SCALAR CONTROL OF THE BRUSHLESS DOUBLY-FED INDUCTION MACHINE

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***Abstract* – This paper presents the main characteristics of the brushless doubly-fed machine. Its principle of operation is described. A scalar speed control scheme is presented, which is validated with laboratory results.**

KEYWORDS

Doubly-fed induction machine, speed control, scalar control.

I. INTRODUCTION

The development of power electronics providing more reliable and cheaper power converter units, along with the necessity for energy conservation, has promoted an increase in the use of adjustable speed drives and variable speed generators. However, more widespread use of such systems has been hampered by the cost of the power converter which is still high. Therefore there is a great interest in a system which reduces the converter rating requirements.

A system with this characteristic has been presented by Wallace, Spée and Lauw [1] and has been titled `brushless doubly-fed machine (BDFM)'. The machine is part of a system which is represented schematically in figure 1. It is claimed that the BDFM system will provide the following features and advantages:

- reduced cost, compared to a conventional drive using a cage induction motor;
- precise synchronous operation over a wide speed range;
- possibility of working as a normal induction motor in case of power converter failure.

The aim of this paper is twofold. First the main features of the BDFM system are presented. Then a scalar speed control scheme is presented, which is validated with laboratory results.

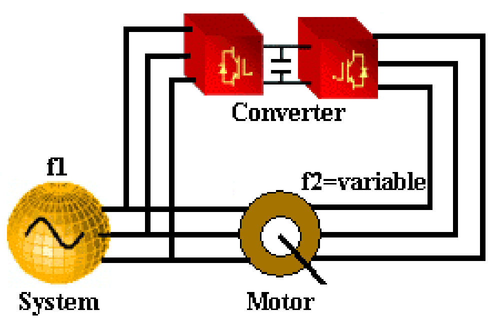


Fig. 1 Brushless Doubly Fed Machine System

II. BRUSHLESS DOUBLY FED MACHINE

The machine evolved from the self-cascaded machine proposed by Hunt [2]. Hunt presented a self-cascaded machine, which incorporated the effect of two cascaded induction motors into one single frame. He showed that this could be accomplished by furnishing the stator with two three-phase windings of differing pole numbers, chosen so that no transformer coupling between them would occur. Being 2p1 and 2p2 the pole-numbers of the stator windings, the self-cascaded machine would be able to operate as an induction motor with (p1 + p2) poles. This required the rotor to be of a special design. Hunt also showed that better performance could be achieved by using only one stator winding with terminals for operation as a 2p1- and 2p2-pole winding. He also presented how a single rotor winding could be used to couple with both stator fields.

Hunt's machine was later re-examined by Creedy [3] who presented an elegant 2/6 poles stator winding system. This winding configuration was used in several self-cascaded machines and in early BDFMs. Creedy also presented a simplified rotor winding.

Undeniably, a significant step was taken by Broadway and Burbridge [4] when they identified that cross-coupling of the stator fields would occur with a cage rotor with Nr bars where Nr = p1+p2. That would render a more robust and manufacturable rotor.

The brushless doubly-fed machine system, as presented in figure 1 was proposed by Lauw [5] for use as a variable speed generator. Shortly after, Wallace, Spée and Lauw presented the BDFM as a candidate for an adjustable speed drive [1,6]. The stator is furnished with two three-phase windings of different pole numbers, 2p1 and 2p2. As both windings share the same magnetic circuit, special care has to be taken when choosing the number of poles of each winding in order to avoid direct (transformer) coupling between them. The cylindrical rotor carries (p1 + p2) sets of concentric loops, as will be discussed below. Generally, one stator winding is connected directly to the supply and the other is supplied from a power electronic converter. Full use of the machine's capabilities is achieved if a bi-directional, variable-frequency, variable-voltage converter is used. However, for some applications the requirements for the converter may be simplified. The key feature for the BDFM operation is the coupling between both stator windings via the rotor. This imposes certain restraints on the rotor design and that is investigated below.

