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SIMULATION OF THE DINAMICS OF AN ECCENTRIC POWER PRESSER DRIVEN BY AN INDUCTION MOTOR USING DIRECT TORQUE CONTROL

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Abstract: *This paper proposes the improvement of the dynamic performance of the eccentric power presser by controlling the driving motor using the DTC (Direct Torque Control) method. For this purpose, the presser operation was simulated in different situations, and the advantages of using this control scheme were punctuated.*

The models of the power presser, induction motor and DTC were realised in Matlab-Simulink.

The simulation results, related to both the motor without control and the motor controlled using DTC are comparatively presented, and are followed by comments and observations.

1. INTRODUCTION

The eccentric power pressers constitute in present days an important group of machine tools for metal plastic cold working, due to their technological capability, simple construction and good rated capacity.

This machine are driven by a three-phase induction motor which is directly network-driven.

This construction has the disadvantage that it is not possible to obtain more working speeds, in order to satisfy diverse technological requirements – given by the type of the operation and the properties of the half – finished material. If more working speeds could be obtained, the same presser could be utilized for a larger range of technological operations.

2. THE DINAMIC MODEL OF THE ECCENTRIC POWER PRESSER

This power presser is of non-geared type. It has a flywheel which rotates directly the main shaft and which is driven by the electric motor using a belt transmission.

The large values of deformatin force, which varies during the processing cycle, explain the presence of the flywheel. The flywheel has an important contribution to the deformation energy and it maintains the uniformity of the movement, leading to the reduction of the dynamic loading – which otherwise could affect the working piece. A part of the kinetic energy stored by the flywheel is absorbed by the deformation process in the active portion of the work cycle. In the remaining portion the motor tends to re-establish the operating speed for the next cycle.

The power presser model is based on the calculus of the crank turning moment M_t produced by the deformation force at the presser shaft [1]:

$$M_t = F_d \cdot R \cdot \left(\sin\alpha + \cos\alpha \frac{R}{L} \cdot \frac{\sin\alpha}{\sqrt{1 - \left(\frac{R}{L}\right)^2 \sin^2\alpha}} \right) \tag{1}$$

where:

R - is the radius of the crank circle;

F_d - is the deformation force, on the direction of translation;

$\alpha = \pi - u\_c$

u_c - is the flywheel current angle $u\_c = 0^o$, at the upper position of the ram

$u\_c = 180^o$ at the lower position.

L - is the length of the connecting-rod;

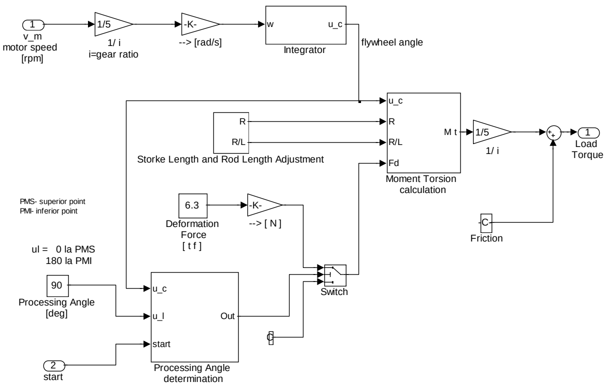


Fig. 1. The dynamic model of the power presser

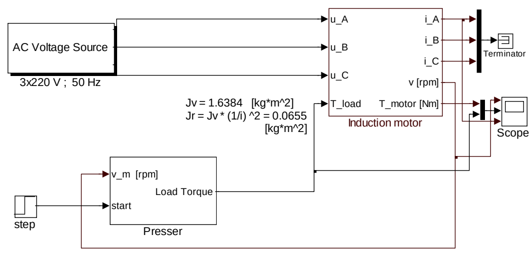


Fig. 2. The model of the system comprising the power supply, the power presser and the induction motor

In figure 1 is presented the dynamic model of an eccentric power presser. The input of the system is the angular speed of the motor shaft (v_m), and the output is the crank turning moment, referred to the motor shaft.

