A MODALITY OF USING DIRECT TORQUE CONTROL FOR IMPROVING THE EFFICIENCY OF THE POWER PRESSES

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Lucrarea prezintă o soluție de îmbunătățire a eficienței preselor mecanice cu excentric echipate cu variatoare de viteză, pentru modul continuu de lucru (cu alimentare automată cu material). Soluția constă în distribuirea uniformă a cuplului motor de-a lungul unui ciclu de lucru, astfel încât porțiunea de mers în gol, atunci când motorul are cea mai slabă eficiență, să fie eliminată. Eficacitatea acestei metode a fost testată prin simulare numerică, folosind un model de presă realizat şi validat experimental de către autori. Sunt prezentate rezultate numerice şi grafice care arată noul comportament al motorului şi randamentul obținut în diferite situații de operare.

This paper presents a solution of improving the efficiency of the punch presses equipped with variable speed drives, in case of working in continuous mode (automatically fed with material). The solution consists in uniform motor torque spreading along a working cycle, so that the no-load portion, when motor has the worst efficiency, is eliminated. The effectiveness of this method was tested by numerical simulation, using a press model which was built and experimentally validated by the authors. There are presented numerical and graphical results showing the new behavior of the motor and the amount of efficiency gained in different operating situations.

Keywords: power press, efficiency, variable speed drive, Direct Torque Control.

1. Introduction

The mechanical punch presses are widely utilized in small and medium size industrial units, due to their simplicity, reliability and low cost. They are used in various operations, such as punching, cupping, stamping, bending, shearing.

Their working principle is based on the rod-crank mechanism. The mechanic eccentric pressers are driven by three-phase induction motors working at

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invariable speed. The press shaft is attached to a flywheel which is driven by the motor. The motor is usually directly connected, but in present the number of presses equipped with variable speed drives (VSD) is increasing. Besides their purpose of varying the motor speed, the VSD's have proven its advantages regarding the energy cost savings in many applications (centrifugal pumps, conveyors), as mentioned in literature [7], [8], [9].

The solution is applicable, in the presented form, in case of motor control strategies characterized by linear torque response with respect to command quantity: vector control or Direct Torque Control (DTC). Due to the advantages of DTC related to this kind of application [5] and the previous studies made by the authors in applying DTC for improving presses dynamics [1], it was chosen DTC as the motor control strategy.

The authors analyzed the efficiency of these machine tools, in case of mechanical presses equipped with VSD's and also proposed a solution for improving it, and the results are presented in this paper. The efficiency analysis was performed by numerical simulation, for different operations and loads of the press. There are presented the press model, the DTC features, the solution proposed for efficiency improvement and the obtained results.

2. The press model

The press model was built by considering the dynamics of the motor-press system, which is expressed by the equation 1:

$$M - M_l = J\frac{d\Omega}{dt} \tag{1}$$

where: M is the motor electromagnetic torque,

M_l is the load torque at the motor shaft,

J is the sum of the rotor and the flywheel moments of inertia (the last one is referred to the motor shaft by considering the gear ratio),

Ω is the angular speed of the rotor.

The load torque M_l is calculated by dividing the crank turning moment M_t by the gear ratio, i, between the motor and the flywheel. The turning moment, M_t, is determined using the equation 2 [2]:

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

where: F_d is the deformation force, on the direction of translation;

α is the press shaft current angle

α = 180°, at the upper position of the ram,
α = 0° at the lower position,
R is the crank radius,
L is the length of the connecting-rod.

The deformation is performed in the lower part of the course, when $\alpha \le 90^o$.

The equation (1) is used in the motor model to obtain the rotor angular speed Ω, having the load torque M_l calculated in the press model. On the other hand, the press model uses Ω to obtain by integration the current press shaft angle α, which is used to determine the load torque M_l. This interdependency between the two models was resolved by calculating the angular speed in a circulatory manner, starting from an initial known value of the load torque (actually from an initial press shaft angle that is bigger than the angle the processing starts from).

In order to make it possible the simulation of the motor-press system dynamics without going deeply into materials science, it was assumed that the deformation force is invariable with respect to the processing speed, being given as a constant depending on the semi-finished piece shape and its material properties. The deformation force is treated as a reactive force, and the motor load torque calculation by means of this force is correct when the mechanic ensemble is moving. In order to complete the model, it was considered also the situation of press locking, in which the load torque is not given by the deformation force, but it equals the motor electromagnetic torque.

