

Implementation of an Elevator's Position-Controlled Electric Drive

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Abstract-- This research is on the implementation of an elevator's position-controlled electric drive. The information contained within this paper serves as a framework to expand the usefulness of electric drives through the addition of digital control systems and switching power supplies. The tests to derive the motor parameters as well as the theory behind the test are covered in depth before the design procedures for creating a cascaded control system are started. Computer simulations are conducted using the parameters and controllers which will be implemented in real-time before experimental testing in the lab begins. The implementation of an elevator driven by a permanent-magnet DC motor with position control is successful and provides an illustrative example to those who wish to apply electric drives to various mechanical systems.

Keywords-- Elevator, Electric drive, Computer simulations, DC motor

I. INTRODUCTION

The physical arrangement of a suspension-type elevator has a direct affect on the forces acting upon its propulsion system. Ideally, a gear system is not used so as to reduce mechanical losses and improve the drive system's response time; however, a drive system without gears requires a motor capable of accelerating the system from a standstill. To aid the drive system, a counter-weight is employed to reduce the overall force needed to drive the system when it is under load. To further reduce the work which must be done by the prime mover, the support cable/belt is configured to spread the load evenly between the drive pulley and the anchor points [1]. These techniques of reducing the load force on the drive system are applied to all commercial elevators of the suspension type regardless of their propulsion system leaving the electric drive to be the defining factor of each company's design.

II. COMMERCIAL ELECTRIC ELEVATOR DRIVE SYSTEMS

Two major international manufactures of elevators using electric drives are Kone and Otis. Both companies use the same approach to suspension of car and counterweight but have developed different electric drive systems for propelling the elevator car and counterweight.

A. Kone System

The Kone EcoDisc elevator electric drive system is a machine-room-less design which places a permanent-magnet, synchronous motor in the hub of the drive pulley as seen in Figure 1. Steel cables are passed over this drive pulley and suspended the car and counterweight; as shown in figure 2, these cables are anchored to the top of the elevator shaft and cable tension is provided by the weight of the hanging car and counter-weight. In this arrangement when the elevator car moves upwards the counterweight moves downwards with cable ends never changing position.



Figure 1: Kone EcoDisc electric elevator drive [2]



Figure 2: Kone Machine-Room-Less Elevator System [3]

B. Otis System

The OtisGen2 electric elevator drive system is a machine-room-less design which uses a flat steel belt in place of woven steel cables to support the elevator car and counter weight [4]. The use of a belt allows for a drive pulley with a smaller diameter which reduces the total volume of the drive system. This smaller drive system is mounted at the top of the elevator shaft which eliminates the need for an equipment room to be built above the elevator shaft, hence the moniker "machine-room-less". Like the Kone system, the OtisGen2 electric elevator drive system is powered by a permanent-magnet synchronous motor. Also like the Kone system, the Otis system has the elevator car and counterweight suspended from the drive pulley with the ends of the belt anchored to the top of the elevator shaft so that the suspended car and counter-weight provide tension on the belt.



Figure 3: OtisGen2 electric elevator drive [5]

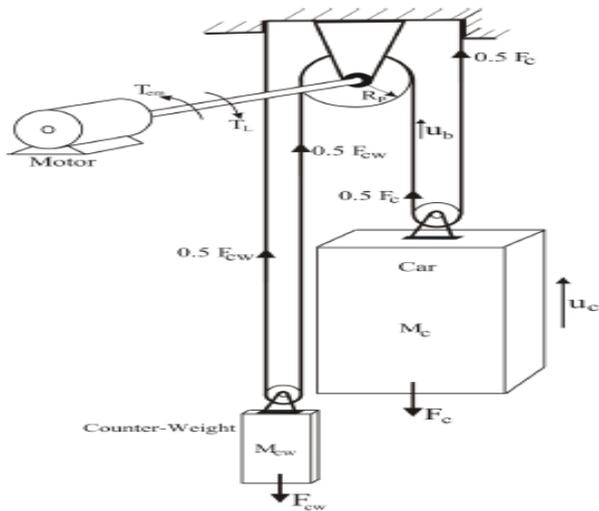


Figure 4: Laboratory model of elevator driven by permanent-magnet DC motor

The elevator electric drive that is proposed for this research is most similar to the Otis methodology. The scheme of proposed structure is shown in Fig. 4. A drive belt is looped over a drive pulley with the ends anchored to the top of the elevator shaft. The electric drive is rigidly attached to the drive pulley without the use of gearing. The car and counterweight, which ride on pulleys, provide belt tension ensuring the toothed belt and drive pulley do not slip. The elevator car and counter-weight are of equal weight so as to reduce load on the motor to only what is placed inside the cart.

