

Educational Set-up for Brushless Motor Drives

Akin Üzel, Diëgo C. Zuidervliet and Peter J. van Duijsen

THUAS, www.dc-lab.org, Delft, The Netherlands
 a.uzel@student.hhs.nl, d.c.zuidervliet@hhs.nl, p.j.vanduijsen@hhs.nl

Abstract—Traditionally the brushed DC motor is the first motor that students encounter in a laboratory assignments on electrical drives. However a number of simplifications are taken into account when explaining the workings of the brushed DC motor. Considering basic knowledge of electromagnetic principles, the attraction between a magnet and a current carrying winding is easily accepted by students. A Brushless DC motor drive, which is based on this electromagnetic principle, is an easy to understand motor drive when it comes to the control of the motor. All underlying physical properties of the brushless DC motor drive are easier to visualize compared to the brushed DC motor with mechanical commutator. Therefore this motor drive more is suited as an introductory course in motor drives. Virtual online experiments as well as lab assignments are demonstrated that visualize every aspect of the brushless motor drive. The basic models for simulation and animation are presented and a typical laboratory set-up is demonstrated.

Index Terms—Brushless, BLDCM, power electronics, virtual prototype, Caspoc, animation, Hall sensor, microcontroller, U4L

I. INTRODUCTION

EXPLAINING motor drives, the working of electrical machines and the way to control them, including all mathematical relations governing all physical quantities can be done in various ways. A simple approach by simplifying all physical quantities and finally ending up with describing only its outer system behavior, can be very attractive during oral lectures, where only the main properties of electric drives are explained. Those system properties include conversion between electrical and mechanical energy and dynamic response. However during laboratory classes, measurements on a practical motor drive have to be done and the inner workings of the electric machine have to be explained.

Most laboratory classes use the brushed DC motor as the first motor for students to learn about electric machines and motor drives. At first sight this seems correct as the relation between rotor angular speed and terminal voltage has a linear relation, as well as current consumption and delivered torque. But when it comes to the question how the brushed motor is actually producing the torque, why the windings are so widely distributed among rotor slots and why the commutator has so many segments, the answers have to be based on the underlying physical properties of the brushed DC motor. Diving deeper into the working of the DC motor, one has to

explain in detail how the connections between the commutator segments and the windings are organized. Even explaining why there is brush-fire and what is happening when the brush is shortening two commutator segments can be very difficult as the underlying principles are not that simple. Especially on the design of the windings and the commutator for DC machines, there has always been a difference in course material. For example [1] is just a simplification of the detailed explanation that was required to fully understand the workings of DC brushed motors [3]. Only explaining the windings of the brushed DC machine did cover a complete set of lectures with its own set of lecture notes [2]. In [4] a chapter is dedicated to winding design of brushed DC machines, but in [5] the brushed DC machine is treated as a system component in an electrical drive.

To explain the basics of Brushless DC Motor drives [BLDCM], experimental set-ups [15]–[18] are very valuable next to virtual prototypes for explaining the operation and control. Since the control of the BLDCM can be demonstrated using a very simple microcontroller or a very simple logic gating circuit build from logic NAND gates, it is an excellent introduction into motor control [7], [8]. Only a basic understanding of the underlying mathematical relations and a clear understanding on how currents are flowing through the motor windings is enough to set-up a working motor drive [11]. This makes the BLDCM suitable for an introductory course in motor control [9], [10], [12].

In this paper after exploring the basics of the brushless motor in section II, we first explore the animation tools that explain the basics of BLDCM control in section III and secondly we demonstrate a power electronics set-up and a simple control method to drive the BLDCM in section V. Measurements on an experimental set up are compared to the simulation results in section VI.

