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Potential of Aggregated Escalator Loads in Demand Response

Semen Uimonen\textsuperscript{a,*}, Toni Tukia\textsuperscript{a}, Marja-Liisa Siikonen\textsuperscript{b}, Matti Lehtonen\textsuperscript{a}

\textsuperscript{a}Department of Electrical Engineering and Automation, Aalto University School of Electrical Engineering, P.O. Box 15500, 00076 Espoo, Finland

\textsuperscript{b}KONE Corporation, KONE Oyj, Keilasatama 3, P.O. Box 7, Espoo 02150, Finland

Abstract

This article uses modeling to demonstrate the potential of utilizing aggregated electrical load of escalators in demand response events and, in particular, for frequency containment reserve markets (FCR). In the paper, we model 3000 commercial and transportation escalators, creating five scenarios, where the ratio of intermittent-operating escalators varies from 0\% to 100\% at intervals of 25\%. The model employs partial speed reduction during an hour as the main method for curtailment of power consumption. The power profiles of the aggregated escalator load are calculated for each hour in each scenario for two methods of power curtailment. In the first method, the speed change happens only when there is no passengers on the escalator to accommodate the safety measures. The second method applies the speed change within one second from the time of initiation, regardless of passengers presence on the escalator. The results clearly indicate that escalators have potential to participate in frequency containment DR events either as a stand-alone aggregated load or as a part of a more complex solution with other technologies. With 3000 escalator units and the ratio of intermittent-operating escalators above 25\%, there is potential for curtailing from 0.5 to 3 MW of power consumption and the possibility to participate in FCR-N and -D markets.

Keywords: Escalators, Vertical transportation, Demand response, Frequency containment reserve, Modeling, Power reduction,
1. Introduction

The increasing share of renewable energy sources (RES) in power generation require power systems to be proportionately more flexible. Driven by the increased demand in flexibility, the progress has led to emergence of demand response (DR) in power systems. DR is a change in the power consumption to better match the demand for power with the current supply. While DR potentials are not yet discovered completely, it provides solutions to increase systems flexibility and ensure power balance [1].

Presently, DR is a popular topic. There are numbers of studies about DR potential and possibilities of various appliances, especially HVAC and lighting systems, in commercial and residential sectors [2, 3, 4, 5]. An escalator is also one of potential appliances which can participate in DR events by reducing its power consumption for some time. The escalator is the best way to transfer large masses of passengers from one floor to another. They can be fixed-speed and intermittent-operating. Fixed-speed escalators are constantly running with the same speed, while intermittent-operating escalators are equipped with a Variable Speed Drive (VSD). VSD enables the escalator to change the speed or to stop, preventing unnecessary energy consumption. Most of the energy consumption relates to friction of transporting masses in the system, which is proportional to the speed of the escalator [6]. Therefore, reducing the speed is a straightforward option to reduce the power consumption. There are about 137 000 escalators in Europe in 2016 [7] and about 5000 are being installed every year [8]. Practically all the new installations are coming as intermittent-operating. The more is the share of intermittent-operating escalators, the more there is room for adjustments with aggregated loads. Since intermittent-operating escalators are already equipped with necessary electronics, speed reduction seems a feasible option.

1.1. Research objectives

The main contribution of the article is the unveiled potential of intermittent-operating escalators in DR, more specifically frequency containment, by modelling the curtailed power consumption through reduction of the nominal speed of an aggregated group of appliances. The article shows that the proposed methods comply with the existing technical requirements.
in frequency containment reserve markets. The paper is based on modelling the aggregated
power consumption of escalators in a large city in five scenarios, with the changing ratio of
fixed-to-intermittent escalators.

Even though escalators are mentioned as one of the optional appliances to participate in
a DR event [9, 10, 11] by switching them off, there are no detailed research articles about
the potentials of the technology in DR and frequency containment.

1.2. Structure of the article

The article is structured the following way. Section 2 presents previous research on
escalators, general information about demand response and frequency containment reserves
and options to enable DR for escalators. Section 3 describes methodology used for modeling
escalators, power consumption, passenger traffic and queuing. Section 4 presents results of
the model and Section 5 discusses shortcomings of the article and future research. Section
6 presents conclusions.

2. Background

This section describes previous research, demand response and frequency containment
markets, and available options for escalators to reduce the power consumption.

2.1. Previous research

Previous research about escalator energy consumption includes Al-Sharif [12, 13], Kuutti
et al. [14], Carillo et al. [15] and Uimonen et al. [6, 16, 17, 18]. Al-Sharif described basis
of energy consumption modeling of fixed-speed escalators and explored its dependency on
mechanical systems of the escalators. Kuutti et al. compared the fixed-speed and the
intermittent speed escalator energy consumption. Carillo et al. described the benefits and
energy savings of two-speed control of escalators. Our previous research focused on modeling
the energy consumption of intermittent-operating escalators in various conditions, such as
various passenger volumes and traffic patterns. As mentioned in the introduction, we could
not find any research regarding potentials of escalators in DR, while there are plenty of
research articles focused on curtailing the aggregated load of other appliances, for example HVAC and refrigerators [3, 5].

