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Assessing the Applicability of Vertical Transportation in Power System Inertial Support

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***Abstract*—Displacement of conventional generation with inverter-fed renewable generation hampers power system stability due to a decrease in rotating masses and spinning reserves. This reduction in inertial response capability requires more advanced power system design and innovations in frequency control technology and related power system balancing markets. This paper investigates the potential of applying vertical transportation devices to provide the system with virtual inertia to maintain the frequency quality. The study focuses on the Nordic power system and considers the demand response from both elevators and escalators. The results indicate that vertical transportation is able to contribute to the frequency support with little impact on the aggregate travel time of passengers. However, the capability is limited during the most likely periods of low system inertia, which, in the Nordic power system, occur during summer nights.**

Keywords—Demand response, Elevator, Escalator, Inertia, Kinetic Energy

I. Introduction

The increased ratio of renewables, such as wind and solar, is reducing the rotational kinetic energy typically involved in the generation mix of large power systems. This decrease in the system inertia threatens the power system frequency stability as the power system is less resilient to mitigate the frequency deviations caused by power imbalances. Moreover, the intermittency of renewable power generation also causes regional imbalances [1].

Researchers have proposed multiple means to strengthen the frequency stability. One approach is to emulate the dynamic behavior of rotating machines with power electronics attached to an energy source or storage, such as a battery [2]. Secondly, power electronics could also be applied to operate the renewable generation below the maximum power point, i.e., sub-optimally, to secure additional power reserves [3]. On the other hand, these features could also be combined [4]. Wind power plants also possess other means to control the power output. For instance, the blade pitch angle can be adjusted to reduce or increase the instantaneous power generation [5]. A third source of inertial response can be obtained from the demand side. Apart from the more traditional demand response by industry and, more recently, the tertiary sector, considerable expectations have arisen from the residential sector. For example, the potential of employing thermostatically controlled loads, such as direct electric space heating and refrigerators, have been extensively examined in the literature [6], [7]. Other examples of controllable loads are electric vehicles and household appliances, such as washing machines [8]. These loads could be equipped to monitor the system frequency and automatically reduce their consumption or switch off when a fast rate of change of frequency (RoCoF) is detected [7].

In this paper, we expand the demand-side inertial support to vertical transportation devices (VTs): elevators and escalators. Even though performing demand response actions in vertical transportation has some obvious disadvantages, such as the decreased flow of people, these appliances have one major advantage in contrast to household appliances. The advantage is the relatively minor additional cost to incorporate the measurement and control electronics into these devices in comparison to the large initial investment costs. Furthermore, the rate of new instalments and retrofits of VTs combined with regulatory changes demanding RoCoF detection and automated power consumption rundown could offer a low friction path for this type technology into the power system.

The objective of this study is to assess the amount and rate of power which can be injected from VTs and the subsequent effect on the frequency restoration. To achieve this aim, we first introduce the applied methodology of modeling elevators and escalators as well as the frequency dynamics of the Nordic power system.

II. Methodology

This section depicts the applied consumption models and control strategies for vertical transportation devices. Furthermore, we introduce the employed simulation model and assessed cases.

A. Elevator model

The elevator consumption model is based on basic mechanic equations employed in [9]. The instantaneous power demand of an elevator is a result of the movement and concurrent loading as well as of the applied technology. The energy consumption during a start depends also on the duration of the start which is related to the overall travel distance. For simplicity, this paper applies average characteristics of elevators installed in Europe [10], [11] and traffic profiles derived from previous research [9], [12]–[14].

According to an energy efficiency monitoring campaign [10], [11], the total quantity of elevators in the Nordic countries (here Denmark, Norway, Sweden, and Finland) is approximately 265 thousand. The elevators are commonly divided into three different types of buildings: industrial, tertiary, and

TABLE I. NUMBER OF ELEVATORS ESTIMATED FROM [10], [11]

Region	Tertiary	Residential
Sweden + Denmark + Norway	85,000	100,000
Finland	15,000	35,000

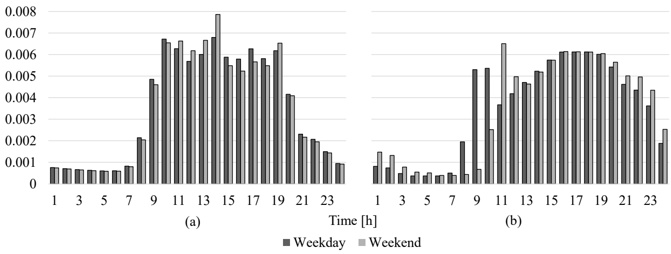

Fig. 1. Employed 5-minute start probability distributions for (a) tertiary and (b) residential elevators.

residential. As the industrial elevators are mostly low-rise and with little usage, they are out of the scope of this study. The installed number of elevators by building type is provided in Table I. Due to Finland's position on a different time zone (+1 hour), it is considered separately.