II. BRUSHLESS MOTORS

The brushless DC motor is in principle an AC machine as it requires at least a three phase AC voltage. However if we consider the brushless motor as a replacement for the brushed DC motor, we can explain that the mechanical commutator is going to be replaced by an electronic commutator. By doing this the motor can, on the system level, be treated as a generic machine, where electrical power and mechanical

power are exchanged, see Fig. 1. At this moment the machine constant $K[Nm/A]$ or $K[V s/Rad]$ can be introduced, linking the mechanical to electrical quantities, which is basically related to the field or Flux $\Phi[Wb]$ in the motor.

$$U = K \cdot \omega = pp \cdot \Phi \cdot \omega \quad (1)$$

$$T = K \cdot I = pp \cdot \Phi \cdot I \quad (2)$$

$$P = \omega \cdot T \quad (3)$$

$$P = U \cdot I \quad (4)$$

where $pp[.]$ is the number of pole pairs, $U[V]$ is the DC voltage at the inverter, $I[A]$ is the motor current, $\omega[Rad/s]$ is the angular(electrical) speed of the rotor, $T[Nm]$ is the torque produced by the motor and $P[W]$ being the electrical and mechanical power.

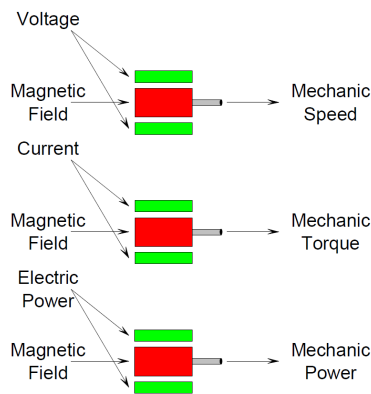


Fig. 1. Coupling of electrical and mechanical quantities by a generic machine. From top to bottom voltage-speed relation, current-torque relation and electrical-mechanical power relation, all related by the magnetic field.

The next step is to demonstrate the back-emf voltage of the motor, when the rotor is rotating. This can be done using a simple set up, with either a multimeter to measure the RMS value of the voltage at the machine terminals or by observing the back-emf on a digital storage scope. Here the machine constant K can be determined, being the product of the number of pole pairs pp and the magnetic field Φ from the measured rotor speed and terminal voltages.

$$K = pp \cdot \Phi \quad (5)$$

Also the position and functioning of the Hall sensors has to be explained before explaining the control of the motor. It is instructive to show the output from a Hall sensor when the rotor magnets pass the Hall sensor. In an open machine, the students can see how each rotor magnet is aligned in front of a Hall sensor and measure the output from the Hall sensor, see Fig. 3.

III. ANIMATION FOR CONTROL

Once the Hall sensors are explained, the relation between the back-emf, winding current and position of the rotor by means of the Hall sensor outputs has to be explored. An animation where the rotor position can be adjusted by the



Fig. 3. View on the inside of a brushless motor to show the position of the Hall sensors relative to the rotor magnets. By rotating the rotor, the students can see how the rotor magnets pass each Hall sensor and observe the output of the Hall sensor on a oscilloscope.

students manually and directly see what should be the waveform reveals, how the motor should be controlled. This relation could also be explored in a laboratory set up, but equally well in an animation. In the laboratory set up the rotor should rotate with a constant speed and a trigger signal should be created from one of the Hall sensor outputs, to have quasi-static view on the oscilloscope. However only the back-emf and Hall signals can be visualized using the oscilloscope.

Using animation [13] the principle of the Hall sensor signals and the back-emf of the motor can be demonstrated, see Fig. 2 for 60° displaced Hall sensors. This virtual experiment can be repeated in a laboratory set-up, but requires a 10 channel oscilloscope, to display the three motor voltages, three motor currents, three Hall signals and the position of the rotor, for which a resolver or incremental encoder would be required. Animation of a virtual experiment is much easier and reveals the same information to the students in such a way, that students can play with it to fully understand all aspects at their own pace.

Not only the back-emf voltages and Hall sensor outputs are visible, but also the currents that have to be controlled through the rotor stator winding can be displayed, see Fig. 2. In this way, the animation shows when a current through each winding should flow in order to produce torque. The line-line voltages $V - W, W - U, U - V$ are displayed in the upper window. The phase-neutral and phase-inverter-ground voltages are displayed in the three following windows. The inverter output voltage is the voltage measured between the output of the inverter and the ground of the inverter. This is usually the voltage as being measured by a sensorless control. If the neutral connection of the three phase winding would be available, the student could measure the phase voltage of each winding, but in practice this is seldom. In the animation, this voltage is easily displayed next to the line-line voltage and inverter output voltage.