The current angle of the flywheel is obtained by integrating the angular speed of the motor shaft, allowing for the gear-ratio. The following parameters can be adjusted: the ram course, which is equal to 2R, the length of the connecting-rod L and the work angle u_l [1].

The deformation force, F_d, is applied between the position corresponding to the work angle (u_l) and the lower position, corresponding to the angle of 180^o.

The load moment at the motor shaft is calculated by dividing the torsion moment M_t by the gear-ratio "*i*":

$$M_r = \frac{M_t}{i} \qquad i = \frac{\Omega_{motor}}{\Omega_{flywheel}}$$

The effective moment of inertia at the motor shaft is given by the expression [7]:

$$J_e = J_m + \left(\frac{\Omega_{motor}}{\Omega_{flywheel}} \right)^2 J_v$$

where:

J_m = the moment of inertia of motor

J_v = the moment of inertia of the flywheel, obtained from instruction book.

J_e is one of the parameters of the induction motor model.

3. WHY DIRECT TORQUE CONTROL?

The goal of the proposed numerical electric drive is both the possibility of an adjustable work speed, and the ability to apply a certain speed profile along the fast duty cycle. Therefore it is necessary to use a control scheme which can provide a fast torque response and the availability of the peak torque even at low speed.

These requirements can be satisfied by using Flux Oriented Control schemes (FOC) or Direct Torque Control schemes (DTC).

DTC was preferred for this application due to some of its advantages comparing with the FOC [2]:

- the control scheme is simpler – there is no need for voltage decoupling circuits (required in voltage-source vector drives), coordinate transformations or separate voltage modulation block; only the sector where the flux-linkage space vector is located, and not the actual flux-linkage space vector position has to be determined;
- less computation burden;
- it is easier to implement a sensorless control.

The most important disadvantage of a conventional DTC – the high torque ripple, does not affect the performance of the drive, due to the large flywheel moment of inertia.

In figure 3 is presented the model of the drive system, cosisting of the induction motor, supplied by the Voltage Source Inverter (VSI), which receives the control signals from the DTC block.

The DTC scheme is shown in figure 4. In principle, the DTC method selects one of the inverter's six voltage space vectors in order to keep the stator flux and torque within a histeresis-band around the demanded flux and torque magnitudes. If the stator ohmic drops is neglected then $\underline{u}_s = \frac{d\underline{\psi}_s}{dt}$. It follows from this equation that in a short Δt time, when the voltage space-phasor is applied, $\Delta\underline{\psi}_s = \underline{u}_s \Delta t$. Thus the stator flux-linkage space phasor moves by $\Delta\underline{\psi}_s$ in the direction of the stator voltage space phasor.

In the control model – figure 4 – the actual flux and torque magnitudes are estimated using the machine terminal voltages and currents. The stator flux-linkage components are obtained from the stator voltage equations in the stator reference frame. The DTC needs only the actual sector of 60^o in which the stator flux space phasor is located – the trigonometrical circle is divided in 6 equal sectors corresponding to the 6 voltage space-phasors which are available at the terminals of the VSI.

The reference values of the flux and torque magnitudes are compared to their corresponding estimated values using the hysteresis comparators [2]. Depending on the outputs of this comparators and the sector in which the flux space-phasor is located, the proper voltage space-phasor is selected, in the inverter switching table.

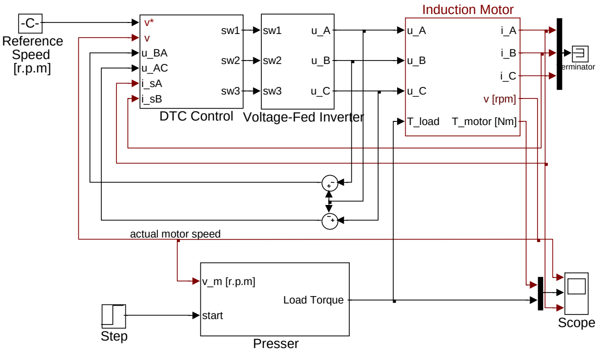


Fig. 3. The model of the system the power presser, the induction motor, the VSI and DTC scheme.