Around 24% of all the elevators installed in Europe are hydraulic [10] and the rest are traction elevators. As the hydraulic elevators are mostly located in low-rise buildings and typically run only at fixed speed, the simulation results can be considered to represent only traction elevators. The overall ratio of regenerative elevators in the modeled elevator population is set at around 5%, as the true figures are unknown. The hoisting efficiency is presumed to be 75%.

The two different building types are considered to have unique traffic patterns (see Fig. 1). The probability distributions are composed by weighting the distribution profiles with the amount of estimated elevators in Finland versus the rest of the Nordic elevators.

B. Escalator model

The number of escalators in the examined countries is presumed to have a similar ratio in contrast to elevators as in the rest of the Europe. In [10], the escalator-elevator ratio was 0.02. Around three quarters of these were reported to be in commercial sector and the rest installed in connection with public transportation. Table II concludes with the overall estimate.

The escalator energy consumption depends on the type of the escalator. Escalators can be fixed-speed and intermittent-operating. Fixed-speed escalators are constantly in motion, regardless of the passenger flow. Intermittent-operating escalators are equipped with a Variable Speed Drive (VSD), which enables energy saving during times when there is no passenger flow. This article uses average escalator properties calculated with an internal simulation tool [15] of a large population of escalators (see Table III). The simulation tool input values and the actual power consumption model were based on previous research by [14], [16] and ISO 25745-3 standard [17]. Only intermittent-operating escalators are considered to participate in demand response.

TABLE II. ESTIMATED NUMBER OF ESCALATORS IN THE NORDIC POWER SYSTEM

Region	Commercial	Public transportation
Sweden + Denmark + Norway	4,800	1,500
Finland	1,700	700

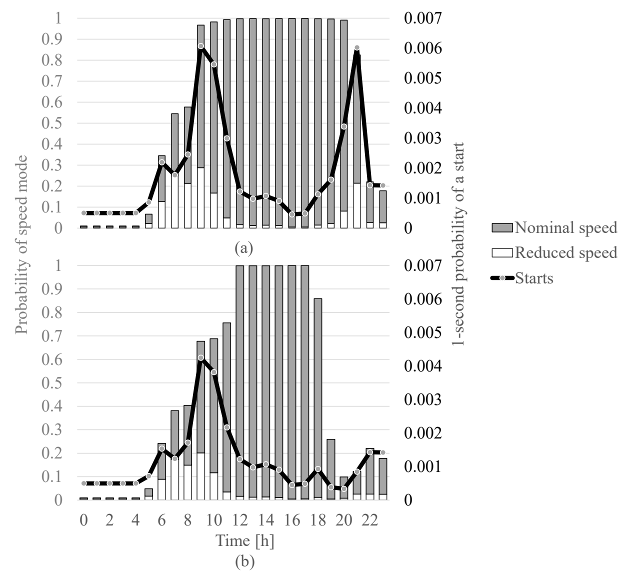

Fig. 2. Employed probability distributions for escalators during (a) weekday and (b) weekend.

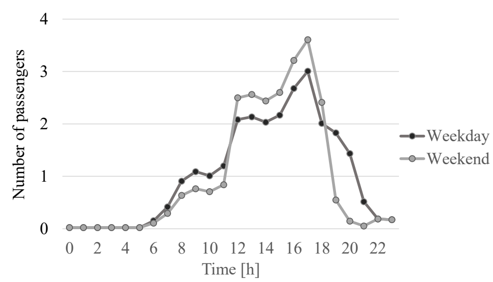

Fig. 3. Average number of passengers riding an escalator at each instant of time.

The employed traffic distributions are shown in Fig. 2. The distributions consider the impact of the dispersion of escalators between Finland and the rest of the studied countries. The figure clearly depicts that during the high-traffic hours ($\approx$ 8 a.m. to 8 p.m.), most of the escalators are constantly running at nominal speed, while during the morning, there is an increased probability of a new start (from standby or reduced speed).

C. Simulation setup

The simulation setup is based on a Simulink model emulating the frequency dynamics of the Nordic power system as presented in [4], [6]. The system operation point (2.7 s inertia constant and 225 MW/Hz of load self-regulation) is selected to represent a low load summer day, which is a challenging condition from the power system frequency stability perspective. In addition, also other power system model parameters are kept the same as in [6]. The RoCoF threshold value is set at 0.027 Hz/s.

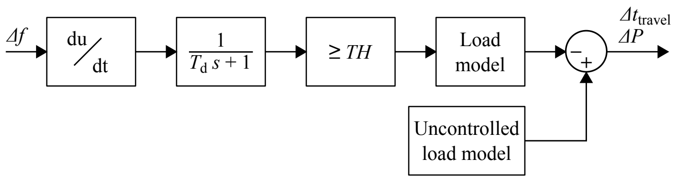

Fig. 4. The control block modeling the participation of vertical transportation in inertial response.

