EVALUATION OF INTELLIGENT CONTROLLERS FOR IMPROVING ELEVATOR ENERGY EFFICIENCY

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Abstract

In recent years, conservation of energy without degradation in performance has become a major trend in the transportation sector. Elevator operations have two modes: running and stand-by. In this study, the authors developed an algorithm to achieve notable energy savings in elevator systems and designed an energy-saving elevator system capable of manipulating its speed in the running mode. Speed was varied based on the load carried and acceleration was varied based on the number of floors traveled. The total travel time of the system was examined in the context of enhancing overall performance. The algorithm was tested with various traffic patterns during peak and non-peak hours. Simulated performance was compared with that of constant-speed elevators. This method produced a 12.35% energy savings and 5.49% reduction in travel time during non-peak hours and 5.06% energy savings and 1.32% reduction in travel time during peak hours of traffic.

Introduction

In recent years, energy savings in electrical systems has grown into an important consideration for sustainable development. With the growing urban population, the use of elevator systems has increased rapidly over the last 20 years. Figure 1 illustrates the approximate number of elevators installed in some major countries [1]. Surprisingly, efforts towards reducing energy consumption tend to degrade system performance. Thus, optimization in terms of performance and energy (facing a trade-off) is necessary.

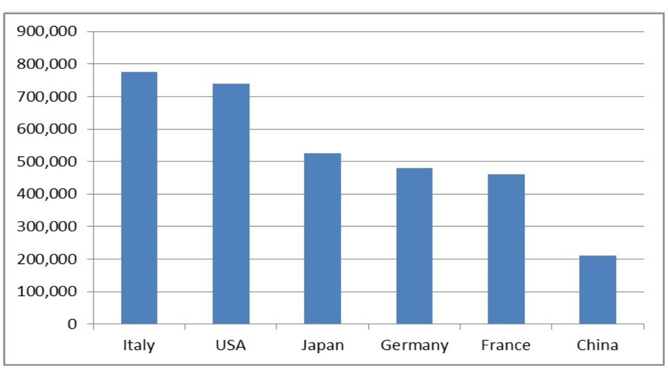

Figure 1. Installed Elevators across Different Countries

Various mechanisms are involved in the movement of elevators. Traction lifts have become prevalent in recent years. In traction lifts, the car is suspended by ropes wrapped around a sheave that is driven by an electric motor. The weight of the car is usually balanced by a counterweight that equals the mass of the car plus 45% to 50% of the rated load. The main purpose of the counterweight is to ensure that a constant potential energy is maintained in the system [2]. There are two types of traction: 1) geared lifts, typically used in midrise applications where high speed is not a prime factor, with a reduction gear to reduce the speed of the motor; and 2) gearless lifts, used in high-rise applications where the sheave is directly driven by the motor, thereby eliminating the losses in the gear. In such cases, both motor and sheave rotate at the same speed [2] and the counterweight balance ensures that sufficient tension is maintained in the suspension system. It enforces adequate traction between ropes/belts and the drive sheave. Also, the entire system maintains a near constant potential energy level, heavily reducing energy consumption [2].

There has been a significant development in optimization of elevator controllers in terms of energy efficiency and reducing average waiting and transit time. A recent study includes implementation of artificial intelligence and fuzzy logic in elevator controllers to optimize the passenger service. This paper examines speed manipulation of the elevator based on load to achieve energy savings. A trade-off between speed and the load torque is kept such that their product is constant.

Related Work

In the recent past, several ideas have been proposed for energy savings in elevator systems. In this study, several methods for energy savings were considered: regenerative energy feedback, loss reduction to obtain optimum energy utilization, energy storage and discharge using capacitors [3], and speed manipulation. Similar other studies were carried out using super capacitors [4] and pulse width modulation (PWM) converters [5]. Another study [6] proved that, when observed for a prolonged duration, there exists a traffic pattern in multi-level buildings that repeats day to day. Furthermore, a simulation method was developed to analyze energy consumption based on elevator load and traffic patterns. This method compared the energy savings of various drive systems and machinery as well as control systems. This provided insight for this current study on energy consumption of elevator systems.