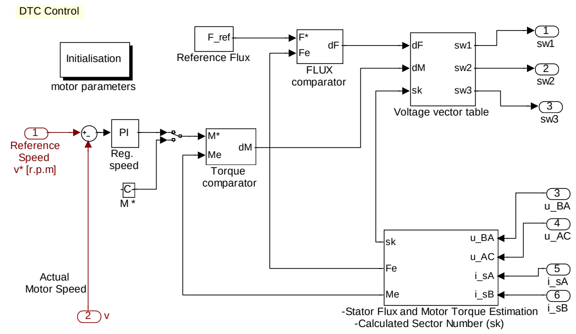


Fig. 4. The DTC model

4. THE RESULTS OF THE SIMULATIONS FOR DIFFERENT POSSIBLE WORKING SITUATIONS OF THE POWER PRESSER

For the modeling it was used the power eccentric presser PAI 6,3, driven by an induction motor with rated power Pn=750 W, two pole pairs and rated torque M_n=5.15 Nm.

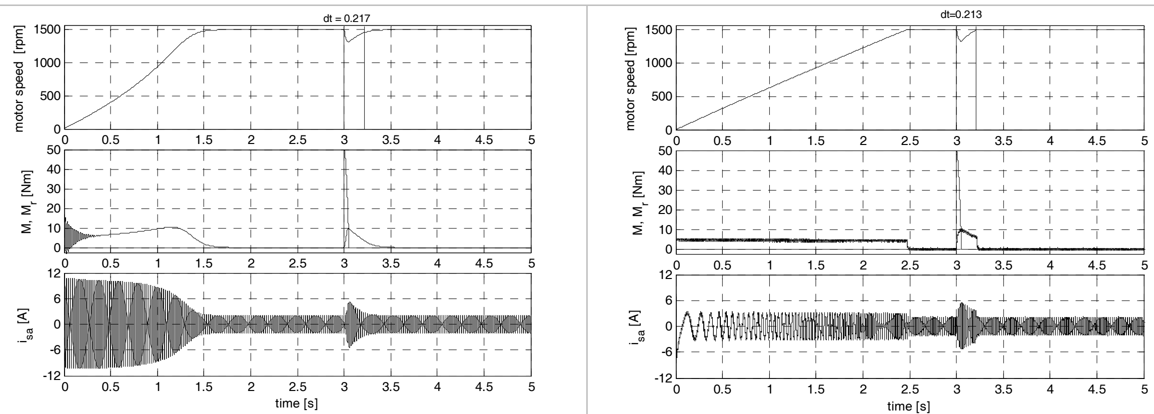
In every diagram the following presser working parameters are specified:

- deformation force Fd (the maximum allowed value is Fd_{max}=6.3 tf);
- current angle u_l, wich is the flywheel angle corresponding to the beginning of the deformation;
- ram course, equal to the diameter of the crank circle; the presser has 4 steps to which the ram course can be adjusted: ram_course = 8; 21; 35; 48 mm.

The evolutions of the following quantities are plotted: the motor speed [rpm]; the motor torque M, and load torque Mr [Nm]; stator current in phase “a”, i_sa [A].

The first case considerred is the starting of the machine – figure 5. The presser parameters are: deformation force Fd=6,3 tf; work angle u_l=90°; ram_course =8 mm. The high value of the flywheel moment of inertia enlarge the period of this transient regime, which is characterised by high currents. The overburden of the motor can be easily avoided in the case of controlled motor because it is possible to limit the electromagnetic torque and implicitely the current. The torque limitting is applied only for the starting period and then it is cancelled.

The period “dt”, which corresponds to a complete turn of the flywheel, starting with the stroke moment, is marked down for every cycle on the speed plots.