C. Mathematical Model of Elevator Electric Drive

The equations governing the operation of the elevator can be attributed to the motor’s electrical circuit and to its mechanical system.

a. Motor’s Electrical Equations

The elevator is driven by a permanent-magnet DC motor. The equivalent circuit of the permanent-magnet DC motor is confined to the armature circuit which is illustrated in Fig. 5.

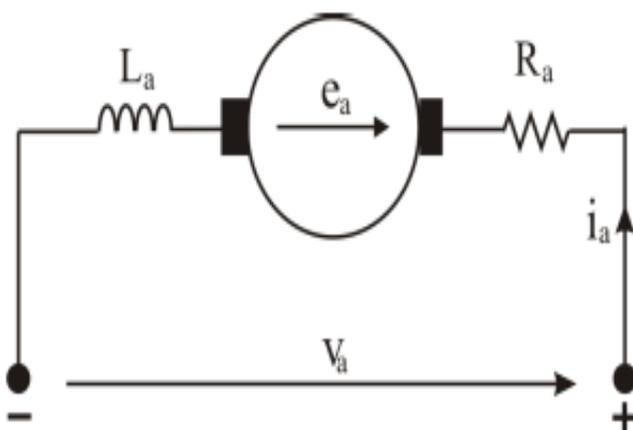


Figure 5: Equivalent circuit of armature of DC motor [6]

The motor voltage equation of the armature circuit is:

$$V_a = e_a + R_a \cdot i_a + L_a \frac{di_a}{dt} \tag{1}$$

Where:

- $e_a = K \cdot \omega_m$ is the electro-motive force developed in the armature’s winding
- K is the motor constant

- ω_m is the angular speed of the motor’s shaft
- V_a is the voltage difference between the armature terminals
- R_a is the resistance of the armature circuit
- i_a is the current flowing through the armature circuit
- L_a is the inductance of the armature circuit

The electro-magnetic torque T_{em} developed by the motor is expressed as:

$$T_{em} = K \cdot i_a \tag{2}$$

b. Mechanical System’s Motion Equations

In order to derive the motion equation that describes the elevator’s mechanical system it is assumed that the mass of the drive belt is ignored due to its material composition and length. In practice, the drive belt or drive cable is constructed from steel and its significant mass contributes to the load torque in a non-linear fashion depending upon the position of the car. The motion equation of the entire system from the motor’s perspective is:

$$T_{em} = J_M \frac{d\omega_m}{dt} + B \cdot \omega_m + T_L \tag{3}$$

where:

- J_M is the motor’s moment of inertia
- ω_m is the angular speed of the rotor
- B is the friction coefficient of the motor
- T_L is the load torque placed on the motor’s shaft

III. DESIGNING OF CONTROL SYSTEM

The digital control system for implementation of position, speed, and current control of the elevator’s electric drive is composed of three cascaded loops which are coordinated to work together using information obtained from the motor’s position sensor and power supply’s current output. Knowing the motor’s steady-state and dynamic parameters the individual control loops are each designed to perform a specific task using a specific input. Using Matlab’s Simulink software package these separate loops are integrated into one digital control system which is then compiled into machine language, loaded on the dSpace DS1104 hardware, and then executed in real time.

A. Feedback Control of Electric Drive

Feedback controllers are implemented with the goal of precisely and quickly regulating a system based upon real-time input obtained from the system itself without the need for correction from any outside observer. A properly designed control system will bring the steady-state error of a process to zero in a short time frame with few oscillations and minimum overshoot.

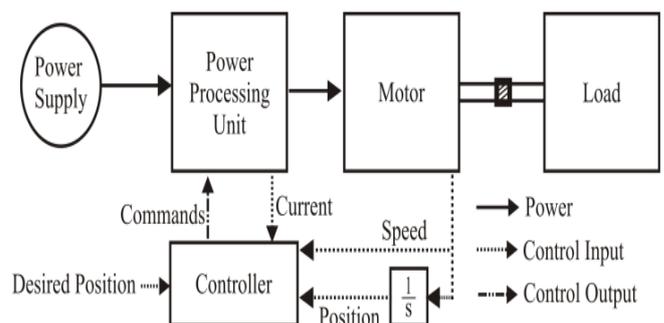


Figure 6: Feedback control system of DC motor

Fig.6 is a block representation of the elevator’s electric drive and feedback control system. A Direct Current (DC) power source is connected to the motor via a Power Processing Unit (PPU). The speed of the motor is captured by sensor and fed back to the controller. The position of the motor is obtained by integrating the speed of the drive over time and is also fed back to the controller. The current flow out of the PPU is monitored and reported back to the controller as well. With these three real-time inputs the controller can bring the motor to the desired position. A closer examination of the controller block reveals three nested loops . Two loops contain a Proportional-Integral (PI) controller which is well suited to the task of regulating the electric drive’s current and speed and one loop that contains a Proportional (P) controller which will adequately correct errors in the drive’s position.

