# Design of a Flux Weakening Control Scheme for DC Motor Drives Featuring Full Voltage Operation

S. Bolognani, *Member, IEEE,* A. Faggion, L. Sgarbossa, *Member, IEEE,*
Electric Drives Laboratory, Department of Electrical Engineering, University of Padova,
via Gradenigo 6/A, I-35131 Padova (ITALY), e–mail: edlab@die.unipd.it

*Abstract*— **This paper deals with an effective drive control scheme for separately excited DC motors. Distintive feature of the work is the modelling of the motor as a two-input single-output non linear system that allows the armature voltage to be maintained to the maximum full output voltage of the converter during flux weakening operation while the armature current is controlled by the excitation one. Experimental results confirm the expected drive performances that get advantages in sizing the power electronics.**

*Index Terms*— **Separately excited DC motors, Flux Weakening algorithm, DC motor control scheme.**

## I. Introduction

Even if AC motor drives using synchronous or induction motors had a continuous growth in the most of the drive applications, DC motor drives are still widely used in many industry processes such as rolling mills, paper machines, and unwinding and rewinding machines. Some reasons justify their use. A first reason is that they have been installed when the use of AC drives was not yet common practice; they are still satisfactory working, fed by low cost line-commuted AC/DC converters, that may have been subjected to a revamping intervention to modern mainly their control and communication features. A second reason may be the drive cost: DC motor cost is generally higher than induction motor cost, but related power electronic costs may counterbalance the cost difference with advantage of the DC solution in some cases. This justify the interest still alive of improving the DC motor drive performance, exploiting any new advances in signal processing and power electronic components.

In a separately excited DC (SeDC) motor drive system, linear control techniques are easily applied to the system represented by linear equations in the constant flux armature control region. However, system nonlinearities begin to appear once the motor is operated in the flux weakening region, [1], [2], [3]. The traditional way of circumventing such nonlinearities is by linearizing the system equations around an operating point and designing linear controllers based on the linearized system model.
Recent advances in nonlinear control systems, however, resulted in the development of more sophisticated controllers based on the feedback linearization techniques [4]- [8]. Regardless of being computing intensive in real-time control, the applicability of these techniques has been justified particularly in motion control. This factor explains the surge of research interest in nonlinear control applicable to motion control, especially where a high dynamic performance is required in the closed-loop control design of motor drives.
However such sophisticated controllers exhibit in some cases a rough control of the armature current with possible overcurrent occurrences. Limit operation of the power supplies is also sometimes managed in a non effective way requiring a voltage margin to be guaranteed for a good performance of the drive.
In addition feedback linearization techniques require often to be merged with load-adaptive strategies to reach the desired performance increasing still further the complexity of the control.

The task of this work is the torque control design of SeDC motor drives in the flux weakening mode, by an effective and simple new approach based on describing the motor dynamics by a two-input single-output non linear model. According to this approach, the torque control can be designed to allow full armature voltage operation under flux weakening region while the armature current is controlled by the excitation one.
The paper is organized as follows. Drive modelling is at first illustrated in Sect. II. The new flux weakening control scheme is then proposed in Sect III. Then simulation and experimental results are given and discussed in Sects. IV and V respectively. Some conclusive remarks end the paper.

## II. Drive Modelling

In a separately excited DC (SeDC) motor drive system, linear control techniques are easily applied to the system represented by linear equations in the armature control region. However, system nonlinearities begin to appear once the motor is operated in the flux weakening region due to the electromagnetic torque being a product of field flux and armature current, the back electromotive force (EMF) being a product of field flux and speed and due to magnetic saturation too. The well known block diagram of the motor is shown in Fig. 1, where the magnetizing characteristic is shown in graphical form.