Furthermore, several efforts have been established attempting to reduce waiting and transit time of the elevators as well. Current research has focused on implementation of artificial intelligence (AI) and neural networks in elevator group control systems, which assigns the elevator cage based on its demand at that instant in time. In these efforts, elevators undergo a training period in which the system establishes a definite traffic pattern corresponding to the building. This helps in the process of prioritizing the floors based on the requirement during up-peak and down-peak hours of the day. Energy consumption is reduced even in optimal assignment of an empty cage based on the historical need of each hour [7], [8].

Energy conservation is also made more effective in elevator group systems with intelligent algorithms to control all the lifts in the system, which requires optimal assignment of each cage to a particular floor [9]. This reduces energy use and improves passenger wait time. A recent study based on an ant colony algorithm documented improvement of energy conservation in elevators for peak traffic flow [10]. Another study examined a genetic algorithm designed for energy savings, which supports a 23.6% increase in conservation but also causes a significant increase in average service time [11]. Thus, energy savings beyond a particular limit may degrade the performance of the elevator; hence, the aim of this current study was to optimize energy savings without adversely impacting system performance.

Development of the Idea

The authors considered energy conservation in traction elevators driven by electric motors. Normally, traction elevators move at a constant speed irrespective of the load they carry. This leads to inefficient use of energy. Adjustment of speed based on load is needed for more energy-efficient operation [12].

Basic Algorithm of the Elevator System

With the aforementioned focus, elevator speed was varied based on the load carried by the cart. In determining the load, consideration was given to the counterweight of the elevator. Also, travel time was measured in order to estimate overall performance. A simple algorithm, by which a single elevator can decide how to move and where to stop, can be summarized as follows:

1) Continue traveling in the same direction while there are remaining requests in that same direction.
2) If there are no further requests in that direction, then stop and stay idle, or change direction if there are requests in the opposite direction.

According to the calls, the elevator determines the direction of movement and satisfies them based on a fixed priority (floors along the direction of movement are given priority). A constant-speed elevator moving at 1m/s was considered as the reference for this study. A MATLAB plot of elevator speed of such an elevator with respect to time is given in Figure 2 for a fixed traffic pattern. The elevator either travels at 1m/s (after acceleration) or remains idle at 0 m/s (after deceleration).

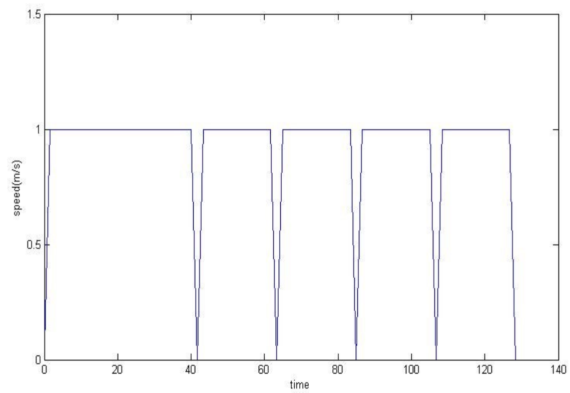

Figure 2. Plot of Elevator Speed between Various Floors

Proposal of the Idea

The drive motor of a traction lift is required to move the load in the elevator cart. In order to reduce the size of the drive motor, the weight of the car plus a proportion of the maximum weight of the passengers (the rated load) is balanced by a counterweight. The commonly used value for counter balancing is 50%. For an elevator with 50% counter balancing, when it is partially full with passengers, the motor only needs to overcome a much smaller load in order to move the elevator. The rating, R (in N-m/s), of an elevator motor with efficiency ç is related to the out-of-balance load, B (in kg), and rated speed, v (in m/s), as given in Equation (1) [13]:

$$R= 9.81 * (B * v) / (ç) \qquad (1)$$

Thus, for a fixed efficiency, any change in load gets compromised by a subsequent variation in the speed of the elevator. The initial idea is as follows:

1) Operate the motor at its rated full load power in order to achieve the maximum possible efficiency.
2) Vary the steady speed of the elevator, based on the weight carried, in a way that the motor operates closer to its rated full load power.
3) The upper limit on speed, taking passenger comfort into consideration, is decided by: *TimeConstant ≥ 4*TimeAccDecel*, which is termed as the time constraint equation, where, TimeConstant is the time the elevator runs at constant speed, and TimeAccDecel is the time for acceleration or deceleration.

