gamma one, this is the one, gamma one.

Now, because of the voltage space vector, assuming it is the machine is excited with sinusoidal current, so because of this voltage space vector; now this voltage space vector, it has an alpha component and beta component. Also, the projection of these Vs along the ABC axis will give the instantaneous values or the excitation values for the ABC voltages. So, if you know the instantaneous position of Vs and its magnitudes, we can find out the alpha beta as well as ABC. So, we do not require the three phase quantities. Here, one quantity is sufficient that is the voltage space vector; the one quantity in polar form, the magnitude and the angle with respect to alpha axis.

Now, when the machine is excited with a voltage spaces, there will be a current space phase also and current space where will not be, these two vectors will not be collinear, there will be phase different. Let us take the i_s, i_s is somewhere here; i_s, the angle instantaneous angle is gamma. So, it will be equal to i_s magnitude e raise to j gamma. Now, the rotor is rotating. So, if you see, the rotor ABC axis will have will have a vary angle with respect to starter ABC angle and the angle or the rate of change of angle is proportional to the rotor speed. So, let us say, the rotor axis is somewhere here, rotor A phase axis; I will write it bold, rotor A phase axis. So, this is moving with an angle sigma, sigma is also a function of t. What is d sigma by dt no d epsilon by dt? Epsilon by dt is equal to omega r, rotor speed. So, rotor also has ABC axis.

So suppose, if you measure the rotor current with respect to rotor ABC axis, the angular velocity of the rotor current space vector will be proportional to the slip frequency. So, let us see, there is a rotor current i_r, i_r is equal to with respect to the rotor axis, i_r is equal to let us take this is theta, e raise to j theta where d theta by dt is equal to omega slip but theta is the angle, we are always measuring the angle and there is no rotor excitation voltage because rotor is short circuited. Now, relative position of the rotor voltage, starter voltage, starter current and rotor current is this one.

So, let us write down the rotor and the starter, voltage space vector based equation that is starter and rotor equations; this is space phasor based equation. We are not using the ABC component and alpha beta, these are all called space phasor or space vector based equation. Let us start with the rotor, applied voltage Vs. When the rotor is or when the starter is applied with a space vector Vs, it will have the startup drop, this is the space vector i_s plus starter self-inductance mutual plus leakage that will represent as Lss, this is called self-inductance into d by dt of i_s.

So, the moment d by dt of i_s, we are taking into consideration, i_s has a magnitude as well as angle; both are varying. So, d by dt we are taking into consideration the variation of both, here we will take care. Now, due to rotor current, due to rotor current and as a mutual inductance between the starter and rotor, there is a coupled voltage to the starter due to the rotor current. So, what will be that? So, due to the mutual inductance m into d by dt, if you see here, i_r is defined with respect to rotor axis that is i_r into e raise to j epsilon.

See originally, i_r is defined with respect to rotor axis that is here. Now, all the quantities, now starter means everything we have to represent with the same axis. So, what happens? We have to multiply by e raised to j sigma. This i_r is equal to, i_r into e raise to j theta. This we are multiplying with e raise to a theta so that this is defined with respect to starter, respect to starter alpha axis. See, how this is done? Let us go to the vector notation; this is very easy, let us take this way.

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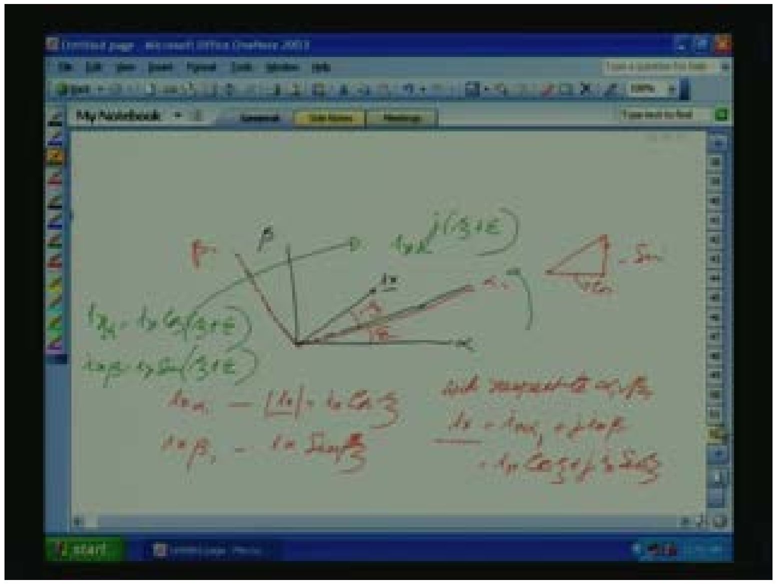

Say, there is an alpha beta axis, there is a current i_r; this current i_r is defined with respect to this axis. This axis means there is a perpendicular axis also for that one; so, we require a perpendicular axis for that also, this is our angle of theta. So, that means this i_r will have a component along this alpha one axis and beta one axis. What is i_r alpha one? It is equal to i_r, i_r magnitude is equal to i_r into cos theta and i_r beta one, along beta component is equal to i_r cos beta.