A. Principle of operation

The torque production in cylindrical rotating electrical machines requires the fields produced by the stator and rotor to have the same number of poles and to be stationary with respect to each other. These requirements can be used to control the speed of the machine. Generally, if the rotor currents produce a field which rotates at angular velocity f' with respect to itself, that field will be seen by an observer stationary with respect to the stator as having an angular velocity f, in revolutions/second, given by f = fr + f', where fr is the rotor angular velocity. In order to produce steady torque, f must equal the angular velocity of the stator field fs.

Therefore, if the frequency of the rotor current can be controlled by external means, so can the rotor speed. This speed is referred to as the synchronous speed and the machine is said to be operating synchronously. If a power electronics converter is used, this arrangement has the advantage in that only the slip power must be processed by the converter, thus reducing the cost of the system. It has however the disadvantage in that it requires the use of slip rings, which increase the cost and reduce the robustness and reliability of the system. The possibility of controlling the frequency of the rotor currents without the need of slip rings is quite attractive and that is the idea behind the brushless doubly fed machine.

It has already been pointed out that some restrictions are imposed on the rotor in order to obtain synchronous operation. These restrictions may now be identified [7]. Assume, in the first instance that the rotor carries a standard cage design, with Nr bars, equally spaced. The two stator windings are assumed to be ideal (i.e. no stator space mmf harmonics) and carry pure sinusoidal currents. These windings will set up airgap fields, which can be expressed in the stator reference frame by

$$b_1(\theta,t) = \hat{B}_1 cos\left(\omega_1 t - p_1\theta + \alpha_1\right) \quad \text{, and} \qquad (1)$$

$$b_2(\theta,t) = \hat{B}_2 cos\left(\omega_2 t - p_2\theta + \alpha_2\right) \qquad (2)$$

where, ω_1 and ω_2 are the excitation angular velocities (rad/s) of winding 1 and 2 respectively. α_1 and α_2 are phase angles. B_1 and B_2 are the peak values of the magnetic flux densities. b1(θ,t) and b2(θ,t) are the instantaneous values of the magnetic flux densities at an instant of time t and at a position θ around the airgap. The fields described by (1) and (2) will induce currents in the rotor bars and these currents will in turn produce airgap fields, which can be expressed in the rotor reference frame by

$$b_1{}^{p_1 - q_1 N_r}(\theta',t) = \hat{B}_{r1} cos\left((\omega_1 - p_1\omega_r)t - (p_1 - q_1 N_r)\theta' + \alpha_{q1}\right) \quad (3)$$

and

$$b_2{}^{p_2 - q_2 N_r}(\theta',t) = \hat{B}_{r2} cos\left((\omega_2 - p_2\omega_r)t - (p_2 - q_2 N_r)\theta' + \alpha_{q2}\right) \quad (4)$$

where ω_r is the rotor angular velocity (rad/s) and α_{q1} and α_{q2} are phase angles. q1 and q2 are integers. θ′ is measured with respect to a reference frame, which is fixed to the rotor. Values of q1 and q2 other than zero are the rotor slot harmonics. Equation (3) shows that the current induced in the rotor by an airgap field of 2p1 poles will produce not only a flux of 2p1 poles but also fluxes of 2(p1 - Nr), 2(p1 + Nr), 2(p1 - 2Nr), 2(p1 + 2Nr) poles, etc. The second stator excitation similarly results in rotor slot-harmonic fields of 2(p2 - Nr), 2(p2 + Nr), 2(p2 - 2Nr), 2(p2 + 2Nr)… poles.
The rotor fields given by (3) and (4) can be expressed in the stator reference frame, using the co-ordinate transformation $\theta = \omega_r t + \theta'$.
Steady torque will be produced if one of the slot-harmonic fields, arising from the second stator excitation (i.e. $q2 \neq 0$), interacts with the fundamental field produced by the first (q1 = 0). Equating frequencies and pole numbers, as required, yields

$$\omega_2 - q_2 N_r \omega_r = \omega_1 \quad \rightarrow \quad \omega_r = \frac{\omega_1 - \omega_2}{-q_2 N_r} \qquad (5)$$

and

$$p_2 - q_2 N_r = p_1 \quad \rightarrow \quad -q_2 N_r = p_1 - p_2 \qquad (6)$$

Substituting from (6) into (5) yields

$$\omega_r = \frac{\omega_1 - \omega_2}{p_1 - p_2} \quad \rightarrow \quad f_r = \frac{f_1 - f_2}{p_1 - p_2} \qquad (7)$$

