

# Virtual Electric Machines Laboratory, Requirements and Practical Realization

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**Abstract**—A fully equipped electrical machine laboratory can become a costly factor. However the look and feel of electrical machines behavior in operation, is indispensable and very informative for students. Not only do they learn how to connect and operate the machines, but also the limitations of each type of machine, becomes visible. Not only equipment is costly, also laboratory room space, service and safety can become an issue. To reduce those laboratory costs, often simulation is used as an alternative. However, the look and feel of the real machines, is in many cases lost. In this paper a virtual electric machines laboratory is proposed, where students can be trained, using digital twins of the electric machines from the laboratory. The look and feel of the digital twins, the way the machines are connected electrically and mechanically, should represent their physical counterparts in such detail, as required in a real physical training set-up. Nameplate parameters ease the selection of machines size and power level. Adding measurement devices, such as voltage and current meters, as well as measuring torque and rotational speed, should resemble the real measurement set-up as close as possible.

The size and power level of the electrical machine, is given by its nameplate. In the virtual electrical machine model, those parameters are entered, instead of the electrical parameters mostly encountered in simulation programs.

**Index Terms**—Virtual workbench, electric machines, simulation, animation, education, laboratory

## I. INTRODUCTION

Virtual electrical machines laboratories, will not be the replacement of a real physical laboratory. However, when teaching large numbers of students, with limited availability of costly laboratory equipment, it requires an alternative. A virtual laboratory would be the first thing that comes into mind when thinking about costs reduction. However, using such a virtual laboratory, places constraints on the way the virtual laboratory looks like. The main requirement for a practical realization of such a virtual laboratory, is simply that it should look and behave similar.

An overview and role of a laboratory for teaching electrical machines is an ongoing topic in the society meetings of the IEEE [1]. Especially in graduate courses, the use of simulation to replace the physical laboratory is a topic, that is discussed over the years. The first approaches only discuss the replacement of the laboratory by simulation [2]. The simulations are still only numerical, in the beginning of the application of computers in education [3]. The limitations of computer graphics, hampered the introduction of useful

simulation environments. Also the complicated mix of block-diagram models, not representing physical component, makes simulation unattractive for undergraduate courses. Only graduate courses can profit from simulations, as these students understand the mathematics behind the electrical machines, and thus can apply the numerical models simulating the electrical machines, as for example presented in [4]. Also using equivalent electric circuit models, to model the electrical machines, is only dedicated towards graduate students, understanding the differential equations describing both the electrical machines and electric circuit components [5]. Remote labs [6], tried to fill the gap, and replace the laboratory with access to a remote laboratory. However also this remote laboratory could only be used by a limited number of students. The use of simulation programs alone, mainly remained a dedicated set of complex simulation models, requiring understanding of the models and parameters [7]. All of these simulation approaches are not fully applicable in vocational training. Vocational training requires models based rated values or nameplate parameters. Internally these models contain the complex equations, modeling all the phenomena, existing in a physical laboratory set-up. For undergraduate graduate students, the level of complexity can be increased and brushless motors and their controls are usually employed in laboratory experiments [8]. The topic of field oriented control is usually seen in graduate laboratory experiments, mostly in the form of simulation experiments [9], [10].

The main reason for implementing a virtual laboratory is given in section II. In section III the requirements on a virtual laboratory are outlined. The structure of a virtual laboratory is described in section IV. The objectives are the same as for a physical laboratory and outlined in section V. Examples of an induction machine and universal motor are presented in section VI. The next step in going more into detail, requires simulation and animation, and two typical examples, are discussed in section VII

## II. VIRTUAL LABORATORY

The main reason for introducing a virtual laboratory for education, are not the costs related to a real physical laboratory, but the main reason is that in a virtual laboratory, you can set-up experiments very quickly, and without any risk whatsoever. You can do any experiment, without damaging the laboratory equipment, and no matter how extraordinary, you can build

