A MATLAB/Simulink Based Journey-Based Lift Energy Consumption Model

Lutfi Al-Sharif, Mohammad Al-Ahdab

Mechatronics Engineering Department, School of Engineering,
The University of Jordan, Amman 11942, Jordan

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Abstract. A number of different approaches have been used in order to calculate the energy consumption of lifts. Such approaches have ranged from simple rules of thumb, to lookup tables, more detailed equation-based models and simulation-based models. This paper presents an approach based on the use of MATLAB/Simulink to model the various components used in a lift in order to calculate the power drawn during the lift journey as well as the total energy consumption. The model comprises a number of modular blocks, such as the variable speed drive, the induction motor, the gearbox, the ropes, the lift car, the counterweight as well as the passenger load.

The main advantage of this model is that it models the energy accurately based on the mechanical and electrical design of the system, as well as the kinematic parameters Moreover, the model is open source, transparent and intuitive (as it is based on the dragging and dropping of modules). The model offers a platform for any lift system designer to calculate the energy consumption of the system based on the electrical and mechanical components of the system.

1. INTRODUCTION

Much work has been carried on the topic of lift energy consumption. The basis for these pieces of work can be categorised into three categories: simple rules of thumb, lookup tables, equation-based models and simulation-based models. Some of these use analytical equations developed from first principles [1], others employ measurements of real systems [2], and there are models that use the measurements of real systems to calibrate the analytical equation based models [3, 4]. A general overview of the different energy consumption models and research can be found in ([5], [6], [7]). An example of using the energy measurement in order to find the parameters of the lift system can be found in [8]. An analysis that analyses the payback period that could result from adding a variable frequency drive to a lift system can be found in [9]. Energy consumption has also been suggested as a performance parameter to be compared between different systems [10].

The motivation for modelling energy consumption in lifts is to allow the user of such a model to predict the instantaneous, daily or annual energy consumption of the lift without the need to carry out actual measurements on the lift, for the following reasons [2]:

1. Convenience: It is much easier and more convenient to be able to calculate the expected energy consumption under different scenarios without the need for measurement.
2. Restriction or difficulty of access and the requirement for resources: access to assets is often restricted due to operational requirements. Carrying out measurements requires specialised equipment and much care during the process of measurement (e.g., measuring at the correct incoming point of the supply; distinguishing between the main asset and the ancillary equipment; using three-phase equipment in cases where the load on the three phases is not balanced). Moreover, the results from the measurement are only applicable to the specific

conditions prevalent at the time of the measurement (e.g., number of passengers on that specific day; mechanical condition of the asset at the time of measurement).

3. The lift might not have been built yet: this is especially true for product designers who need to assess the effect that their design decisions will have on the expected future energy consumption of the product. An example of a study looking at the effects of mechanical design on power consumption can be found in [11]. A good example of such a system is a hypothetical two-dimensional lift system in a large building [21, 22].

4. The proposed modification or operational change has not been implemented on the asset yet: this is especially true where a client is offered a design modification or an operational change on the asset and he/she needs to determine the expected effect that such a change will have on the energy consumption. The expected energy saving can be weighed against the cost and risk of the proposed design modification or the operational change (e.g., the effect of lift traffic is analysed in [12], the effect of the group control algorithm can be found in [24, 25], the effect of passenger traffic on escalator energy consumption can be found in [13]; and the effect of lift velocity can be found in [14]). Another good example is for a system that attempts to feed electrical power from one lift to another in order to avoid passenger entrapments in case of a power failure [4].

As with all other means of transport, the energy consumption of lifts does not solely depend on the asset itself (mainly defined by its electrical and mechanical design). The energy consumption of any means of transportation asset depends on the following four important factors:

1. The electrical and mechanical design of the asset (e.g., the effect of the mechanical design on escalator energy consumption [15]).

2. The quality of asset maintenance: maintenance has an important effect on the efficiency of a mechanical asset and associated frictional losses.

3. The methods of control and operation: this factor has great importance in lift systems. It is well known that the energy consumption of a group of lifts depends on the method of allocation of the landing calls to the lifts [24, 25].

4. The characteristics of the passengers using the asset (e.g., number of daily passengers, their arrival pattern, and their behaviour) [12]. For this reason, any lift energy consumption tool would need to be intricately linked to a lift traffic simulator. Research has been carried out to link the energy consumption to passenger demand response [23].