The Simulink model of the press is shown in Fig. 1. The inputs of the model are the motor angular speed, the motor torque and the start signal, which commands the shaft rotation start (the clutch command on the real press). The outputs are the motor load torque and other calculated quantities, for monitoring purpose. The geometrical parameters (length of the rod, crank radius) and the process related parameters (deformation force, processing depth) are introduced as constants. The press shaft current angle, u_c, is obtained by the angular speed integration, which starts from 0°, when the start input command is on. This angle is increasing from 0° to 180° for positive angular speed, so the angle α required by the equation 2 will be $\alpha = 180 - u\_c$. It is then calculated the ram displacement (measured from the lowest point of the course), and when it equals the processing depth, that is at the beginning of the deformation, a signal is generated to apply the deformation force.

Based on the deformation force and the current angle, it is calculated the torsion moment, M_t, using equation 2. Then M_t is divided by the gear ratio to obtain the load torque, M_l. If the shaft angular speed is zero, the load torque becomes equal to the motor electromagnetic torque.

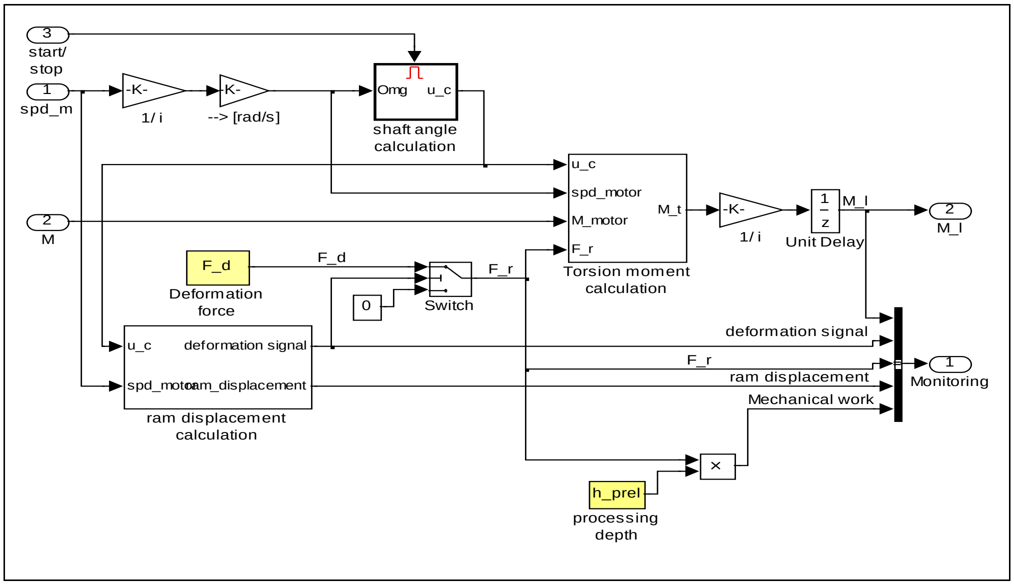

Fig. 1. The dynamic model of the punch press

Further, to ensure the presses start at no load, it is checked whether the motor torque is bigger than the load torque. If it is, the load torque is taken equal to the calculated value; otherwise it results from the zero speed tests, as stated above. The block diagram where the load torque is calculated is presented in Fig. 2.

Before going to the press model output, the load torque is delayed with one simulation step, in order to take into account the interdependency between the motor model and the press model (as stated before) and to avoid an algebraic loop. It is also calculated the mechanical work in each press cycle, as the product of the deformation force and the processing depth.

The dynamic model of the press was made on the purpose of studying the press drive system behavior in various operating conditions and different drive control techniques. Therefore, the press model was first validated by making measurements on a real press and comparing the experimental and simulation results.