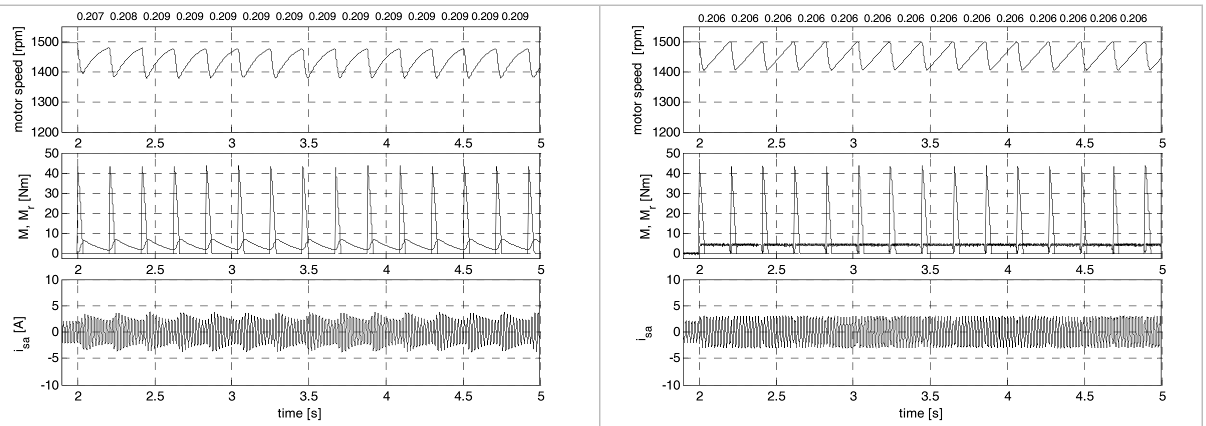
a) The motor is supplied directly from electrical network

b) The motor is supplied by the VSI using DTC

Fig. 5. Simulations results for the start transient followed by a single stroke.

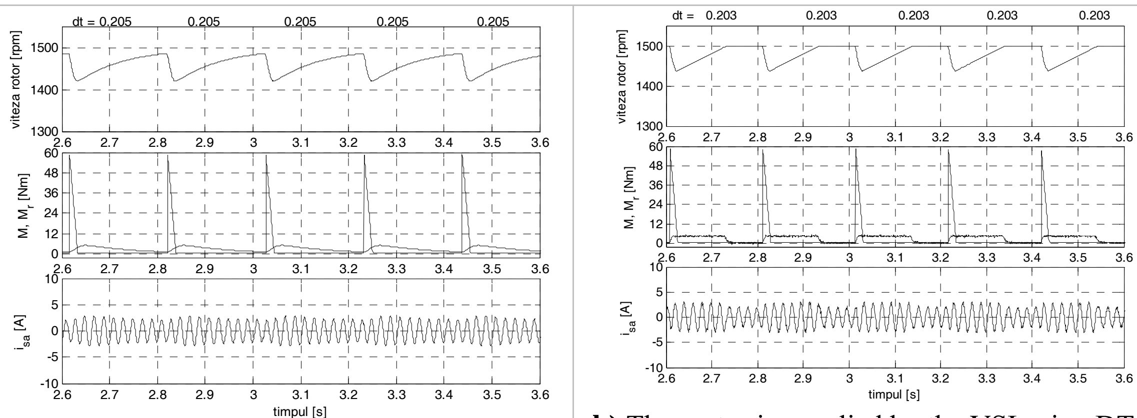
In figure 6 and 7 are presented two cases of automatic working of the presser, corresponding to different values oe deformation force, working angle and ram course.

The load torque is larger when the working angle is closer to 90^o and the deformation force and ram course are bigger.



a) The motor is supplied from electrical network **b)** The motor is supplied by the VSI using DTC

Fig. 6. Simulations results in automate mode (repeated strokes)
deformation force Fd=6,3 tf; work angle u_l=120^o; ram_course =8 mm.

