

# Field reversal DC machine braking with DCM drive

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**Abstract:** This paper gives a detailed description of implementation of braking by field reversal at laboratory setup of DC machine with modern Siemens DCM drive. The main focus of the paper is implementation of braking procedure of the DC machine using field reversal through didactic approach suited to students of electrical engineering within the course of the electric drives at Faculty of Technical Sciences Čačak. The laboratory test bench allows students to upgrade parts of the setup and test different operation regimes of DC and AC machines, as well as gaining experience of tuning and optimization of the overall motor-load system.

**Keywords:** DCM drive; Braking; Field reversal; Laboratory setup; Siemens sinamics;

## 1. INTRODUCTION

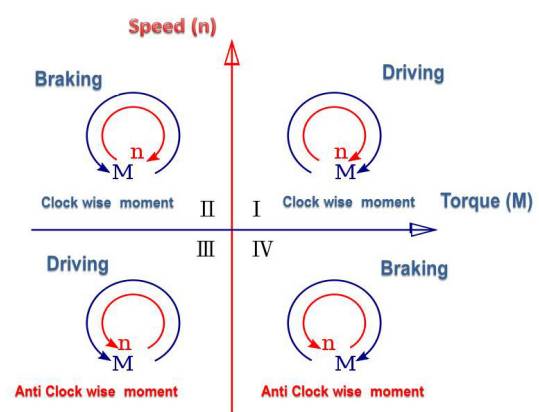
DC machine is an unavoidable part of electric drives in industry. In the past they were used for industry processes that require a wide range of power and speed as well as high accuracy in terms of torque, speed and position control.

Nowadays the majority of all electromotor drives in industry are AC drives, but even today there are obsolete or even new implemented DC drive running. Retrofitting those existing DC drives with AC machines and AC drives sometimes can be more expensive than just repairing and adding new DC drive, making economically unjustifiable a change it to AC drive [1]. Because of this reason, the principles of operation and control of DC drives are still studied in courses of electrical machines and drives at universities around the world.

The software capabilities of modern converters and drives with the development of power electronics are becoming more complex and sophisticated. Different control principles and various states of electric drive systems are today accompanied by numerous parameters that can be set on the modern converters and drives, prior electric drive commissioning and operation. For this reason, EMPA laboratory of Faculty of Technical Sciences Čačak [2], has developed laboratory setup with four-quadrant (4Q) operation of conventional DC and AC (induction) machines [3]. The system is dedicated to practical laboratory exercises where students can get familiar with different operation regimes of motor-load system, defining configuration, setting various converter parameters, testing possibilities and drive dynamics gaining in that way necessary practical knowledge.

## 2. THEORETICAL BACKGROUND

Electric machine can operate in motor or generator regime, depending on the energy flow, that is direction of speed and torque of the machine shaft. Accordingly, machine operating point can be positioned in one of the four quadrants on machine torque-speed characteristic. In the odd quadrants (I and III) the machine works as a motor, while in the even quadrants (II and IV) it works as a generator [4].



In odd quadrants the direction of power is positive (electric power is converted into mechanical power - driving), while in even quadrants the direction of power is negative (mechanical power is converted into electric power - braking). Depending on the type of electrical machine and accompanying power converter, the electric drive can be one-quadrant, two-quadrant and four-quadrant drive. One-quadrant (1Q) operation of the electric motor means that the electric machine can only work in motor mode (energy flow from grid to drive) for

only one direction of rotation, which is a consequence of the control system that the drive has. In the case of two-quadrant (2Q) operation of electric drive works in motor mode (energy flow from grid to drive) but with the choice of direction of rotation. In that case, energy during generator regime cannot be sent to the grid but it should be spared on the braking resistor. In the case of four-quadrant (4Q) operation of electric motor drive electric machine can work in all operating modes (energy flow in all directions) and in both directions of rotation thanks to the ability of power convertor to send the generated energy to the grid.

Since each electric machine can work both as a motor and as a generator according to the fulfilled working conditions, the quadrant operation of the drive is usually determined by the characteristics of the accompanying power converter (its ability provide energy flow from the machine to the grid). In that sense, user, prior drive installation, should anticipate possible working regimes of the drive and subsequently chose 2Q or 4Q taking into the account all economical aspects.

**2.1. Braking using field reversal**

In 4Q DC drive operation in all 4 quadrants during the normal motor operation or during the braking is possible without the need to change the direction of the field circuit. On the other hand, when using a 2Q unit (with only one armature current flow direction) operation in additional quadrants of the speed-torque characteristic is possible (direction of rotation reversal and braking) by reversing the current in the excitation winding of the DC motor (field reversal).