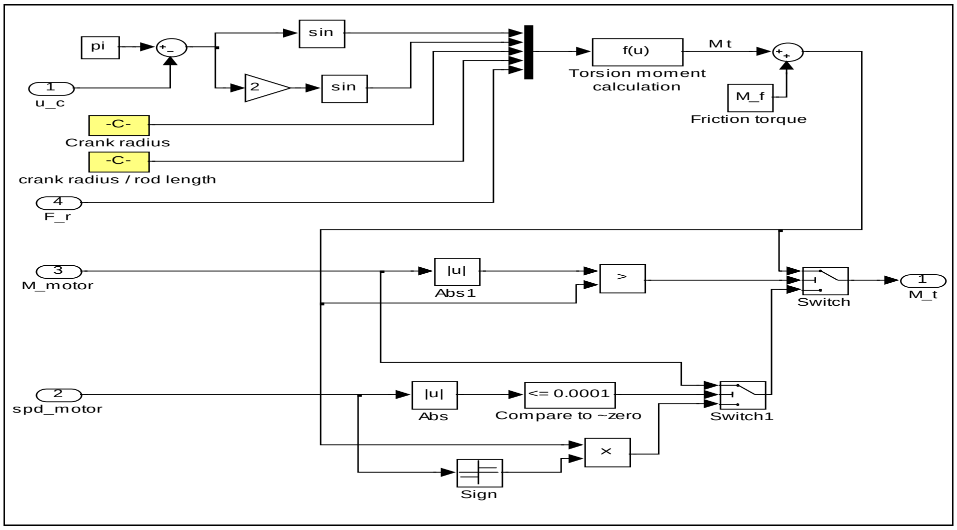

Fig. 2. The model block where the load torque is calculated

For the data acquisition and modeling it was used the mechanic eccentric press PAI 16, driven by a 1.5 kW induction motor.

Experimental setup: National Instruments data acquisition board NI DAQ-Card 6062E; Measurement Bridge N2314, IEMI Bucharest; Incremental encoder TIRO 500; Hall Effect current probes, LEM PR430.

The application used for data acquisition was developed in LabVIEW environment. There were simultaneously acquired the stator's currents, the deformation force, the ram displacement and the motor angular speed. The current was measured using Hall Effect transducers, which also assure a galvanic separation between the power line and the acquisition board.

In Fig. 3 (a) there are presented the measurements results for the stator phase current, deformation force, ram displacement and motor speed when the press motor is directly connected. The measured values of the deformation force and the corresponding ram displacement in the deformation phase were used to build a look-up table, which was used afterwards in the press simulation model.

The corresponding simulation results are illustrated in Fig. 3 (b).

It can be observed that the simulation and experimental results presented in Fig. 3 are close, with the following observations and differences:

- Only the measured values above 500 daN are representative, considering the conversion characteristic of the utilized strain transducer; therefore, the large noise exhibited at low force should not be taken into account
- The displacement curve in the experimental results exhibits a rapid change of slope when the deformation force appears. This is due to a

mechanical play of several millimeters in the ram joint, and this play was not simulated

- The motor angular speed has a fall, followed by a rise, before the deformation force occurs. When the flywheel, in movement, is coupled by the clutch with the press shaft, at the up most point of the ram, the flywheel is slowed down by the supplementary friction and inertia of the shaft and ram. When afterwards the ram begins to fall, its gravity force contributes in the acceleration of the ram, and the motor angular speed rises. These oscillations do not appear in the simulation results because the ram mass and inertia were not taken into account in the press model.