2.2. Demand response, frequency control, aggregators

One of the basic classifications for DR programs is dividing them into incentive-based and price-based. Price-based programs aim to affect the consumer behavior by adjusting the electricity price with accordance to the needs of the grid. Incentive-based programs aim to provide flexibility to cope with unexpected events in the grid. One example of incentive-based DR can be load reduction during a critical event, such as a change in power systems frequency [1].

It is a common knowledge that there always needs to be a balance between power generation and power consumption at every moment in time, which is the responsibility of the transmission system operator (TSO). The balance is indicated by the frequency of the electricity grid. In Europe, the nominal value is 50 Hz and if consumption is greater than production, then the value drops below the 50 Hz. If, on the other hand, production is greater than consumption, then the frequency exceeds the nominal value. Normally, in Nordic countries, the allowed frequency values are within the boundaries of 49.9-50.1 Hz. The TSO maintains the energy balance either by activating balancing bids from the balancing power markets or by reserving capacity [1, 19].

The frequency control process consists of several parts:

- Frequency Containment Reserve for Normal operation (FCR-N). FCR-N is constantly used for automatic control of the frequency in the grid [19].

- Frequency Containment Reserve for Disturbances (FCR-D). FCR-D is used to provide stability to the power system in case of a large fault or disconnection of a large production unit [20].

- Automatic Frequency Restoration Reserve (aFRR). aFRR returns the frequency to its nominal range of values and releases the activated reserves back into normal use [21], hence this is not in the scope in this article.
Minimum technical requirements must be achieved to participate in the reserves [20]. Requirements are provided in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Min. size</th>
<th>Load type</th>
<th>Activation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCR-N</td>
<td>0.1 MW</td>
<td>Various loads</td>
<td>In 3 min after frequency step change of ± 0.1Hz</td>
</tr>
<tr>
<td>FCR-D</td>
<td>1 MW</td>
<td>Power plant reserves</td>
<td>5s / 50% 30s / 100%, with frequency 49.50Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relay-connected loads</td>
<td>Immediately with frequency 30s ≤ 49.70Hz or 5s ≤ 49.50Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Idle reserve power machines</td>
<td>Reserve should be activated, when frequency 30s ≤ 49.70Hz</td>
</tr>
</tbody>
</table>

Participation in FCR with a number of low-power appliances is possible with the help of aggregators. They are intermediary actors that play a critical role on the energy market. Aggregators provide flexibility on the market by enabling distributed energy sources (DERs) to be impactful at scale [22]. In addition to assisting with DR in the grid, aggregators can accumulate loads to participate in reserve markets. Aggregation is a combination of several capable of regulating consumption or production units into a bid made on the markets. It is aggregators job to make the bid meet the requirements of the marketplace [22].

2.3. Escalator Options

An escalator, as one of the appliances in the aggregation of loads, may participate in the DR events by providing peak load curtailment. This subsection describes several ways to enable escalators to participate in the DR events.

One of the possible solutions that could be potentially used with both fixed-speed and intermittent-operating escalators is switching off. It could be listed as the most “radical” way of reducing the power consumption, mainly because this method provides the most discomfort to the passengers. Satisfaction of passengers is highly affected with queuing and trip delays. For example, it is generally considered that refraining passengers from taking escalator routes directly correlates with reduction of sales in retail buildings.

If the escalator is fixed-speed, then retrofitting with a VSD is certainly a valid approach to reduce the overall consumption, post-upgrade components cost and maintenance. Furthermore, it can improve the building’s green certificate level and reduce the carbon footprint.
There is a large number of fixed-speed escalators installed in the past, but most of the new units are coming as intermittent-operating, while others are being retrofitted. The main drawback of retrofitting is the large initial cost of investment.

Essentially, most of the power consumption of the escalator is related to overcoming friction during the transportation [6]. Thus, reducing the speed of the escalator is a straightforward way to curtail the power consumption. This option allows flexibility with customers satisfaction level and, at the same time, it allows participating in DR events with the help of aggregators. However, this method is constrained to only intermittent-operating escalators. With a VSD installed, power electronics reduce the speed of the escalator when necessary.

One of the main concerns for changing the speed and using VSDs is safety. According to [23], accidental falls are the highest source of minor injuries on escalators. Falling often occurs due to escalator suddenly stopping or rapidly changing speed. The study also reports that downwards-running escalators might not be able to stop under heavy load despite the escalator stop being initiated. This could lead to escalator runaway, when it may accelerate under load exceeding the nominal speed values. Since brakes cannot stop the escalator, it results in passengers piling at the bottom [23]. Thus, changing the speed of the escalator while there are passengers on-board may lead to injuries.