Braking using field reversal also known as braking by changing the polarity of the inductor field or reverse current braking or plugging. Theoretical background of reverse current braking relies on the rule of 4 factors, which says that change in any of 4 factors of DC machine requires consequent change of one another factor. This means that following 4 factors are changing in pairs.

Rule of 4 factors includes:

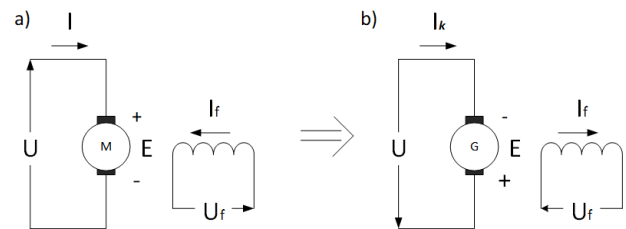
1. Machine regime - motor or generator,
2. Direction of machine rotation – clockwise or counterclockwise,
3. Direction of machine armature current,
4. Direction of machine field current.

As mentioned, the rule says that the factors change in pairs, change of one of the four factors causes the inevitable change of another.

By adding an electric circuit for manipulating the direction of current through the field circuit, the role of the machine (motor) is directly affected. Since the direction of current through the armature and the direction of rotation are the same for this type of braking, by changing the direction of current through the field circuit (field reversal), the

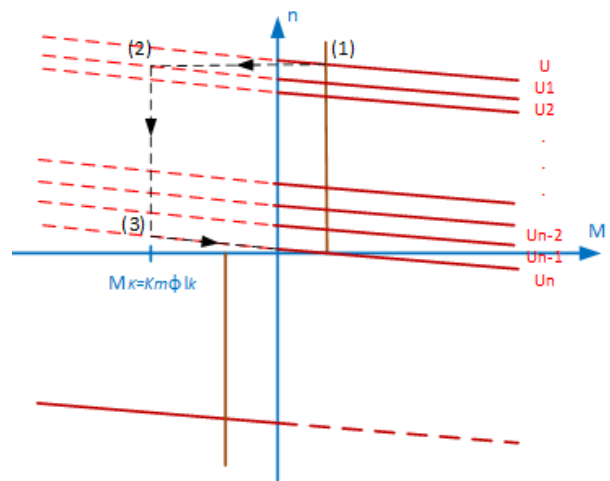
only factor that can be changed is the role of the electric machine (from motor to generator).

The machine enters the generator mode in terms of changing the polarity of the electromotive force (EMF) caused by field reversal, while the motor speed and armature current keeps their directions same as before braking. The armature voltage during the braking is changing in such way that maintains the required value of the armature current necessary for developing the defined deceleration ramp.



**Figure 2.** Equivalent scheme of DC drive in a) motor mode and in b) braking mode

From the picture above it can be concluded that the flow of energy through the power converter is always in one direction, which is a characteristic of two-quadrant drive due to the retention of the same direction of the armature current.



**Figure 3.** Change of torque/speed characteristic during field reversal braking sequence

The Fig. 3 shows step by step the braking of DC machine using field reversal. At a first the DC machine operating point (position 1) defines motor mode operating point prior braking. By changing the direction of current through the field circuit the machine tends to reach a new intersection point (position) on torque-speed characteristic depending on the armature voltage, motor speed and load intensity. Keeping the appropriate armature current intensity, armature voltage is accordingly reduced with motor deceleration. At the end of braking period when machine reaches zero speed the controller (drive) turns OFF itself.

$$U > U_1 > U_2 > \dots U_{n-2} > U_{n-1} > U_n \quad (1)$$

This transition from point 1 (motor mode) to the coordinate beginning takes place gradually through several iterations of mechanical characteristics of different armature voltages, since the speed and direction of rotation cannot be changed instantaneously. Therefore, to avoid high braking torque and thus high braking current that could damage the armature circuit, the power controller during each iteration of mechanical characteristics takes care that the braking (armature) current is always within the allowable limits. This limit depends on the defined values of the acceleration and deceleration ramps in the converter.

The consequence of this gradual lowering of the mechanical characteristics by changing the armature voltage is braking of the DC machine during which back electromotive force (EMF) (2) and speed are reduced rapidly.

$$E = k_e \varphi n \quad (2)$$

### 3. REALISATION FIELD REVERSAL BRAKING WITH SIEMENS DCM DRIVE

In order to realise braking by filed reversal, two contactors Kf and Kr are needed in the field circuit of DC machine in order to change the direction of the field current. The contactors are controlled by a Siemens DCM drive whose digital outputs (DO 0 and DO 1) had been programmed to constantly send excitation (control signal) to the Forward field contactor (Kf). Start of braking is associated with a digital input DI 3. When DI 3 is activated, the controller turns OFF the Forward field contactor (DO 0) and turn ON the Revers field contactor (Kr) using another digital output (DO 1).

