Energy Saving during modern Lift operation

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Abstract -- In this work, an active regenerative braking converter using a bidirectional Buck-Boost converter is adopted in order to improve the overall efficiency of modern building lifts. The converter is connected in parallel to the inverter DC-bus. Energy is stored in a set of supercapacitors during regeneration and it is transferred back to the DC-bus when the elevator accelerates. In order to test the effectiveness of the proposed converter, a simulation model of the whole lift has been developed and simulation tests have been carried out. To illustrate operation of the whole system, characteristic results are presented and discussed.

Index Terms -- Energy consumption, Motors, Energy efficiency, Supercapacitors.

I. INTRODUCTION

During last decades, significant improvement of the quality and safety of modern lifts has taken place worldwide. Moreover, the reduction of energy consumption has become a key factor for the competitiveness of elevators as it can essentially improve the total energy efficiency of a building.

In order to produce more eco-friendly lifts, starting from the late 80’s, elevator manufacturing companies have replaced the geared motor generator systems with digitally controlled AC gearless drives, reducing so the total energy demand of the system. Additionally, the introduction of more sophisticated driving techniques and the use of modern power electronic converters have further improved the efficiency of the elevator system.

However, the determination of the total energy consumption of an elevator is a complicated task due to the stochastic use and the variety of load and trip distance in annual basis. To this direction, specific guidelines for the energy consumption measurements have been set. The VDI4707 [1] is a generally accepted guideline for the classification of the elevators in energy classes (A to G) based on their power demand under travelling and standby mode.

Nowadays, the research and development efforts of the elevator industries have mainly focused on adopting energy saving methods in order to classify their products in the higher classes according to the VDI 4707 guideline. Several studies [2]-[5] have shown that the standby mode energy consumption is a very important part of the total elevator system consumption (may reach up to 80%) in annual basis. Hence, switching off the lighting and the inverter circuits during intervals that the lift is not used reduces the energy consumption. Another way to reduce the energy consumption is to adopt intelligent decision making methodologies [6], to avoid elevator operation when it is not necessary.

Moreover, the energy demand in travel mode can be reduced in modern elevators by adopting active regenerative braking techniques. Such techniques are already widely used in electric and hybrid vehicles’ applications [7]-[11]. Energy regeneration can be achieved in elevator systems when the lift decelerates, when it descends under heavy loaded cab or when it rises unloaded. Without active regenerative drives, this energy is wasted, as it is transformed into heat in the elevator machine room. Using active regenerative drives, this energy can be transmitted back to the grid or to energy storage units, thus improving the total energy saving amount of the building. Additionally, the cooling requirements of the machine room are also reduced. However, when the generated power is supplied to the building electrical installation power quality problems may rise – due to its pulse waveform. Furthermore, this methodology requires replacement of the control unit and the power converter and cannot be retrofitted to existing installations.

In the present work, the authors propose an active regenerative braking system using a bidirectional Buck-Boost converter. The converter is connected in parallel to the inverter’s DC-bus. The regenerated energy is stored in a set of supercapacitors during the intervals that the elevator decelerates and it is transferred back to the DC-bus when the elevator accelerates. This way, energy has not to be transferred to the utility grid during regeneration. This fact gives the proposed topology a significant advantage: For existing installations in which the DC link of the inverter is fed by a diode bridge, it can be easily applied without changing the topology. Moreover, it is advantageous for newer installations, avoiding energy quality problems that arise if the regenerated energy is fed to the local grid.
In the following sections, the elevator model with all its subsystems is described, including the proposed regenerative braking device (which is analyzed in detail). Moreover, characteristic simulation results are presented.

II. MODELING OF THE ELECTRIC LIFT ELECTROMECHANICAL SYSTEM

The main target of the present investigation is to provide a simulation tool in order to investigate the behavior of an electric lift with given specifications, so that it can be possible to estimate its dynamics, energy consumption and to test its operation when energy saving is being performed, by applying appropriate techniques. Having this in mind, an electric lift model has been constructed. In order to create a more generalized model for the system, the electric motor, gearbox and pulley are modeled as separate parts. For most modern lifts, which are gearless, this model can work as well if a speed ratio of 1:1 and unitary efficiency is defined for the gearbox and assuming that the correct parameters are given for the motor model. Amongst the rest system parts, the electric drive, the mechanical system and the power saving unit will be described in the following paragraphs. The block diagram of the full system is shown in Fig. 1; the active regenerative braking device is connected to the DC bus. The two switches permit the connection and disconnection of the passive braking device and the active regenerative braking device (buck-boost converter), so that different topologies can be tested.