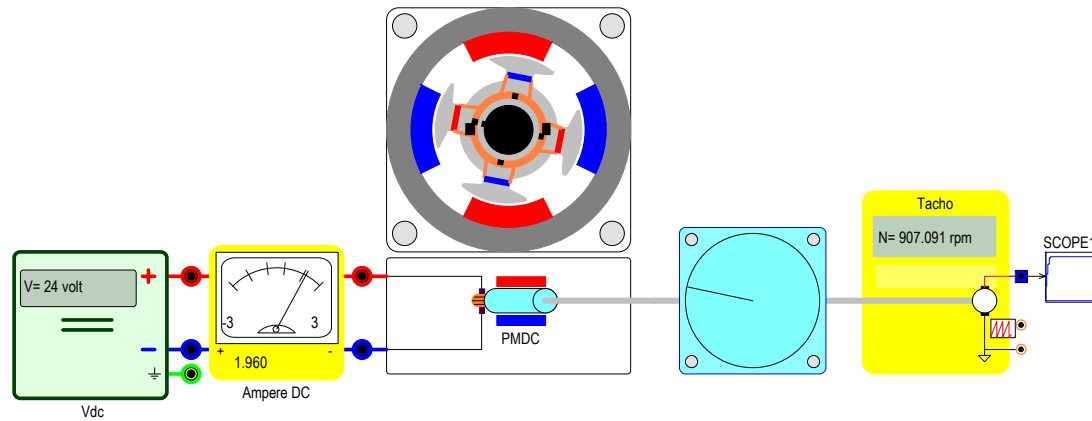


Fig. 1. Permanent Magnet DC motor driving a fan. Current is measured using an analog current meter, while a tachometer measures the speed of the rotor.

the most unrealistic experiments and learn from the mistakes. This is the main reason, since learning from mistakes is mostly what is remembered best. The background level of the students is the same as they need for a physical laboratory experiment.

#### A. Motivation

Students should get a low entry-level access, into laboratory experiments. The look and feel is important, but also the experience of doing things wrong, adds to the knowledge of the students. Especially the freedom to create experiments, that in real life would cause damage, contributes to the knowledge and experience level of the student. As long as the laboratory components have the same look and feel, as the real laboratory components, it contributes to the practical training of students.

#### B. Challenges/Risks

A virtual laboratory is undoubtedly cheaper than a physical laboratory. Students can have access to the virtual laboratory at any time and place they like and are not bounded to availability of the laboratory space. This also creates the possibility to use the virtual laboratory as demonstration during oral lectures.

The virtual laboratory experiments should be carried out in the same way, as a face-to-face traditional laboratory is organized. The tutor also has the same role during the experiments.

However, the risk is that students do not get access to a real laboratory environment, once the virtual lab is implemented. Management could cancel the physical laboratory for costs saving reasons.

#### C. Results

Due to the faster set-up of a laboratory experiment, without any risk of doing something wrong or destroying something, students can get results quicker. Instead of doing a single experiment, what-if scenarios are possible, not only by the students, but also by the teachers, when preparing lectures or experiments.

#### D. Outcomes

Application of the virtual laboratory in Delft [11], showed that students got a deeper understanding of the operation of electric machines, because they had the possibility to virtually experiment with the electric machines of any size and power level. The examples from section VI are implemented and tested, in a second year undergraduate course on electric machines in Delft [11]. The drive simulation from section VII, are to be used in a third year undergraduate or second year graduate course. The examples from section VI can also be implemented in second and third year vocational training. However, here it is advised to have pre-programmed examples, where students only have to change parameters like power level of an electric machine, or power supply output voltage.

### III. REQUIREMENTS

To prepare students, to do practical laboratory tests, requires them to train using simulation tools. However simulation tools do provide nice models for electrical machines, but also require parameters. This is manageable by undergraduate and graduate students, but impossible for students of vocational training and first semester undergraduate students. For them, the nameplate parameters are the first encounter, in identifying electrical machines.

