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Teaching Field Oriented Control using Animation

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***Abstract*—Teaching the principles of control of electrical machines is a tedious job. Especially the required knowledge that has to be transmitted to the student is large, before a complete overview of the whole topic can be made. Also a solid background in both electrical machine dynamic behavior as well as in control theory is required for the student, before entering a course on Field Oriented Control [FOC] of electrical machines. However once the students have enough background information and if the new teaching material contains enough methods to practice the underlying theoretical contents, it is possible to teach students the basic concepts and practical implementation of FOC.**

***Index Terms*—Field oriented control, education, simulation, animation, generic machine, current control, Caspoc, modulation, Park, Clarke, FOC, IRCTF**

I. Introduction

THERE is a fast amount of literature available on the subject of FOC. An introduction of motor control is found in [3], whereas a more detailed overview of FOC is given in [7], [5] and [4], [6]. It is interesting to note however that the origins of FOC are based on the works of [1] and [2]. Nonetheless nowadays FOC is well described in application notes from various microcontroller vendors, trying to support their products. For teaching, these original books include the required information, however, they are very mathematically oriented. Most textbooks start with explaining the various reference frames along with a complicated transformation of the three phase motor equations into motor control equations. An alternative approach is to start rehearsing the motor control using a generic machine, then to explain current control using an ideal power electronics inverter and only then to dive deeper into the concept of having a field producing current and a torque producing current. Explaining this using mathematical relations is possible, yet tedious. By using simulation and animations of virtual machines and going step by step, the concept of FOC can be broken down into smaller steps with limited mathematical content.

The basics of FOC could be explained by first discussing the detailed machine modeling, then continue with discussing the transformations and the various reference frames and finally explaining per motor type the control methods based on the various reference frames. The mathematical modeling of machines is already elaborated in [1], [2], [4], [5], [7], but in [8] the Ideal Rotating TransFormer [IRTF] is introduced to enhance the modeling principles and make a clear separation between the stator and rotor model.

An alternative approach is to start with the generic motor and to explain the basics of the field producing current and the torque producing current. Although very similar to the theory of separately excited DC machines, the focus is on the generic machine principle. Once the basics of torque control for the generic machine is understood, the three phase motor can be introduced. The fact that current control is required is at this moment already know from the lecture on the generic machine. The next step is to explain how current control using PI controllers, see Fig 1, is working and from there the students will understand that they are able to generate any desired current in a three phase motor winding. Using design tools as for example shown for a complete AC drive in Fig. 2 allows automatic calculation of control parameters and direct visualization of the dynamic response.

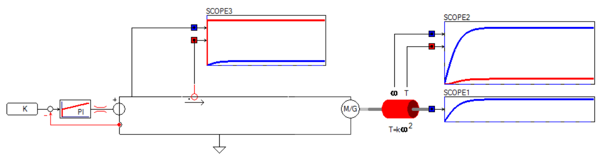

Fig. 1. Generic machine with current control. This basic concept used in DC motor control is extended towards AC machines using Field Oriented Control

In this paper first the basic theoretical topics required for FOC will be presented. For each topic, simulation and animation can be used to visualize the behavior of the electric machine and its interaction with the control. The topics are organized as

- Generic motor basics
- Current control of an R-L load
- Field and torque control of the generic motor
- Current control of a three phase R-L load
- Basics of permanent magnet machines
- Field orientation inside a permanent magnet machine
- Current orientation inside a permanent magnet machine
- Field and torque control of a permanent magnet machine
- Basics of induction machines
- Field orientation inside an induction machine
- Current orientation inside an induction machine
- Field and torque control of an induction machine