According to [24], no speed change should take place on the operation of the equipment when there are travelling passengers on-board. Despite safety concerns, in Europe and Asia, mentioned energy saving technologies have been adopted successfully for over a decade. In the US, however, according to [25], prior to 2010, ASME A17.1 ”Safety Code for Elevators and Escalators” standard prohibited the use of intermittent-operating escalators. Presently, ASME A17.1-2010/CSA B44-10 [25, 26] permits the escalator speed to be changed, provided that there are no passengers using the escalator.

However, the technical standards also set limitations in maximum allowed acceleration and deceleration in escalators. The technical reports ISO/TR 14799-1 [27], ISO/TR 14799-2 [28], compare American ASME A17.1 2010 [26], European EN 115-1 2010 [29] and Japanese escalators and moving walks safety codes and standards. The comparison is provided in Table 2, adapted from [30].
Table 2: Comparison of maximum allowed acceleration and deceleration in escalators, adapted from [30].

<table>
<thead>
<tr>
<th>Property</th>
<th>Safety codes and standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EN 115-1 (EU)</td>
</tr>
<tr>
<td>Max. acceleration, m/s²</td>
<td>0.50</td>
</tr>
<tr>
<td>Max. deceleration, m/s²</td>
<td>1.00</td>
</tr>
</tbody>
</table>

In the present article, the authors focus on changing the speed of the modeled escalator to reduce the power consumption. To correspond to the safety codes and concerns mentioned above, we model two situations for comparison. First, we model the speed change only when there are no passengers on-board the escalator. Later, we compare the first model to changing the speed within 1 second time from initiation, regardless of passengers on-board. Values of maximum acceleration and deceleration allowed by the safety standards in Table 2 are coherent to 1-sec response time in acceleration or deceleration during the DR used in the model.

3. Modelling methodology

This section describes the methodology used for modeling. Flowchart of the modeling process is presented in Fig. 1. The modeling approach consists of several parts. First, the escalator units are created with the unique parameters, presented in Section 3.1. The second large part is the power consumption model that is applied in normal operation and at the times of the DR event, presented in Sections 3.2, 3.3. Next, there are the passenger distribution and queuing models, presented in Sections 3.4, 3.5. The aim is to distribute passenger groups according to measured distributions and apply queuing that depends on the escalator capacity. Finally, the result of the model is the recovered power profile that is presented as a subtract between the aggregate power consumption profile with DR and without DR.
In general, the article attempts to mimic the situation of a large city. To portray the potential of escalators, we model 3000 escalator units, where 300 escalators do not have a pair and are upwards-running, while the rest are 50% upwards- and 50% downwards-running. As an example for comparison, there are around 8000 escalators in the Nordics, while there are more than 35 000 units in Germany alone [8]. According to [31], there are about 2800 escalators in a city of the size of New York.

In this article, the five modeling scenarios featured the increasing number of intermittent-operating escalators, from 0 to 100% at intervals of 25%. For each scenario, all the escalators are re-created, hence, their properties vary. The following subsections describe parts of the modeling process in more detail.

3.1. Approach to escalator modelling

The approach to escalator modelling involves creating each escalator separately with unique parameters that affect length and time of the travel, queuing and, as a result, power.
consumption. The parameters used in modelling process are described in Table 3.

Table 3: Modelled escalator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Fixed-speed or intermittent-operating escalator</td>
</tr>
<tr>
<td>Segment</td>
<td>Public transportation or commercial building</td>
</tr>
<tr>
<td>Direction</td>
<td>Upwards or downwards</td>
</tr>
<tr>
<td>Regeneration</td>
<td>10% of modelled downwards escalators have regeneration</td>
</tr>
<tr>
<td>Number of passengers</td>
<td>Daily number of passengers, Fig. 4</td>
</tr>
<tr>
<td>Energy class</td>
<td>Normally distributed classification indicator that describes the impact of both the efficiency of active parts and the friction of passive escalator components [32]</td>
</tr>
<tr>
<td>(\alpha, ^\circ)</td>
<td>Escalator angle 30 or 35 degrees</td>
</tr>
<tr>
<td>(H, m)</td>
<td>Vertical height of the escalator, Fig. 2</td>
</tr>
<tr>
<td>Dimensions (A,B,C,D)</td>
<td>Dimensional reference values derived from [32]</td>
</tr>
<tr>
<td>(\mu_{SB/PB})</td>
<td>Friction coefficient of step/pallet</td>
</tr>
<tr>
<td>(m_{SB/PB}, kg)</td>
<td>Mass of step/pallet</td>
</tr>
<tr>
<td>(v, m/s)</td>
<td>Nominal speed</td>
</tr>
<tr>
<td>(t, s)</td>
<td>Calculated travel time at nominal speed</td>
</tr>
<tr>
<td>(\eta_{nl})</td>
<td>Escalator efficiency at no load</td>
</tr>
<tr>
<td>(m_{chain}, kg/m)</td>
<td>Mass of chain band per meter</td>
</tr>
</tbody>
</table>

