Fundamentals of Electric Vehicles: Technology and Economics
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Lecture - 58
Three Phase AC - Part 2

So in the previous class, we discussed about AC current, in particular, three-phase AC current; how we can generate three-phase AC voltage and hence three-phase current by using a DC source, which is the battery.

And this is very good because this is what the motor is, the motor requires AC current. But we also discussed that when we want to do control, what is called PI control, proportional integral control, we need to compare a reference value with a measured value, and based on the difference between them which is called the error, we apply the PI control methodology to correct it and bring the motor back on course.

Now, you cannot compare two values which are oscillating. So you cannot do PI control with AC current.

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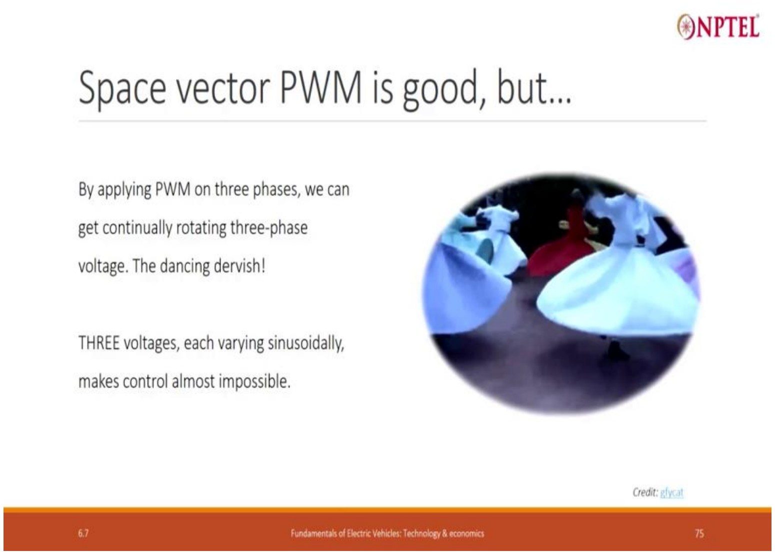

So the challenge is that while the motor needs AC, for us to be able to control the motor we need to look at everything from the d-q reference frame, where all the entities are DC. And so, while we apply PWM on the three phases to generate the AC, and the actual picture of the motor is that the magnet is rotating and around it, the currents are rotating and remember, this is called the PMSM motor, permanent magnet synchronous motor.

The meaning of the word synchronous is that the rotor is rotating at the same speed as the speed with which the current is, current vector is rotating, both are going at the same speed. And we use this idea to look at everything from the rotor reference frame, which means we put a chair on the rotor, then relative to us, the, since the reference frame of the rotor itself is rotating at the same speed as the current, we see the current as a stable unchanging entity.

And this view is what will help us to do the control. So we need to move the battery voltage from DC and apply it as an AC voltage to the motor in the three phases to make the motor function, but to make sense of how well it is running and to apply any corrective action, we take measurements of the current, which are flowing through the motor but we have to convert it back to this rotating reference frame which is the d-q frame and then, view the current as a DC current and then, compare it against our target.

So all the control that we do happens in the DC domain, which is inside the controller, and all the physical activity that happens, which is at the motor end is in the AC. So we have to keep switching from DC to AC and then back from AC to DC. This is how the motor is controlled. This is because it is only a steady value which we can control by using PI control.

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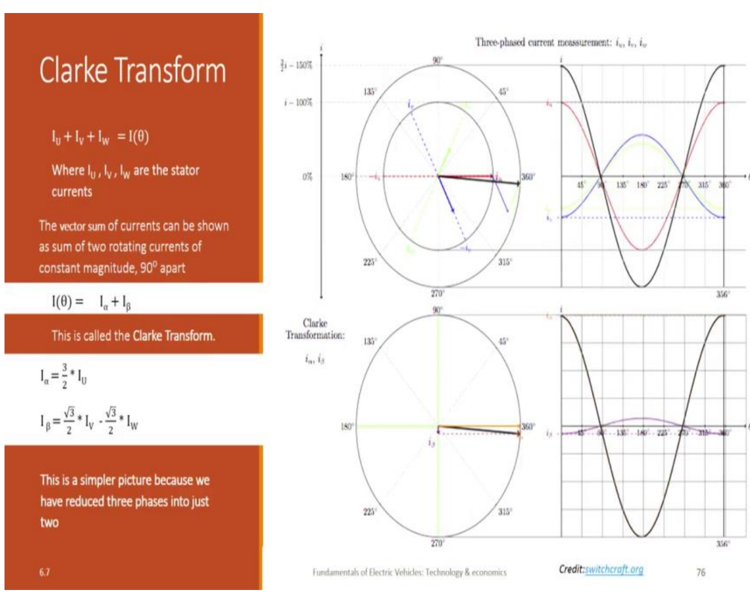

So how do you convert from AC to DC? We do it in two steps. The first step is called the Clarke Transform. We have already seen that when there are three oscillating currents in the three phases, they are 120 degrees apart from each other.

