Robust design and control of linear actuator dedicated to stamping press application

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ABSTRACT
In this paper, we present a robust design and control approach of all converter linear actuator dedicated to stamping press application. The linear actuator is designed by a systemic design approach taking into account the constraints of the application such as displacement limit and interactions between the design and the control. The model developed is implanted under the simulation environment Matlab/Simulink. The obtained results encourage the industrialization of the studied structure of the stamping press machine.

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1. Introduction
Several research works address the problem of design and variable speed driving of linear motors for industrial applications requiring an accuracy of the position and speed of the movable shaft.[1–3] These studies have shown several drawbacks of linear motors stepping and variable reluctance [1–3]:

• Vibration.
• Average precision of the position control.
• Complication control algorithms of reluctance linear motors since the inductance is variable depending on the position of the movable shaft.

Our application is to automate a stamping press to make repetitive cycles to transform pieces of sheet metal in average thickness in parts to be used in industrial applications such as manufacturing of the yokes of the electric machines. Indeed, a piece of magnetic sheet is clamped to a table carrying the punch of female tool capable of supporting a higher pressing strength (1500 N). This piece of steel is intended to be cut into identical pieces and assigns a specific form dedicated to the manufacture of a transformer ferromagnetic core. Therefore, it is proposed to use a stamping press having a linear motor carrying the male punching tool by means of its shaft. The latter resulted in a repetitive cycle of speed imposing attack strength for a cut sheet metal without deformation.[4–8] Our choice was directed on an innovated linear motor: cylindrical-type structure with permanent magnets. This type of motor is with concentrated winding to reduce congestion and inductance of end winding. The procedure for manufacturing of this type of actuator is easy to automate. The control law chosen is a scalar-type control in front of view to monitor the speed and moving force of the movable shaft. This control law is simple for the implantation under DSP or FPGA electronic cards and presents an elevated precision of the speed and position control. The movable shaft carries the sheet metal punch tool.

In this context, this paper presents a systemic design and modeling methodology of the actuator basing on works in [9–12], and illustrates the scalar control algorithm developed and implemented under the simulation environment Matlab/Simulink, ending with a description of the simulations results.

2. Sizing of the linear actuator
2.1. Analytical sizing of the actuator
The linear motor structure with permanent magnets is illustrated by Figure 1.

Several research studies show that the analytical method is recommended for the design of electrotechnical devices since it leads to sizing models highly parameterized and compatible thereafter for large optimization problems. In addition, certain factors need to be adjusted by the finite element method which can be cited as an example, the coefficient of leakage flux. This method is also based on well-justified simplifying assumptions. For this, we set to establish an analytical model adjusted by the finite element method. The method chosen is then a hybrid analytic/finite element method. This method combines the advantages of the analytical method as compatibility with large optimization programs and advantages of the finite element method with the high accuracy of the results.[13–34]

2.2. Modeling of the actuator
The motor is controlled by a DC–AC converter with two voltage levels controlled in current by pulse width modulation. The
converter feed voltage is derived from a three-phase rectifier connected to a three-phase 220 V/380 V–50 Hz sector.

The average rectified voltage is estimated by the following equation:

\[ U_{dc} = \frac{3 \times \sqrt{3} \times V_{max}}{\pi}, \]  

where \( V_{max} \) is the maximal phase voltage of the sector.

The actuator electric constant is expressed by the following relation:

\[ K_e = 2 \times L_{ra} \times N_{sph} \times B_e, \]  

where \( L_{ra} \) is the width of the radial opening of the magnets in meter, \( N_{sph} \) is the phase number of turns, and \( B_e \) is the flux density in the air gap.

The maximal value of the back electromotive force is expressed by the following relation:

\[ E = K_e \times V, \]  

where \( V \) is the velocity of the movable stem.

We deduce the expression of the electromagnetic force of attraction of the moving stem:

\[ F_{em} = 2 \times L_{cm} \times N_{sph} \times B_e \times I, \]  

where \( I \) is the maximal phase current.

The average length of a coil turn is expressed by the following relation:

\[ L_{sp} = 2 \times \left( \frac{D_{cm}}{2} + H_a + e + \frac{H_d}{2} \right) \times \alpha \times \pi + L_{enc} \]  

\[ + 2 \times \left( \frac{D_{cm}}{2} + H_a + e + \frac{H_d}{2} \right) \times A_{denth} + L_{enc} \]  

where \( D_{cm} \) is the movable stem diameter, \( e \) is the air gap thickness, \( H_a \) is the magnet thickness, \( H_d \) is the tooth height, \( \alpha \) is the tooth opening coefficient in the radial direction, \( L_{enc} \) is the slot width, and \( A_{denth} \) is the angular teeth opening in the axial direction.