Escalator heights were modelled using Gamma distribution. Example of the distribution for the scenario with 50% intermittent-operating escalators is presented in Fig. 2.
Escalator width was selected to be constant at 1000mm. Other physical dimensions and parameters, such as angle, nominal speed and energy class are variables for calculation of no load power consumption and are presented further in the power consumption model.

3.2. Escalator energy consumption

In this article, the authors model a large number of escalators which are represented by the cumulative power consumption profile. Escalator power consumption can be divided into variable, mechanical and ancillary power consumption. Total power consumption can be expressed with Eq. 1, adopted from [32].

\[
P_{\text{total}} = P_{\text{variable}} + P_{\text{mechanical}} + P_{\text{ancillary}}
\]  

Variable power consumption is related to masses that are being transported by the escalator besides its own mass, basically, the passengers. Variable power consumption is the
same, whether the escalator is fixed-speed or intermittent-operating. It can be calculated with Eq. 2

\[ P_{\text{variable}} = \frac{N * m * v * g * \sin(\alpha)}{\eta_{\text{var}}}, \]  

where \( N \) is number of passengers, \( m \) is average mass of a passenger, \( v \) is the momentary speed of the escalator, \( g \) is the gravity constant, \( \alpha \) is the inclination angle and \( \eta_{\text{var}} \) is the efficiency of the escalator.

Mechanical power consumption is related to the part of total consumption that does not include passengers. Basically, it is the power consumed to overcome the friction of the escalator parts, such as steps, chains, handrail and power used for control system. In a fixed-speed escalator, mechanical power consumption is constant throughout the working hours of the escalator. In intermittent-operating escalators, the mechanical energy consumption is not constant. Since the escalator is equipped with Variable Speed Drives (VSD), the mechanical power consumption varies through different modes of the escalator. These changes in power consumption can be described with a power demand cycle [16], which is described in the following subsection.

Ancillary power consumption is the power consumption of the lights, fans and other electronics that may be equipped on the escalator [33, 32]. Mechanical power consumption together with ancillary power consumption represent the no-load power consumption of the escalator.

The no-load power consumption can be expressed with Eq. 3.

\[ P_{\text{nl}} = P_{\text{nl handrail}} + P_{\text{nl step/pallet}} + P_{\text{nl control}}, \]  

where \( P_{\text{nl handrail}} \), \( P_{\text{nl step/pallet}} \) and \( P_{\text{nl control}} \) are the power consumption of handrail, power consumption of steps and power consumption of the control unit under no load condition [32]. The no-load handrail power consumption can be calculated according to Eq. 4. The no-load step consumption can be calculated with Eq. 5, while \( P_{\text{nl control}} \) is often given as a constant value for modeling [32].
\[ P_{nl\ handrail} = \frac{2 \cos(\alpha) \times \left(A \times \frac{H}{\tan(\alpha)} + B\right) \times v}{1000 \times \eta_{nl}}, \] (4)

where \( A \) and \( B \) are the dimensional reference values from [32] and \( \eta_{nl} \) is the no-load efficiency.

\[ P_{nl\ step/pallet} = \frac{\left(2 \times \left(m_{SB/PB} \right) \times g \times \mu_{SB/PB} \times \frac{H}{\tan(\alpha)} + C\right) \times v}{\eta_{nl}}, \] (5)

where \( C \) and \( D \) are the dimensional reference value from [32], \( m_{SB/PB} \) is the mass of a step/pallet, \( m_{\text{chain}} \) is the mass of the chain, \( \mu_{SB/PB} \) is the friction coefficient of the step/pallet band and \( H \) is the height of the escalator.

The following subsection describes the power demand cycle, which is used to model the mechanical power consumption of intermittent-operating escalators.

### 3.3. Power demand cycle

Power demand cycle is a modelling approach to emulate the behaviour of energy saving modes in intermittent-operating escalators by means of a VSD [16]. The modelled power demand cycle consists of the following stages, presented in Fig. 3 and Table 4.