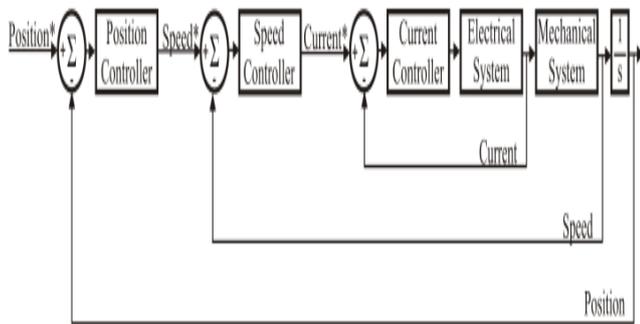


Figure 7: Cascaded control system

As shown in Fig.8 is a diagram of a PI controller. The difference between the desired input $X^*(s)$ and the actual output $X(s)$ is known as the error $E(s)$. Two corrective values are generated from the error $E(s)$. The value $V_{c,p}(s)$ is the product of the error $E(s)$ and the gain k_p ; this provides a swift and proportional correction to system disturbances. The value $V_{c,i}(s)$ is the product of the error $E(s)$ and the gain k_i with the result being integrated over time; this provides a slow and gradual correction to counter system disturbances. The two corrective values, one to ensure the system adequately follows the desired reference value and one to reduce steady-state error, are summed and applied to the plant $G_p(s)$. The process’s corrected output is compared to the reference input and the error $E(s)$ is recalculated, continuing the cycle indefinitely.

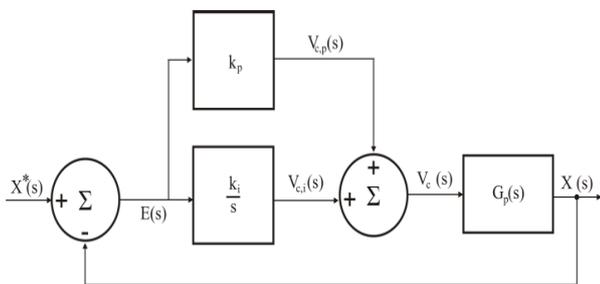


Figure 8: PI Controller Diagram

The error $E(s)$ which is fed into the PI controller can be expressed as:

$$E(s) = X^*(s) - X(s)$$

The proportional gain multiplies the error $E(s)$ times a constant k_p ; a larger error will produce a larger correction $V_{c,p}(s)$ and a small error will produce a smaller correction $V_{c,p}(s)$ as demonstrated in equation 4.2:

$$V_{c,p}(s) = k_p E(s)$$

The proportional gain acts in a linear fashion and can produce a steady-state error in response to a step-change so an integral gain is added to the controller so as to compensate for the proportional gain’s deficiencies. By responding over time to the system’s changing output the integral controller is able to gradually reduce the steady-state error to zero. The correction produced by the integral controller $V_{c,i}$ is expressed as:

$$V_{c,i} = \frac{k_i}{s} E(s)$$

A derivative gain is not used for the control of the elevator’s electric drive because a derivative gain is susceptible to noise in the measurement system and could cause unwanted disturbances.

The open-loop transfer function of the PI controller seen in Fig. 4.2 is:

$$\frac{V_c(s)}{E(s)} = \left(k_p + \frac{k_i}{s}\right) = \frac{k_i}{s} \left[1 + \frac{s}{k_i/k_p}\right]$$

B. Performance of Simulated Electric Elevator Drive with Position Control

For computer simulation the permanent-magnet DC motor parameters determined earlier and the cascaded control system designed earlier are used to build a Simulink model in Matlab which mimics the performance of the actual physical model.