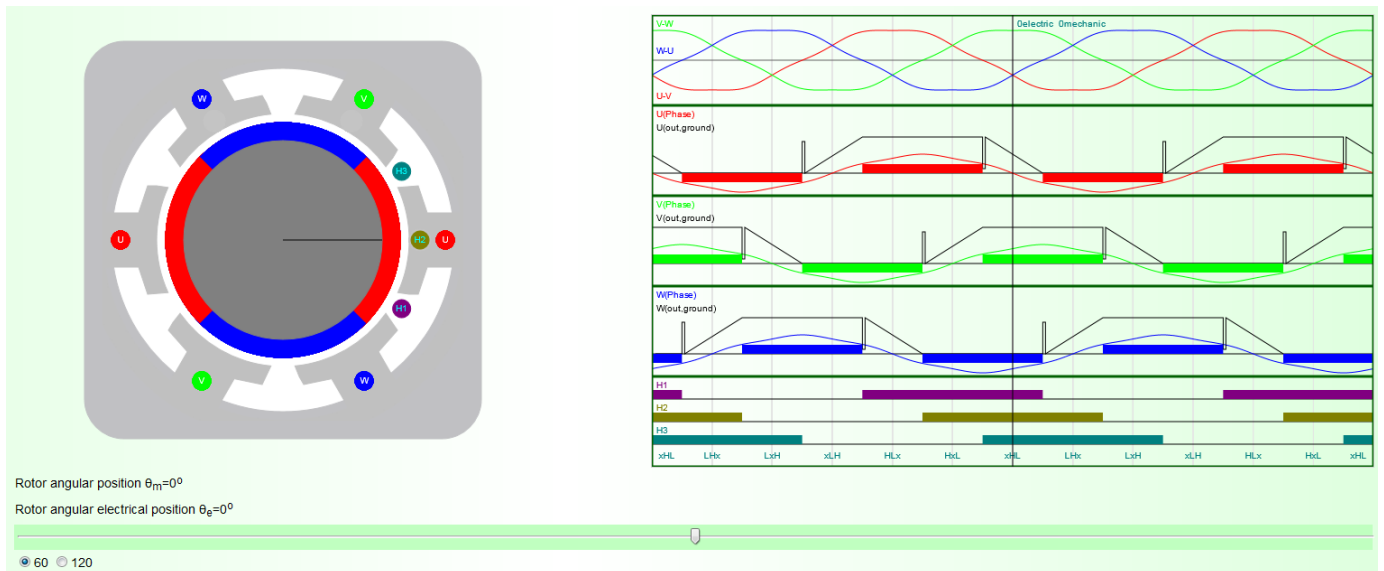


Fig. 2. Animation [13] of the control, the student can rotate the rotor manually and see the position of the rotor magnets compared to the hall sensors and on the right side, he sees the value of the terminal voltage, back-emf and required current (colored areas) as well as the hall sensor output and the gating. From top to bottom: line-line voltages V-W (Green), W-U (Blue), U-V (Red), Phase voltages U (Red), V (Green), W (Blue) as well as the inverter output voltages (Black) and their corresponding currents. The bottom window shows the three Hall signals H1, H2 and H3 and finally the gating of the inverter, where xHL indicates the status of each inverter leg, x: open, H: High side closed, L: Low side closed. Hall sensors 60° displaced.

IV. ANIMATION OF THE BLDCM

To show the start up of the BLDCM in a simulation, the animation of the rotor and its relative position to the Hall sensors is of value when explaining the control, see Fig. 4. During the animation in Caspoc [14], the rotor rotates and the hall signal wires are colored when active. The corresponding Mosfet and Diode in the inverter as well as the current path through the winding is highlighted, so students can follow the commutation process. Important is the fact that all signals are visible and that while the animation is running, the rotor is rotating during the animation. The control is implemented by a look-up table, see Table. I.