<table>
<thead>
<tr>
<th>Power demand cycle mode</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient start(^1)</td>
<td>-</td>
</tr>
<tr>
<td>Acceleration to nominal speed</td>
<td>( P_{nl} \times 2.2 )</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>( P_{nl} )</td>
</tr>
<tr>
<td>Deceleration to reduced speed</td>
<td>( P_{nl} \times 0.2 )</td>
</tr>
<tr>
<td>Reduced speed</td>
<td>( P_{nl} \times 0.5 )</td>
</tr>
<tr>
<td>Stand-by (stop)</td>
<td>( P_{stby} )</td>
</tr>
<tr>
<td>Acceleration from reduced speed to nominal speed(^2)</td>
<td>( P_{nl} \times 1.8 )</td>
</tr>
</tbody>
</table>

Escalators equipped with a VSD typically accelerate from zero to nominal speed just before the passenger steps on the escalator. Usually, the nominal speed persists for some time.

\(^1\)The following model omits the transient start, because it was difficult to detect with a measuring device.\n
\(^2\)In cases when a passenger appears while the escalator is still in reduced speed mode.
amount of time after the passenger has reached the final destination in case there might be more traffic. After some time, the escalator goes into a slow-speed mode, sometimes also called "crawling mode", where the speed is reduced up to 50 percent. After another time delay, if there are no incoming passenger, the escalator stops.

![Figure 3: Example of a power demand cycle in the modeled escalators [16].](image)

Power saving modes may vary from escalator to escalator, however, for simplicity, this model utilizes the same power demand cycle for all modeled appliances.

### 3.4. Passenger traffic modelling

Passenger traffic plays the key role in modeling the power consumption of intermittent-operating escalators. Approaching passengers trigger the escalator to start operating at their nominal speed and, hence, it starts the power demand cycle presented in Subsection 3.3. It follows that passengers activate the aforementioned mechanical power consumption, $P_{\text{mechanical}}$, and, while they are being transported, variable power consumption, $P_{\text{variable}}$, which both constitute to the power consumption profile of the escalator and, hence, the aggregate power consumption.

Passenger traffic modelling consists of several parts illustrated in Fig. 1. First, the daily
number of passengers is assigned for each escalator according to the distribution presented in Fig. 4.

Figure 4: Modelled distribution of daily number of passengers for scenario with 50% intermittent-operating escalators with 100 bins, bin size equal to 251.58.

This is the amount of passengers that board the escalator during the modelled 24 hours.

Once the number is generated, the escalator is also assigned a building segment, which is either a commercial or a public transportation segment. The building segment is necessary for selecting the proper distribution of passenger groups along the timeline of the modelled day. Table 5 presents the typical segmentation of escalator passengers in various building types [32].
Table 5: Typical amount of passengers in specific building types, derived from [32].

<table>
<thead>
<tr>
<th>Daily passengers</th>
<th>Building type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3 000</td>
<td>Shops; museums; libraries; leisure facilities; stadiums</td>
</tr>
<tr>
<td>Up to 10 000</td>
<td>Department stores; shopping centers; regional airports, railway stations;</td>
</tr>
<tr>
<td>Up to 20 000</td>
<td>Major airports, railway stations, underground railways;</td>
</tr>
<tr>
<td>&gt; 20 000</td>
<td>Larger airports, railway stations, capital city underground railways;</td>
</tr>
</tbody>
</table>

In this model, escalators with daily passenger number more than 10 000 are considered to be in transportational segment.

Then, these passengers are divided into groups of passengers of the size of 1 to 5 according to a probability distribution. Probability distribution of passenger group sizes was measured in our previous research and is illustrated in Fig. 5 [17].

![Group Size Probabilities](image)

Figure 5: Passenger group size probabilities [17].

After daily passengers were distributed into groups of appropriate sizes, the groups are then distributed along the timeline of the modelled day. The passenger probability distribution pattern is selected according to the escalator segment. Fig. 6 presents the passenger probabilities for commercial and public transportation buildings. The groups of passengers are assigned into a 5-min slots according to the appropriate probability distribution. Later, each of the groups is assigned a random spot inside the 5-min time bin to match the 1-sec
Finally, the acquired 1-sec resolution distribution of groups of passengers in time is redistributed according to the escalators maximum capacity with the queuing model presented in the following subsection.

3.5. Queuing model

Modelled escalators vary in speed and dimensions and so does their capacity to transfer passengers. The following queuing model was developed for the study. When the passenger arrives, for example, in the peak hour, there may already be a queue of other passengers willing to board the escalator. Since the passenger capacity rate of an escalator is proportional to its speed, $v$, the amount of passengers that are in the queue during time $t$ can be expressed with Eq. 6:

$$N_q(t, v) = \begin{cases} 
\lambda(t) + N_q(t-1, v) - \mu_{\text{cap}}(v), & N_q(t) > \mu_{\text{cap}}(v) \\
0, & N_q(t-1, v) \leq \mu_{\text{cap}}(v) \land t = 1
\end{cases}$$  \quad (6)

where $t \in [1 : 86400]$, $v \geq 0$, $\lambda(t)$ is the arriving amount of passengers in time $t(s)$ and

Figure 6: Passenger traffic probability graphs for commercial and public transportation buildings, adopted from [16].
\( \mu_{\text{cap}}(v) \) is the escalator passenger capacity per second.