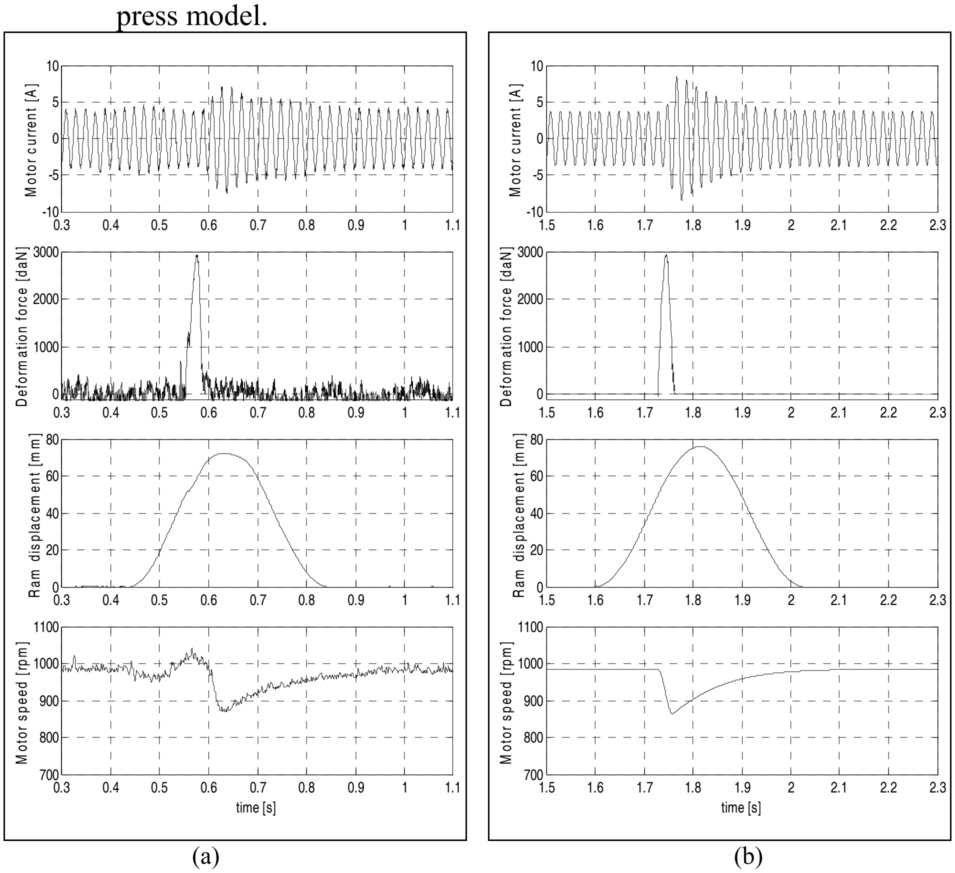

Fig. 3. Experimental (a) and simulation (b) results for press motor supplied directly from power grid

2. The proposed solution for press efficiency improvement

As stated in the introduction, it was used DTC as the motor control strategy. The basic idea of DTC is to choose the best inverter switching pattern in order to control both stator flux and electromagnetic torque of machine simultaneously [8]. It is characterized by a very fast torque response and a relatively simple control scheme [4].

The scheme of the press drive is presented in Fig. 4. The DTC algorithm receives the torque reference from a speed controller.

The torque reference calculator block, between the speed controller and DTC, is used only to adjust the torque reference according to the solution proposed for efficiency improvement.

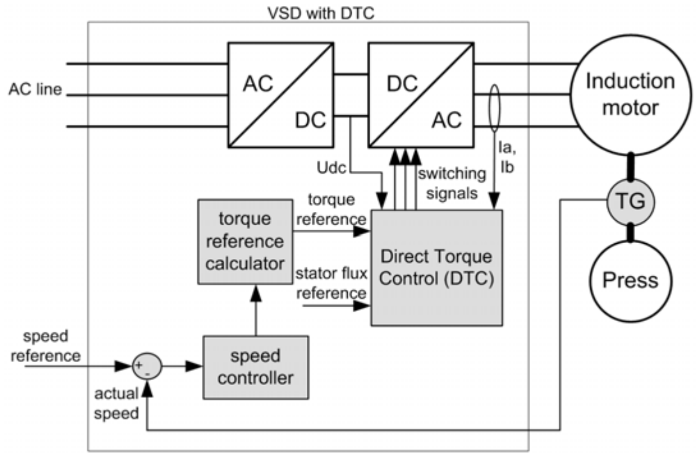

Fig. 4. Basic scheme of the press drive

The solution consists in uniformly spreading the motor torque over a working cycle, so that the no-load portion, when motor has the worst efficiency, is substantially reduced.

The solution is applicable when the press is working continuously, performing an operation every cycle. It is implemented in the control scheme by means of the torque reference calculator, illustrated in Fig. 4.

In an initial phase, for a few cycles, the torque reference is provided directly by the speed controller. In the same time, it is calculated the average torque per cycle, using equation 3,

$$\tilde{M} = \frac{1}{T_{cycle}} \int_{0}^{T_{cycle}} M(t)dt\,, \tag{3}$$

where T_{cycle} is the cycle period.

After the initial phase, the torque reference provided by the speed controller is limited at the previously calculated average torque, which is increased by 10%, in order to take into account that the real load torque is not exactly the same from one cycle to another.

In order to illustrate the behavior of the press drive, there are represented in Fig. 5. the evolution in time of one phase current, motor and load torque and the motor speed, before and after the torque spread adjustment according to the proposed solution. The results were obtained from the simulation of a cupping process. The quantities are expressed per unit, taking the corresponding rated values as the base values.