The electrical scheme is given in the Fig. 4, where the change of direction is provided through the H bridge realized with the NO contact of two independent contactors (Kf and Kr). The contactors Kf and Kr are mutually locked by means of respective NC contacts in their excitation circuits as it is shown in Fig. 5.

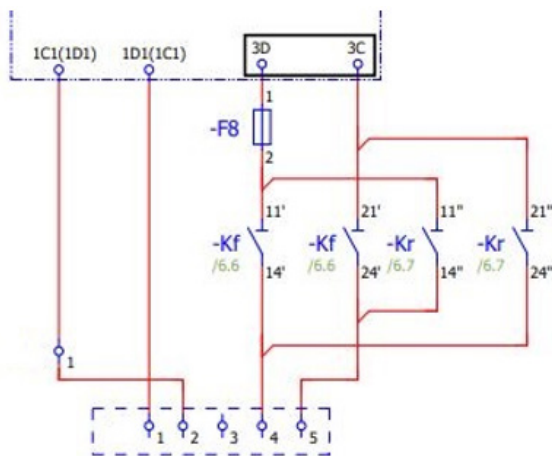


Figure 4. Electrical scheme of H bridge circuit

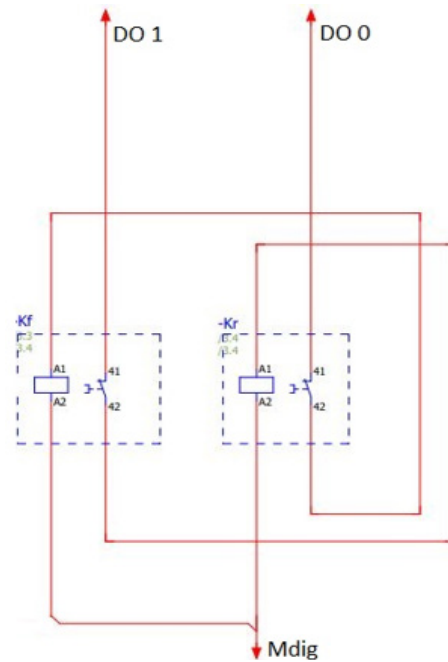


Figure 5. Electrical scheme of control circuit

#### 3.1. Definition of digital outputs of SIEMENS DCM DRIVE

Parametrizing of the DCM drive prior commissioning is done through STARTER software [3, 5]. Before starting the braking by reversing the machine field, it is necessary to assign functions to the digital outputs DO 0 (r53195.0) and DO 1 (r53195.1), which are used to control the field contactors.

- r53195.0 - state (read) parameter of positive filed polarity and
- r53195.1 - state (read) parameter of negative filed polarity.

These states should be assigned to the digital outputs DO 0 and DO 1 as it is shown in Fig. 6.

#### CUD input/output terminal >

##### Digital outputs → CUD DO 0 и CUD DO 1:

r53195[0] → DO 0 → X177.19 → Excitation signal for positive polarity filed contactor Kf.

r53195[1] → DO 1 → X177.20 → Excitation signal for negative polarity filed contactor Kr.

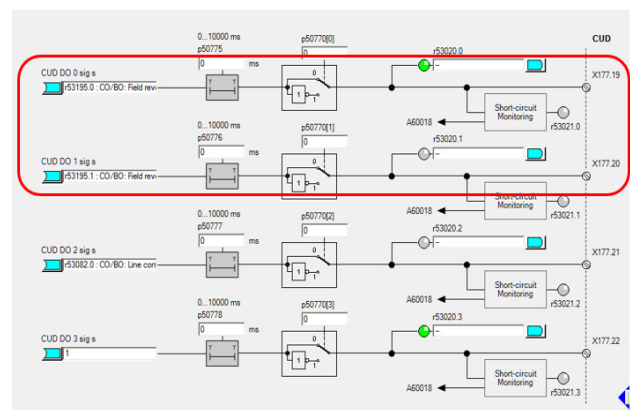


Figure 6. Setting up digital outputs DO0 and DO1

### 3.2. Definition of digital input of SIEMENS DCM DRIVE

In order to initiate the braking function of the digital output DI 3 should be assigned to parameter p50581 (Fig. 7) and physically connect it to a push button or switch that activates braking process.

- p50581 [0] - parameter setting the start of braking by field reversal.