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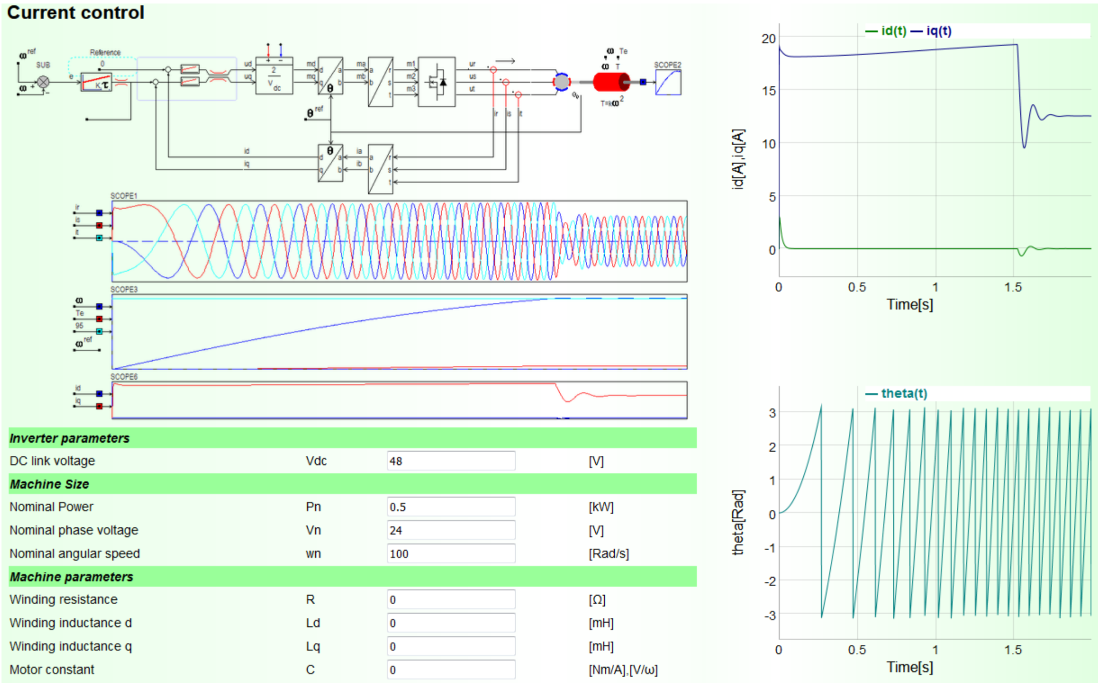

Fig. 2. Design tool [10] simulating FOC of a PMSM Drive. Depending on the drive parameters, the immediate response of the drive is calculated and displayed in the scopes on the right side. If control parameters are not defined, they are automatically calculated and displayed to the user.

In section II the various topics are discussed and how animation is applied here. In section III the basics of modeling for electrical machines is elaborated, where mainly the similarities among the AC machines is discussed. The concept of modeling is further explained in section IV, where the concept of the Ideal Rotating Circuit TransFormer [IRCTF] is explained, based on the IRTF from [8]. The field oriented control of each machine type is then discussed with examples in section V.

II. Overview

The principles of an electrical drive are best explained by starting with generic machines, see Fig. 1. Using generic dc machines, the principle of cascaded position-speed-current control can be visualized in [10]. The concept of a PI controller to regulate the current and how to determine the parameters for the PI control can be explained using this simple example simulation. The dc generic model can then be extended towards a generic AC model and using generic inverter and control models, the principle of FOC can be explained in terms of positioning the current vector depending on the rotor field position. Fig. 3 shows the animation in [10] where the position of the current vector relative to the angular rotor position in a Permanent Magnet Synchronous Machine [PMSM] is displayed. From the simulation result the torque dependence on the position is calculated and displayed for a fixed rotor position.

Once the generic machine principles are explained, the focus for each type of machine is on the cascaded speed current control. The current control can be explained for a generic machine, but taking the PMSM as example, the location of the stator winding and how to measure and control the three phase current in that winding is illustrative and explanatory. Again the parameters for the current control can be determined and using a simulation the response of the current in a three phase winding can be visualized.