TABLE I
GATING SIGNALS FOR THE MOSFETS IN RELATION TO HALL SENSORS

Step	Gate	Inverter voltage	H1	H2	H3
0	HLx	U_H, V_L, W_x	1	1	0
1	HxL	U_H, V_x, W_L	1	0	0
2	xHL	U_x, V_H, W_L	1	0	1
3	LHx	U_L, V_H, W_x	0	0	1
4	LxH	U_L, V_x, W_H	0	1	1
5	xLH	U_x, V_L, W_H	0	1	0

In this way, the relation between the rotor position, back-emf and Hall signals can be observed [14]. Using the "Freeze and Go Back feature" in Caspoc [19], the user can replay the simulation/animation and show the instantaneous values for each moment in time, or similar, for each rotor position.

V. POWER ELECTRONICS SET-UP

The Universal Four Leg [U4L] [6], [7] as seen in Fig. 5 consists of 4 half bridges and a collection of logic functions surrounding each half bridge.

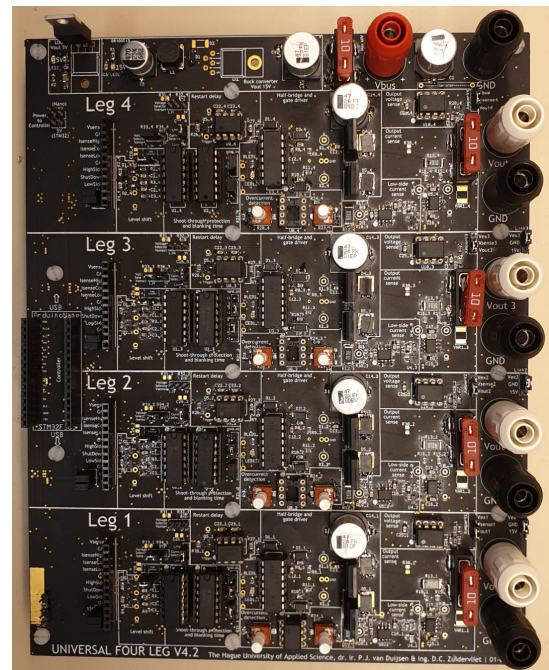


Fig. 5. Universal 4 Leg.

The schematic in Fig. 6 shows the power circuit of the board, the half bridge and gate driver. A half bridge works like a switch that's used to control the voltage level at the inverter output. With the use of three half bridges, each phase can be powered and with the right sequence, the motor will start spinning. In addition, the direction and speed of rotation can be manipulated with the use of half bridges. A half bridge consists of a high-side Mosfet (Q3) and low-side Mosfet (Q4), see Fig. 6. With the drain from the high-side Mosfet connected to the DC