A. The drive system

As shown in Fig. 1, the lift is powered by a three-phase motor, fed by a three-phase inverter. The control unit has been designed to operate in two modes: a) test mode and b) running mode. In test mode the control unit calculates the appropriate control signals in order to drive the motor to the desired speed, using an auxiliary speed profile. Thus, different speed profiles can be applied by setting the reference signal. This mode is implemented in order to have the flexibility to test the system operation in open loop (without any position feedback). On the other hand, running mode uses position feedback and so it provides more realistic operational conditions, including elementary elevator automation logic (e.g. if the cabin has to stop at x-floor, deceleration must start n-secs before the arrival at this floor).

B. The mechanical system

The mechanical system consists of the following main parts:

1) The gearbox model

A realistic model has been developed for the gearbox, based on a simplified approach. The main model equations are:

\[ N = \frac{\omega_1}{\omega_2} \]  
\[ P_1 = \omega_1 \cdot T_1 \]  
\[ T_2 = \eta \cdot N \cdot T_1 \]

where \( N \) is the gear ratio, \( \omega_1, \omega_2 \) are the angular velocities of the input and output shaft respectively, \( T_1, T_2 \) are the torque values at the input and output shaft respectively, \( \eta \) is the nominal gearbox efficiency. Note that the input shaft is defined as the shaft in which the energy enters the system; therefore it is a different one for normal operation and for regeneration mode.

The efficiency factor is used in order to take power losses into account [12]. This is achieved by storing a normalized friction profile in memory and adapting it to the system considering nominal efficiency.

![Fig. 1. Block diagram of the system under study.](image-url)
2) The cabin dynamics

Supposing that \( L \) is the active length of the rope that supports the elevator cabin and \( x \) is the distance between the cabin and the pulley, the necessary force \( F \) for the cabin vertical motion is,

\[
F = g_w(L - 2 \cdot x) + G_C + G_P - G_A
\]  

(4)

where \( G_C \) is the cabin weight, \( G_P \) is the passenger(s) weight, \( g_w \) is the specific mass of the rope and \( G_A \) is the weight of the elevator counterweight.

Given that \( D \) is the driving pulley diameter, the load torque \( T_{\text{load}} \) is given by:

\[
T_{\text{load}} = F \cdot D/2
\]  

(5)

The equivalent moment of inertia \( J_{\text{equiv}} \) of the linear system, normalized to the subsystem input axis, is:

\[
J_{\text{equiv}} = (g_w \cdot L + G_C + G_P + G_A) \cdot D^2/4
\]  

(6)

Given these basic equations and by adding a simple model for friction losses, the mechanical model of the cabin has been created. The parameters’ settings of the cabin and the related motion system have been incorporated in a dialog window, as shown in Fig. 2.

C. The active regenerative braking unit

1) Structure of the active regenerative braking converter

A bidirectional buck-boost converter [13]-[17] has been designed and simulated as shown in Fig. 3. The converter input is connected in parallel to the DC bus and its output is connected to a set of supercapacitors. It operates as a buck converter when the elevator generates energy, charging so the supercapacitors. On the contrary, it operates as a boost converter when the elevator consumes energy discharging the supercapacitors. As it is presented in Fig 3, the upper IGBT controls the buck operation while the lower IGBT controls the boost operation. Both IGBTs operate at the same switching frequency while their duty cycle is determined by the DC bus voltage, which in turn depends on the elevator’s state of operation.

Both buck and boost converters have been designed to operate in continuous conduction mode (CCM) in which the inductor is partially discharged during any switching period.

The DC voltage transfer ratio for the CCM in Buck operation is given by (7), while (8) gives the DC voltage transfer ratio in Boost operation. In both equations \( V_O \) is the supercapacitors’ bank voltage value and \( V_S \) is the DC bus voltage value. Additionally, \( D_{\text{buck}} \) and \( D_{\text{boost}} \) are the duty cycle values for buck and boost operation, respectively.
According to the above equation set, the inductance value has to be higher than the maximum of these two boundary values; these two boundary values are [16]:

\[
\frac{v_g}{v_s} = D_{buck}
\]

(7)

\[
\frac{v_s}{v_o} = \frac{1}{1-D_{boost}}
\]

(8)

The minimum inductance value in order to keep the converter within CCM area is different for buck and boost operation modes; these two boundary values are [16]:

\[
L_{Fb,buck} = \frac{v_s}{f_s I_{o,min,buck}} \frac{D_{buck}(1-D_{buck})}{2}
\]

(9)

\[
L_{Fb,boost} = \frac{v_o}{f_s I_{o,min,boost}} \frac{D_{boost}(1-D_{boost})}{2}
\]

(10)

According to the above equation set, the inductance value has to be higher than the maximum of these two boundary values; in this way, CCM operation is reassured for both operation modes. It is noted that \( f_s \) is the converter constant – regardless the operation mode – switching frequency and \( I_{o,min,buck}, I_{o,min,boost} \), are the minimum output current values for buck and boost operation respectively, for maintaining within the CCM area. Obviously, the lower the minimum output current requirement the higher the necessary inductance.