The lower limit for the elevator speed is the speed at which the elevator would run if the variable speed algorithm were not applied. This proposed algorithm will hereafter be referred to as "*variable speed*."

Implementation of the Algorithm

The time constraint equation previously explained prevented excess energy usage during acceleration/deceleration time. The algorithm was tested under varied traffic conditions and the result was compared with a constant-speed elevator. The algorithm was successful in producing energy savings and travel time reduction during non-peak hours of traffic, while during peak hours, it was found that more energy was consumed than the constant-speed method. Hence, appropriate manipulation of the algorithm was required in order to produce significant energy savings under varied traffic patterns during the day.

Revised Algorithm to Increase Efficiency under Varied Traffic Intensity

The following changes were made to the algorithm:

1) Increase the speed range of operation by a small amount (the lower limit was decreased and the upper limit increased by a small amount).

2) Vary the acceleration based on number of floors the elevator has to move, relaxing the time constraint condition to 'Time constant >= 3*TimeAccDecel', thereby significantly reducing the travel time. For example, in a 10-floor building, it would mean an acceleration value (u m/s^2) for moving eight levels would be different from an acceleration value (v m/s^2) for moving six levels. This modified version of the algorithm will hereafter be referred to as "speed variation II."

Analytical Model

The diagram representing the traction system considered in the simulation is shown in Figure 3 [14]. The maximum load on the elevator is 400 kg with a counter weight of 300 kg. T_M is the Motor Torque (in N-m), v is the speed of elevator (in m/s), and R is the radius of the pulley (in m). Equations (2)-(5) represent various relationships.

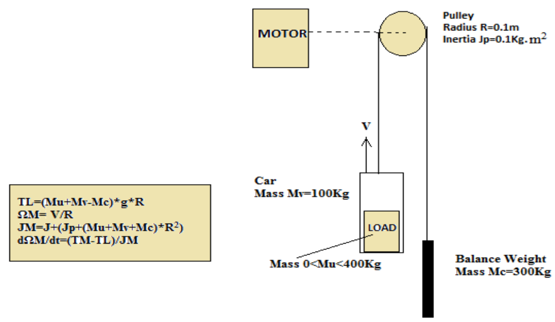

Figure 3. Schematic Representation of the Elevator System under Study

$$\text{TL, Load Torque (in N-m)} = (Mu + Mv – Mc)*g*R \quad (2)$$

where, Mu is the mass of the load; Mv is the mass of the elevator cart; Mc is the mass of the counterweight; and, g is the gravity.

$$\text{JM, Moment of inertia (in kg-m2)} = J + Jp + (Mu + Mv + Mc) *R^2 \quad (3)$$

where, Jp is the inertia of the pulley.

$$\Omega M\text{, Angular velocity (in radians/second)} = v / R \quad (4)$$

$$d(\Omega M) /dt\text{, angular acceleration} = (TM - TL) / J \quad (5)$$

The basic operation of a constant speed elevator system is shown in Figure 4. According to the calls, the elevator controller determines the direction of movement and satisfies the calls based on a fixed priority (floors along the direction of movement are given priority).

The modified version of the algorithm is shown in Figure 5. This algorithm uses the "load on the elevator" to determine the speed of movement and the "number of floors to move" to determine acceleration. The elevator then satisfies the calls similar to the constant-speed case. Figure 6 shows how the calls are satisfied in a five-floor building using this algorithm.