A virtual laboratory [10], should mimic the real laboratory [11]. Each component in the virtual laboratory should reassemble a physical component from the real laboratory. Not only should the look and feel be the same, also connecting the components should be the same as if the students would connect the physical machines, see figure 1.

Models should also have the limitation of the real set-up, for example, measuring the angular speed using a tachometer, gives an indication of the angular speed in the range of 0 to 5 volts. The students will understand that there is a conversion factor, when going from RPM to an analog voltage, that can be measured in an electric circuit.

Figure 2 shows a typical laboratory set-up. An inverter is driving a three-phase brushless motor, and a tachometer is measuring the speed. Students can change the DC voltage of

the inverter, and this changes the amount of current supplied to the brushless motor. As this is a typical experiment for vocational training, the DC voltage to drive speed relation can be measured using DC voltage meters.

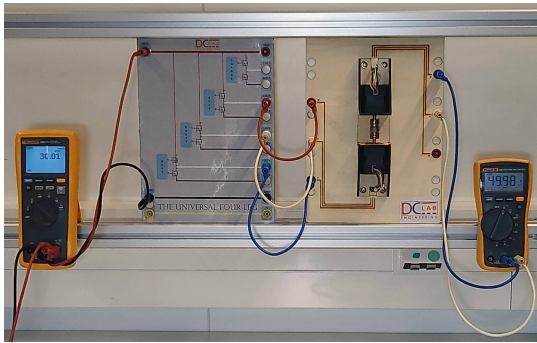


Fig. 2. Physical laboratory set-up, of three phase inverter U4L [11] with brushless DC motor and DC motor acting as tachometer.

To convert the laboratory experiment from figure 2 into a virtual laboratory experiment, the virtual experiment has to fulfill some constraints. The virtual laboratory model should have realistic parameters. The brushless motor from figure 2 has typical manufacturer data like nominal voltage, nominal speed and power level. This has to be supplied by the student in the virtual experiment, see figure 3. Also the student should carry out the measurement in the same way as in the real experiment. In simulation, graphic display of waveforms and numerical results are easy to obtain, but in this virtual experiment, the student has only access to a multimeter and eventually an oscilloscope for recording the waveforms. Finally the virtual workbench should show an animation of what would happen in the real experiment. For electrical machines, this can be done by showing the rotation of the rotor and, additionally, the rotation of electromagnetic fields in stator and/or rotor.

To mimic the laboratory experiment as realistic as possible, a virtual laboratory assignment should include:

- Connecting the components via wires with banana-plugs.
- Set parameters and/or choose the size/power rating of a component.
- Connect measuring devices like analog voltage or current meters, or digital multimeters.
- Start the experiment, instead of turning on the power supply, the simulation/animation has to be started.
- Observation of the results from the measuring devices.
- Change parameters(power/size rating) and observe their influence on the results.
- Validate the observation of the results.

#### IV. STRUCTURE

The structure of a virtual laboratory should be able to Conceive, Design, Implement and Operate the experiments in an engineering environment, being creative and value added according to the CDIO-Initiative [12]. Each phase of the experiment can be structured according to this initiative.

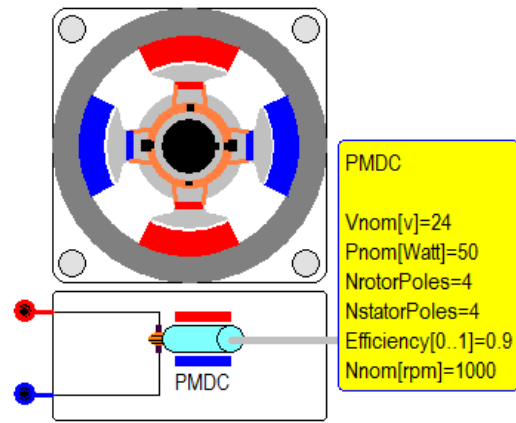


Fig. 3. Name plate parameters of the Permanent Magnet DC motor, including the number of rotor and stator poles for the animation of the motor.