After understanding how current control is implemented it can be used on any machine type to explain the torque production. Depending on the machine type, the position of the current can be explained and in the case of the PMSM the simulation from Fig. 3 in [10] explains in detail the production of the torque. Here also the concept of motor and generator mode is easily explained, as the torque can be either positive or negative, depending on the current position.

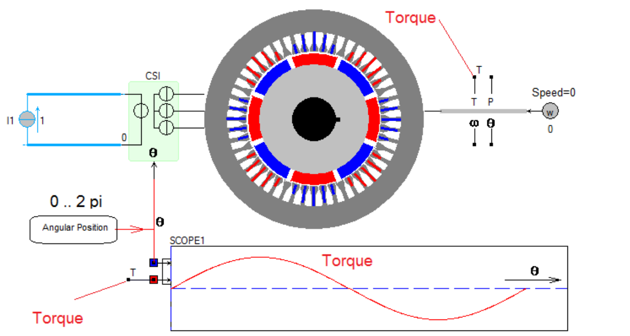

Fig. 3. Torque production as function of current position is displayed in scope 1. The rotor is fixed and the current vector position is varied from 0 to 360°

For each type of machine the method of torque production will be explained, however finally the general AC machine model will be presented and it will be shown that both the induction machine and permanent magnet machines are controlled in the same manner, as will be shown in section V.

The reason why a permanent magnet machine is chosen, is because it is easily understood by the students. Especially the back emf is something that can be visualized and from there the concepts of torque generation can be explained by looking at the amount of consumed power by the machine.

When the concept of FOC is understood by the students, the FOC of the other machine types like Induction Machine [IM] and Synchronous Reluctance Machine [SynRel] can be discussed.

To perform a simulation of a complete drive system can be a tedious task in eduction, especially if parameters for the control are not known. Therefore design tools are developed that automatically calculate the control parameters and directly perform a simulation of the start up of such a drive. Just altering machine or load parameters is enough for students to see the impact on drive control parameters and overall behavior, see Fig. 2.

III. Electric Machine Modeling

Before starting with the Field Oriented Control, it is instructive to discuss the various AC machine types to be controlled. Instead of only looking at the permanent magnet synchronous machines and induction machines, it is fruitful to explain that all three phase machines are essentially very equal when it comes to control. Instead of presenting the two different machines, the permanent magnet and the induction machine, it is better to explain that the difference lies in the way the field in the rotor is created. From this perspective, it is easier to explain the influence of reluctance in the rotor for SynRel and Interior Permanent Magnet [IPM] machines as well as the influence of damping in the rotor as present by the squirrel cage for IM and the eddy currents in permanent magnet machines, see Fig. 4.

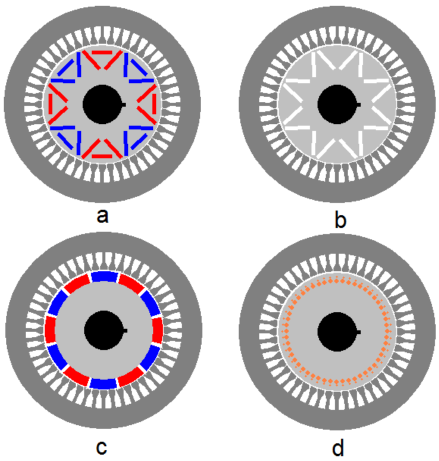

Fig. 4. AC machine types, (a)Interior Permanent Magnet Synchronous Machine, (b)Synchronous Reluctance Machine, (c)Surface mount Permanent Magnet Synchronous Machine, (d)Induction Machine.