It is thus meaningless to talk about the energy consumption of an asset solely based on its electrical and mechanical design, without taking into consideration the level of maintenance, the method of operation and control as well as the characteristics and behaviour of the passengers using it.

This paper used MATLAB/Simulink for lift energy modelling and simulation. The blocks can be adapted to suit the actual components used within the lift being analysed. Simulink has been widely used to model and simulate electrical machines in general ([16], [17]). It was also used to Mechatronic system education by modelling the operation of a DC motor operated lift [18].

Section 2 provides a high-level overview of the model and the rationale for using it. Section 3 describes the components of the model in detail. Section 4 provides some representative results.

2. OVERVIEW OF THE MODEL

This paper develops a Simulink based model for the evaluation of the energy consumption of a traction lift system. It is mainly based on the model that can be found in [19]. A similar approach was used in [20] but with a different set of equations. The model in [20] calculates the required value of the torque, while the model described here divides the net torque by the second moment of mass and then feeds back the resultant rotational speed. The model uses a widely available installation of lifts on the market that assumes the following:

1. The lift system uses a squirrel cage induction motor.
2. The induction motor is driven by a variable frequency drive system. The variable frequency drive system employs an uncontrolled six pulse rectifier, followed by a capacitor and then a six pulse IGBT inverter. The inverter employs flux-vector control. It is acknowledged that lift variable speed drive systems employ different types of inverters, such as flux vector control, direct torque control (DTC) and scalar control. By changing the block used, it is possible to simulate the different types of drives as well as their effect on the energy consumption.
3. The system runs under closed loop control and it is assumed that some form of feedback for the motor speed is provided to the controller (e.g., using an incremental shaft encoder).
4. The ropes have been modelled within the system. Only the suspension ropes have been modelled. It is possible in a future version to include the compensation ropes as well.
5. It has been assumed that the system employs a gearbox to match the speed and torque from the motor to the load.
6. The car mass has been assumed to be equal to the passenger rated load, and the counterweight ratio can be changed by the user. The user can easily change the assumption about the mass of the car and the rated load being equal. This is just a simplification.
7. Other mechanical aspects are incorporated into the model, such as the viscous friction and the gearbox efficiency.

In order to initialise all the parameters, a MATLAB script file is used that will be run at the beginning and assign all the parameters their intended value.

Some of the blocks have been used without any change from Simulink, but other models have been built from scratch. This feature from Simulink allows any user to adapt the model to his/her application. The following are two of the limitations of this model:

- It only provides the energy consumed for one journey. So, it would need too be linked to a traffic simulator in order to aggregate the energy consumed over a day or a year.
- The parameters of the mechanical model are embedded inside the blocks, rather than being modelled as mechanical components.

The model is effectively open source, and this gives it a great educational advantage. A link is given at the end of this paper for those interested in downloading it. The next section provides a detailed description of the blocks of the model.

3. DESCRIPTION OF THE BLOCKS IN THE SIMULINK MODEL

This section describes the simulation model used in detail. A block diagram of the whole model is shown in Figure 1. It shows a modular approach to building the model. The main advantage of this method of energy modelling is that it takes into consideration the dynamic characteristics of the system. This offers the advantage of being able to alter the control algorithm in order to optimise the energy consumption. The model comprises the following eight modules:

1. The speed time profile generator: this block generates the speed time profile for the lift journey. It uses four parameters, namely: the journey distance, the rated speed, the rated acceleration, and the rated jerk. This forms the basis of the operation of the model, as the system uses the speed-time profile curve as the set value for the closed loop speed control system. This block specifically mirrors a similar block that is available in all variable speed drive systems in modern lift speed controllers.

2. The Flux Vector Control: this block contains the PI parameters. It forms the controller for the closed loop control system that controls the motor in order to produce the required torque and speed. Although PID (proportional-integral-differential) controllers are widely used in many industrial control systems, lift controllers usually only use PI (proportional-integral) due to the slowly changing nature of the reference signal generated by the speed time profile.

3. The rectifier block: this block contains the six-pulse uncontrolled rectifier that converts the supply from the three phase source into dc. It also contains the components necessary for the regenerative feature.

4. The Inverter Block (IGBT inverter): this unit contains the six IGBT's the control the squirrel cage induction motor (SCIM). The firing pulses for the six-IGBT's are received from the Flux Vector Control unit.