So, with respect to alpha one and beta one, i_r the current space phasor is equal to i_r alpha one plus j i_r beta one. This is equal to i_r cos theta plus j i_r cos theta sorry this is theta, this is the one. Now, this i_r, we have defined with respect to alpha beta, this can also be defined with alpha beta, any axis we can define it. Now, if you see here, if this difference between the two axes, suppose this is theta; then what is the component i_r alpha now?

Let us take the i_r alpha is equal to, magnitude is the same; i_r into cos of theta plus epsilon where in the new axis, i_r beta is equal to again the magnitude i_r into sine, this is sine; here also i_r beta is not cos, it is sine, orthogonal. That means the i_r, we are splitting into one real component and imaginary component. So, this will contain the cosine component, this will contain the sine; so, i_r sine here, theta plus epsilon. So, this in space vector notation, magnitude is the same; i_r is equal to i_r into e raise to j theta plus epsilon. So, when we transfer to this axis, when movement is in this direction, angle we are measuring in this direction, angle is increased, they are theta plus theta plus epsilon. Now, if you have an axis somewhere here, then that angle has to be subtracted depending on the rotation.

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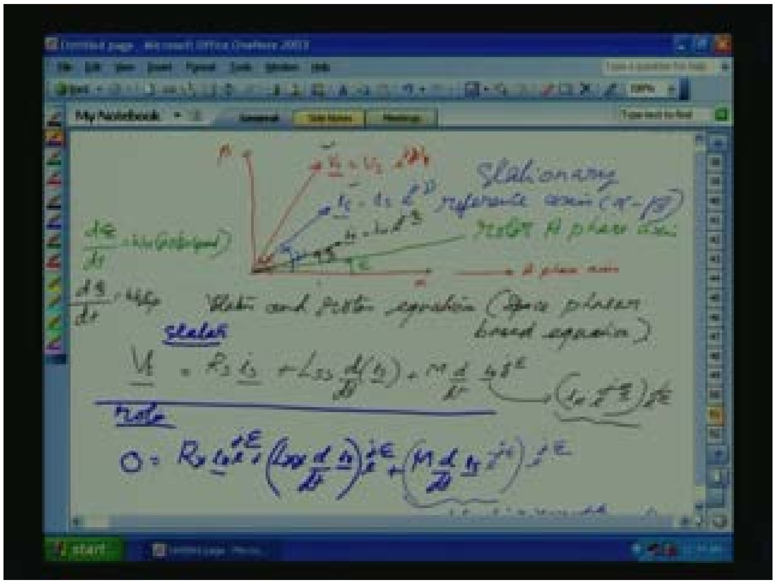

So, in the previous case, here, originally the i_r was defined with respect to rotor axis; now we are defining with respect to the starter axis that is why e raise to j epsilon here. So, that means all the voltage term appearing in the starter whether due to the starter current or the rotor current, are defined with respect to the common reference axis alpha beta. So, if you transfer this into the real and imaginary component, you will get the alpha beta component or if you transfer this to the ABC component, you will get the equivalent ABC component. So, this one equation is sufficient get the alpha beta or ABC component, this is for the starter.

Now, let us take the rotor equation. So, let the rotor equation be we will take the rotor equation in different colour; this is the starter, there you will take the rotor, rotor applied voltage is zero because it is short circuited. But still there is a rotor current; so you have R_r into i_r. See here, if you want to have an equivalent circuits, steady state equivalent circuit, dynamic equivalent circuit; both the starter and the rotor we have to define with respect to the common reference phrase axis.

Now, the common reference axis is alpha axis placed along the A phased axis that is R_r i_r into e raise to j epsilon that means this i_r underscore means it is a space vector, it has a magnitude and angle define the originally with respect to the rotor axis; then multiplied by a sigma, the whole thing is defined with respect to the starter A phase axis, i_r into … ((33:37)) plus rotor self-inductance, mutual plus leakage, Lrr into d by dt i_r. So, the current which has a frequency of slip frequency, which will produce due to a self-inductance, there is a rotor voltage. Now, this rotor voltage, you want to transfer to the starter. So, this is space vector quantity; this space vector quantity if you want to transfer to the starter reference axis, you have to multiply it by e raise to a epsilon.

So here, this e raise to j epsilon is the voltage term we are transferring to the starter. So, this will not come into the d by dt. So, d by Lrr into d by dt i_r underscore, this is the voltage appearing in the rotor circuit due to the rotor frequency or self-frequency. Now, this we are, this voltage turn we are transferring to starter that is why, e raised to j epsilon.