**CUD input/output terminal > Digital input → CUD DI 3:**

X177.14 → DI 3 → p50581[0]

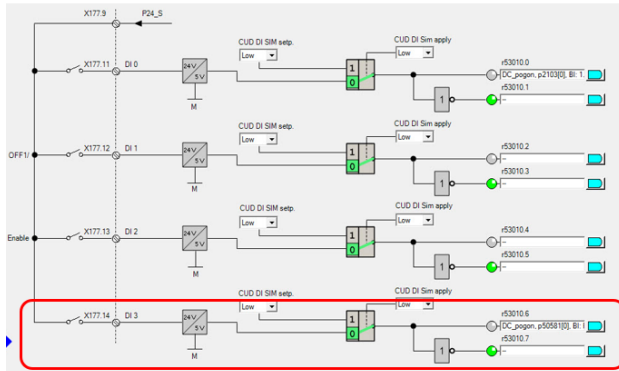


Figure 7. Definition of digital inputs

### 3.3. Defining time intervals of the field reversal braking process

In order to achieve fast and dynamic braking to the input command of the digital input DI 3, it is necessary to further define the time constants and delays related to braking procedure. Fig. 8. shows the shape of armature and field current with corresponding residual values and time delays related to field contactor excitations timings (r53195.0 and r53195.1).

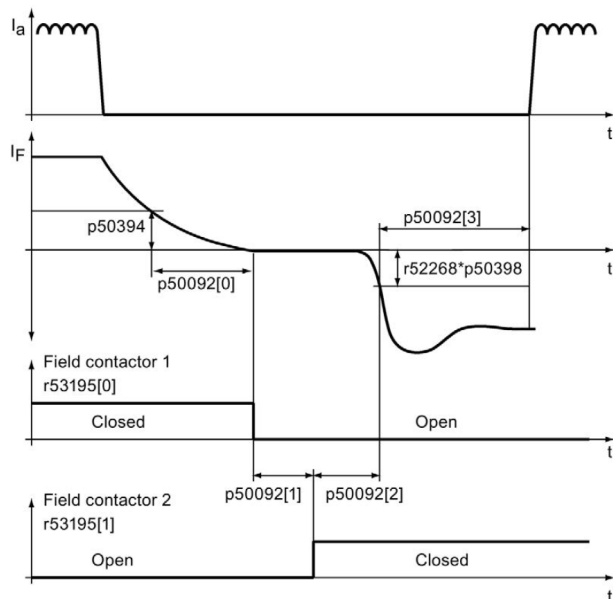


Figure 8. Shape of the armature and field currents with the field excitation signals during the braking transient process.

In Siemens DCM drive user has the ability to observe and define all the parameters of the power converter within the *Expert list* section, as shown in Fig. 9 and Fig. 10 below.

706	p50091[0]	Sequence control setpoint threshold
707	p50092	Field reversal wait times
708	p50092[0]	Field decay
709	p50092[1]	Control new field contactor
710	p50092[2]	Enable field firing pulses
711	p50092[3]	After field build up before armature enable
712	p50093	Sequence control line contactor ON delay

Figure 9. Seething up parameters of braking procedure

The following parameters of braking must be set:

- p50394 = 3 [%] - value of residual field current prior to switching OFF Kf contactor
- p50092 [0] = 0,1 [s] - time delay of Kf switch-OFF
- p50092 [1] = 0,1 [s] - dead time between operation of two contactors Kf and Kr
- p50092 [2] = 0,1 [s] - time delay between switching ON contactor Kr and turning ON field current and
- p50092 [3] = 0,1 [s] - settling time of field current before switching ON the armature current.

In order to achieve the most dynamic response of the controller in the process of braking, it is necessary to define the parameters time delays to the lowest possible value. However, these values should be in respect with machine armature and field currents dynamics in order to avoid possible short circuit during the field reversal procedure.

In order to define maximum braking torque of the Sinamics DCM drive, it is necessary to define the limiting acceleration and deceleration parameters as it is shown in Fig.9:

- p50303 [0] = 3 [s] - acceleration ramp (irrelevant in our case of braking)
- p50304 [0] = 1.2 [s] - deceleration ramp (braking speed)

869	p50302[0]	D	RFG ramp-up integrator operating mode
870	p50303[0]	D	RFG ramp-up time 1
871	p50304[0]	D	RFG ramp-down time 1
872	p50305[0]	D	RFG initial rounding 1

Figure 10. Acceleration and deceleration ramp parameters

### 3.4. Field reversal braking procedure with SIEMENS DCM drive

The sequence of operations and events during process of braking using field reversal is as follows:

1. The DC motor rotates clockwise,
2. By pressing the start braking button (activation DI 3) for time period longer than 30 ms,
3. The armature current is turned off,
4. The field current starts to decrease,



5. At the moment when the field current is less than the set reference value - parameter r50394, the process of reversing the polarity of the inductor field begins,

6. Wait time according to p50092[0], after which both contactors r53195[0]=0 and r53195[1]=0 are turned OFF,

7. Then there is a moratorium of time period defined by parameters r50092[1] and r50092[2],

8. Control new field contactor, r53195[1] = 1 contactor Kr is turned ON,

9. After the time r50092[3] has elapsed, the armature current is switched ON back

10. At the moment of stopping the motor (speed close to zero) the DC drive is switched OFF completely.

#### 4. Laboratory experiment and results of measurement

The laboratory setup with DCM converter is described in detail in [2] while DC machine parameters are given in the appendix at the end of the paper.