There are several similarities between the AC machines in Fig. 4. The PMSM with surface mount magnets is shown in Fig. 4c is equal to the IPM from Fig. 4a. The difference being important for the control is the fact that $L_s = L_D = L_Q$ for the PMSM compared to $L_D < L_Q$ for the IPM. The difference between the IPM and SynRel is the absence of magnets in the SynRel in Fig. 4b. For both the IPM and SynRel the stator inductance is $L_D < L_Q$. At higher speed, the increasing field current I_D mostly creates a field $L_D \cdot I_D$ stronger than the field Φ from the permanent magnets. Therefor the control of the motor in the higher speed regions is equal for the IPM and SynRel. The induction machine has a squirrel cage winding, in which a rotor current circulates. Because of the ohmic resistance of the squirrel cage, there are losses and due to the slip this generates the torque in an induction machine [1]. The PMSM and the IPM have magnets in the rotor where eddy currents cause losses in the rotor. In the model of the motor this is the damper cage modeled by a series connection of a resistor and inductor, showing the same behavior as the squirrel cage winding in an IM. The next section on the general AC machine model reveals the similarities more in detail.

IV. General AC machine model: IRCTF

The concept of the Ideal Rotating TransFormer [IRTF] as introduced by [8] allows to teach the influence of the various parameters in the electrical machine, without going into detail on mathematical relations for the electric machine. Originally the IRTF model is a bond-graph model as introduced in [8], but representing the IRTF as an Ideal Rotating Circuit TransFormer [IRCTF] simplifies the visualization of the underlying mathematical relations of a rotating reference frame. For example, Fig. 5 shows an PMSM configured as generator simulated in [10].

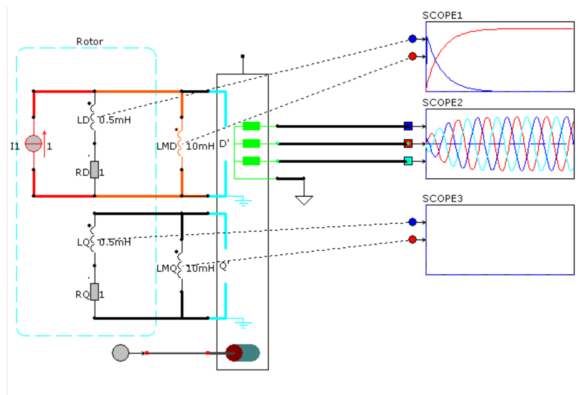

Fig. 5. IRCTF model for an PMSM. Magnetizing inductance LMD, LMQ, losses in the permanent magnets via damper windings LD, RD, LQ, RQ and equivalent permanent magnet magnetizing current $I1$. Scope 2 show the generator voltages, scope 1,3 show magnetizing and damper winding currents in D and Q

On one side the rotor circuit is modeled and on the other side the stator circuit is modeled. The mechanical connection is modeled as a mechanical model where torque and angular speed are modeled by 1-dimensional dynamic models. In Fig. 5 the PMSM generator is modeled in [10], where on the left side of the IRCTF the field and torque producing circuits are modeled, on the right side it is connected to a three phase AC grid and the mechanical input power from the turbine is connected on the left side.

The IRCTF can be used as a general model and depending on the configurations of the rotor circuit either a IM, PMSM,