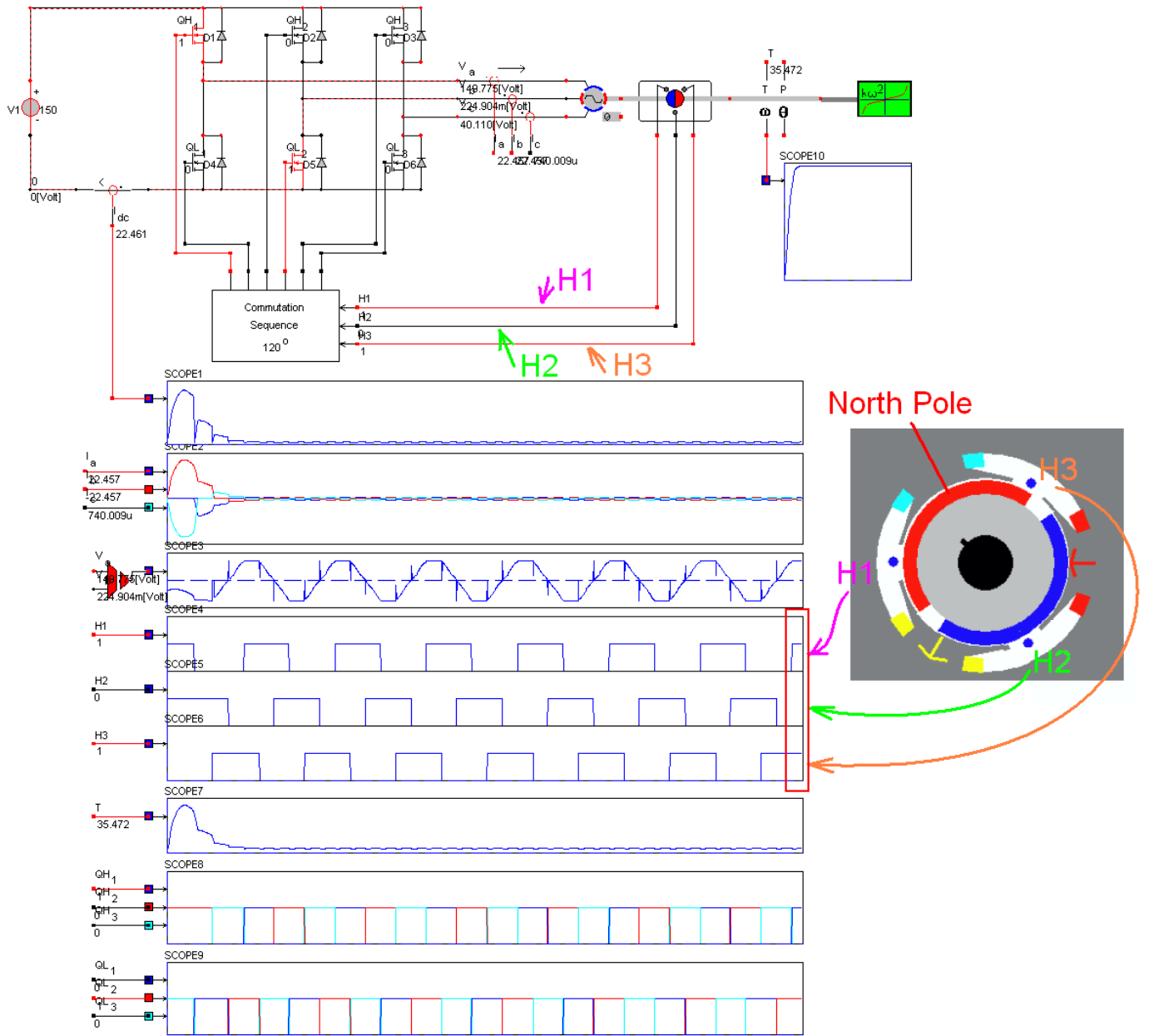


Fig. 4. Animation of the BLDCM in [14], showing a rotating rotor and the current path through the mosfets, belonging to the highlighted hall sensor signals H1, H2 and H3. From top to bottom in the scopes: Scope 1: Inverter input current, Scope 2: Three phase machine currents, Scope 3: Line-Line voltage between phase 1 and 2, Scope 4,5,6: Hall sensor signals H1/H2/H3, Scope 7: Torque, Scope 8: High side gating signals, Scope 9: Low side gating signals. Scope 10 shows the angular speed of the motor.

bus voltage and the source from the low-side Mosfet connected to the ground. These Mosfets are turned on and off by the gate driver. Logic signals are sent from the microcontroller and received by the gate driver. The gate driver then drives either the gate of the high-side or the low-side Mosfet. For a brushless motor drive it is important to have the ability in the gate driver to have both the high-side as well as the low-side mosfet turned-off. This is marked by the "x" in the bottom line in Fig. 2.

A. Sensorless control

Zero crossing detection can be used to implement sensorless control. The back-emf voltage has to be sensed and upon zero-crossing of the non-powered phase, the commutation to the next step, see Table I, has to be done. A virtual neutral is created in the zero-crossing detection circuit in Fig. 7. Using an RC filter the measured output voltage is filtered before the zero-crossing is detected using a comparator, implemented by a simple LM393. The outputs of these comparators require a pullup resistor, but connect directly to the inputs of a microcontroller. In this way sensorless position control is achieved, saving the need for hall sensors and wiring.