The obtain result of the laboratory experiment and result of measurements are shown in this chapter. The main idea of this laboratory experiment is the realization and adjustment of parameters of the driver itself in order to achieve the shortest and most dynamic braking of the DC drive. During the braking characteristic motor values will be monitored, recorded and subsequently analysed with respect to parameter values set in chapter 3.3.

The laboratory experiment consists of three parts:

- Stopping the motor based on the set reference (deacceleration ramp),
- Braking motor using field reversal with the set deceleration ramp 2 seconds and
- Braking motor using field reversal with the set deceleration ramp 1 seconds.

The following drive quantities were recorded using the *Device trace* STARTER software option:

- Speed - actual value - r63 [1],
- Armature current actual value - r50019,
- Feld current controller actual value - r50035 and
- Active power actual value - r82 [0].








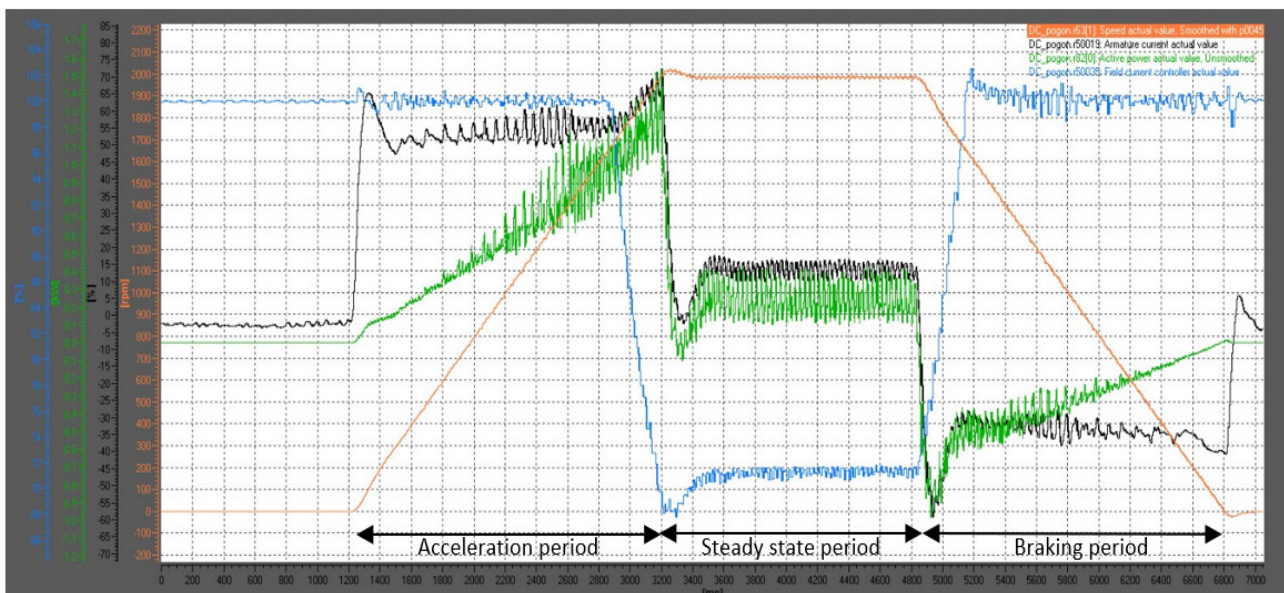
	Color
DC_pogon.r63[1]: Speed actual value, Smoothed with p0045	 ▼
DC_pogon.r50019: Armature current actual value	 ▼
DC_pogon.r82[0]: Active power actual value, Unsmoothed	 ▼
DC_pogon.r50035: Field current controller actual value	 ▼
DC_pogon.r53195: Field reversal contactor signals	 ▼
	 ▼
	 ▼

Figure 11. Recorded characteristic quantities

#### 4.1. Braking motor based on the set reference

Fig. 12. shows the motor operation at set speed reference value of approx. 2000 rpm at defined acceleration and deceleration ramps of 2 seconds. The motor operation frame consists of the acceleration period, the steady state period and the deacceleration period as it is shown in Fig. 12.