The same analysis may be carried out on the assumption that a slot-harmonic field produced by the first excitation interacts with the fundamental field due to the second, and will give the same result as in (7). For practical values of p1 and p2, values of q1 and q2 other than unity will produce a rotor cage with a very small number of bars. Therefore (6) may be rewritten as $|p1 - p2| = N_r$, which gives the requirements for the number of rotor bars in order to have the BDFM operating synchronously. Equation (7) gives the associated synchronous speed and suggests that changing one of the stator frequencies can control the rotor speed.

Another condition for the synchronous operation arises if it is noted that (4) may also be written as using cosθ=cos-θ. Equating the frequency and displacement terms and carrying out the same analysis as before, yields a new set of rotor requirements and synchronous speed. Therefore, for a given pair of stator frequencies there are two rotor configurations that allow for the machine to run synchronously.

Condition 1

$$N_r = \left|p_1 - p_2\right| \quad and \quad \omega_r = \frac{\omega_1 - \omega_2}{p_1 - p_2} \qquad (8)$$

Condition 2

$$N_r = \left|p_1 + p_2\right| \quad and \quad \omega_r = \frac{\omega_1 + \omega_2}{p_1 + p_2} \qquad (9)$$

For practical values of p_1 and p_2 it is more convenient to choose Nr as given by Condition 2 because it results in a cage with higher number of bars. Therefore the rotor speed for synchronous operation can be calculated by

$$\omega_r = \frac{\omega_1 \pm \omega_2}{N_r} \quad (10)$$

The positive sign arises when both stator fields rotate in the same direction in the stator reference frame. On the other hand, the negative sign arises when they rotate in opposite directions. It may be noted that if winding 2 is excited with direct current (f_2=0), (10) gives the synchronous speed of the cascade connection of two induction motors. However, the main purpose of the BDFM is to change the synchronous speed by varying the frequency f_2. Therefore in this work the term synchronous speed refers to the rotor speed which is given by (10). The speed obtained when f2=0 is referred to as the natural speed [8]. Then, if the stator fields rotate in the same direction with respect to the stator, the machine will operate above the natural speed and if the fields counter-rotate the machine will operate below the natural speed. The same analysis can be carried out for the case where the number of rotor bars is calculated from the difference of the number of poles.

B. Rotor configurations

Whatever the way N_r is chosen, for any realistic combination of pole-pair numbers p_1 and p_2 it will result in a cage rotor with a low number of bars, yielding a very high referred rotor leakage reactance [4]. As pointed out by Broadway, the referred rotor leakage reactance decreases as the number of rotor slots is increased from a low value. Therefore steps must be taken in order to increase the number of rotor slots while still complying with the requirements of the effective number of rotor bars. Fig. 2, Fig. 3 and Fig. 4 present three typical BDFM rotor configurations in which this is achieved. In Fig. 2 the rotor bars are connected to produce a set of nests, each formed of a number of individual concentric loops. In Fig. 3 all the loops are connected at one end to a common end-ring. In Fig. 4 the outermost loops of each nest form a cage with N_r bars. The other loops are connected to one common end-ring.