Now, let us see the mutual inductance. Due to the current in the starter; there is a coupling, there will be a flux generator. That flux is proportional to that current and mutual inductance which will be coupling to the rotor. Now, this i_s, m into d by dt i_s, i_s is originally defined with respect to the starter. Now, when this current, how much of this current or what way it induced voltage in the rotor means this current turn, we have to find the component of, we have to define this current with respect to the rotor axis. Then multiply it by B, m is the voltage turn induced in the rotor due to the starter current. So, i_s we have to bring back to the rotor circuit. If you see here, i_s is originally defined with respect to the alpha; now we have to define with respect to the rotor, so we have to go this way.

Previously for the rotor, it was plus j epsilon; here, we are going this way, angle is reducing. So, i_s into e raise to minus j epsilon; this is the voltage turn appearing at the rotor due to the starter current. Now, this voltage term also we have to bring it to the starter side. So outside, we have to multiply by i raise to j sigma. Why? This term is defined with respect to rotor axis; this term is defined with respect to rotor axis. Now multiplying by e raise to j epsilon; this will bring this rotor voltage also along the starter axis that means common reference axis. So now, we have the starter as well as the rotor voltage terms with respect to a common reference axis. So, now split it to an ABC alpha beta axis component, you will get the dynamic equations for the starter and the rotor.

So, here if you see, all the voltage and voltage of starter and rotor, we defined with respect to a alpha beta axis where alpha is placed along the A phase axis, this is called stationary reference frame axis, stationary reference frame axis because alpha is placed along the starter A phase axis that is stationary. So, it is called stationary reference axis that is the alpha beta. So, this is very simple; I will again go through this equation so that you will be you will be able to understand the transformation from one reference to other reference. So, if you see here, I will again explain for clarity. See, you want to define the starter voltage and rotor current with respect to a common reference axis. So, if you see here, this is the alpha axis, this is the beta axis and the alpha is placed along the A phase axis and beta is perpendicular to that.

Now, when the machine is excited with sinusoidal currents or sinusoidal voltages in the starter, starter will have an ABC current, so it will have a equivalent current space phasor i_s. Now, let us say the voltage space phasor Vs is defined as Vs underscore Voltage space phasor, it has a magnitude and angle, angle we are referring with respect to the alpha axis which is placed along the A phase axis. Now, this voltage space phasor generate three phase currents, so we have an equivalent current space phasor definition. But this voltage and currents are not collinear, there is a phase difference. But instead of varying about the phase difference, we are worrying, we are only taking the angle of the space phase, space vector with respect to the A phase axis. So i_s, i_s has an amplitude and e raise to j, one gamma here.

Now, those are the relative motion, there is a flux generated and relative motion of the starter and the rotor, rotor will have a rotor current and we know that previously we studied the rotor current frequency will be proportion to the slip frequency. So, if you assume rotor also as an, rotor also assumed to have an equivalent ABC equivalent or the rotor current is also generated due to an equivalent ABC phases same like starter and if you see, the rotor A phase axis is here but the rotor A phase axis will be moving away from the starter A phase axis because of the rotation. So, the instantaneous angle is epsilon.

Now, with respect to rotor A phase axis, if you stand on the rotor A phase axis, the rotor current space vector, you have a magnitude and you will have an angle theta, it would be varying from the rotor A phase axis with the speed equal omega slip that is the d theta by dt is equal to omega slip. Now, if you stand on the rotor, you will see that rotor a phase axis moving away from the starter with an angle epsilon that is due to the rotation and d epsilon by dt is equal to rotor sum. So, the relative position of the voltage and current space vector, we have defined.

Now, we want to want to have the equivalent voltage space vector equations. So, the Vs underscore is equal to, when the machine is excited with Vs voltage space vector is equal to it will have a resistance drop R_s plus i_s, i_s is our induction machine total current space vector i_s, plus Lss plus d by dt of i_s. Now, i_s is originally defined with respect to our axis. So, this resistance slope and self-inductance of the starter are defined, that voltages are defined with respect to the A phase axis.

Now, the goes off for rotor current, there can be a voltage induced at the starter due to the mutual inductance. Why mutual inductance? All the flux due to i_r will not couple to the starter, there is a mutual plus leakage part is there. So, due to mutual only, there is link between the starter and the rotor. So, if you see here, m into d by dt i_r, i_r underscore, i_r underscore is the one the current defined with the respect to the rotor axis. Now, the voltage time, this current originally defined with respect to the rotor axis, we have to bring to the starter axis that is why angle is increased now; rotation is in this direction, so now the new angle is theta plus epsilon, theta is already inside this one i_r underscore, so this is the current. Now, the rotor current is defined with respect to the starter axis, then the voltage term is equal to the m into d by dt of this one.