5. The motor block which contains the model of squirrel cage induction motor (SCIM) used as the hoisting motor and the processing necessary to extract the torque from the motor and feed the actual speed.

6. The Mechanical System block which contains the details of the system inertia (second moment of mass) referred to the low speed shaft (LSS), the passenger mass, the frictional model and the implementation of the rotational equivalent of Newton's second law applied on the low speed shaft (LSS). Even though MATLAB/Simulink contains some advanced dedicated mechanical component blocks (in SimMechanics), these have not been used in this model due to their drastic impact on the running time of the simulation.

7. The power supply: This comprises the three-phase source and contains components that enable the regenerative feature.

8. The Power Meter: This unit measures the real power flowing from the power source to the lift system.

It is worth mentioning that the model allows for full regeneration back into the power supply when the lift is over-hauling. The voltage of the dc link (i.e., the voltage on the capacitor of the dc bus) is continuously monitored and compared to a pre-set value of 725 V. It is assumed that rated three phase supply voltage is 400 V rms (line to line), based on a phase voltage of 230 V rms. This gives an average dc link voltage from the output of the six-pulse uncontrolled rectifier of 538 V dc. Thus, the threshold for the dc link has been set higher than this value assuming that the voltage rating of the dc link capacitor is 1000 V dc.

Whenever the voltage on the dc link exceeds this pre-set value, the regenerative unit starts operating. An inverter starts producing a three phase AC voltage from the dc bus and feeding the three phase AC voltage back to the supply. A low pass filter comprising a series inductor and a shunt capacitor is used to filter the voltage. A controlled current source is then used to feed the energy back into the supply. This feature can be used to show the effect of selecting a fully regenerative drive system.

4. SOME REPRESENTATIVE RESULTS

The model was setup for a typical small size lift installation. It was run for one single journey of 4.5 m. Some results are shown below to illustrate the possible outputs that can be extracted from the model.

The system is set up to log the following: three phase currents drawn by the motor, the power drawn by the system from the three phase source, the motor speed, the torque from the motor, the displacement against time, the speed against time, the acceleration against time and the jerk against time, the voltage on the dc bus (i.e., on the capacitor), whether the system requires braking or driving at one point.

Figure 2 shows the instantaneous values of the three-current drawn by the motor during the full lift journey. It is obvious how the frequency of the current is low at the beginning, high in the middle of the journey and then low again at the end of the journey, corresponding to the speed of the motor during the journey. It can also be seen how the magnitude of the current is large at the beginning due the large toque required at the beginning to accelerate the translational and rotational masses.

Figure 3 shows the plot against time of the active (real) power drawn by the system from the source. It is worth noting that for most of the time the power is drawn from the supply, but for a short period of time no power is drawn. This is the period of braking. Figure 4 shows the speed-time profile (reference speed and actual speed) against time. It shows how close the two values are similar to each other, showing how effective the closed loop control system is in keeping the speed equal to the reference value