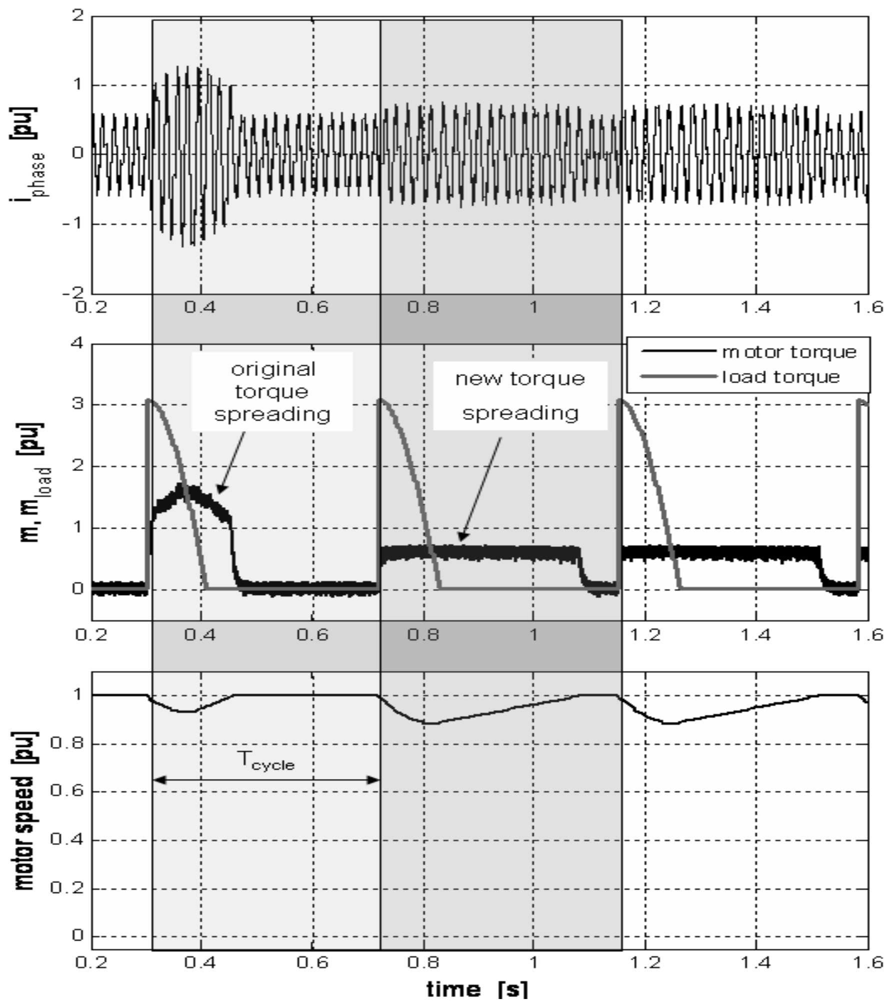

Fig. 5. The presses drive behavior before and after the torque adjustment: motor phase current (top), motor and load torque (middle) and motor speed (bottom)

It can be observed that when the torque adjustment and correspondingly the new torque spreading are applied, the motor still reaches the no-load speed before the next stroke occurs, and the no-load duration is decreased. In the same time, as expected, the current overshoot is much lower than in the case when no torque adjustment was applied.

4. Results

In order to reveal the effectiveness of the proposed efficiency improvement solution, there were conducted numerical simulations of the press performance in case of directly connected motor and DTC drive controlled motor, with and without torque adjustment. Some results, obtained for a continuous cupping process, are comparatively presented in Fig. 6, where the press efficiency is represented as function of the press loading (expressed by the deformation force). The deformation force is expressed per unit, taking the maximum press force as the base quantity.

The press efficiency was defined as in equation 4:

$$\eta = \frac{L}{W}, \tag{4}$$

where L is the mechanical work in a press cycle and W is the energy absorbed by the motor in a press cycle. In the case of drive controlled motor, the efficiency was multiplied by 0.92, which is a usual value of drive efficiency.