The vector sum of the three currents, merely the algebraic sum of the three currents is already 0, we know that because of Kirchhoff's law. The total current at the star junction must be 0. But if we take the vector sum, the vector sum is one and a half times as big as the amplitude of any of the oscillating phases and it is a rotating vector.

Now, if you, if I have a vector which is rotating, which means at any point its magnitude is constant but its direction is going on changing, then we know, that we do not need three axes to describe it as you see in this picture. I can just use a convenient X, Y pair of axes, which are perpendicular to each other.

Instead of calling it X and Y, we call them alpha and beta. And I can resolve three phases into two components, which means I am converting, mathematically speaking, a three-phase current into a two-phase current, which is what the picture below is showing you.

At any given point of time, the resultant of the three phases can be expressed as two perpendicular components, alpha, and beta. And this is called the Clarke transform, and with a little bit of trigonometry, I will not burden you with all the derivation but you can derive it yourself or look at standard references, and you will find that the alpha component and beta component are related to the U, V and W phases, phase currents, by this trigonometric relationship.

And this is a somewhat simpler picture than what we started out with in the beginning because we have only two phases instead of having three phases. So this is the first step in the simplification.

Now, when you look at the picture below where we have only two phases, we know that the current vector is rotating at a certain angular speed but we should also keep in mind that inside the stator there is also a rotor with a magnetic axis, which is called the d-axis and perpendicular to it is what is called the q-axis. And that rotor is also rotating at the same synchronous angular speed.

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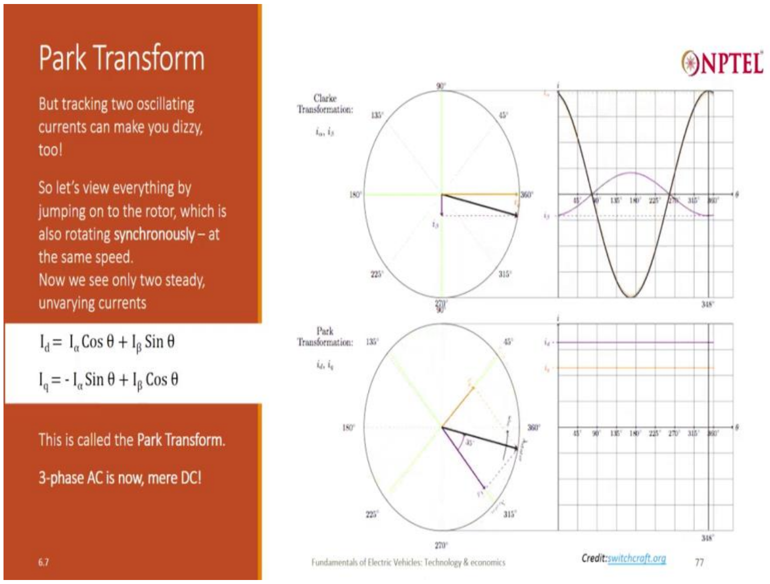

And we take advantage of this knowledge to do what is called the Park Transform because even with two phases if I were to go on looking at them and try to see where is it compared to where I want it to be and try to adjust and correct the error, it is very confusing, we cannot do it.

So we view everything from the rotor's reference frame, which is a rotating reference frame and suddenly, the picture below is just a DC. If I am sitting on the rotor and looking at the current, I have a d-axis, which is the direction in which my magnetic field is. I have a perpendicular axis, which is perpendicular to the magnetic field, and the current is somewhere in that direction and we are all rotating together. So the current is always in the same direction, it is not changing.

And again, with the little bit of trigonometry, you can relate the steady current, you can resolve it into two components; one along the d-axis, another along the q-axis, and you can find out what their values are. They are both unvarying, Id and Iq are steady DC values, and the angle between the stator current and the d-axis is not changing, the angle between the stator current and the q-axis is not changing, because they are all rotating together.

We already know that the angle between the stator current and the q-axis is called, what is it called? The phase advance angle. And we also figured that in order to extract the maximum possible torque, we have to keep the phase advance angle negative, how much negative depends upon the magnitude of the torque or the magnitude of the total current. And that is the first of the two important algorithms in motor control, and what is it that algorithm called? MTPA, maximum torque per ampere, which is the most efficient point.

And the second important algorithm in motor control is when we go beyond the rated speed and we want to extend to the operating range; without losing too much torque, we apply a extra d-axis current in order to weaken the back EMF, so that without surpassing my voltage limit, I can hit higher speeds. This also we have seen, and what is that technique called?

Student: Flux weakening.