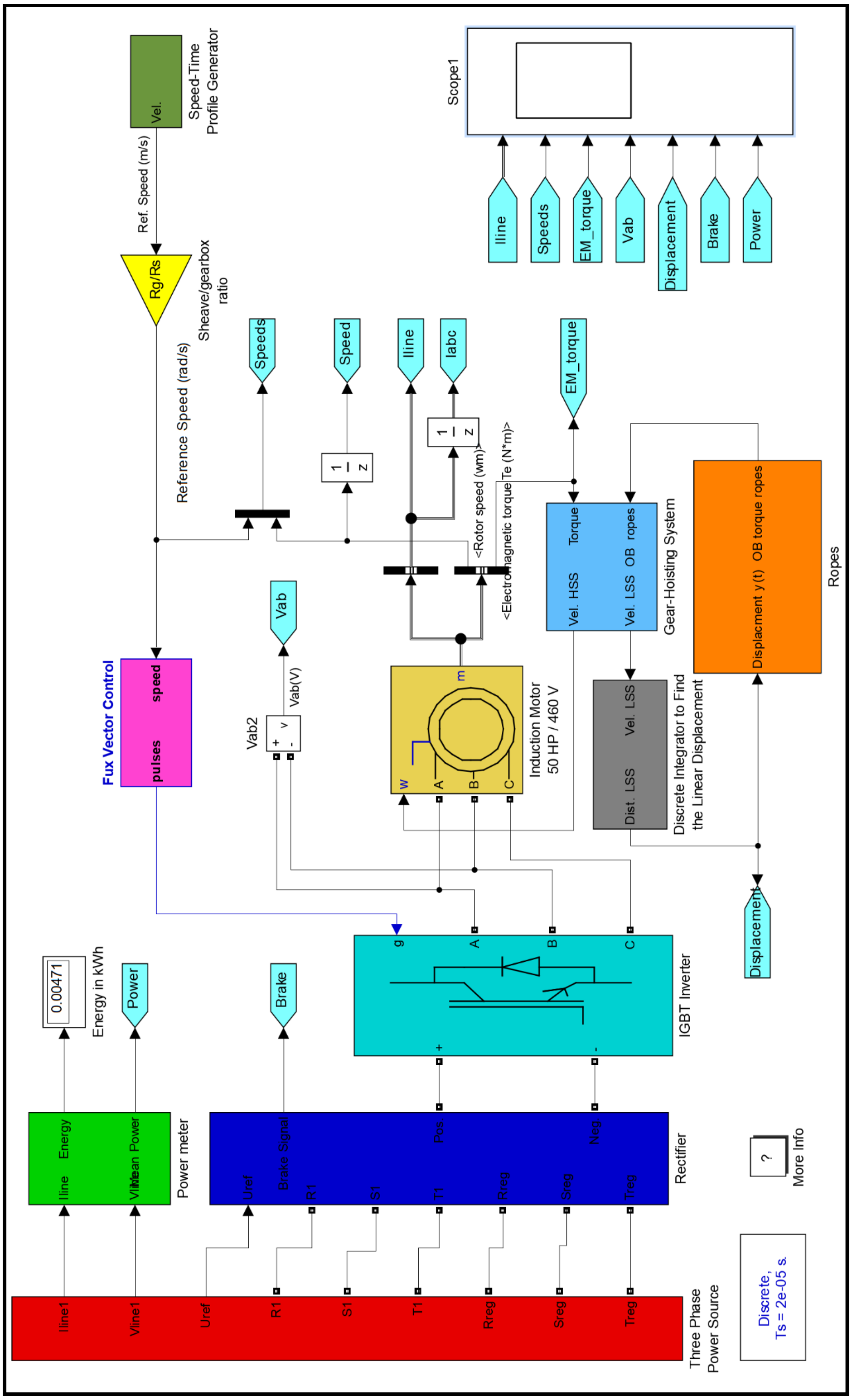

Figure 1: Block Diagram of the Energy Model from Simulink.