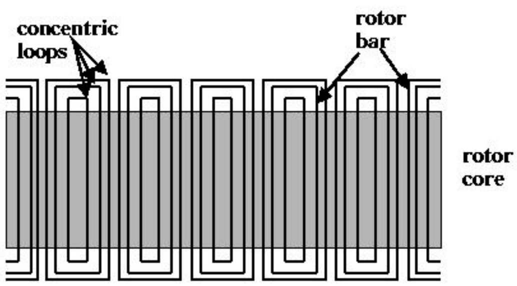


Fig. 2. BDFM rotor configuration 1

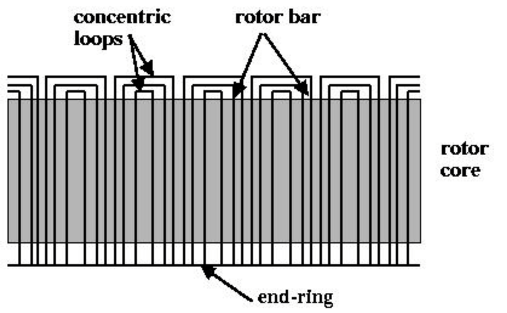


Fig. 3. BDFM rotor configuration 2

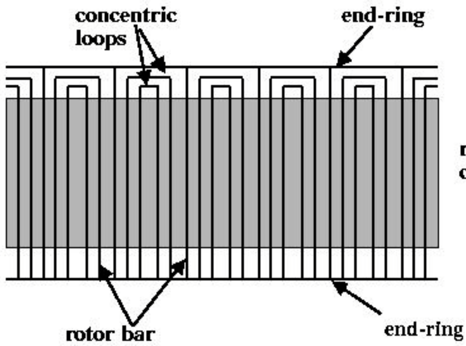


Fig. 4. BDFM rotor configuration 3

III. BDFM CHARACTERISTICS

This section will present some of the BDFM characteristics when operating at synchronous speed. In this analysis, the winding connected directly to the supply is referred to as power winding or winding 1, and the winding fed from a converter is referred to as control winding or winding 2. The simulations were carried out with a steady-state model developed previously [7,9].

A. Power balance

The division of power between the stator windings is related to the frequency at which they are excited. Neglecting all the copper losses we may write:

$$\left|\frac{P_1}{\omega_1}\right| = \left|\frac{P_2}{\omega_2}\right| = 3\,\frac{V_1 V_2}{L\,\omega_1\,\omega_2}\sin\delta \quad (11)$$

where P_1 and P_2 are the power flowing in windings 1 and 2, V_1 and V_2 are the rms voltages applied to the windings, ω_1 and ω_2 are the angular frequency of the voltages, L is an inductive term and δ is a load angle. Although the relationship presented in (11) is modified when copper losses are taken into account, the general concept that the winding that is supplied at higher frequency carries more power still holds. This can be seen in Fig.5 and Fig. 6, where winding 1 is supplied at 50 Hz and winding 2 at 30 Hz. Those figures suggest that if winding 2 is supplied at low frequencies (e.g. 0 – 5 Hz), the converter may be rated for a fraction of the total system rating.

B. Effect of converter on performance limits

It was shown in the previous section that for operation in a limited speed range, the converter used in the DFM system might have a reduced rating compared to the overall system rating. Also of interest is the effect of the converter on the drive performance. A first insight into this effect may be get from Fig. 7, which shows plots of calculated maximum torque as a function of speed and maximum voltage in winding 2. The stator currents were limited to 20 A due to thermal considerations and winding 1 was supplied at 100 V. Fig. 7 shows that the machine has almost the same torque capability operating either as a motor or as a generator. It can also be seen that the major effect of limiting the voltage of winding 2 is to determine the range of operating speeds. However it does not affect the maximum torque available. Fig. 7 also shows symmetry about a line drawn through the speed of 500 rpm. That speed may be recognized as the natural speed of the machine, where winding 2 is supplied with DC current. Fig. 7 also shows the effect of imposing a stricter limit on the current in winding 2. Namely the maximum current allowed was reduced from 20 A to 10 A, and the figure shows a reduction on the maximum torque.

C. Power flow in the control winding

The operation over the full operating limits of Fig. 7 would require the use of a bi-directional converter. A further step in order to reduce the cost of the BDFM system may be taken if an unidirectional converter could be used. It can be shown that, to a good approximation, the direction of power flow in the control winding depends on the quadrant in which the drive is operating, i.e. above/below the natural speed and generating/motoring. This implication can be better illustrated in Fig. 8, which depicts one of the torque-speed characteristics presented in Fig. 7. In this case V1=V2max=100V and I1max =I2max=20A. The (+) and (-) signs indicate the direction of power flow in the converter, where the plus sign indicates that power is flowing into the BDFM and the minus sign indicates that power is being extracted from the machine to the system as in a slip-energy recovery mode.