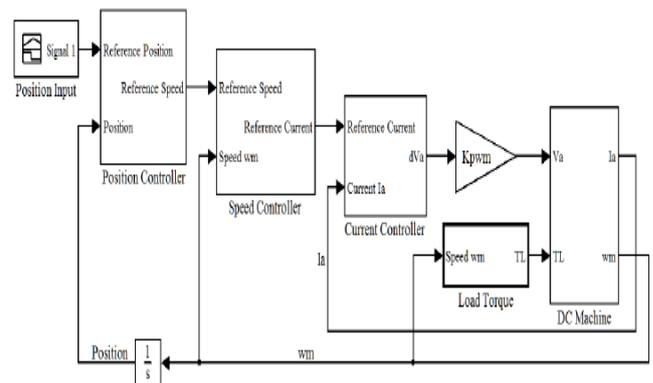


Figure 9: Simulink model of elevator electric drive with position control

Fig.9 shows the cascaded control system and DC drive constructed in Matlab’s Simulink allowing for simulation of the elevator’s electric drive position control. Contained within this model is a subsystem which emulates the permanent-magnet DC motor used to drive the system in addition to the position, speed, and current control subsystems; the load torque placed on the permanent-magnet DC motor is determined within its subsystem. The position input is generated by a signal block which produces a step change in reference position. Also seen in Fig. 9 is an integrator which obtains position from the mechanical speed of the motor and also seen is the gain k_{pwm} which represents the gain of the PPU. The PPU’s output voltage V_a is the product of the DC power supply’s voltage and the duty-ratio dV_a generated by the current controller.

During simulation the position reference signal is generated using a signal builder block which produces a step change in desired height over time. This step input emulates the desired position change by a button press as elevators in the real world often have a button for each floor.

IV. RESULT

Fig. 10 shows the elevator car rising from 0 to a height of 1 meter. Fig. 11 shows the elevator car descending from a height of 1 meter to 0.

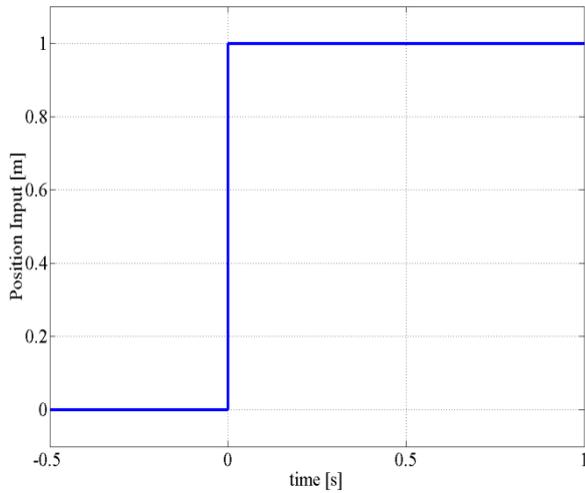


Figure 10: Simulated reference position of elevator electric drive with ascending car

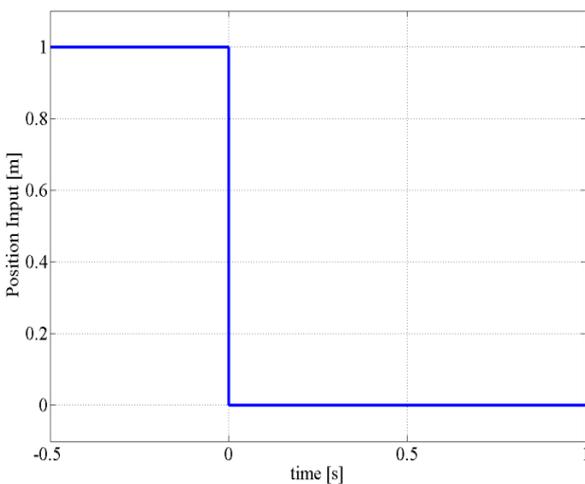


Figure 11: Simulated reference position of elevator electric drive with descending car

The response of the elevator electric drive for the elevator car containing a 1kg load is shown in Fig. 12 through Fig.15 for both the ascending and descending motions.

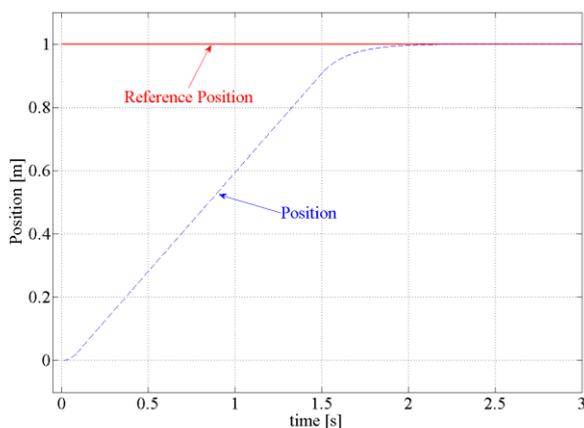


Figure12: Simulated position response of elevator electric drive with ascending car