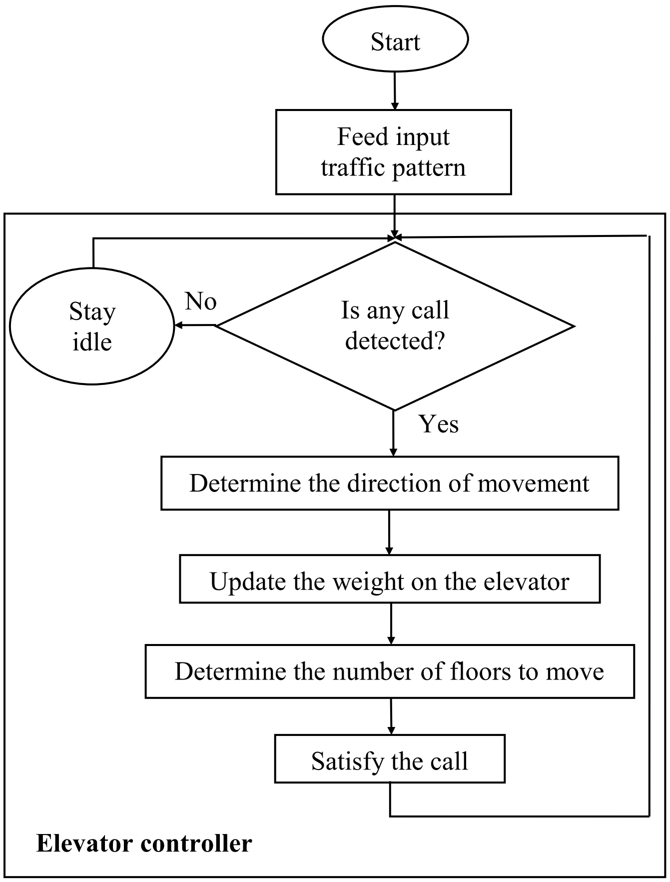

Figure 4. Flow Diagram Elaborating the Algorithm of the Constant-speed Case

Result and Analysis

Testing the Algorithms

The following three algorithms were simulated under multiple traffic patterns and the simulation results tabulated and compared.

1) Constant speed case: elevator running at a constant speed of 1m/s. This was used as the reference for comparison of energy consumption and travel time.
2) Speed variation I: elevator changing its speed based on load but fixed acceleration.
3) Speed variation II: elevator changing its speed based on the load as well as changing acceleration based on the number of levels moved. (This is a modified version of "speed variation I.")

Case 1: Consider an elevator of maximum load 400 kg, running in a 10-level building during peak-hour traffic pattern. The three algorithms were simulated and the results tabulated for analysis. In this simulation, peak hours of traffic intensity as mentioned by Cortés et al. [15] was used. Figures 7 and 8 depict the arrival rates at different halls during lunch-peak traffic. Most of the workers go out for lunch in the first hour (1-3600s), as shown in Figure 7, and return to the building during the second hour (3600-7200s), as shown in Figure 8.