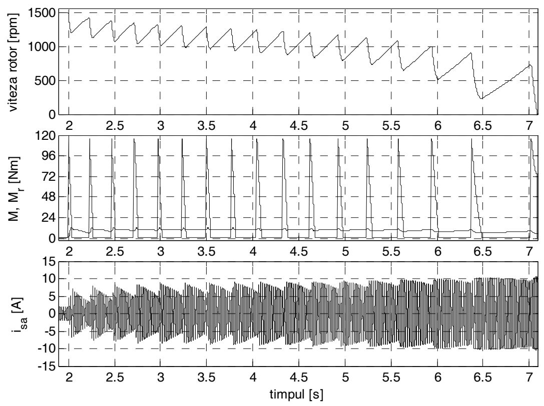


a) The motor is supplied from electrical network **b)** The motor is supplied by the VSI using DTC

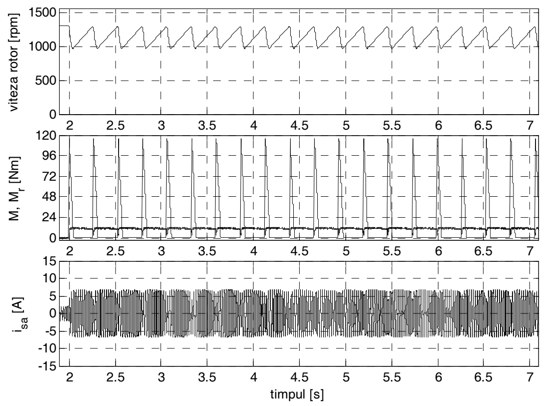
Fig. 7. Simulations results for automate mode, different parameters
deformation force Fd=3,15 tf; work angle u_l=150^o; ram_course =35 mm.

In both situations, the torque in the control scheme was limited, on purpose, to the rated torque. In this condition, two aspects can be noticed, by comparing to the case of the motor with no control. The first one, related to the situation presented in figure 6, is that the controlled motor is working with no current shocks, unlike the motor supplied directly from the mains. The second aspect, featured in figure 7, is that the controlled motor speed has a constant value along a significant portion of the cycle. This is due to the fast torque response, wich is a characteristic of DTC. Moreover, in both situations, the average speed of the controlled motor is a little higher (the periods "dt" are smaller), despite the fact that the refference torque was limited to the rated torque.

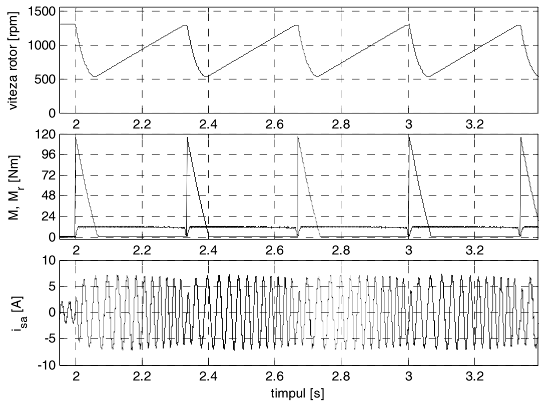
In figure 8a is presented a working case in wich the presser locks, after a certain number of cycles, when it is driven by the motor with no control. On the contrary, when the presser is driven by the controlled motor, in the same conditions, it is working correctly and the motor is not overheated. The presser parameters are: deformation force Fd=6,3 tf; work angle u_l=120^o; ram_course=21 mm.