#### • *Conceive: Theory*

A short introduction on the theory behind the experiment from the textbook. Here the basics of the functioning should be outlined, without going into detail on the operation.

#### • *Design: Simulation*

Simulation or animation, with simple model to explore working principle using simulation or online tooling [10]. This will reveal the operation as explained in the theory.

#### • *Implement: Set-up*

Virtual laboratory set-up, with virtual components and animation. Select and place components and interconnect them.

#### • *Operate: Validation*

Run the experiment. Validation of the virtual laboratory results, with the theoretical and/or simulation results. Comparison with expectations, and explanation of the observed laboratory results.

#### V. OBJECTIVES

In the virtual electric machines laboratory assignment, the objectives are the same, as for a physical laboratory. They can be extended with giving insight in phenomena's, that are only visible through animation.

##### A. Electromechanical

An easy start for undergraduate students is the permanent magnet DC motor, see figure 1. The only important parameter is the motor constant.

$$U = k \cdot \omega = k \cdot \frac{2\pi}{60} N \quad (1)$$

$$T = k \cdot I \quad (2)$$

where  $k$  is the motor constant describing the most important relation between electrical and mechanical quantities. However, for undergraduate students, this motor constant can be hidden as a parameter, if the student only has to enter machine nameplate parameters like, nominal voltage, nominal speed

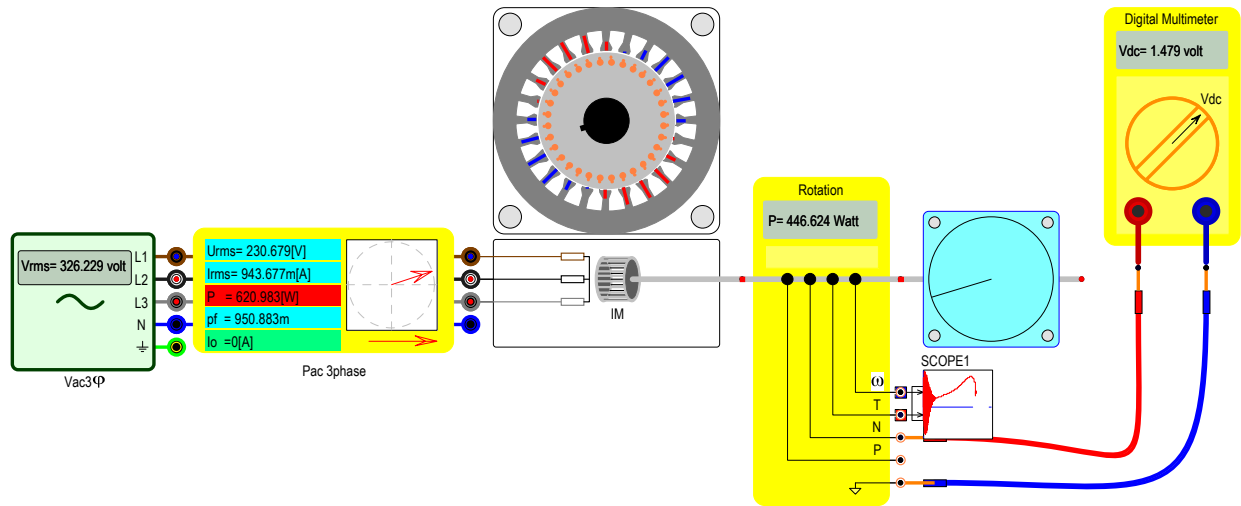


Fig. 4. Simulation of the torque-speed characteristic of an induction machine driving a fan.

and nominal power, see figure 3. From this data, the machine constant  $k$  is calculated using (1), and used internally in the model. Vocational training students, can simply choose the motor based on voltage and power level. Undergraduate students can calculate the motor constant  $k$  and verify (1).