D. Power factor control

The BDFM was developed from the concepts used in induction motor design. However, when operating synchronously, it behaves like a synchronous machine. In this sense, Fig. 5 and Fig. 6 indicates that the input power to each stator winding has a closely linear relationship to the load applied to shaft. Furthermore, a load-angle characteristic is suggested in (11). If the parallel between the BDFM and a synchronous machine is to be completely established, the machine should provide means of power factor control. This can be seen in Fig 9 which shows how the reactive power in winding 1 is affected by a variation of the voltage applied to winding 2. In this case the machine is running with no mechanical load connected to its shaft. It is easy to relate the curves presented in Fig. 9 to the V-curves of synchronous machines. The voltage in winding 2 acts as the field winding in a synchronous machine.

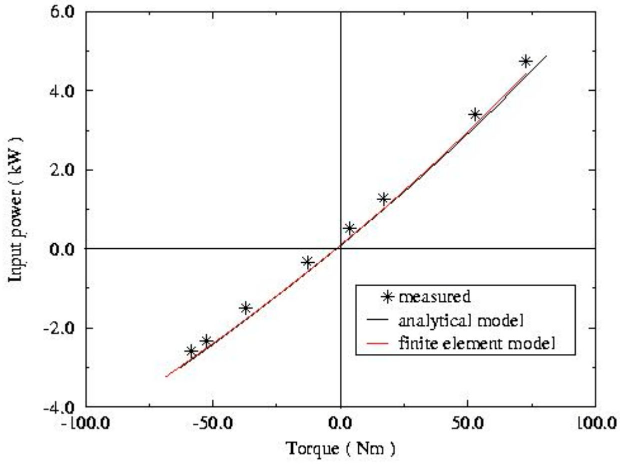


Fig. 5. Winding 1 input power

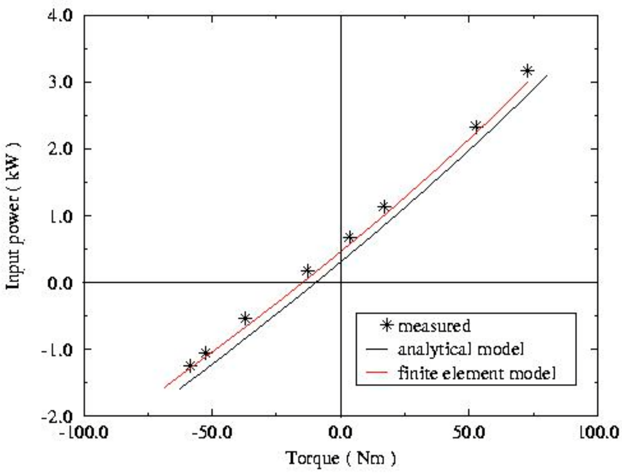


Fig. 6. Winding 2 input power

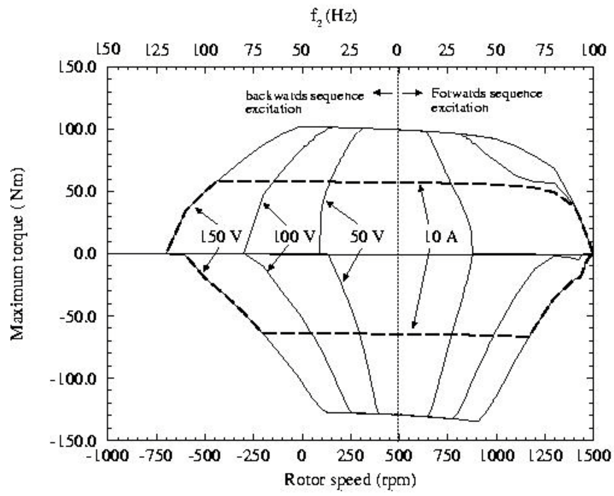


Fig. 7. Maximum torque/rotor speed limits

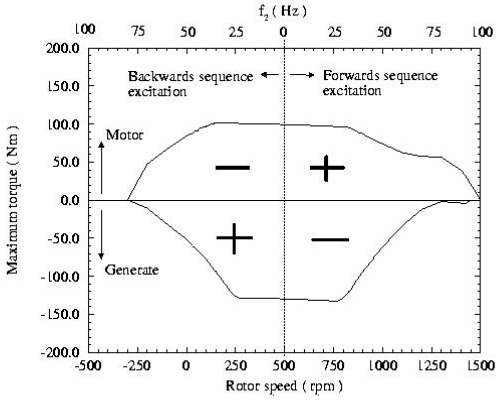


Fig 8. Operating quadrants for the BDFM related to power flow in the converter

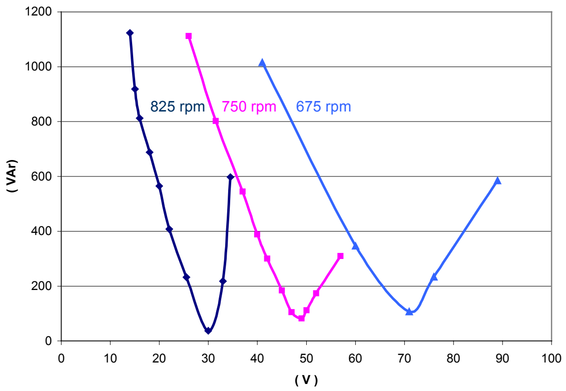


Fig. 9 Reactive power in winding 1 as function of the voltage in winding 2.