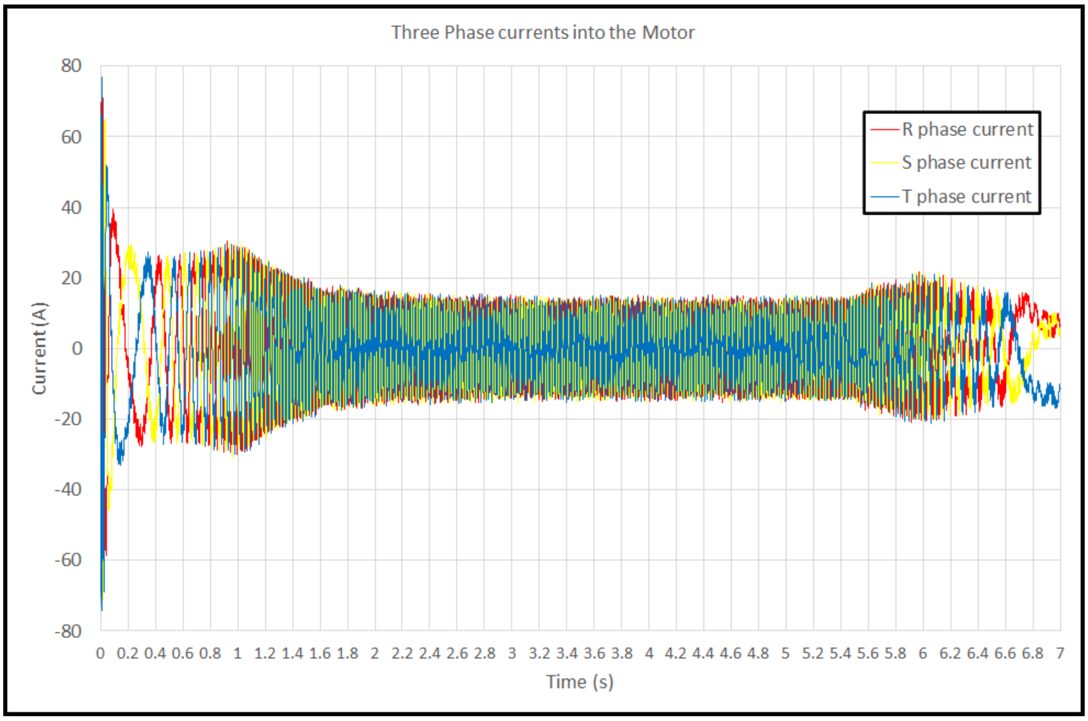

Figure 2: The three phase currents drawn during the journey.

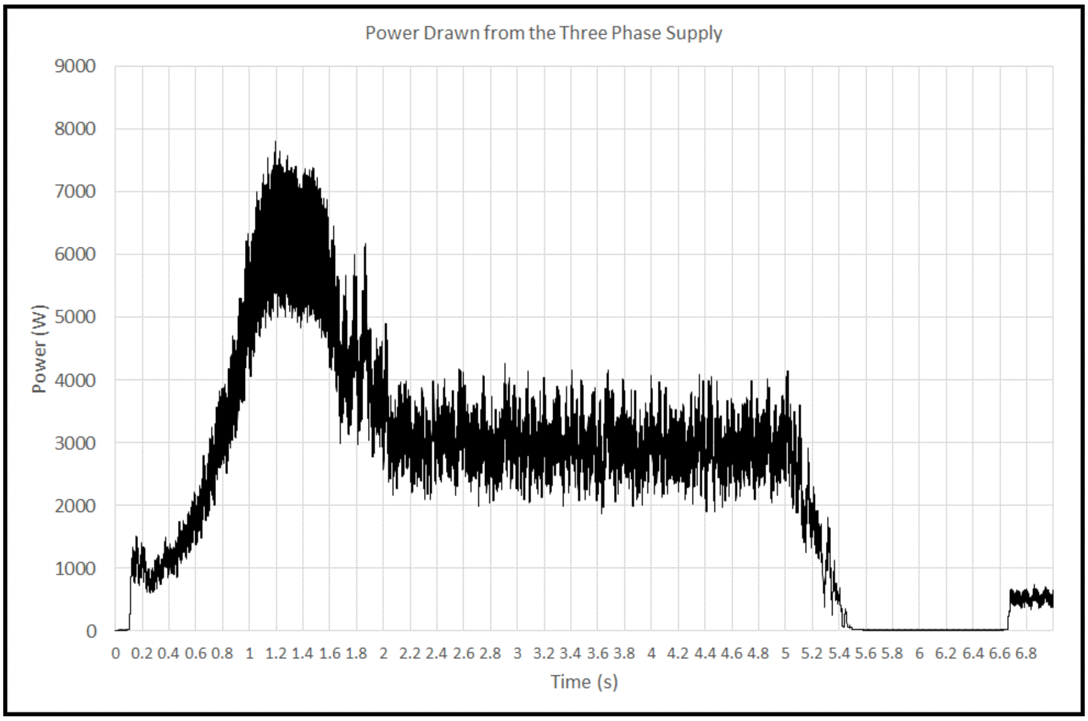

Figure 3: Power drawn by the motor during the journey.