#### B. Winding resistance

The winding resistance is the first parameter that defines the losses of the electrical machine. It can be measured at an early stage, using a simple multimeter. The influence of the damping effect of the winding resistance on regulation and stability, is not yet to be measured in this stage of a virtual laboratory, however it can be noticed in the dynamic behavior.

#### C. Winding inductance

If the machine is kept at standstill using the dynamometer, the impedance of the winding can be measured. Impedance can be measured using an AC signal generator and AC current meter. Since the winding resistance is already known, the winding inductance can be estimated. Knowing the impedance, one can set the correct parameters in a proportional-integration [PI] controlled, current regulated AC drive. Graduate students can measure the winding resistance and inductance, and use this for calculating the PI parameters of the Field Oriented Control [FOC] [9].

#### D. Magnetic field of the stator and rotor

Understanding what is happening inside the machine, can be visualized using the animation in the virtual laboratory. A revolving field inside the motor alongside the revolving currents in the windings, is shown as animation. Students can see the asynchronous fields in induction machines, and synchronous commutation of phase currents in brushless machines. Especially vocational training student and undergraduate students, have a need for visualization of magnetic fields, as their curriculum does not incorporate 2D/3D electromagnetic field analysis.

#### E. How is Torque created?

The concept of torque creation by the outer product between current and field  $T = \Psi \times I$ , is easily visualized in animation. It is also numerically visible in the measuring device. The linear relation between current and torque in DC motors, can be measured by the vocational training and undergraduate students, by simply adjusting the power supply. Graduate students are challenged to express and verify this relation, using the outer product of current and field.

#### F. How does terminal voltage arise?

Adjusting the angular speed of the motor using the dynamometer, or changing the field producing current in a DC shunt motor, shows the variation of the terminal voltage of the motor. This is a typical experiment for vocational training, as it is intuitive to see the proof of the mathematical relation from (1).

## VI. EXAMPLES

#### A. Induction Machine

An induction machine laboratory set-up, can be used for many different experiments, see figure 4. Typically for induction motors, compared to DC and brushless motors, is the fact, that most of the induction motors are designed and thus only operate at the operating voltage they are designed for. This means that most of the smaller induction machines, with affordable power rating for a laboratory are rated for 400volt/1kW. In vocational and undergraduate laboratory classes, this can be a problem because of safety. There are some exceptions [13] working on 23/40volt, but especially in vocational training, measuring rated voltage and current levels, gives more insight for the student on what to expect. The 23/40volt motors are especially suited for control experiments using a low voltage inverter, since students can touch all wires during operation. In the virtual laboratory, the machine ratings

are like in a real drive. This means, that students can perform measurements on 100kW motor, without any safety issues.

The winding resistance of the induction machine is simply measured using a digital multimeter, see figure 5. From this the winding losses can be estimated, if the induction machine is in operation.

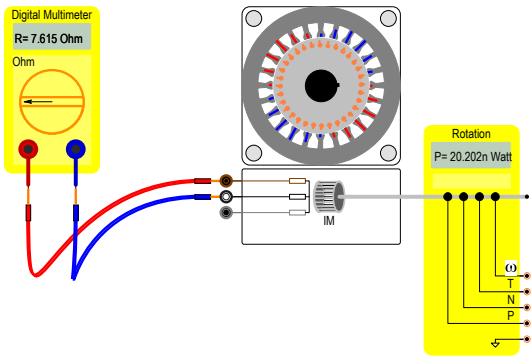


Fig. 5. Measuring the winding resistance using a multimeter.

The simulation of start-up in a virtual laboratory, allows the recording and visualization of the torque-speed characteristic of the induction machine, see figure 4. Interesting for students is many times the observation, that is looks slightly more complicated during start-up, than the ideal characteristic as seen in most textbooks, see Scope1 in figure 4.