We deduce the expression of the phase resistance in function of the temperature of copper:

\[ R = r_{cu} \left( T_{e} \right) \times N_{sph} \times L_{sp} \times \frac{I_{dim}}{\delta}, \]  

where \( r_{cu} \) is the copper resistivity, \( I_{dim} \) is the dimensioning current, and \( \delta \) is admissible current density in the copper.

An average value of resistance is considered for a copper temperature that is maintained constant at 80 °C, assuming that the motor is cooled by a cooling system controlled in temperature (the temperature of the copper equal to 80 °C) by acting on the thermal convection coefficient of the refrigerated fluid.

The phase inductance is expressed by the following relation:

\[ L = \mu_0 \times \frac{N_d}{3} \times \frac{N_{sph}^2}{\left( \frac{N_d}{3} \right)^2} \times \frac{\delta^2}{2 \times (H_a + e)} \times C_{id} + \frac{L_{cm} \times H_d}{L_{enc}} + \frac{L_d \times H_d}{L_{enc}} \]  

where \( N_d \) is the total number of teeth, \( S_d \) is the teeth section, \( C_{id} \) is a coefficient taking into account the three-dimensional effects, \( \delta \) is the dimensioning current, \( L_{cm} \) is the width of the radial opening of the tooth, and \( L_d \) is the tooth width in the axial direction.

The phase mutual inductance is expressed by the following relation:

\[ M = \mu_0 \times \frac{N_d}{3} \times \frac{N_{sph}^2}{\left( \frac{N_d}{3} \right)^2} \times \frac{\delta}{2 \times (H_a + e)} \times C_{id} \]  

The \( C_{id} \) coefficient is identified by a two-dimensional finite element model of the motor after a cutting along a horizontal plane passing through the axis of the actuator. The model is obtained by spreading the two portions of the actuator.

### 3. Finite element validation of the analytical model

The actuator is studied in two dimensions based on the following assumptions:

- Three-dimensional effects are neglected since the radial opening of the teeth and the magnets is important.
- The motor is axially symmetrical, and only half of the actuator is investigated.
- Mesh is refined in the air gap to increase the accuracy of calculations.
• The problem is solved by varying the static position of the movable axis with a step size equal to 26.66 mm by Maxell-2 D software.
• With all these assumptions, the two-dimensional model of actuator with refined mesh is shown in Figure 2.

The distribution of field lines at load in the planar portion of the actuator is shown in Figure 3:

The geometric parameters of the linear actuator are adjusted by finite element simulations in order to minimize the harmonics of order greater than 1 effect on the sinusoidal back electromotive force wave form. In addition, the theoretical coefficient of flux leakage among magnets is close to 1. But in reality, there are flow leaks among magnets. Therefore, the finite element method was used to calculate with good accuracy this coefficient. Several simulations are initiated by varying the position of the movable rod and led to an average value of this coefficient equal to 0.98.

Finally, the finite element method has supplemented and adjusted the analytical model sizing the actuator.

4. Control model of the stamping press

4.1. Motion equation

The motion equation is derived from the fundamental relationship of dynamics:

\[ M_m \times \frac{dV}{dt} = F_{em} + F_p - F_f - F_{mec} - F_{pr}(d) \]  \hspace{1cm} (9)

\( M_m \) is the movable stem mass, \( V \) is the movable stem velocity, \( F_{em} \) is electromagnetic attraction strength, \( F_p \) is the gravity strength, \( F_f \) is the strength due to iron losses, \( F_{mec} \) is the strength due to mechanical losses, \( F \) is the stamping press resistance force, and \( d \) is the movable stem displacement.

The movable stem displacement is deducted from the following relation:

\[ d = \int V \times dt \] \hspace{1cm} (10)

The gravity strength is expressed by:

\[ F_p = M_m \times g \] \hspace{1cm} (11)

where \( g \) is considered equal to 9.8 N kg\(^{-1}\).