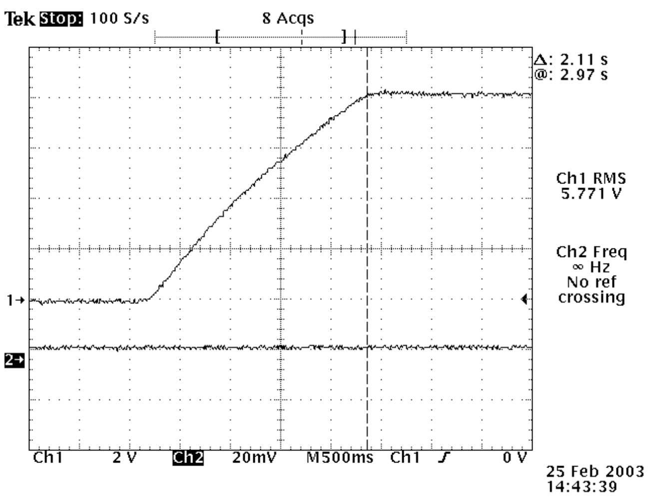
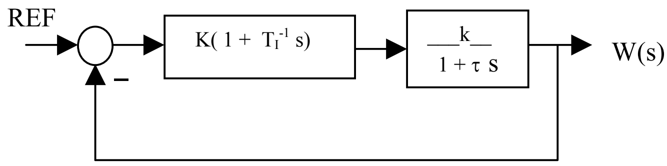


Fig 10. Speed response to a step in the control voltage

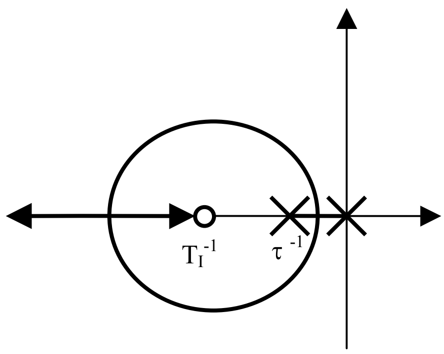
IV. SCALAR SPEED CONTROL

The dynamic behaviour between speed and control voltage was obtained in the laboratory with the step response shown in Fig. 10. It can be given by a first order system with time constant $\tau = 500$ms.

A speed control with adjustable step response and zero speed error can be achieved with a PI controller as suggested in Figs.11(a) and (b).



(a)



(b)

Fig 11 (a) Speed control closed loop. (b) Root Locus

For the laboratory prototype, a speed controller with parameters K=10 and $T_I = 500$ ms was implemented. An anti-reset windup strategy was also considered. The step response for a speed increase can be observed in Fig. 12. The overshoot, if not desirable, can be adjusted changing the controller parameters or introducing a pre-filter in the speed control loop. For a speed decrease, the response can be seen in Fig. 13. As the converter used to supply the control winding do not have regenerative behaviour, the speed decay is just due to mechanical friction. A regenerative converter, with operation in all quadrants of the speed x torque plane, is necessary to achieve identical response time in both directions.