Professor: Flux weakening. So motor control is all about applying MTPA, up to the rated speed and beyond the rated speed, applying flux weakening; there is nothing more than that. But both of these algorithms work in the d-q reference frame, which is the DC reference frame. So unless I know what is Id and Iq, actually versus the Id and Iq that I want, which is the target or the setpoint, I cannot do any corrective action which is called PID, PID control.

This is why we transform the AC currents into two axes in the rotating frame, which is alpha, beta, and then move the reference frame to the rotating frame and convert the rotating current into stationary current, a pair of stationary currents, which is Id and Iq.

So this is the Park transform. Is this clear? It is visually very simple, easy to understand and the mathematics behind it is also not very complicated, it is just some elementary trigonometry. So now, we have successfully converted a three-phase AC into DC, a pair of DC, DC currents. Is this fine? Is there any questions? Feel free to ask me.

So these two transforms, Clarke transform and Park transform, allow us to go from the motor to the controller. The motor works in the AC and the controller works in the d-q reference frame, which is DC. And then, once we figure out what is the control corrective action to be applied, the result is again a pair of DC voltages, Vd and Vq, which have to be applied to the motor in the AC domain.

So we have to transition once again back from a pair of DC voltages to three AC voltages and that journey is called the Inverse Park and Inverse Clarke transform.

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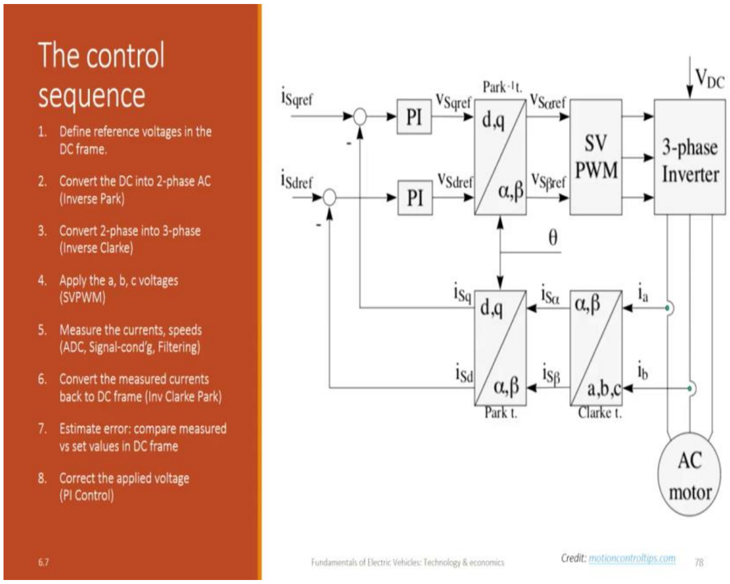

So having understood this, we can now understand how the whole control sequence works in the controller. Essentially, the first thing that we do is I want the motor to deliver certain torque, which means it must take a certain current and it must be running at a certain speed, which means a certain pair of Vd and Vq voltages have to be applied. This is what the controller decides.

The definition of Vd and Vq that comes from the control algorithm gets translated into I alpha and I beta, which is what you are seeing here. The Vd ref & Vq ref, both of which come from the stator voltage. The stator voltage is resolved into VSq and VSd. The reference values are then converted from the d-q reference frame to the alpha, beta reference frame and this is the Park inverse transform. And then the alpha, beta voltages, VS alpha, and VS beta are converted into three AC voltages. The VA, VB, and VC or you can call it VU, VV, VW; U, V, and W.

And this conversion which is actually the inverse Clarke transformation happens in the state vector pulse-width modulation sequence, which we looked at earlier. And this SVPWM, state vector PWM, is actually the switch that I told you is turning on and off 10000 times every second, and that gets applied to the hex bridge inverter, which also we have looked at in the earlier part of this lesson, and that results in VA, VB, VC; three AC voltages getting applied to the three phases of the motor.

As a result of this voltage that is getting applied, current is flowing through the motor, the motor is rotating. We can measure the speed using any speed measurement device, encoder, resolver, hall-sensor, et cetera. We can also measure the current by using a current sensor and knowing what the current is and what the speed is, is not enough because with the current, knowledge about the current that we have is in the AC domain. So we take the AC and convert it back into alpha, beta which is the Clarke transform, and then convert it again back into the d-q frame, which is the Park transform, and then supplied it to the controller.

So we get the actual values of Id and Iq to the controller, whereas the controller has already decided that it wants so much current to flow, Id and Iq based on whether it is an MTPA or in field weakening. And it compares and sees, this is what I wanted, this is what is happening, are they the same or is there a gap? And if there is a gap, that error is taken into the PI control loop and corrected. And again, a fresh set of Vd and Vq get supplied.

So the error is estimated and then we correct it using the PI. So this is all there is to the controller. So we come to the end of this section, which is about the controller, field-oriented control getting applied in an AC machine using a d-q reference frame in the controller, which is essentially a DC frame of reference. If there are any questions about it, I will take it or we can move on to the next chapter. Are there any questions?