The strength due to iron losses is expressed by the following relation [14–34]:

\[ F_f = s \times |F_{em}| \times \left( \frac{\nu}{2} \right) \times \frac{1}{R_e} \times \left( M_{ds} \times B_d^2 + M_{cs} \times B_{cs}^2 \right) \] \hspace{1cm} (12)

where \( f \) is the frequency of the stator currents, \( M_{ds} \) is the mass of the stator teeth, \( M_{cs} \) is the mass of the stator yoke, \( B_d \) is the flux density in the teeth, and \( B_{cs} \) is the flux density in the stator yoke.

The strength due to mechanical losses is expressed by [14–34]:

\[ F_{mec} = sgn(F_{em}) \times \left( s + n_u \times abs(V) + x_i \times V^2 \right) \times \frac{1}{R_e} \] \hspace{1cm} (13)

where \( s \) is the dry friction coefficient, \( n_u \) is the viscous friction coefficient, \( x_i \) is the fluid friction coefficient, and \( R_e \) is the movable stem bore radius.
the reference speed and response speed of the movable stem.

Simulink model of the current regulator is illustrated in Figure 6:

4.4. Model of the back electromotive forces

The back electromotive forces are expressed by the three following equations [14–34]:

\[ e_1 = K_e \times V \times \cos \left( p \times \frac{V}{R_e} \times t + \frac{\pi}{2} \right), \]  

(14)

\[ e_2 = K_e \times V \times \cos \left( p \times \frac{V}{R_e} \times t - \frac{2 \times \pi}{3} + \frac{\pi}{2} \right), \]  

(15)

\[ e_3 = K_e \times V \times \cos \left( p \times \frac{V}{R_e} \times t - \frac{4 \times \pi}{3} + \frac{\pi}{2} \right). \]  

(16)

where \( K_e \) is the electric constant of the motor and \( V \) is the linear velocity of the motor, and \( p \) is the number of pole pairs.

These equations are implanted under Matlab/Simulink environment according to Figure 7:

4.5. Generator of control signals

The control signal generator compares the three reference voltages to a triangular signal having a frequency much greater than the voltages provided by the regulators of the currents. The output of each comparator drives a hysteresis variant between 0 and
where $R$, $L$, and $M$ are, respectively, the resistance, inductance, and mutual inductance of the motor, $K_e$ is the electric constant of the motor, and $i$ and $V$ are the current and the voltage of the phase $i$.

The electromagnetic torque is given by the following relation:

$T_e = R \times i + (L - M) \times \frac{di}{dt} + K_e \times V \times \cos \left( \theta - \frac{2\pi}{3} \right)$,

where $R$, $L$, and $M$ are, respectively, the resistance, inductance, and mutual inductance of the motor, $K_e$ is the electric constant of the motor, and $i$ and $V$ are the current and the voltage of the phase $i$.

4.6. Model of the motor–converter

The motor is powered by a two-level voltage inverter with IGBTs. Each phase of the motor is equivalent to a resistor in series with an inductance and a back electromotive force.

The three-phase models of the motor are described by the following equations:

$V_1 = R \times i + (L - M) \times \frac{di}{dt} + K_e \times V \times \cos \left( \theta + \frac{\pi}{2} \right)$,

$V_2 = R \times i + (L - M) \times \frac{di}{dt} + K_e \times V \times \cos \left( \theta - \frac{4\pi}{3} + \frac{\pi}{2} \right)$,

$V_3 = R \times i + (L - M) \times \frac{di}{dt} + K_e \times V \times \cos \left( \theta - \frac{2\pi}{3} + \frac{\pi}{2} \right)$,

Figure 6. Simulink model of the currents' regulator.
4.7. Global model of the power chain

The coupling of different models of the power system leads to the global model implanted under the Matlab/Simulink simulation environment according to Figure 10:

5. Description of the simulation results

The three phase fluxes at load captured by one coil in the computation of finite element method are illustrated by Figure 11.

The fluxes are close in form and value to those estimated analytically. This validates the analytical design procedure.

The back electromotive forces with movable stem speed equal to 2 m/s are calculated by finite element method, as illustrated by Figure 12.

The back electromotive forces are also close in form and value to those estimated analytically. This further validates the analytical design procedure.

The electromagnetic strength calculated by finite element method related to a current value (200 A) is illustrated by Figure 13.

The electromagnetic strength is close in form and value to that estimated analytically. This validates the analytical design procedure entirely.