A typical assignment in an induction machine laboratory is to measure the torque slip curve, see figure 6. Using a dynamometer, the mechanical load of the rotor can be adjusted, by specifying the load torque. The speed of the rotor can be measured and tabulated, see table I.

Torque[Nm]	Speed[rpm]	slip[%]
-5	.	.
.	.	.
5	.	.

TABLE I  
TORQUE-SPEED CHARACTERISTIC TO BE COMPLETED BY THE STUDENT

### B. Universal motor

Running an universal motor from the mains AC power grid, reveals a vibrating noise. In a virtual laboratory, using oscilloscopes, the origin of this audible noise can be visualized, see figure 7. Although the students select an universal motor and only specify nominal operating values, the underlying model is more complex. It includes the saturation of the stator and rotor iron in the internal model, however, this is not directly visible to the students as a separate parameter. The internal parameters are calculated from the rated values of the machine, simplifying the set-up for the students.

First of all, power delivered from a single AC source is pulsating at double supply frequency. Secondly the saturation of the stator and rotor iron in the universal machine, gives

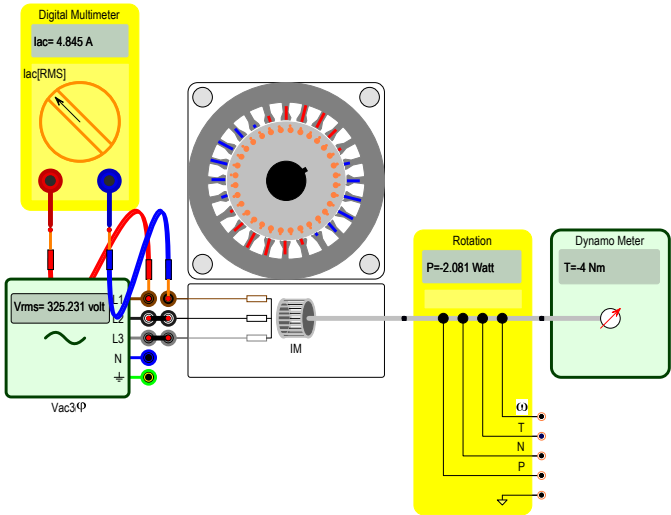


Fig. 6. Application of a dynamometer to measure the slip of the induction machine for varying load.

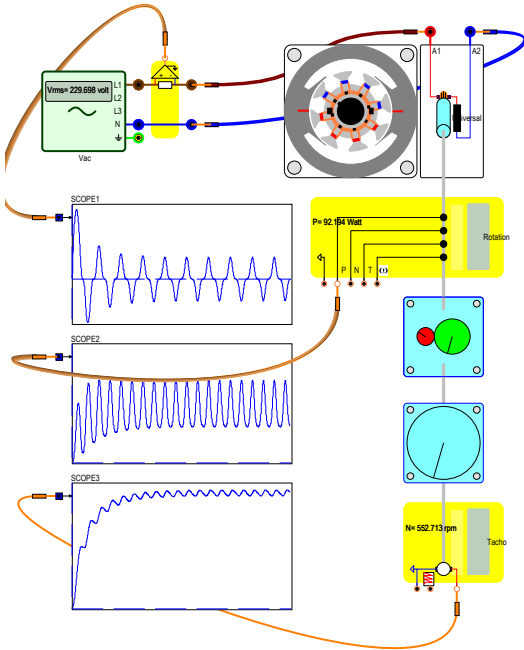


Fig. 7. Universal motor driving a fan, showing the typical torque harmonics.

rise to higher harmonics in the waveform for the current, see Scope 1 in figure 7. Observing this current waveform, makes explaining the torque pulsations easier, see Scope2 in figure 7. Finally the resulting rotor speed can be seen, see Scope3 in figure 7, explaining the audible noise.