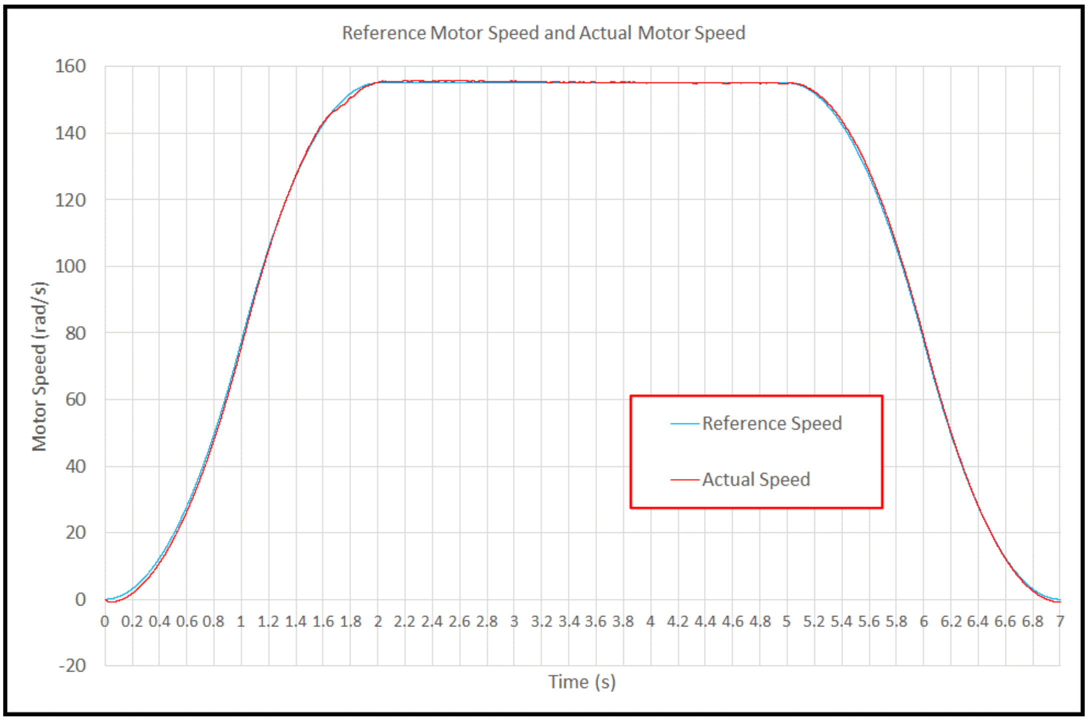

Figure 4: Reference motor speed and actual motor speed in rad/s.

5. CONCLUSIONS

A component-based energy lift model has been designed and tested in Simulink. The main components were explicitly represented in the model including the squirrel cage induction motor, the variable frequency drive (including the rectifier, the capacitor on the dc bus and the inverter), the regenerative unit (that is used to feed power back into the mains), the closed loop feedback controller (PI controller in this case), the viscous friction, the inertia of the rotating and translating masses, the ropes, the mass of the car, passengers and counterweight. The model simulates the full system in real time, timeslice by timeslice, thus providing a micro-scale view of the flow of energy, as well as faithfully representing the dynamic response of the system.

The model contains a speed time profile generator, that produces the exact speed profile that the system should follow. The output from this block becomes the reference value and is used in the closed loop control system to drive the speed of the motor and thus the lift. Such a system captures the dynamics of the system very accurately.

One of the main advantages of a component-based-model is that it clearly segregates each component of the model mathematically and even graphically, which makes it easy and transparent for the user to change the parameter of each component or even change the complete component. Although in real life systems, a time-lag exists between the consecutive blocks, this has not been simulated in this model. It is possible in the future to use one or more timeslice delay blocks (z^{-1}) between the consecutive models.

A numerical example of a lift system was run and samples of results were shown in the paper, including the reference and actual speed time profiles against time, the power drawn from the supply and the instantaneous three phase currents drawn by the motor.

Further work will be carried out in carrying out detailed comparisons between the model results and logging data from real lift sites.

Source Code: The following is the link to the Simulink file and the associated script file: **DOI:** 10.13140/RG.2.2.33365.65762

BIOGRAPHICAL NOTES

Lutfi Al-Sharif is currently Professor of Electrical Engineering at Al-Hussein Technical University in Amman/Jordan and jointly Professor of Building Transportation Systems at of the Department of Mechatronics Engineering, The University of Jordan. He received his Ph.D. in elevator traffic analysis in 1992 from the University of Manchester, U.K. He worked for 10 years for London Underground, London, United Kingdom in the area of elevators and escalators.

In 2002, he formed Al-Sharif VTC Ltd, a vertical transportation consultancy based in London, United Kingdom. He has over 30 papers published in peer reviewed journals the area of vertical transportation systems and is co-inventor of four patents and co-author of the 2nd edition of the Elevator Traffic Handbook.

He is also a visiting professor at the University of Northampton (UK), member of the management committee of the annual Symposium on Lift & Escalator Technologies and a consultant for Peters Research Ltd.

He is a passionate believer in making higher education simple and accessible for engineering students and has a You Tube channel on engineering that has more than 55 000 subscribers and around 8 million views. He has also been working as a member of the METHODS Erasmus+ Project that aims to improve teaching methods in higher education in Jordan and Palestine. He is also the author of the Mechatronics Engineering Module on Saylor.org.

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