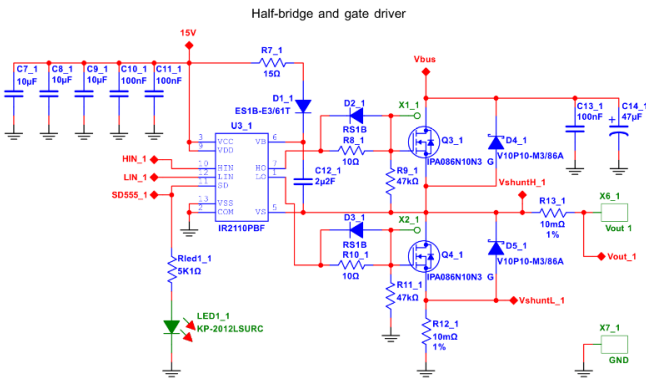


Fig. 6. Half bridge and gate driver. The gate driver IR2110 [20] includes a bootstrap circuitry consisting of D1 and C12 to power the high side driver. The antiparallel diodes D2 and D3 increase the turn-off time of the mosfets. Output current is measured differentially across R13.

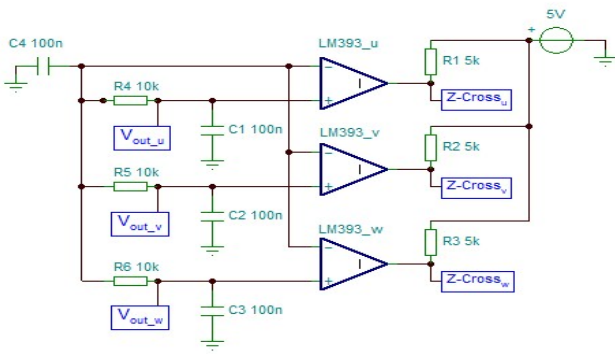


Fig. 7. Zero crossing detection using a virtual neutral.

VI. MEASUREMENTS

A four channel oscilloscope is required to show both three phase signals and one of the winding currents, see Fig. 8.

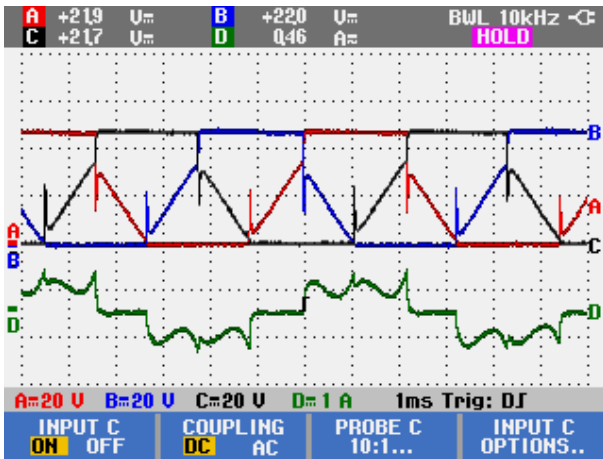


Fig. 8. Inverter output voltage measured between tip:X6 and X7 in Fig. 6 and corresponding phase current.

The current is actually measured at the power electronics set-up, that includes a current sense resistor in the output terminals R13, see Fig. 6. Clearly visible is that the current

is positive during the period that the output voltage is positive and negative during the period that the output voltage is zero. Note that the measured and displayed voltage is measured between tip X6 and X7 in Fig. 6. The current waveform shows some ripple, as was also shown in the simulation in Fig. 4 in Scope 2. This has to do with the fact that during the period where a winding is energized there is also a single commutation process, giving rise to a transient response of the current.

To measure the line-line voltages, a differential probe is required. If not available the math function on the scope can be used, but a noise free measurement through the probes and short ground connection for the probe is essential. However it clearly demonstrates the line-line voltage and shows the commutation instants, see Fig. 9.

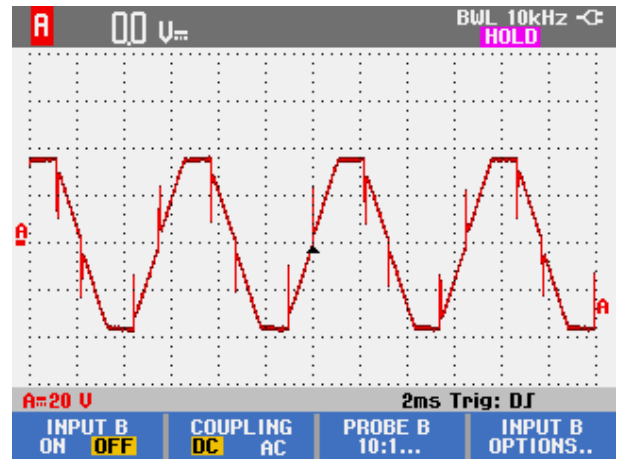


Fig. 9. Line to line voltage

The measured voltage waveform in Fig. 9 is in accordance with the simulation result in scope 3 in Fig. 4. The commutation process is clearly visible and the next step is to verify the commutation in relation to the Hall signals.