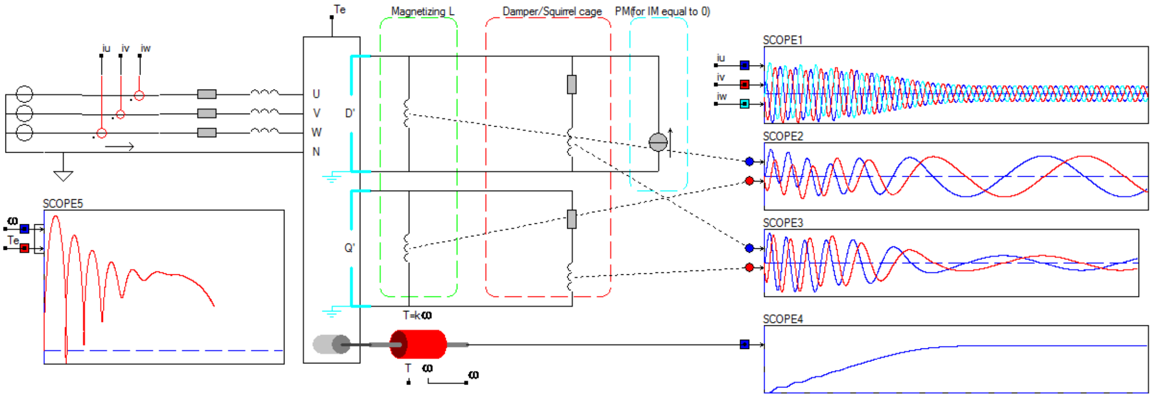

Fig. 6. Configurable general IRCTF model. An induction machine(22kW) start up in 0.5seconds is configured by the magnetizing inductance and squirrel cage winding. Scope 5 shows the torque-speed diagram during start up and on the right side from top to bottom: Scope(1);AC input currents, Scope(2);Magnetizing currents I_md and I_mq, Scope(3);Rotor currents I_rd and I_rq, Scope(4);Angular rotor speed[Rad/s]

IPM or SynRel can be configured [10], see Fig. 6. The field in the airgap is always modeled by the magnetizing inductance, where L_D and L_Q are parametrized depending the type of machine. For the IM and PMSM the magnetizing inductance $L_D = L_Q$ and for the IPM and SynRel $L_D \neq L_Q$. In Fig. 6 the magnetizing inductance is linear, but a non-linear model including saturation could also be used here. The currents in the magnetizing inductance are measured in the Synchronous Reference Frame [4], which is rotating with the rotor speed and are displayed in Scope(2). This means that the rotor currents in the squirrel cage are rotating with the slip frequency for an induction machine, but the rotor currents in a damper winding in a synchronous machine will eventually decay to zero, see scope 1 and 3 in Fig. 5. In Fig. 6 the rotor currents are displayed in Scope(3). Since there is no permanent magnet in the rotor circuit, the value of the equivalent magnetizing current from the permanent magnet is set to zero. The stator leakage inductance and stator winding resistance is modeled on the stator side by a series connection of an inductor and resistor.

V. Field Oriented Control

The basics of FOC are best explained visually, where the rotation of the current vectors is explained by looking at the resulting waveforms. From the simulation in Caspoc [10] in Fig. 7 it is clearly visible that using a synchronously rotating reference frame, the currents in the dq frame are stationary values that can be easily controlled using a low bandwidth PI controller. The scopes on the left side in Fig. 7 show stationary voltage u_{dq} and current i_{dq} that is controlled by a PI controller with a relatively low bandwidth. Changing id^{ref} and iq^{ref} show immediate response on the AC side in the simulation. Using this type of simulation demonstrates both the structure of FOC in an electric drive and the influence of control parameters in the PI controller. These PI control parameters are first calculated and verified using the design tool from Fig. 2. The concept and functioning of the Park and Clarke transformations [4] is visualized by the various scopes in this simulation. Clearly visible is where three phase AC values are transformed into two phase quantities and finally into stationary quantities. With the aid of this simulation in Fig 7 also the role of the Space Vector Modulation [SVM] modulation as being the inverse of the Clarke transformation is visualized and even the waveform after a typical space vector modulation, continuous or discontinuous [11]–[14] can be seen.

To see the effect of current placement in an interior permanent magnet machine, the projection of the stator current induced field in accordance to the position of the rotor magnets is visualized in Fig. 8 in [10]. Here the field on the stator winding rotates synchronously with the rotor magnets during the animation of the drive. By changing the values of id and iq the stator field positions itself relative to the rotor position. From this animation the relation between the position between the stator current and angular rotor position as given by the generic simulation in Fig 3 is repeated and now the effect in the complete drive becomes visible. Scope 6 on the left side shows the current values measured and transformed into d, q and the angular mechanical rotor speed ω is displayed in scope 1 on the right side. Since the simulation model includes a complete inverter model with thermal model, also the losses are simulated and the influence of the current level on the losses can be studied.