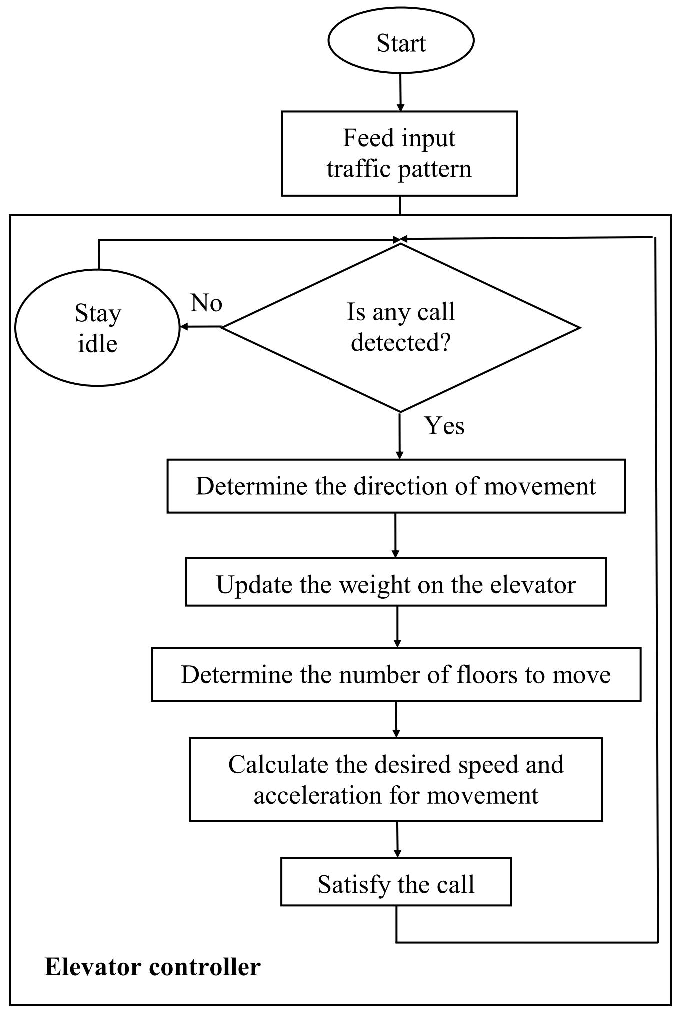

Figure 5. Flow Diagram Elaborating the Algorithm of the Modified Version

Speed versus time of the speed variation algorithm is shown in Figure 9. The simulation results of all of the algorithms over the same traffic intensity (peak hour) are tabulated in Table 1. In accordance with Table 1, using the speed variation II algorithm, both energy consumption and travel time were reduced significantly when compared to the constant-speed type. Hence, energy savings were achievable at a reduced travel time for peak-hour traffic patterns using "speed variation II" during peak travel hours.