The Hall signals can be captured on the scope while the machine is rotating, see Fig. 10. The 120° phase shift can be observed. In a laboratory experiment, the students have to measure the back-emf of the motor and display the back-emf together with the Hall signals on the scope. Only then they can see the relation between the generated back-emf and the Hall signals. The commutation moments in time are then clearly visible and students can observe the similarity between the measured signals and back-emf from experiment with the animated signals from the simulation in Fig. 4.

The final experimental set up that students have to create in a laboratory exercise [21] is a running brushless motor controlled from an inverter with an Arduino Nano [22] as low-cost microcontroller, see Fig. 11. The motor as well as the Hall sensor signals have to be correctly wired to the inverter board and the control program containing Table I has to be programmed into the Arduino. By simply exchanging two Hall signal wires, the speed of the motor is reversed. Changing the voltage of the external power supply to the inverter allows a simple yet effective speed control of the motor. The consumed current is either measured as voltage over the current sense

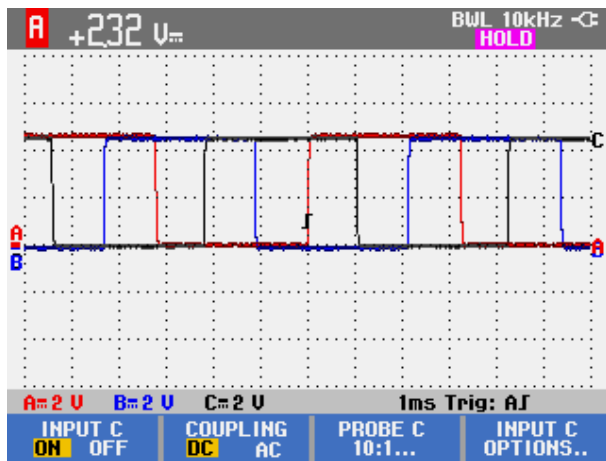


Fig. 10. Output voltage from the three Hall-sensors, the three signals Red, Green and Blue are 120 degrees shifted in phase

resistor in the output terminals R_{13} , see Fig. 6 or simply by reading the output current from the external power supply.

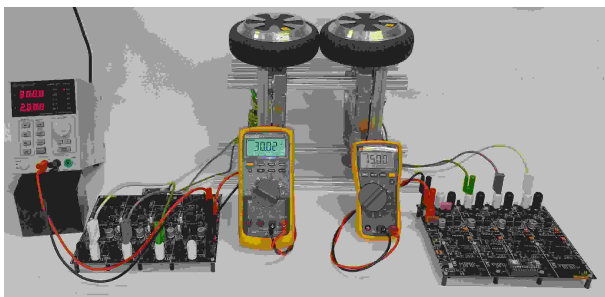


Fig. 11. Experimental dual set up [21] including the inverter with microcontroller, brushless motor and sensorless control.

By connecting two motors mechanically, a mechanical power exchange can be made and thereby mechanically loading the motor. As a result the torque production should be higher, showing larger currents.

VII. CONCLUSIONS

The brushless DC motor is suited as a first introduction to motor control. The simplicity of the control structure as well as the fact that torque production can be calculated without going into detailed mathematical relations makes the brushless motor attractive. The students can use a virtual experiment to train themselves before entering the laboratory assignment. Topics like using Hall sensors for position control, reversing speed by exchanging two hall signals as well as speed control by changing the DC link voltage are among the many experiments that students can perform to get a better feeling with motor control. The brushless DC motor reveals many topics in motor

control, without going to deep into motor control theory. Simulation and Animation shows the basic principles and relations between voltage and current waveforms and Hall signals.