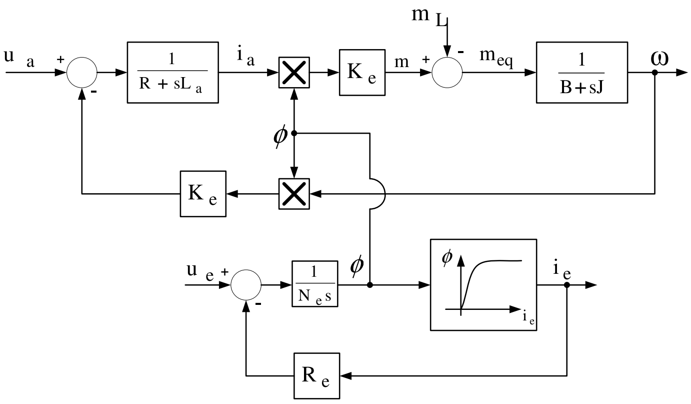


**Fig. 1:** Schematic of a Separately Excited DC Motor

For the field winding, the following voltage equation can be written

$$u_e = R_e \cdot i_e + \frac{d\lambda_e}{dt} \quad (1)$$

where the flux linkage is related to the pole flux $\Phi$ by

$$\lambda_e = N_e \cdot \Phi \quad (2)$$

with $N_e$ equal to the total field coils turns (properly increased to account for leakage flux).
On the other side, pole flux is defined by the excitation current amplitude by the magnetizing characteristic $\Phi = \Phi(i_e)$.

For the armature winding, the following voltage equation can be written

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \quad (3)$$

where the EMF voltage is given by $e_a = k_e \Phi \omega$.

At last the electromagnetic motor torque is

$$m_{em} = K_e \Phi i_a \quad (4)$$

which is part of the mechanical dynamic torque equation given by:

$$m = J \cdot \frac{d\omega}{dt} + m_L(t, \omega) = J \cdot \frac{d\omega}{dt} + B \cdot \omega + m_L(t) \quad (5)$$

with the second equality applying for linear mechanical loads.
As indicated above from (1), DC motors and drives generally contain nonlinear relations that are difficult to model.
In addition, in a number of cases, even when the available model is accurate, the exact system parameters are difficult to measure or estimate.

Modern nonlinear control techniques, in conjunction with improved power electronics and fast digital signal processing tools, can be used to overcome the nonlinearity of the system and to ensure that the system behaves in the desired manner.
A block diagram of the motor with a linearized field model is depicted in fig. 2, useful to outline the control algorithm and for simulation purposes.

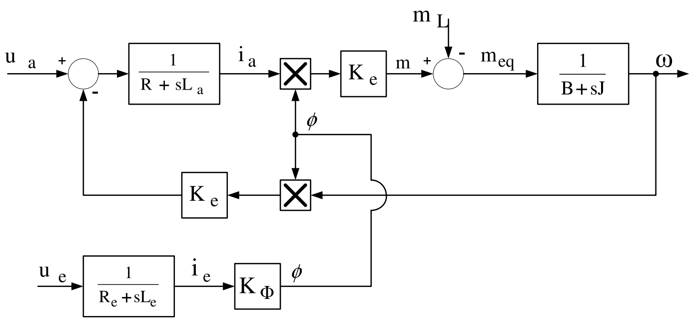


**Fig. 2:** DC Motor block diagram with linearized field model

Both the models point out that the motor can be assumed as a two–input, $u_a$ and $u_e$, single–output, $m$ or $i_a$, non linear system. This is the base assumption used in the proposed control as described hereafter.

## III. Flux Weakening Scheme Design and Control Task

The task is the torque control design of an SeDC motor drive in the flux weakening mode. The model can be considered as a two-input single-output non linear system that can be designed to allow full voltage (maximum power stage output voltage) operation of the motor under flux weakening mode. This is a distinctive feature that allows the power electronic sizing to be minimized for given motor shaft performance. On the contrary, in conventional SeDC motor drive a margin is fixed between the maximum output voltage of the converter and the nominal voltage of the motor to control the armature current, resulting in an oversized power stage.

Fig. 3 shows the proposed control scheme with the flux model obtained from the linearized model of Fig.

2. In the drive scheme of fig.3 the speed loop is also included, where a conventional PID solution is adopted.

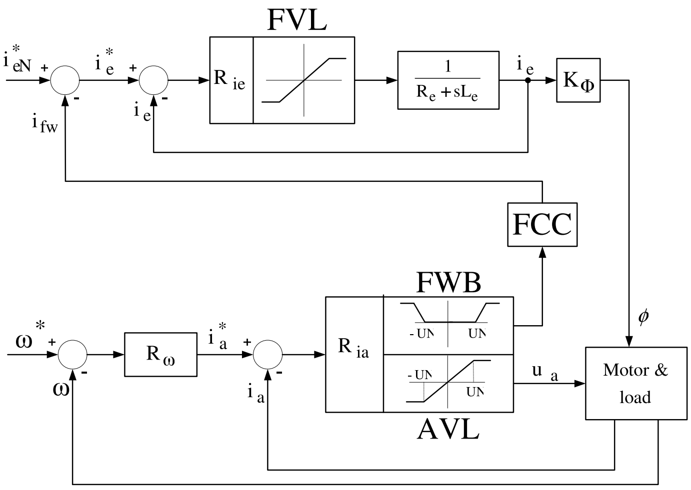


**Fig. 3:** SeDC Motor Drive Control Scheme

Inside the current regulator there is not a saturation but the Armature Voltage Limiter (AVL) which guarantees the voltage applied to the armature within its nominal value in any operating condition, where that nominal value is fixed equal to the maximum output voltage of the armature converter.