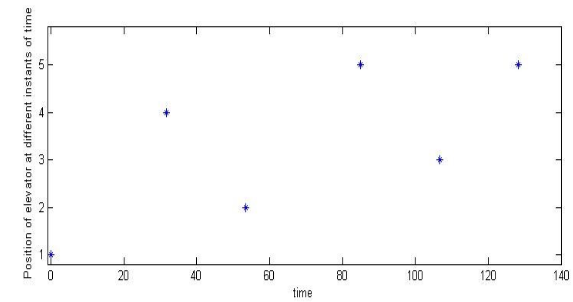

Figure 6. Call Satisfying Pattern for 5 Floor Building

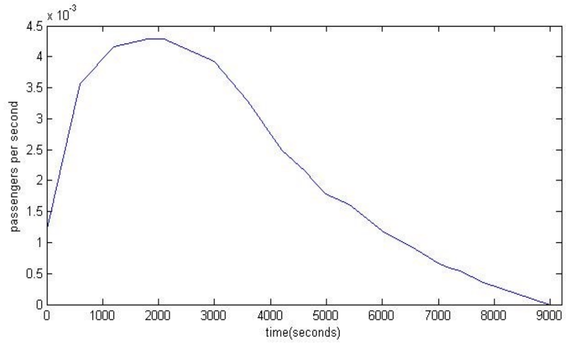

Figure 7. Arrival Rate to the Hall of Other Floors

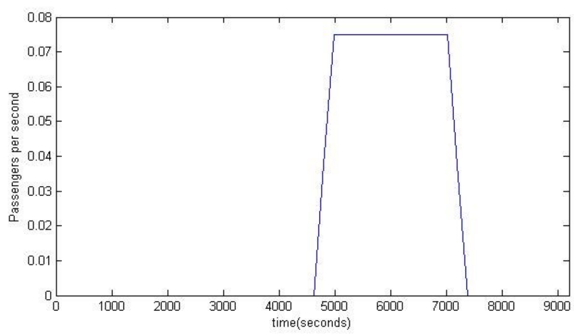

Figure 8. Arrival Rate to the Hall of the Ground Floor

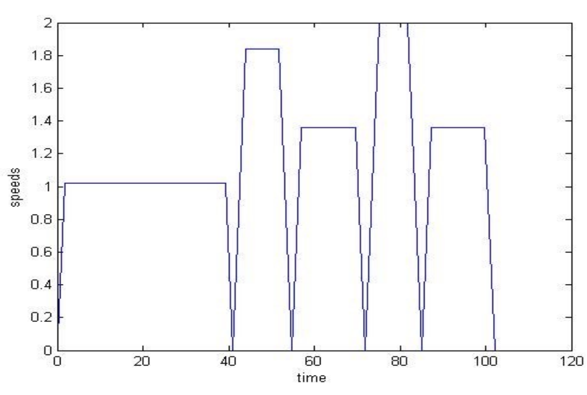

Figure 9. Plot of Speed versus Time for the Speed Variation Algorithm

Table 1. Simulation Results for 10-floor Peak Hour Traffic

	Constant speed	Speed variation I	Speed variation II
Consumption (KJ)	3.45×10^3	3.65×10^3	3.27×10^3
Losses (KJ)	388.83	360.98	394.22
Regeneration (KJ)	-2.88×10^3	-2.92×10^3	-2.81×10^3
Equivalent energy (kJ)	570.1	732.1	465
Total travel time (s)	4.45×10^3	4.21×10^3	4.39×10^3
Efficiency (%)	88.72	90.10	87.96

Case 2: Consider an elevator with a maximum load of 400 kg, running in a 10-level building with a non-peak-hour traffic pattern. The three algorithms were simulated and the results tabulated for analysis. The pattern in which the calls were satisfied was very similar to that shown in Figure 7. All three algorithms were simulated using non-peak hours of traffic intensity. This traffic pattern was also used by Barney [16]. The resulting speed-versus-time plot of the speed variation II algorithm was also very similar to that shown in Figure 8. The simulation results of all of the algorithms over the same traffic intensity (non-peak hour) are tabulated in Table 2.

Table 2. Simulation Results for 10-floor Non-peak-hour Traffic

	Constant speed	Speed variation I	Speed variation II
Consumption (KJ)	4.19×10^3	3.96×10^3	3.68×10^3
Losses (KJ)	400.62	337.83	365.00
Regeneration (KJ)	-3.21×10^3	-3.79×10^3	-3.17×10^3
Equivalent energy (kJ)	0.99×10^3	0.18×10^3	0.50×10^3
Total travel time (s)	5.27×10^3	4.88×10^3	4.9761×10^3
Efficiency (%)	90.44	91.46	90.04

For the speed variation II algorithm, both energy consumption and travel time were significantly reduced when compared to the constant-speed type. Hence, energy savings were achievable at a reduced travel time for a non-peak-hour traffic pattern using "speed variation II."

Case 3: Consider an additional case of an elevator with a maximum load of 400g, running in a 20-level building, using a non-peak-hour traffic pattern. The three algorithms were simulated and the results tabulated for analysis. The pattern in which the calls were satisfied was very similar to that shown in Figure 6. All three algorithms were simulated using non-peak hours of traffic intensity, as used by Barney [16]. The simulation results of all of the algorithms over the same traffic intensity (non-peak hour) are tabulated in Table 3.

Table 3. Simulation Results for 20-floor Non-peak-hour Traffic

	Constant speed	Accelera-tion I	Accelera-tion II	Speed variation II
Consumption (KJ)	3.44×10^3	3.39×10^3	3.31×10^3	3.27×10^3
Losses (KJ)	388.82	388.58	401.60	394.22
Regeneration (KJ)	-2.88×10^3	-2.84×10^3	-2.66×10^3	-2.81×10^3
Equivalent energy (kJ)	570.1	545.5	654.5	465
Total travel time (s)	4.45×10^3	4.41×10^3	4.35×10^3	4.39×10^3
Efficiency (%)	88.716	88.52	87.88	87.96

From Table 3, it is clear that the speed variation II algorithm consumed less energy among the three for a fixed traffic pattern, irrespective of the number of floors in the building. Thus, from the tabulated analyses, it can be seen that the speed variation II algorithm produced significant energy savings in both peak and non-peak hours of traffic intensity. Additionally, the travel time of the elevator was reduced, thereby enhancing its overall performance. The authors further tested the algorithm by adding small variations in acceleration. From the simulation results for peak and non-peak hours of traffic intensity, the percentage of energy savings and travel time reduction of both the speed variation I and speed variation II algorithms with respect to the constant-speed case is shown in Table 4 [17].