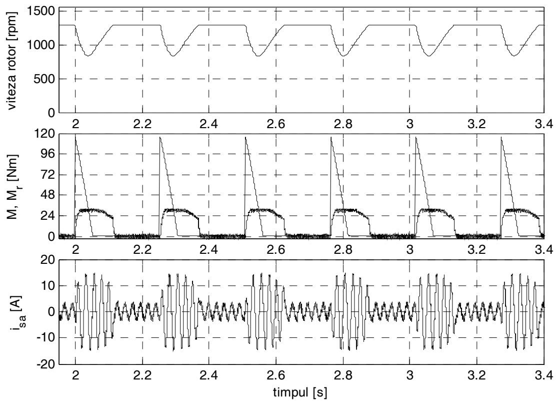
a) The motor is supplied directly from electrical network



b) The motor is supplied by the VSI using DTC; v_ref =1300 rpm



c) The motor is supplied by the VSI using DTC; Pn=0,75 kW; J_v reduced



d) The motor is supplied by the VSI using DTC; Pn=1,5 kW; J_v reduced

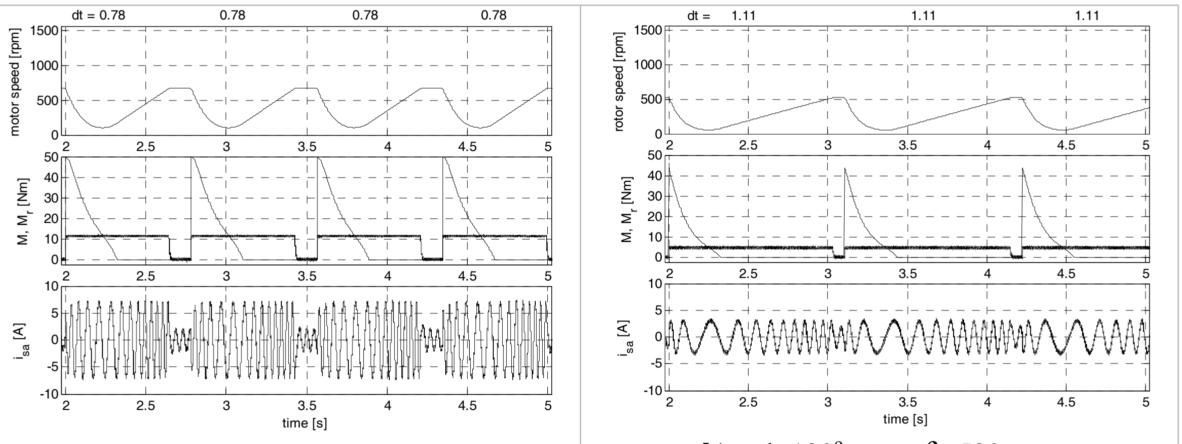
Fig. 8. Critical situation in the presser work

On the purpose improving the dynamic performances of the drive, the authors propose, in addition, the reduction of the flywheel moment of inertia by replacing it by a flywheel with smaller mass. On the other hand, considering the high values of the load torque, the active torque must be increased. This can be done by replacing the motor by another one, with a higher rated power.

In the figures 8c and 8d is represented the work of the presser with a flywheel moment of inertia reduced to half, driven by the initial motor and, respectively, by a motor with double rated power. The speed reference is v_ref=1300 rpm.

It can be noticed that in the first case – figure 8c – the motor speed decreases much more than in the situation corresponding to the initial flywheel (figure 8b). The speed decrease is attenuated when the motor with double rated power is used, but it still remains larger than in the case of initial flywheel.

The figure 9 shows the possibility of the presser to work at low speed, set by the operator, when the control scheme is used.