Since the motor rated speed value is 1540 rpm, during the acceleration to 2000 rpm motor enters field weakening regime at the end of acceleration period which is characterized by field current less

than nominal - about 70%), as can be noted in Fig. 12. The motor reaches the set speed (2000 rpm) in 2 sec with an overshoot of 40 rpm, and selling time of 0.2 sec with the help of integrated PI controller.

After reaching the reference motor is in a steady state regime characterized by lower active power consumption and lower armature current (which varies between 10 [%] and 15 [%] rated values) and is only responsible for covering friction and ventilation torque.

The active power released during the braking is negative, because SIEMENS DCM drive brakes with regenerative generator braking and returns energy directly to the grid. During the braking, the active power is highest at the beginning transient period and its intensity depends on braking dynamics i. e. deceleration ramp (0.8 kW for 2s ramp and 1.5 kW for 1s deceleration ramp). It can be noted that during the stationary period active motor power is only 0.25kW responsible for friction, ventilation and active power losses in the machine.

**4.2. Braking using field reversal with the set deceleration ramp of 2 s**

The results obtained during the realized field reversal braking with deacceleration ramp set to 2 sec are shown in the Fig. 13.

Fig. 13, as previous one, also show period of acceleration, steady state period and braking period. This time braking is realised through described field reversal procedure allowing us to track field current decreasing, change of field direction and braking dynamics with different intensities of armature current. The zoomed part of Fig. 13 during the braking is shown in Fig. 14.

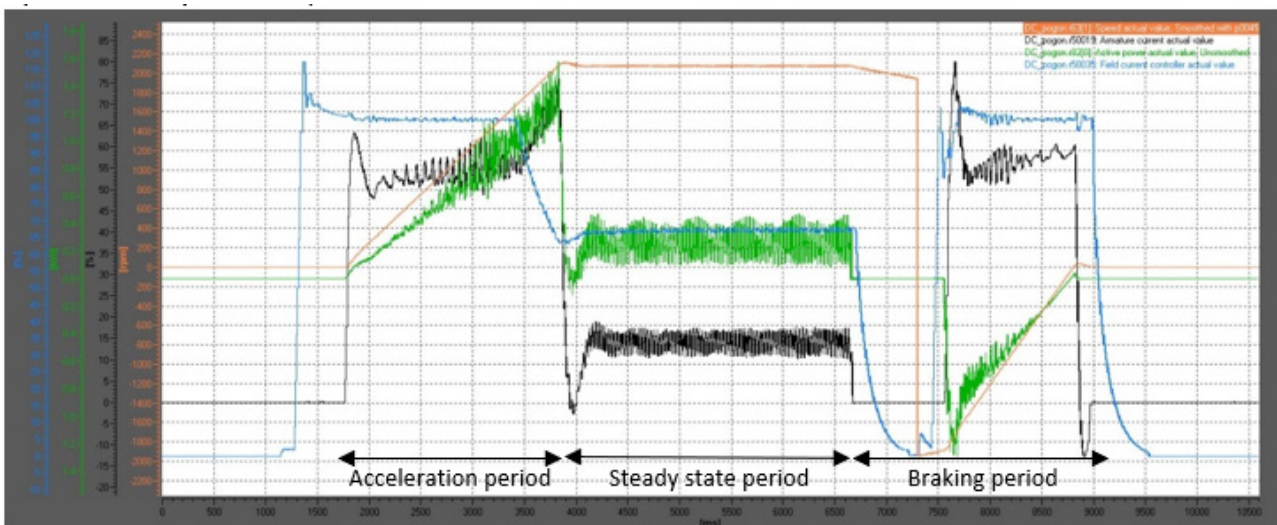
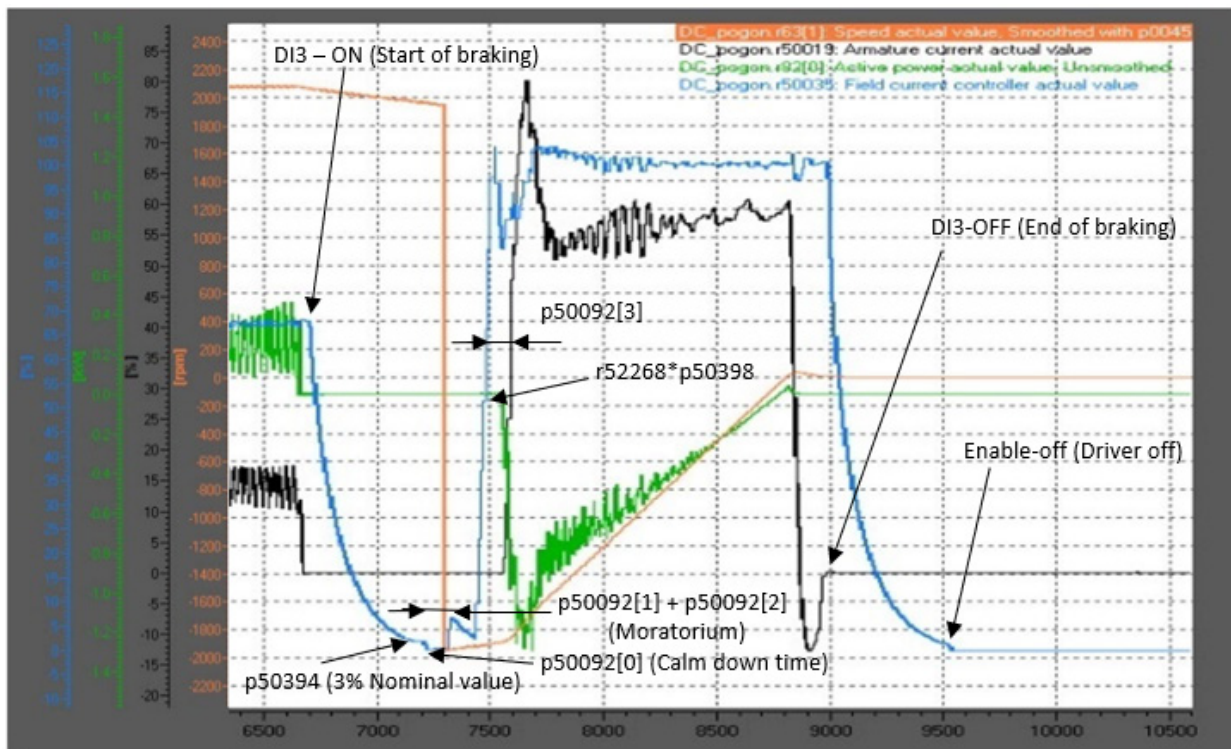