To show the similarities between FOC of an PMSM, IPM, SynRel and IM, multiple virtual prototypes can be compared. The current regulation and transformations are shown to be equal and this is best demonstrated by comparing the various AC motor drives, see Fig. 9. The induction machine is controlled using an indirect FOC, where an Indirect Field Orientation [IFO] block [7] is used to calculate the slip frequency ω_{slip}. A current command $i_q = 154A$ is given and the final speed of an electric vehicle is shown in scope 1 on the right side. In the same scope 1 the speed of an electric vehicle is displayed based on a FOC of an IPM. For the IPM, also a current command $i_q = 154A$ is given. The acceleration and final speed of both electric drives is nearly equal, but also

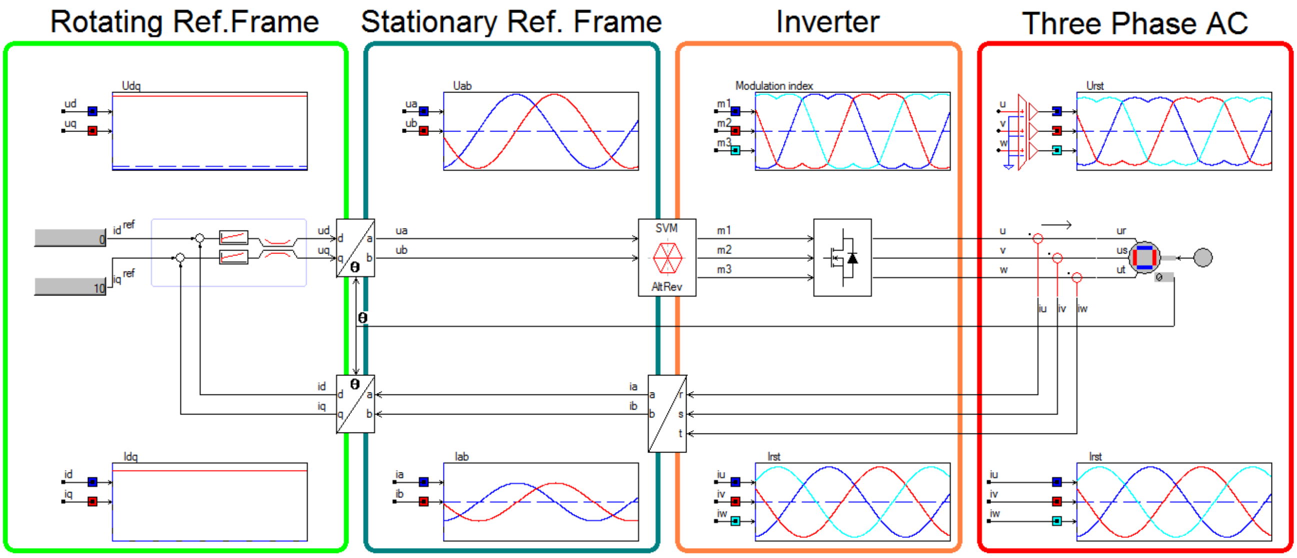

Fig. 7. Field oriented control basics. From right to left are the three phase AC voltages and currents at the machine terminals, the three phase AC voltages and currents in the inverter, the voltages and currents in the stationary reference frame α, β and on the left side the voltages and currents in the rotating reference frame d, q. Transformation matrices and modulation between the inverter with machine and the stationary and rotating reference frame.