The excitation current is obtained by the Flux Weakening Block (FWB) and the Field Current Corrector (FCC) block. The first one limits the non-saturated armature voltage between $U_N$ and $2U_N$ (in absolute value) when the input is greater than $U_N$; otherwise, the output is null. The FCC instead is a dynamic block that improves the torque control stability under flux weakening operation and may compensates different time constants in the armature and excitation paths.

Below the base speed, the armature voltage is inside its limits, while the FWB is in the dead zone so that its output is null. Consequently, the excitation current reference is equal to the nominal value because $i_{fw}$ is null.

Above the base speed the AVL clamps the armature voltage at its maximum allowed value and the FWB operates in the linear zone. The FCC block provides $i_{fw}$ on the basis of the value of the non–saturated armature voltage. Then, the current reference $i_e^*$ (given by the difference between $i_{eN}^* - i_{fw}$) drops down the nominal value, weakening the flux of the machine.

## IV. SIMULATIONS

The scheme presented in Fig. 3 has been simulated in order to verify the reliability of the control techniques during the flux weakening control mode.

To this purpose, a step speed reference is imposed, with a final value of $1600rpm$, greater than the base speed. After that, when the speed has reached the final value, a step torque is imposed by the load.

The responses of the input signals $u_a(t)$ and $i_e(t)$ are reported in Fig. 4 and the output signals $\omega(t)$ and $i_a(t)$ are plotted in Fig. 5. All signals are normalized respect to their nominal values.

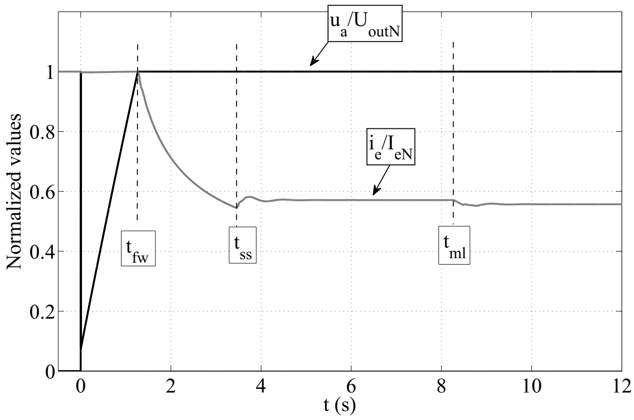


**Fig. 4:** Armature voltage and excitation current behaviour

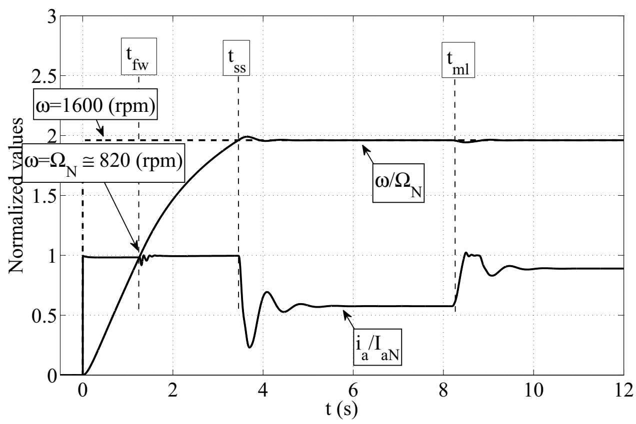


**Fig. 5:** Speed and Armature Current behaviour

One can realize that at the instant $t_{fw}$ the speed reaches its base value and, in fact, the armature voltage is saturated. Starting from this instant the control gets in the flux weakening mode and then the excitation current decreases inversely with the speed.