a) u_l=90°; v_ref =670 rpm; **b)** u_l=120°; v_ref =520 rpm

Fig. 9 The operation at low speed reference with DTC, Pn=0.75 kW

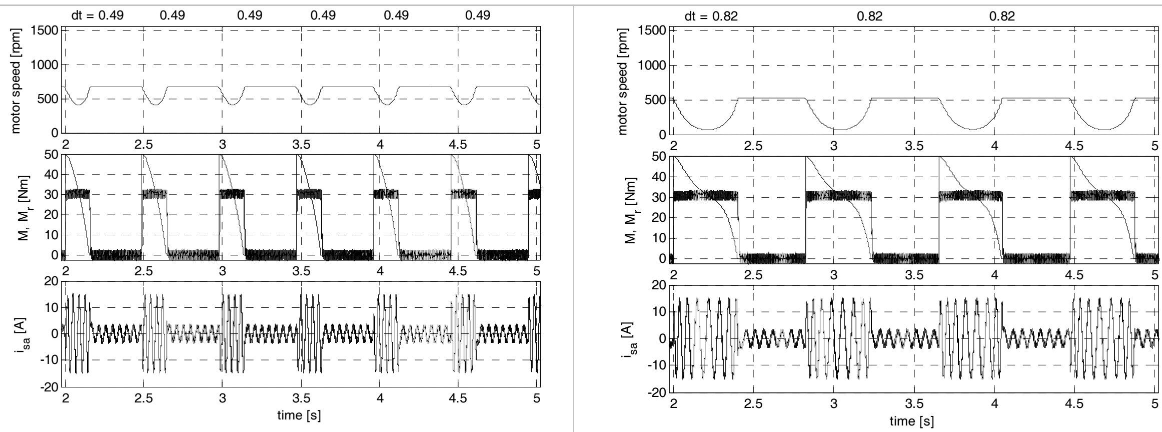
Evidently there is a minimum value (v_min) at which the speed reference can be set, so that to keep the real speed above 0. This value depends both on the presser characteristics (motor rated power, flywheel moment of inertia etc), and technological parameters. In the situation represented in the figure 9a, v_min=670 rpm, in the following conditions: deformation force Fd=6.3 tf, ram_course=8 mm, work angle u_l=90°.

In figure 9b is represented a case in which the motor torque reference is limited, on purpose, to the rated torque. The operating conditions are the same, excepting the work angle, which is set to a larger value – u_l=120^0, which means that smaller mechanical work is required. v_min=520 rpm represents the minimum reference speed that can be set in this conditions.

It can be observed, in figure 9a,. that the induction motor is able to generate its peak torque along the whole speed range.

In figure 10 is presented the working of the presser at low speed reference, with a fywheel having half of the initial moment of inertia and a motor of double rated power. Comparing to the case presented in figure 9.a, it can be seen that, in the same conditions, a lower reference speed is allowed when using a motor with a higher rated power.

Conclusively, the presser equipped with a reduced flywheel and a motor with double rated power is suitable to work at low speed. This can be explained by the fact that the kinetic energy of the flywheel decreases as the speed decreases.



a) v_ref =670 rpm **b)** v_ref =530 rpm

Fig. 10 The operation at low speed reference with DTC, Pn=1.5 kW; J_v reduced

5. CONCLUSIONS

The simulation results of the analyzed situations show the advantages offered by the use of DTC in the electric drive of a power presser:

- Significant improvement of the dynamic performances, due to the fast torque response which is a characteristic of DTC;
- The maximum torque can be limited, if the operation conditions allows it, in order to limit the peak values of the current;
- DTC method is suitable for a sensorless control (without speed transducer), which leads to reduced costs and increased reliability of the drive;
- It makes possible the improvement of the presser dynamic at low speed, by using a reduced flywheel and a motor with a higher rated power;

Evidently there are some disadvantages:

- The total cost of the presser rises, which is inherent, due to the presence of the controller board and the Voltage Inverter;
- Variable swithing frequency at the inverter;
- There is a high torque ripple, but due to the flywheel moment of inertia the ripple does not affect significantly the speed;

The most important advantage of DTC, the fast torque response, makes possible the applying of an adequate speed profile, depending on the technological requirements, in order to achieve better performances in the plastic deformation process. Thus the same presser can be used for more types of operations.

In addition, the number of strokes per time unit can be increased, when the process characteristics allows it, in order to improve the presser productivity.

Note:
Induction motor parameters:
Pn=750 W; U_{fn}=220 V; I_n=2.1 A; f_n=50 Hz; M_n=5.15 Nm; p=2; J=0.00442 kg*m^2; R_s=10 Ω; R_r=6.3 Ω; $L_{\sigma s} = L_{\sigma r} = 0.0401$ H; $L_m = 0.4212$ H; M_{max}=10.7 Nm;

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