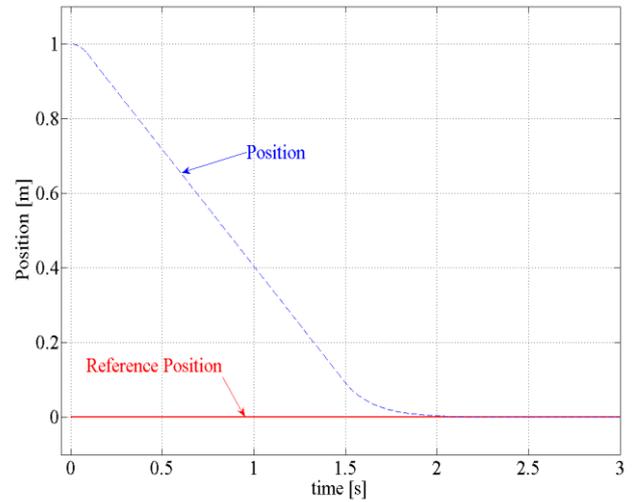


Figure 13: Simulated position response of elevator electric drive with descending car

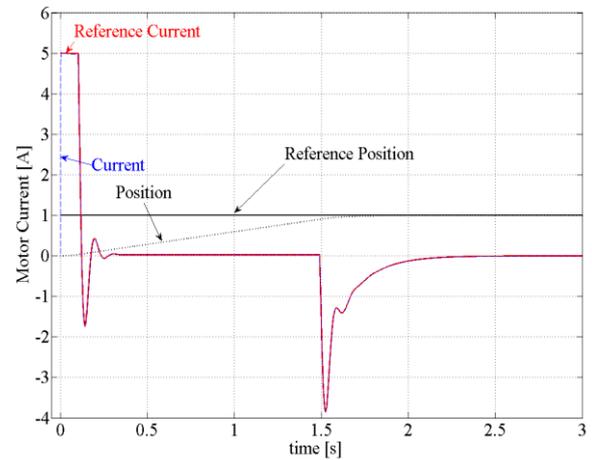


Figure 14: Simulated current response of elevator electric drive with ascending car

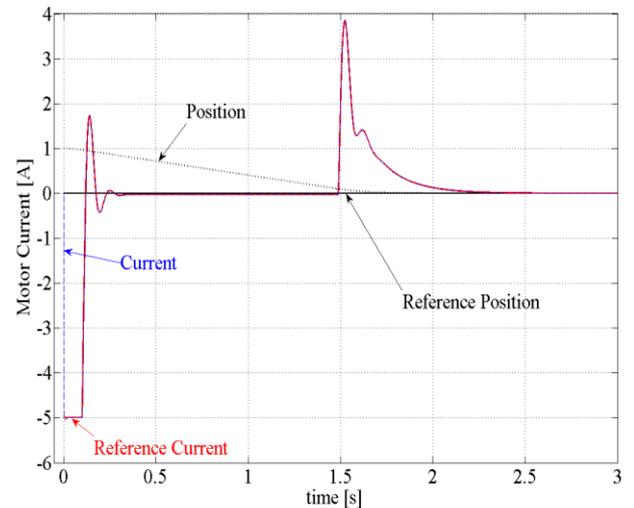


Figure 15: Simulated current response of elevator electric drive with descending car

From Fig. 12 and Fig.13, it is observed that the elevator is able to move a load a distance of one meter in under three seconds.

The current response to the step-change in position is immediate (see Fig. 14 and Fig. 15)

To generate the maximum amount of torque at start-up, the reference current is at its maximum value until the motor's speed matches the reference speed at which point current through the motor is reversed to obtain braking torque in order to prevent the elevator car from accelerating beyond the speed limit. During steady-state operation current remains nearly zero as only friction and gravitational forces must be overcome. As the elevator car approaches the desired set point the motor must once again overcome inertia but in the opposite way as before. To start reducing the speed of the car a braking torque is applied; this torque starts at its maximum value and diminishes exponentially as kinetic energy is bled off from the system.

CONCLUSION

The implementation of position control of an elevator's electric drive was analyzed in this thesis. Forces involved in the mechanical system were determined allowing for the calculation of torque generated by the motor and torque placed on the motor by the load. The electric circuit parameters and mechanical system parameters of the permanent-magnet DC motor were empirically derived using a series of measurements collected from experimental test conducted in the laboratory. Using these parameters the current, speed, and position control loops were designed for the elevator's electric drive. The cascaded control system and permanent-magnet DC motor were modeled in Matlab's Simulink package and position control of the elevator's electric drive was simulated for no load conditions and loaded conditions. With the simulated performance of the elevator's electric drive's ability to arrive at a desired position recorded, testing was conducted in the lab using the permanent-magnet DC motor and scale elevator constructed by the author to collect data on the elevator electric drive to arrive at the desired height in a timely and accurate manner.

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