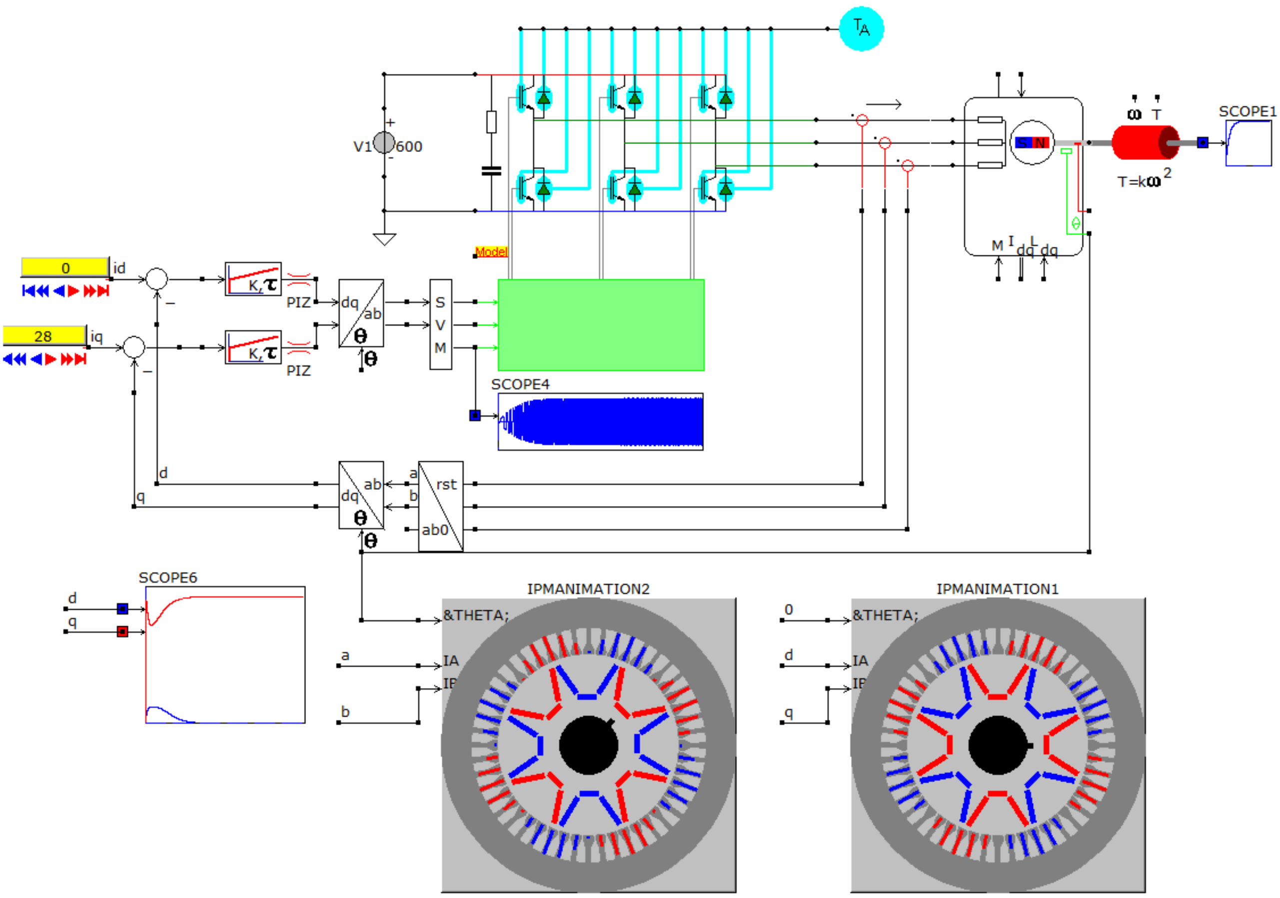

Fig. 8. Animation [10] of the FOC an IPM. The animation shows the IPM in the stationary reference frame on the left side and in the rotating reference frame on the right side. During the simulation, the animation visualizes the position of the current vector (i_d, i_q) relative to the position of the rotor. The current vector is not shown as a vector, but visualized by the position of the stator field relative to the field from the rotor magnets. The rotor with magnets and the stator field are rotating in the animation on the left side and at stand still in the animation on the right side.