2) Control of active regenerative braking operation

During elevator operation, the converter charges the supercapacitor (buck mode) whenever the traction motor inverter regenerates energy. As the diode bridge rectifier cannot send energy to the grid, regeneration can be sensed in the overvoltage which occurs when power flows from the motor windings to the DC link. Thus, the control logic of the active regenerative braking uses the filtered DC link voltage value to activate. Generally, the control logic of the regenerative braking unit can be summarized as follows:

- During startup, the supercapacitor is charged until a minimum voltage level \( V_{achv} \) is reached.
- During normal operation, the converter that charges the supercapacitors (buck mode) whenever the DC link voltage exceeds the threshold value \( V_{dbuck} \).
- Following a regenerative braking, whenever the traction motor requests energy, the boost mode is activated, transferring electric energy to the DC link. This action is permitted as long as the supercapacitor bank voltage remains higher than \( V_{achv} \).
- Whenever the supercapacitor reaches a high charging level (\( V_{achv} \)), it should be discharged, transferring energy to the DC link. However, if this is not possible, because the elevator is in standby mode or is still in regeneration mode, no more energy can be stored. If this limit is reached, then the active regenerative braking converter is not effective anymore.

It becomes apparent that sizing optimization for each individual component of the system is essential for efficient operation of the regeneration function. However, as the reach of certain limits depends on the cabin load and the operating conditions as well, the classical passive regenerative breaking device is retained in this configuration for security reasons.

III. SIMULATION RESULTS

The whole system has been modeled in Simulink environment and extended simulation tests have been carried out. The elevator parameters’ settings for these tests are shown in Table I.

<table>
<thead>
<tr>
<th>TABLE I ELEVATOR MODEL PARAMETERS</th>
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<tbody>
<tr>
<td><strong>Motor Nominal Power</strong></td>
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<tr>
<td><strong>Cabin weight</strong></td>
</tr>
<tr>
<td><strong>Passengers weight</strong></td>
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<tr>
<td><strong>Counterweight</strong></td>
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<tr>
<td><strong>Vertical distance between floors</strong></td>
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The following simulation results stand for the elevator operation during two cycles. Each one of them consists of a transition to the higher floor (e.g. from 1st to 20th) and vice versa. In Fig. 4 the cabin speed profile during this operation is depicted. Additionally, Fig. 5 illustrates the current in the active regenerating converter coil, while Fig. 6 and Fig. 7. present the supercapacitor voltage and the converter energy flow, respectively. Moreover, Fig. 8 and Fig. 9 show the total energy consumption and the heat dissipation to the brake resistance respectively, with and without the application of active regenerative braking operation. Finally, the DC link voltage with and without the application of active regenerative braking is illustrated in Fig. 10. It is worth noting that according to Fig. 8, although the braking action starts only if DC-link voltage value exceeds 750 V, in order to store in the DC-link as much energy as possible (leading also to higher voltage stresses on the semiconductor switches), there is still a significant improvement in energy consumption.

**Fig. 4. Cabin linear speed as a function of time.**

**Fig. 5. Current in the active regenerative braking converter coil. Positive values indicate the operation in buck mode, while negative values indicate the operation in boost mode.**
IV. CONCLUSIONS

In order to test the proposed regenerative braking system, a full system simulation has been carried out. In this paper the elevator electromechanical system has been described and key parts have been analyzed. Moreover, the structure and modeling concepts of the regenerative braking model have been presented. Simulation results indicate that a significant amount of energy can be restored under certain design directions and operational circumstances; thus, further investigation and development of the proposed concept has to be carried out. Also, the simulation process takes significant time to complete, even for the simulation of a few seconds of operation. For this reason, a next step on this project is to use advanced simulation techniques in order to achieve reasonable simulation times without deteriorating the accuracy of the energy saving calculations.

V. REFERENCES


VI. BIOGRAPHIES

Epaminondas D. Mitronikas was born in Agrinio, Greece, on March 31, 1973. He received the Dipl.-Eng. degree in electrical and computer engineering from the Department of Electrical and Computer Engineering, University of Patras, Rio-Patras, Greece, in 1995. He received the Ph.D. degree in Electrical Engineering in 2002. He is currently an Assistant Professor at the Department of Electrical and Computer Engineering, University of Patras. His research interests include electrical machines, power electronics, simulation and digital control of electric motor drive systems and control of low power electromechanical systems. Prof. Mitronikas is a member of IEEE and the Technical Chamber of Greece.

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