REFERENCES

- [1] Richter R., Kurzes Lehrbuch der Elektrischen Maschinen: Wirkungsweise · Berechnung · Messung, Springer Verlag 1949, ISBN 978-3642925344
- [2] Sequenz H., Die Wicklungen Elektrischer Maschinen, Band 2, Wenderwicklungen, Springer Verlag 1952, ISBN 978-3709132326
- [3] Richter R., Elektrische Maschinen: Erster Band: Allgemeine Berechnungselemente, Die Gleichstrommaschinen, Springer Verlag 1967, ISBN 978-3034840668
- [4] Pyrhonen J., Design of Rotating Electrical Machines, Second edition, Wiley 2014, ISBN 978-1-118-58157-5
- [5] Boldea I., Nasar S.A., Electric Drives, 3rd ed., CRC press 2016, ISBN 978-1498748209
- [6] van Duijsen P., Woudstra J., van Willigenburg P., Educational setup for Power Electronics and IoT, 2018 19th International Conference on Research and Education in Mechatronics (REM), 2018, pp. 147-152, doi: 10.1109/REM.2018.8421802.
- [7] van Duijsen P. J. , Zuidervliet D. C., Woudstra J. B., Electronic Learning Experience Setup : Power Electronics and Electrical Drive Education, 2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO), 2020, pp. 1549-1554, doi: 10.23919/MIPRO48935.2020.9245230.
- [8] Kenjo T., Nagamori S., Permanent-Magnet and Brushless DC Motors, Oxford University Press, 1986, ISBN 978-0198562146
- [9] Krishnan R., Permanent Magnet Synchronous and Brushless DC Motor Drives, CRC Press 2009, ISBN 978-0824753849
- [10] Hendershot J. R., Miller T., Design of Brushless Permanent-Magnet Machines, Motor Design Books LLC, 2010, ISBN 978-0984068708
- [11] Sokira T. J., Jaffe W., Brushless DC Motors: Electronics Commutation and Controls, Tab Books 1990, ISBN 978-0830632671
- [12] Xia C.L., Permanent Magnet Brushless DC Motor Drives and Controls, Wiley, 2012, ISBN 978-1118188330
- [13] Simulation Research, Caspoc Multilevel simulation and Animation, [Online] Available: <https://www.caspoc.com>
- [14] Simulation Research, "3-phase Brushless DC Motor control with Hall sensors", [Online] Available: <https://caspoc.com/help/handson/acdrives/brushlessdrive/>
- [15] H. A. Fabelo, J. Cabrera, A. Vega and V. Deniz, A brushless DC motor control software C library based on ATmega64M1 applied to teaching, 2014 XI Tecnologias Aplicadas a la Ensenanza de la Electronica (Technologies Applied to Electronics Teaching) (TAEE), 2014, pp. 1-6, doi: 10.1109/TAEE.2014.6900165.
- [16] H. A. Fabelo, A. Vega, J. Cabrera and V. Deniz, A low-cost control system for BLDC motors applied to teaching, 2014 XI Tecnologias Aplicadas a la Ensenanza de la Electronica (Technologies Applied to Electronics Teaching) (TAEE), 2014, pp. 1-6, doi: 10.1109/TAEE.2014.6900164.
- [17] N. Tadrast and H. Zeroug, "Development of brushless DC motor drive system for teaching purposes using various PWM control techniques for speed control," 2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL), 2014, pp. 1-4, doi: 10.1109/COMPEL.2014.6877150.
- [18] M. Mazo et al., "Teaching equipment for training in the control of DC, brushless, and stepper servomotors," in IEEE Transactions on Education, vol. 41, no. 2, pp. 146-158, May 1998, doi: 10.1109/13.669725.
- [19] P. Bauer and P. J. Van Duijsen, "Challenges and Advances in Simulation," 2005 IEEE 36th Power Electronics Specialists Conference, 2005, pp. 1030-1036, doi: 10.1109/PESC.2005.1581755.
- [20] IR2110, Gate driver, Infineon, Available: www.infineon.com
- [21] DC laboratory, The Hague University, TIS, Delft. [Online] Available: <http://dc-lab.org>
- [22] Arduino Nano, Available: <https://store.arduino.cc/arduino-nano>