Figure 13. Braking period by field reversal with 2 seconds deceleration ramp





After a start braking command, at the 6.7 second, controller turns OFF armature current and begins to reduce the field current, at 7.2 second the condition is met that the field current is less than 3% of nominal value (p50394) and process of reversing polarity of field begins. The field contactor Kf is turn OFF after set time of 0.1 sec (p50092[0]). Then delay time of 0.1 sec (p50092[1]) starts at the end of which field contactor Kr (for the negative filed polarity) is turned ON. After another 0.1 sec (p50092[2]) the opposite direction of field current is lets through the field coil. Time delay of 0.1 sec necessary for filed current to establish its rated value and settle is defined by (p50092[3]) after which controller lets armature current back on. In a moment when armature current is back braking begins. It lasts 1.4 sec as can be seen in the *Device Trace* diagram shown in Fig. 14.

By defining different deacceleration ramp braking torque (armature current) get limited accordingly.

If shorter deacceleration time is defined armature current will be higher during the braking with maximal limit of rated armature current enabling high speed braking. This limitation of maximal armature current can also be modified in controller parameters but the users should be careful in setting higher values of maximal armature currents because it can jeopardise machine brushes and armature circuit.

Field reversal braking with the set deceleration ramp of 1.5 sec and 1 sec are shown in Fig. 15. and Fig. 16 respectively.

It can be noted that braking is obviously quicker with 1s acceleration ramp with higher armature current (saturated at 100% of nominal value) as expected. Also, the corresponding active braking power is higher with a higher braking current (inductor) and follows machine speed (EMF) dynamics as expected during the constant machine field.