Table 4. Energy Savings and Travel Time of a 10-floor Building

	Non-Peak hour traffic	Peak hour traffic		
	Energy saving	Travel time reduction	Energy saving	Travel time reduction
Speed variation I	5.63%	7.47%	-	5.438%
Speed variation II	12.35%	5.49%	5.06%	1.32%

Search for a Near-optimal Algorithm

It is clear that, apart from varying the speed based on load carried by the elevator, acceleration should be varied to produce further energy savings. And, different cases of acceleration variation were tested in order to obtain the optimal value that would produce effective energy savings at a reduced travel time. The algorithm was subjected to minor variations as follows, where two types of acceleration were considered.

1) Acceleration variation—test cases involving different values of acceleration for upward and downward movement:
   - □ Acceleration variation I—downward movement given lesser values than upward movement
   - □ Acceleration variation II—upward movement given lesser values than downward movement
2) Speed variation II—the modified version of the algorithm consisting of the same values of acceleration for upward and downward movement.

As peak-hour traffic patterns tend to set the lower bound on energy savings, all of the algorithms were simulated under peak-hour traffic conditions with the same traffic pattern. Results are summarized in Table 5.

Table 5. Optimal Search Results for 10-floor Peak-hour Traffic

	Constant speed	Speed variation I	Speed variation II
Consumption (KJ)	6.01×10^3	5.99×10^3	5.27×10^3
Losses (KJ)	552.17	418.91	405.86
Regeneration (KJ)	-4.73×10^3	-4.84×10^3	-4.71×10^3
Equivalent energy (kJ)	1.28×10^3	1.14×10^3	0.56×10^3
Total travel time (s)	7.29×10^3	5.86×10^3	5.96×10^3
Efficiency (%)	90.78	93.00	91.90

The amount of energy savings and travel time reduction from the simulation are shown in Table 6. As per the tabulated results previously presented, though acceleration I and II produced energy savings at a reduced travel time, speed variation II still tended to be more efficient in terms of energy savings and travel time reduction. Hence, the speed variation II algorithm was determined to be optimal for obtaining the desired results.

Table 6. Efficiency Calculation for 10-floor Peak-hour Traffic

	Energy saving	Travel time reduction
Acceleration I	1.75%	0.9%
Acceleration II	3.8%	2.25%
Speed variation I	-	5.44%
Speed variation II	5.06%	1.32%

Thus by varying the speed of elevator based on load, and acceleration based on the number of levels moved, provided:

1) significant energy savings for varied traffic intensity;
2) reduction in the travel time for varied traffic intensity; and,
3) energy savings and travel time reduction varied according to peak and non-peak hours of traffic.

Conclusion

Demand for energy efficient elevators is increasing worldwide [18]. In this paper, the authors presented an algorithm aimed towards energy conservation in elevators by manipulating the speed and acceleration of the system based on certain factors. Additionally, due to optimum variation in speed, the algorithm produced a significant reduction in travel time, thereby resulting in enhanced performance with minimal energy utilization. The algorithm was tested under various traffic conditions and the simulation results compared with constant-speed elevators. Results showed a significant reduction in energy consumption (between 5% and 12%) and a reduction in travel time (between 1% and 5%) under the variable-speed algorithm. Another way of optimizing the elevator operation was by implementing all three algorithms and by choosing the one based on the need of the hour. This may lead to additional energy savings and enhanced performance as well.

In future, the idea can be further appended with inclusion of artificial intelligence (AI), fuzzy logic, or neural network into the control algorithm of the system. This would allow the system to adapt to multiple factors in a more refined manner. For example, the prioritization of movement between floors based on load and number of calls obtained.

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