The queuing model is used in the escalator model to update the passenger placement after the initial distribution of passengers. It ensures that the escalators are not overloaded more than their rated capacity at any point in time during the modelling process. Consequently, the queuing model impacts the escalator instantaneous power demand as defined by the equations 1 and 2 and the power consumption cycle in Section 3.3.

### 3.6. Motor efficiency model

The described queuing model simulates the varying escalator load and, at the same time, the efficiency of asynchronous motors varies with the changing load. The data for the variable efficiency model was derived from previous measurements documented in [6] and is depicted in Fig. 7.

![Figure 7: Scatter plot of the measured escalator efficiency against power consumption [6].](image)

Efficiency approximately follows the natural logarithmic function. The model of variable efficiency incorporated in this article can be described with Eq. 7 presented below.

\[
\eta_{\text{drive}} = A \times \ln(P_{\text{drive}}) + B, \tag{7}
\]

where coefficients \( A \) and \( B \) are individually calculated for every modelled escalator depending on its energy class and dimensions, \( P_{\text{drive}} \) is the momentary mechanical power consumption of
the escalator drive. Section 4.4 presents the effect of the variable efficiency on the modelled power consumption.

4. Modelling results

The article includes modelling of 3000 escalators in five scenarios, where the ratio of intermittent-operating and fixed-speed escalators is different. The aim of the article is to describe the potential participation of escalators in demand response and frequency containment reserve markets. Here, we focused on speed change as the main approach. The following section presents the results of the simulation. First, we present the aggregate of power consumption, then the possibilities of changing the speed and, at last, we compare the two methods of the speed control described in Section 2.3.

4.1. Aggregate power consumption and speed change

In this article, the five modeling scenarios featured the increasing number of intermittent-operating escalators from 0 to 100% at intervals of 25%. Since every escalator for each scenario was modelled separately, the parameters of the escalator bundle also slightly vary from scenario to scenario. Table 6 presents several average parameters for each of the scenarios. The main variation for these bundles of escalators is the amount of intermittent-operating and fixed-speed escalators, which results in less power consumption for intermittent-operating escalators, during time of low passenger traffic.
Table 6: Properties of the escalator bundle in five scenarios.

<table>
<thead>
<tr>
<th>Property</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. aggregate power, MW</td>
<td>8.10</td>
<td>8.15</td>
<td>8.20</td>
<td>8.16</td>
<td>8.10</td>
</tr>
<tr>
<td>Avg. $H$, m</td>
<td>5.36</td>
<td>5.39</td>
<td>5.47</td>
<td>5.40</td>
<td>5.38</td>
</tr>
<tr>
<td>Avg. $\alpha$, $^\circ$</td>
<td>30.91</td>
<td>31.05</td>
<td>31.12</td>
<td>31.00</td>
<td>31.08</td>
</tr>
<tr>
<td>Avg. $v$, m/s</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>Avg. daily passengers</td>
<td>7352.76</td>
<td>7418.44</td>
<td>7511.30</td>
<td>7678.96</td>
<td>7551.50</td>
</tr>
<tr>
<td>Commercial escalators</td>
<td>2426</td>
<td>2418</td>
<td>2404</td>
<td>2314</td>
<td>2330</td>
</tr>
<tr>
<td>Transportational escalators</td>
<td>574</td>
<td>582</td>
<td>596</td>
<td>686</td>
<td>670</td>
</tr>
</tbody>
</table>

Fig. 8 depicts the aggregated power consumption profile of escalator bundles in five scenarios. From this figure, we can notice that during the morning time, the impact of energy saving modes on intermittent-operating escalators is highly visible. At the same time, the peak of power consumption happens at the time of passenger peak traffic. Table 6 describes that the maximum power consumption in all five scenarios is relatively similar.

From the overview of the total load, there is about 8 MW of peak power from 12:00 to 20:00, crudely averaged, where speed change can be applied to intermittent-operating escalators resulting in peak power reduction. During the morning period, the power peak varies...
more and depends on the amount of escalators running and passenger traffic frequency. The following subsection describes the two approaches for aggregated escalator load to participate in the frequency containment reserve market. As mentioned earlier, we presume that only intermittent-operating escalators are qualified for speed-change, as they are usually already equipped with all the necessary electronics and a VSD.