### VII. DRIVE SIMULATIONS

Once the students understand the working of machines, the next step in an undergraduate course, is to add the controller and use the machine in a drive system. From the laboratory models, students can measure voltages, speed, current as constant values. But in a drive, the dynamic behavior becomes

important. The simulation becomes more detailed and also the control parameters have to be added. Because of the many wiring details and different required simulation results, the simplified machine and drive models are better suited. Instead of measuring constant values, start up behavior or transient response becomes more important. The simulation in figure 8, shows the start up of a variable speed drive with quadratic load characteristic. Scope2 clearly shows the difference between the motor and load torque, and from this the acceleration of the motor can be explained. When both torque characteristics meet, the drive is at stationary speed. Changing parameters like load mass or inertia, driving voltage, machine size or machine inertia, can be studied using this simulation.

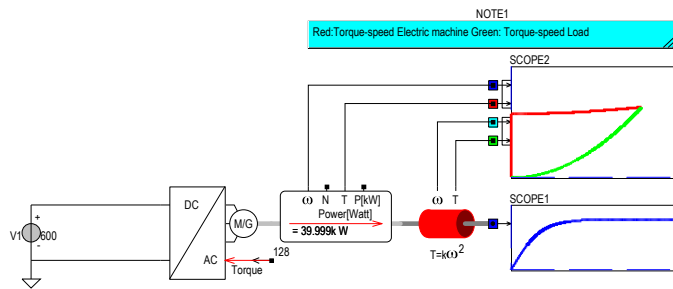


Fig. 8. Variable speed drive with quadratic load. Both motor torque and load torque are displayed in a single scope2 as function of the rotor speed, to show the remaining torque difference responsible for the acceleration of the drive.

The application of a speed or position profile in combination with a variable speed drive, only makes sense when there is adequate control. The variable speed drive blocks includes a PI controller. Setting up such a simulation experiment becomes easier when everything is integrated into a single block and students are not distracted by the many details of the control structure. They only have to set parameters of the PI controller, like they would do in an industrial environment. The simulation in figure 9 shows a given torque, speed and position profile. The speed is the integral of the acceleration, while the position is the integral of the angular speed. Therefore, defining the acceleration profile in the form of a given torque profile, feeding this in the variable speed drive, reveals the final speed of the variable speed drive.

## CONCLUSIONS

For vocational training and undergraduate students, a virtual laboratory can be applied, when the components have the same look and feel as the real components. The students should be able to set-up the virtual laboratory experiment, using banana plugs and multimeters, like the student would do in a physical laboratory experiment. The models require only nameplate and rated parameters, but internally, the models are complex and the required parameters are automatically calculated from the nameplate and rated values. Non-linearity, saturation and harmonics, is included in those models. Since animation can be applied, also the rotation of magnetic fields or the commutation of currents in the machine can be visualized, being an extra educative quantity compared to a physical laboratory.

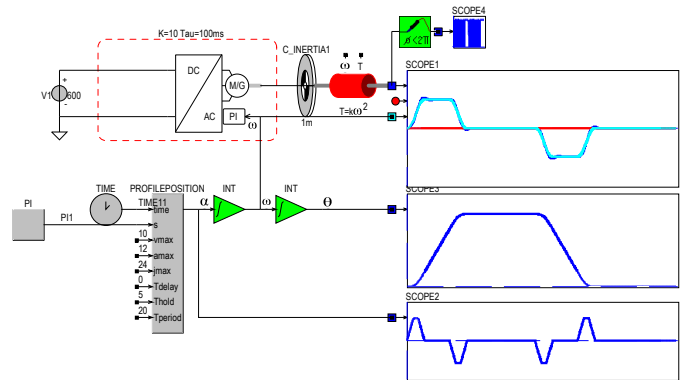


Fig. 9. Variable speed drive, where the angular speed of the machine is set by a defined speed profile. The PI controller finally regulates the speed according to the speed profile.

For last year undergraduate and graduate students, the more detailed drive simulations can be applied.

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