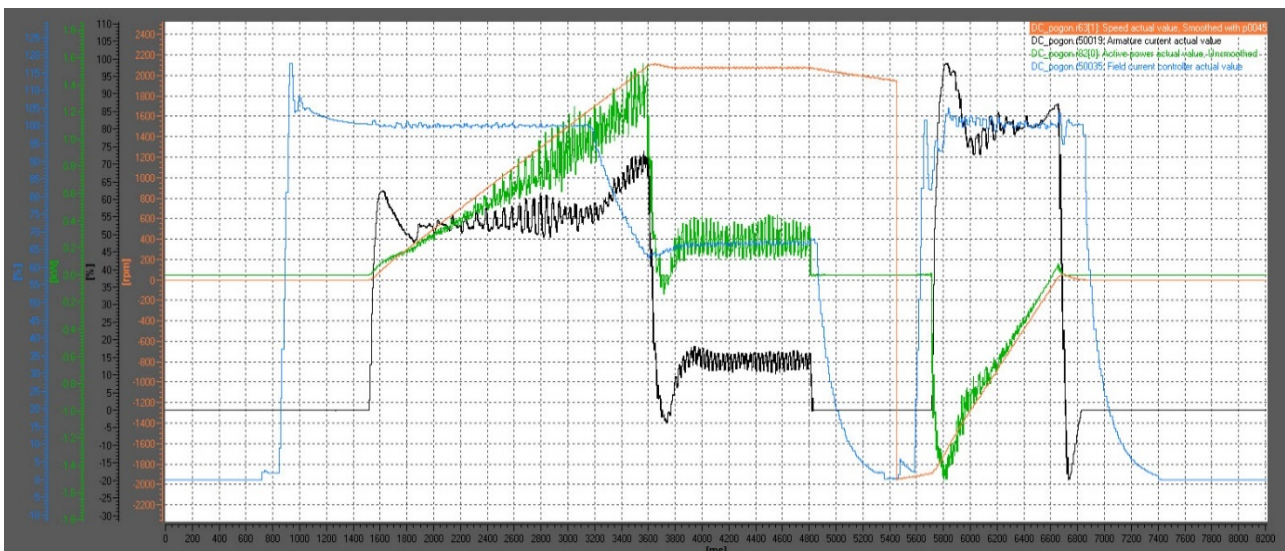


Figure 15. Braking period by field reversal with 1.5 seconds deacceleration ramp

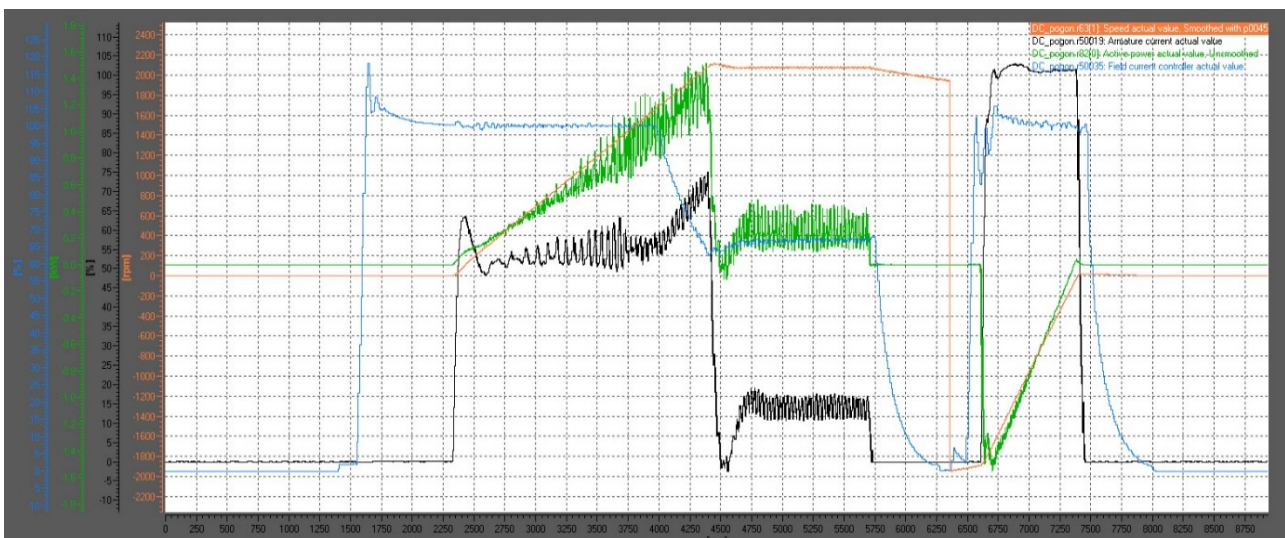


Figure 16. Braking period by field reversal with 1 seconds deacceleration ramp

## 5. CONCLUSION

This paper presents field reversal braking procedure of DC machine with Siemens DCM drive. Short theoretical background is given at the beginning after which hardware configuration of experimental setup and parametrisation of DCM drive is presented. A detailed description of field reversal procedure is shown with description of important parameters necessary to be defined in order to adequately realise field reversal braking. At the end experimental results with recorded characteristic motor quantities are presented followed by proper discussion of critical time frame during the machine braking. Influence of set parameters of DCM drive in braking dynamics is analysed as well.

This laboratory exercise gives students the necessary overview of modern drives parametrisation procedure and help them to understand the basic principles of control of the DC machine, and its dynamics during various operating regimes.

## ACKNOWLEDGEMENTS

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## APPENDIX

**Table 1.** DC machine SEVER ZIN.112N.S parameters

$I_{an}$ [A]	12	$n_n$ [rpm]	1540	$P_n$ [W]	1500
$U_{an}$ [V]	150	$R_a$ [ $\Omega$ ]	0.504	$L_a$ [H]	16.56
$U_{fn}$ [V]	200	$R_r$ [ $\Omega$ ]	276.1	$L_r$ [mH]	37.832

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