4.2. Potential of escalators in frequency containment reserve markets

This subsection describes how modelled escalators could fit the requirements for frequency containment reserve markets. Section 2.2 described the reserve market for normal operation and disturbances. Since there are strict safety requirements regarding escalators, mentioned in Section 2.3, we took two approaches to speed changing. First approach implies changing speed of the escalator only during the time when there are no passengers on the premises. Second approach suggests the possibility of changing the speed with maximum allowed acceleration/deceleration, presented in Table 2, which is virtually in 1 second from the execution time. In this article, we have modelled the speed change 17 times for every hour of escalator operation, where the total duration was one hour. This was selected in an attempt to show the significance of the time of the day on the recovered power during DR. The speed reduction ratio is 50% of the nominal speed in this model.

4.2.1. Method 1: Speed change when there are no passengers on the escalator

As mentioned previously in Section 2.3, changing speed exclusively at times when there are no passengers is an important safety measure [24, 26]. Fig. 9 depicts the 17 recovered power profiles for every hour of the operation, stacked in one figure, during a speed change that lasted for an hour in the scenario with 50% intermittent-operating escalators. The profiles are the remainders of the subtractions of power consumption during the speed change from normal power consumption.
Figure 9: Recovered power profile for each hour, where speed is changed only when there are no passengers on the escalator, 50% intermittent.

It can be noticed from the figure that during earlier hours the maximum of power reduction is lower than during the latter hours. At the same time, during the peak of passenger traffic, at around 18:00, the DR activation time of most of the units is much slower. This happens because, during earlier hours, there is lighter passenger traffic on the majority of the escalators. Even though, for public transportation escalators at 30000 seconds, around 8:00, there is heavy morning traffic, but as mentioned in Table 6, the total ratio of transportation escalators in the aggregate is 0.25 and the overall impact is smaller. This means that, on the majority of escalators, the incoming passengers number and density are much lower and, thus, more escalators are switching to reduced speed and stand-by modes more frequently at the time.

As mentioned in Section 2.2, one of the requirements for FCR-D market is to have the size of reserves at a minimum of 1 MW. Moreover, the maximum activation time of the half of the reserve is five seconds, while the rest of it must be activated within 30 seconds. Fig. 10 depicts the power that can be curtailed during the first five seconds, 30 seconds and the percent of the maximum power reduction possible during the hour for all scenarios.
Figure 10: A: Possible power reduction in five seconds, B: Percent of the maximum power reduction in five seconds, C: Possible power reduction in 30 seconds, D: Percent of the maximum power reduction in 30 seconds. The figure presents every hour and four scenarios, total 3000 units.

It is seen from the figure that 0.5 MW within 5-sec time with 3000 units cannot be achieved with 25% intermittent-operating escalators. With 50% intermittent-operating, most of the time, except mornings, late evenings and peaks of passenger traffic at 17:00 and 18:00, the 0.5 MW value is achievable. Fig. 10 B, shows that during the last couple of hours of the day, the ratio of maximum power that can be reduced is at its highest, however the power value is low. This happens because there are overall more commercial escalators, and their working time of is less than of the transportation ones. During peaks of passenger traffic, possible power reduction ratio is at its lowest since the requirement for speed change is to have no passengers in the premises, while the density of the traffic is at the highest. With 75% and 100% of intermittent-operating escalators and 3000 units, most of the time the requirement of 0.5 MW within five seconds is fulfilled.

Fig. 10 C and D depict the possible power reduction in 30 seconds during every hour. It shows that for 3000 units, the target of 1 MW is not achievable at all for 25% intermittent,
while for 50% it is achievable from 10:00 to 16:00 and from 19:00 to 22:00. With 75% and
100% intermittent-operating escalators, the 1 MW is achievable during every hour, except
early morning and 23:00.

For FCR-N, the requirement is to activate the reserve of minimum 0.1 MW within 3-min.
According to the current data from Fig. 9 and 10, this is achievable at any hour and in any
scenario within 30 seconds window, while for most cases even within five seconds.

4.2.2. Method 2: Speed change with passengers on board

Even though standard ASME A17.1 states that changing speed at times when there are
passengers on the escalator is prohibited [26], this and other standards, mentioned in Section
2.3, provide the maximum allowed tolerable acceleration and deceleration values, mentioned
in Table 2. Therefore, this approach is still considered for comparison. Fig. 11 depicts the 17
recovered power profiles for every hour of the operation, stacked in one figure, during a speed
change that lasted for an hour in the scenario with 50% intermittent-operating escalators.
Just like Fig. 9, it consists of 17 profiles, where the result is a remainder of the subtraction
of power consumption during the speed change from normal power consumption during the
hour.

![Figure 11: Recovered power profile for each hour where the speed is changed regardless of the passenger
presence on the escalator, 50% intermittent.](image)

In this method, the speed change takes place within 1 second from the time of initiation.
Maximum reduced power consumption values for every hour using this method are the same as in Method 1, however it is achieved faster. Using this method, the minimum power reduction constraints, described earlier in Section 2.2, remain the same, but the time constraints of FCR-N and -D fade. As soon as the speed changes, the time to reach the destination increases twice and, therefore, the passenger capacity decreases twice as well. Fig. 11 depicts that after every hour of speed change, there is an increase in the passenger loading for a very short amount of time, about 20 seconds, which results in increased power consumption during that time.