During the acceleration phase a maximum current is imposed by the control, both with full and weakened flux; it is possible to note also that during an armature voltage ramp, an armature current error is required and

then the maximum current isn't properly the nominal one.
At the instant $t_{ss}$ the reference speed value is reached and the armature current falls down at the value needed to overcome the friction load torque (inertia torque disappears).
At the final instant $t_{ml}$ a step load torque is simulated: the control operates even now in the flux weakening mode and then the armature voltage is still saturated.
The speed tends to decrease but the control brings it to the reference value increasing the armature current.To this aim, the $i_e$ decreases because a smallest EMF voltage is necessary to provide the $i_a$ increasing.
A proper control of armature current is than always attained.

## V. Experimental results

Some experimental tests have been done in order to confirm the simulations results presented in the previous Section.
A SeDC motor fed by a four quadrant chopper has been used. The mechanical load consists of a three-phase AC generator closed on a resistive load. The control is implemented on a dSpace 1102 Fast Control Prototyping board.
The test reported in the paper is a start-up of the drive from zero to a speed equal to 1600 rpm (as in the simulations) which is well above the base speed. Therefore flux weakening action occurs during the speed ramp. Fig. 6 shows the behaviour of the armature voltage during the flux weakening mode, as represented by the excitation current given by the grey curve. All the quantities are plotted in normalized value with respect to the nominal output voltage of the converter and to the nominal excitation current respectively. The normalized value of the armature voltage isn't clamped to one because the DC Bus voltage decreases when the motor starts up, due to the limited power of the DC supply. Instead the normalized value is calculated with respect to the nominal value of DC Bus voltage, appearing under no load conditions of the motor.
The worthy features of this algorithm can be realized by looking at the armature voltage in Fig. 6 (the black line): in steady–state the voltage is clamped to full output value of convert voltage, so this flux weakening method allows the motor to work with really full armature voltage.

In Fig. 7, correlated to Fig. 6, the behaviour of armature current and speed of the motor are depicted. In this figure is possible to see the step for the speed reference $\omega^* = 1600\ rpm$ as implemented in the simulations. Base speed resulted in 874 rpm.
As indicated above, when the step torque given by the load is applied ($t_{ml}$) there is a drop down of the bus voltage and this cause the decrease of the excitation current to limit the motor terminal voltage to the maximum dynamic convert output voltage.
Experimental results confirm the good overall performance of the drive, which is able to exploit fully the armature converter ratings.

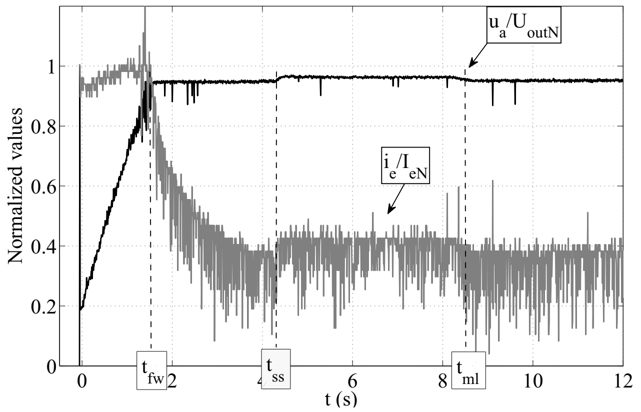


**Fig. 6:** Test bench measurements: Armature Voltage and Excitation Current

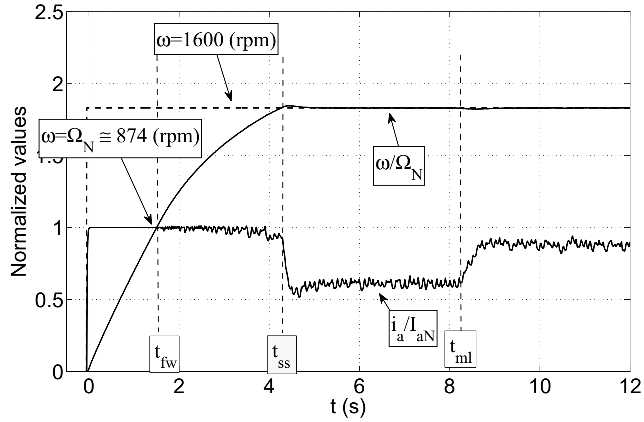


**Fig. 7:** Test bench measurements: Motor Speed and Armature current

## VI. Conclusions

The paper has proposed and experimentally tested an enhanced control scheme for separately excited DC motors that exploits the maximum full voltage of the armature converter in the flux weakening region of operation, nevertheless providing an effective armature current control by the excitation current. Therefore, minimum power sizing of the drive converters is allowed.

## Acknowledgements

Authors would like to thank Mr. Mosè Castiello for the technical support under the experimental tests.


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