The simulation parameters (Table 1) are extracted from the developed design and modeling program of the studied power system.

The response speed of a stamping cycle is shown in Figure 14.

Figure 14 shows that the response speed follows with good accuracy the stamping cycle. This demonstrates the performance of the selected technique of control.

Figure 15 indicates that the displacement of the movable stem is accurate because it is joined to its return, exactly at the initial position \((d = 0 \text{ m})\).

Figure 16 demonstrates that the phase currents present their strong values during the phase of going up since the gravity
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1500 N, slightly higher than the resistance strength (1500 N), since the force of gravity is added (near to 1000 N) to the electromagnetic strength. The duration of the cutting operation is 0.3 s (Figure 18).

Figure 19 shows that the electromagnetic power presents its strong values during the phase of going up because the gravity strength is important. During the attack phase of the sheet, the electromagnetic power becomes positive and is important to overcome the stamping resistance strength.

Figure 20 shows that the strengths due to iron losses and mechanical losses are negligible, which demonstrate the performance of the developed design approach.

strength is important. Figure 17 shows the change of the back electromotive force compared to the phase current.

The phase shift between the current and the back electromotive force is very low leading to a significant reduction in the energy consumed. This characteristic shows the effectiveness of the developed control technique.

During the attack phase of the sheet, the electromagnetic strength becomes positive and important to overcome the stamping strength resistance. The value of the electromagnetic strength increases linearly before this operating point of 0.1 s. At the attack phase, the electromagnetic strength achieves its maximum value (500 N), necessary for cutting the piece of metal sheet without deformation. The strength of the moving rod is close to 1500 N, slightly higher than the resistance strength (1500 N), since the force of gravity is added (near to 1000 N) to the electromagnetic strength. The duration of the cutting operation is 0.3 s (Figure 18).

Figure 19 shows that the electromagnetic power presents its strong values during the phase of going up because the gravity strength is important. During the attack phase of the sheet, the electromagnetic power becomes positive and is important to overcome the stamping resistance strength.

Figure 20 shows that the strengths due to iron losses and mechanical losses are negligible, which demonstrate the performance of the developed design approach.
Figure 9. Simulink model of the motor–converter.

Figure 10. Simulink model of the global system.
Figure 11. Three phase fluxes at load captured by one coil in function of the movable stem displacement calculated by finite element method.

Figure 12. Back electromotive forces in function of the movable stem displacement calculated by finite element method.

Figure 13. Electromagnetic strength in function of the movable stem displacement calculated by finite element method.

Figure 14. Response speed of a stamping cycle.

Figure 15. Displacement of the movable stem.

Table 1. Simulation parameters.

| Parameters                              | Values     | Units         |
|-----------------------------------------|------------|---------------|
| Movable stem mass ($M_m$)              | 102.371    | kg            |
| Switching frequency ($f_{sw}$)         | 20         | Hz            |
| Phase inductance ($L$)                  | 3.663      | mH            |
| Phase mutual inductance ($M$)           | 0.199      | mH            |
| Rotor resistance ($R$)                  | 3.624      | mΩ            |
| Number of pole pairs ($p$)              | 4          |               |
| Electric constant ($K_e$)               | 9.602      | Volt/(rad/s)  |
| DC bus voltage                          | 514.6      | Volt          |
| Flux density in the air gap ($B_e$)     | 0.85       | Tesla         |
| Flux density in stator yoke ($B_{cs}$)  | 1.6        | Tesla         |
| Flux density in rotor yoke ($B_{cr}$)   | 1.02       | Tesla         |
| Stator yoke mass ($M_{cs}$)             | 108.989    | kg            |
| Teeth mass ($M_{ds}$)                   | 318.179    | kg            |
In conclusion, the simulations results validate the parameterized design program and the control algorithm of the linear actuator dedicated to stamping press application.

6. Conclusion

This paper presents a comprehensive approach of robust design and control of a linear motor with permanent magnets dedicated to stamping press application. A design model of the linear motor based on hybrid analytic/finite element method is developed. This model takes into account the constraints of the application and the interactions between the control and the sizing of the actuator. The model developed can be applied to several industrial applications other than the present application. This model is also highly parameterized, and eventually leads to problems of optimization of large dimensions. The proposed study presents an attractive solution to the automation of stamping press.
This study is completed by the development of a robust control law. Simulation results provide the validation of the design and control approach.

**Disclosure statement**

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