Also the commercial converter used in this application maintains the ratio voltage/frequency constant. Improvements could be achieved changing just the supply frequency of the control winding with the same control voltage.

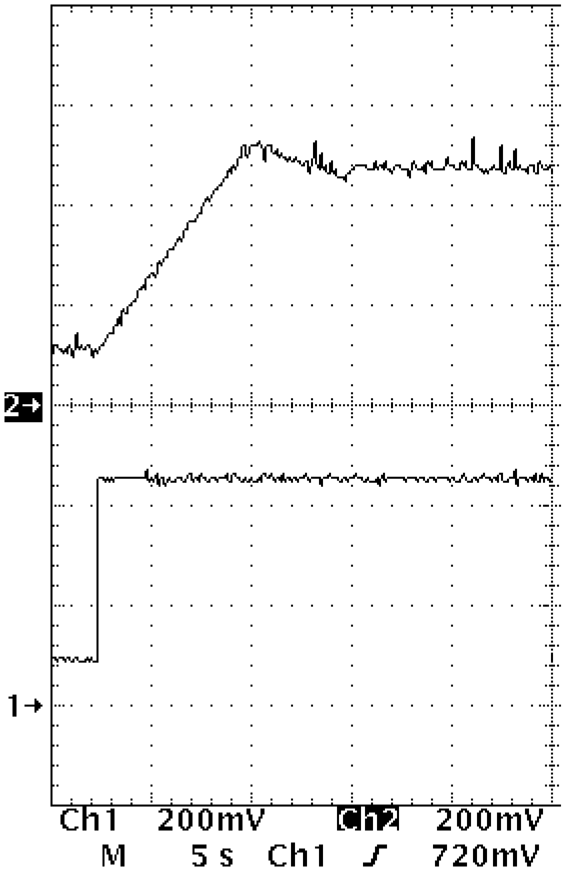


Fig. 12 Speed step increase

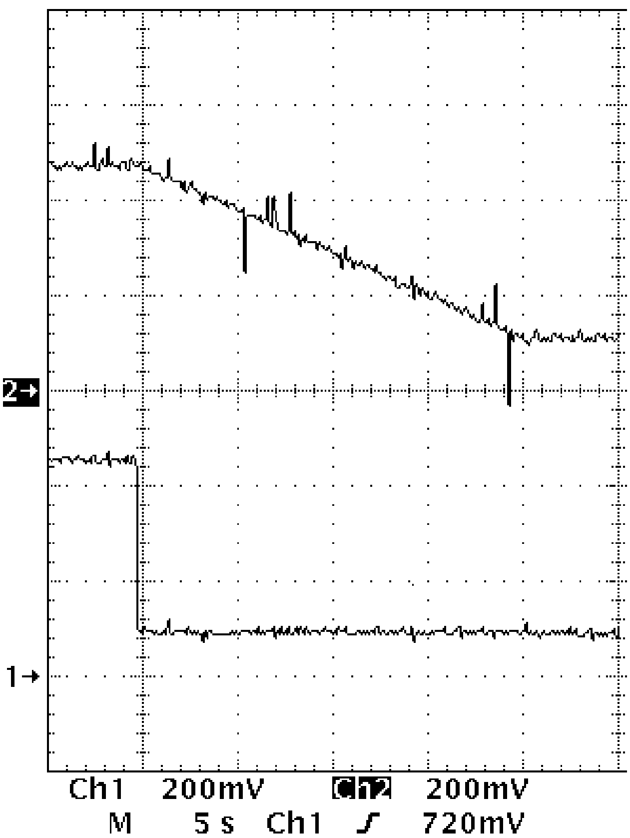


Fig. 13 Speed step decrease.

V CONCLUSIONS

The paper has presented the main characteristics of a system using a brushless doubly fed machine and a scalar speed control scheme. The next step will be the use of a regenerative converter, with independent voltage and frequency adjustments, to supply the control winding.

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