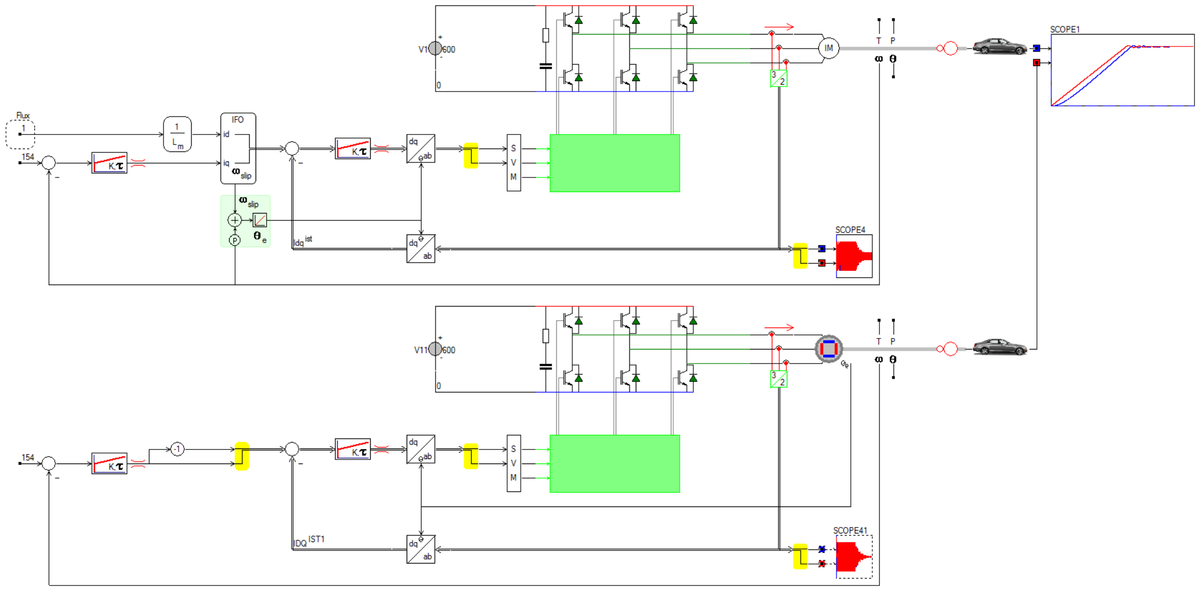

Fig. 9. Comparison of FOC for IM and IPM drive. The upper schematic shows the indirect FOC of an IM, where the slip frequency ω_{slip} is calculated inside the IFO block. From this the rotor field position is calculated.

the similarity between the two FOC is visible in Fig. 9.

Both FOC for the IM and IPM have a reference current i_{dq} compared to a measured current i_{dq}^{ist}, where in both cases the reference current i_{dq} is given as $i_q = 154A$, but the reference current i_d is constructed differently for the IM and IPM drive. In the IM drive the reference current i_d is given by the required field being Φ/L_m where L_m is the magnetizing inductance and Φ the field in the airgap of the machine. In the IPM drive a very simple field weakening [7], [9] is introduced by simply setting $i_d = -i_q$. The rotor field position is aligned with the rotor for the IPM and directly measured using a position encoder, whereas the position of the field in the IM drive is calculated based on the slip frequency from the IFO block and angular rotor speed.

VI. Conclusions

Animation improves the understanding of field oriented control because instead of explaining the theory using mathematical relations, the transformation of currents is visualized. In this way students can see the difference between the various reference frames. Also explaining the principle for current regulation on a generic machine before diving into the FOC itself eases the understanding of position the current vector according to the position of the rotor field for torque production.

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