In this method, the minimum power reduction constraints are just like in Method 1, but the time constraint does not exist, which makes Method 2 less dependent on the passenger traffic density.

4.3. Comparing two methods

The main difference in two methods is the time when speed change takes place. In both methods, when the speed change happens, the passenger travel time increases and incoming passengers start to queue more. After the speed change, in Method 2, the reaction, from the power consumption point of view is immediate. In Method 1, queuing does not cause there is no increase in power consumption over the nominal value as it is during Method 2 because the queuing is resolved while the escalators are at 50% of the nominal speed. For many escalators with Method 1, the inability to change the speed until there is at least a single second when there is nobody on the escalator is a real bottleneck, which creates this long-lasting trail of after effect, as seen in Fig. 9. The escalator operates at slower speed until the queue is resolved. This is why, in the beginning of the day, when the incoming passenger traffic is still dense, it takes longer time for some escalators to switch back to normal speed, while at the end of the day, there is less incoming traffic, and there is more possibilities to perform the change of speed.

On one hand, the mentioned standards [26], [29] prohibit the change of speed with passengers on the escalator, which favors Method 1. On the other hand, Method 2 could be more favorable of the two if the speed change is done within limits of maximum allowed
acceleration and deceleration stated in safety standards in Section 2.3 and it is considered to be safe for the passengers during the DR event.

4.4. Motor variable efficiency effect

Changes in instantaneous loading of the escalator affect the efficiency of the asynchronous motor. This article employs a model for variable efficiency, described in Section 3.6. Fig. 12 illustrates the differences in the models with and without the varying efficiency.

Figure 12: The difference in the aggregates of power consumption during speed change at 6 p.m. with variable and constant efficiency of the asynchronous motor.

The power consumption profiles of the escalators with and without variable efficiency were re-simulated for two hours of DR, 8 a.m. and 6 p.m., to evaluate the impact of varying efficiency in the less and the more dense passenger traffic conditions. The resulting differences of the means of the reduced power consumption were calculated to be less by 6.3% for an hour of reduced speed at 8 a.m. and less by 7.4% at 6 p.m.

5. Discussions

The results show that the aggregated load of intermittent-operating escalators might be a subject for short-term power reduction, in particular, during frequency containment. The
novelty of this article is that it employs a modelling approach to analyze the potential of employing escalators in FCR-N and -D activities.

Among shortcomings of the created model, we could mention the lack of available escalator and passenger flow data. Obviously, more data helps to increase the accuracy of the model and enable modeling of weekends and holidays in addition to working days.

Additionally, every intermittent-operating escalator in the model had an identical power demand cycle. In reality, various escalators are configured differently. As a result, their time delays between power saving modes may vary and some modes, such as reduced-speed, may not be used at all.

One potential shortcoming of the methodology is that the power reduction duration equaled an hour. In reality, the power curtailment for FCR-N and -D is a shorter event. Usually, FCR-D reserve is activated for 15 minutes, while FCR-N is activated continuously throughout the day. However, the idea behind it was to show that time of the day has an impact on the power consumption curtailment, especially the rate of full activation and deactivation.

In this article, the authors mapped the escalator potential for DR and frequency containment. Other research by the authors includes research about the costs of the lost customer hours in vertical transportation DR [34] and applicability of the elevators in frequency containment [35].

6. Conclusion

This paper studied possibilities and the potential of employing escalators in DR, specifically, using intermittent-operating escalators for peak power reduction by means of speed reduction to accommodate technical requirements for FCR-N and -D market participation.

Modeled speed reductions with 3000 escalator units indicate that it is possible to reduce the power consumption from 0.5 MW up to 3 MW depending on the time of the day and to accommodate the FCR-N and -D market technical constraints, depending on the percent of intermittent-operating escalators in use. The results employed two methods for the moment of speed change. In the first method, the speed was changed only when there were no
passengers on the escalator, to accommodate the safety guidelines, which produced a larger bottleneck for escalators with dense passenger traffic that lasted for hours. The second option employed changing the speed within 1-sec from time of initiation regardless of passengers presence on the escalator. The results show that even though the action was immediate, passengers queued, which resulted in slight power increase after the speed was changed back to nominal. Both of the methods compel with technical requirements of FCR-N and -D markets if the maximum reduction of power consumption can be achieved with the existing share of intermittent-operating escalators in the sample.

Overall, both methods provide nearly the same amount of peak power reduction. Despite the second methods activation time was almost instant and minimized queuing, the applicability of speed change is strictly dependent on the safety norms and guidelines of the place where it is implemented, which favors the first method for most situations.

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