Now, let us go to the rotor, applied voltage is equal to zero but due to the rotor current that is i_r underscore will have a voltage equation R_r into i_r underscore here. This is the voltage term defined with respect to the rotor axis. Now, the voltage term if you have to bring to the starter, we have to multiply by here is to j epsilon,

Similarly, the voltage induced the due to the self inductance in the rotor is equal to Lrr d by dt i_r where i_r has a magnitude of i_r and angle is equal to e raise to j theta that is slip frequency into the time. Now, this is the voltage, this voltage also we want to bring to starter. So, we are multiplying by e raise to j epsilon. Now, there is a current term which is originally defined with the respect to the starter axis that will induce a voltage in the rotor. So, this current originally defined with the starter axis asked to be defined with respect to the rotor axis. So, from here, it has to go here; so minus j epsilon. Then d by d tm, this is the voltage term induced at the rotor.

Now, the whole voltage term we are transferring to a starter by e raise to j epsilon. So, the epsilons outside the bracket will not come into the d by dt because the voltage we are transferring to some more axis that is why. Now, as I told, we are defining the starter voltage and current with respect to a common reference space, reference space axis that is alpha beta. That alpha beta, alpha is placed along the A phase axis. This is also called stationary reference frame axis. Now, what we want? We want to find out the instantaneous position of the rotor flux. So, if you know the instantaneous position of the rotor flux; let us go to the next page.

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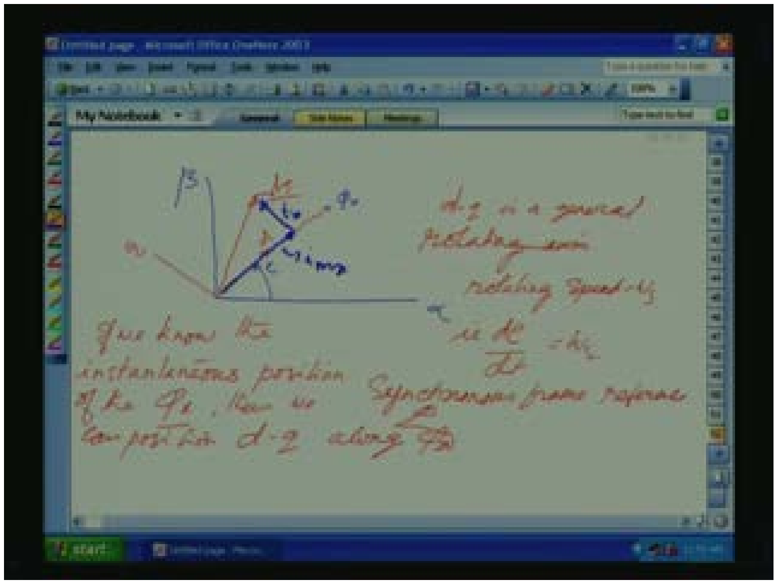

This is your alpha beta; suppose now we have defined our, we have placed the position, relative position of the voltage and current; similar way we can position of the relative flux si r also. Let si r makes an angle rho. Now, for vector control applications, the i_s; as i told, i_s we have to define with respect to si r that means component along the si r are perpendicular to si r, we have to find out. So, if you can find out another axis, define a dq axis sorry this is d, this is q; this d is along, the d is along the si r axis, this is d, this is q.

Now, dq is a general rotating axis. If this rotating speed is equal to omega s that is d rho by dt is equal to omega s, then this general rotating dq axis is moving with respect to a synchronous speed. So, this is called, then the dynamic equations, if you are generating based on the dq is called synchronous frame reference, synchronous frame reference. If this dq is placed along the rotor axis that means as the rotor various, d also placed along the rotor axis; then we can say the dynamic equations developed on this dq is defined with respect to the rotor reference axis.

Now, if we know the instantaneous position of the sorry if you know the instantaneous position of the si r, of the si r; then then we can position dq along si r, this is called synchronous reference. So, what is the advantage? So, if our original i_s is here, then i_s can be split along si r and perpendicular to it. That means there is a current component along this one, this is our original imr and this is the current perpendicular that one will be our i_r.

So, if you know the Phi r and place dq axis along the si r that it is all the time, for any dynamic conditions, d is placed along si r; then the component of is along d will be proportional to the rotor flux producing component Phi r and any component perpendicular with to that i_r will be the torque producing component. So, if we can find out our dynamic equations with respect to dq, a synchronous rotating reference frame with dq placed along si r, then that dynamic condition that dynamic voltage and current conditions are the one useful for our vector control application.

So, what we want to know now here is let us find out our from the stationary reference frame, let us find out the dynamic equations under a general dq, a general rotating dq reference frame; from that one, place the dq along the si r, then get the conditions for the vector control applications such that the is can be split along a component along the si r and perpendicular to it. So, that way we can have a decoupled control same like in a separately excited machine; this we will study in the next class.