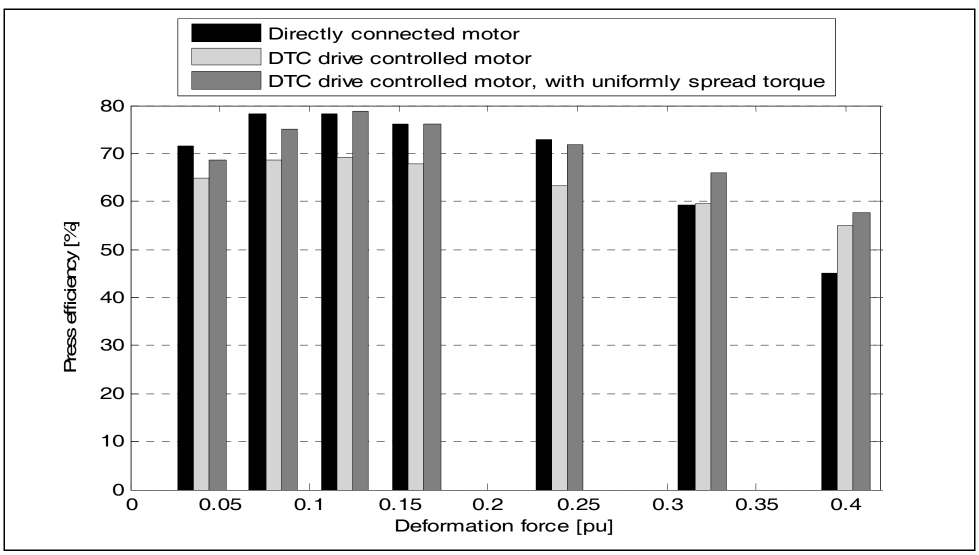

Fig. 6. Press efficiency vs. deformation force, showing the effectiveness of the proposed solution

5. Conclusion

This paper presented a proposed solution of improving the efficiency of the mechanic presses equipped with variable speed drives. The solution was tested

by numerical simulations, using a press dynamic model which was created and experimentally validated by the authors. The results showed that the solution can offer a better press efficiency for a wide load range, comparing to the efficiency obtained by using directly connected motor and drive controlled motor.
The solution, in the actual form, is only applicable for variable speed drives that use vector control or Direct Torque Control. The Direct Torque Control, due to its fast torque response, can be considered suitable for high dynamic requirements of the punch eccentric presser. As further work, the authors intend to extend the solution applicability to the Volt-Hertz control, which is the most widely used motor control type in industry.

R E F E R E N C E S

[1] *S.V. Paţurcă, M. Covrig, C. Cepisca, St. Gheorghe*, "An improvement on the mechanic eccentric punch power press dynamics", Proceedings of the 7th WSEAS International Conference on Application of Electrical Engineering, Trondheim, Norway, pp: 169-174, 2008

[2] *Şt. Velicu*, Bazele proiectării preselor (Fundamentals of Presses Design), (available only in romanian), Publishing Printech, Bucharest, 2003

[3] *B.K. Bose*, Modern Punch Electronics and AC Drives, Prentice Hall PTR, Prentice-Hall, Inc., U.S.A., 2002

[4] *P. Vas*, Sensorless Vector and Direct Torque Control, Oxford University Press; Oxford, U.K., 1998

[5] *S.V. Paturcă, M. Covrig, C. Cepisca, G. Seritan*, "Proposed Schemes for Improving the Steady State Behaviour of Direct Torque Controlled Induction Motor", Proceedings of the 7th WSEAS International Conference on Power Systems (PE'07), Beijing, China, pp. 53-58, 2007

[6] *Fl. Drăgănescu, T. Savu, B. Drăgănescu,* **"**Computer aided data acquisition in punching steel bands on mechanic eccentric press" The Annals of "Dunărea de Jos" University of Galaţi, XVI (XX), p.60 – 69, 1998

[7] *M. Barnes,* "Practical Variable Speed Drives and Power Electronics", Newnes, ISBN 07506 58088, United Kingdom, 2003

[8] ***Mechanical Advantage and Efficiency of Machines, The Columbia Electronic Encyclopedia, 6th ed. Copyright © 2007, Columbia University Press

[9] *** Adjustable Speed Drives as Applied to Centrifugal Pumps, Publication D-7737 – March 2000, Rockwell International Corporation

[10] *S.V. Paturca, M. Covrig, L. Melcescu, C. Cepisca*, "A Study on the Improvement of the Mechanic Eccentric Power Press Dynamics by using Variable Frequency Induction Motor Drives", Proceedings of the 7th WSEAS International Conference on Power Systems (PE'07), Beijing, China, pp. 251-255, 2007.