TABLE III. APPLIED SIMULATION VALUES FOR VERTICAL TRANSPORTATION DEVICES

Elevators	**Tertiary**	**Residential**
Starts per weekday	895	175
Starts per weekend day	545	175
Start duration (≈ nominal speed)	7.9 s	8.8 s
Nominal speed power (up-down net)	4.3 kW	1.9 kW
Nominal speed power (regenerative, up-down net)	1.8 kW	0.8 kW
Passengers per start	0.77	0.42
Escalators		
Nominal speed power (no load)	2.2 kW	
Power per passenger (up-down net)	10 W	
Passenger ride time (nominal)	20.8 s	

Fig. 4 demonstrates the control block of the vertical transportation devices. The control system of every VT is modeled to have a measuring delay of T_{d} (100 ms). When the monitored RoCoF threshold, *TH*, is exceeded, the demand responsive vertical transportation model starts to deviate from the uncontrolled version of the same load population. The power difference, ΔP, and increase in travel time, $\Delta t_{\mathrm{travel}}$, are recorded in the simulation along with the frequency data of the modeled power system.

Two different approaches to reduce the speed of VTs are considered in this paper. In Method 1, the speed is reduced only for new starts occurring during the active RoCoF threshold. In Method 2, the speed is reduced in all the units which are running (at nominal speed) during the time of the threshold violation.

The control parameters of the VTs are tuned to provide a full power reduction response in 400 ms. After the RoCoF threshold has been cleared, elevators are modeled to keep their current speed until the end of their journey while escalators will return to their nominal speed if no passengers are detected during 30 seconds (Method 1) or instantly with the 400-ms slope (Method 2). The results of these Methods are presented in Section III.

III. RESULTS AND DISCUSSION

This section analyzes the simulation results when the system is experiencing a power generation drop of 1450 MW, the largest generation unit in the system, and the two different control approaches for VTs are applied. The speed decrease is set at 50% of nominal. The results are shown for elevators and escalators separately. The initial frequency of 49.9 Hz is selected to match the lowest value allowed in normal operation.

The simulations are run for elevator and escalator populations of 100,000 units. Thus, the results are highly optimistic, especially with escalators, as their installed base is only a few thousand units (see Table II). Fig. 5 illustrates the

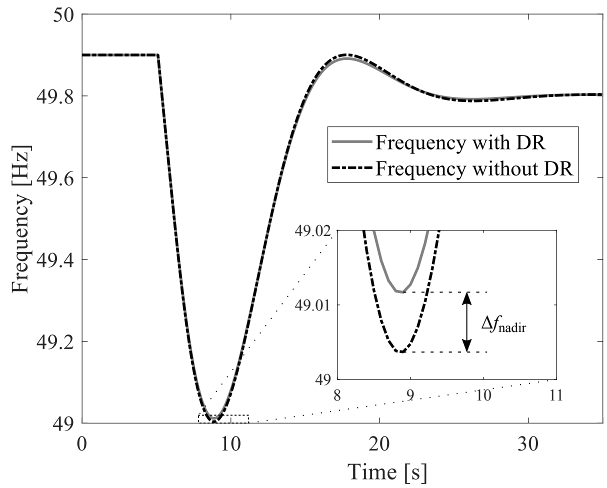

Fig. 5. Example of the effect of demand response on frequency and frequency nadir with Method 1 elevators at 8 a.m. on a weekday.

simulation results for frequency when all elevators running and starting during the RoCoF threshold breach are reducing their nominal speed by half. The power balance disturbance causes a large, rapid drop in the frequency due to the low system inertia and relatively low load self-regulation. The figure also demonstrates the determination of the impact on the frequency nadir, $\Delta f_{\mathrm{nadir}}$, when the DR is applied.

Fig. 6 demonstrates the virtual power obtained from VTs and the related effect on travel times. It should be noted that the model applied in this simulation did not consider the impact on the waiting times of elevators nor on the tendency to walk the escalators or taking the stairs instead, which might occur in reality due to the increased inconvenience to the passengers. Nevertheless, the studied phenomenon is relatively short term which dilutes the impact of these factors.

Fig. 6(a) and 6(c) reveal the rebound issue with elevators. When the travel speed is decreased, the instantaneous aggregate power is decreased, but with the travel speed decreasing the equivalent relative amount, there is an increase in the aggregate power compared to a situation without DR during this prolonged travel period. Fig. 6(b) depicts the power reduction from escalators when only escalators which started during the violation of the *TH* have decreased their running speed from nominal (Method 1). The lag in returning to normal operation (compared to Method 2 in Fig. 6(d)) is caused by the incoming passengers (see Section II-C). This also results in added travel times and, thus, inconvenience to the passengers using these escalators.

Fig. 7 provides the obtained results for frequency nadir with the population of 100,000 units. The linkage between maximum virtual DR power, $\Delta P_{\max}$, and the impact on the frequency nadir, $\Delta f_{\mathrm{nadir}}$, was simulated in the range of 0.3 – 0.7 mHz / MW, depending on the control method and VT type. It should be noted though that when aggregating smaller quantities of DR loads, the predictability of the magnitude and slope of the response becomes worse, which has not been considered in this paper. The presented values are based on a single simulation due to their long computing time.

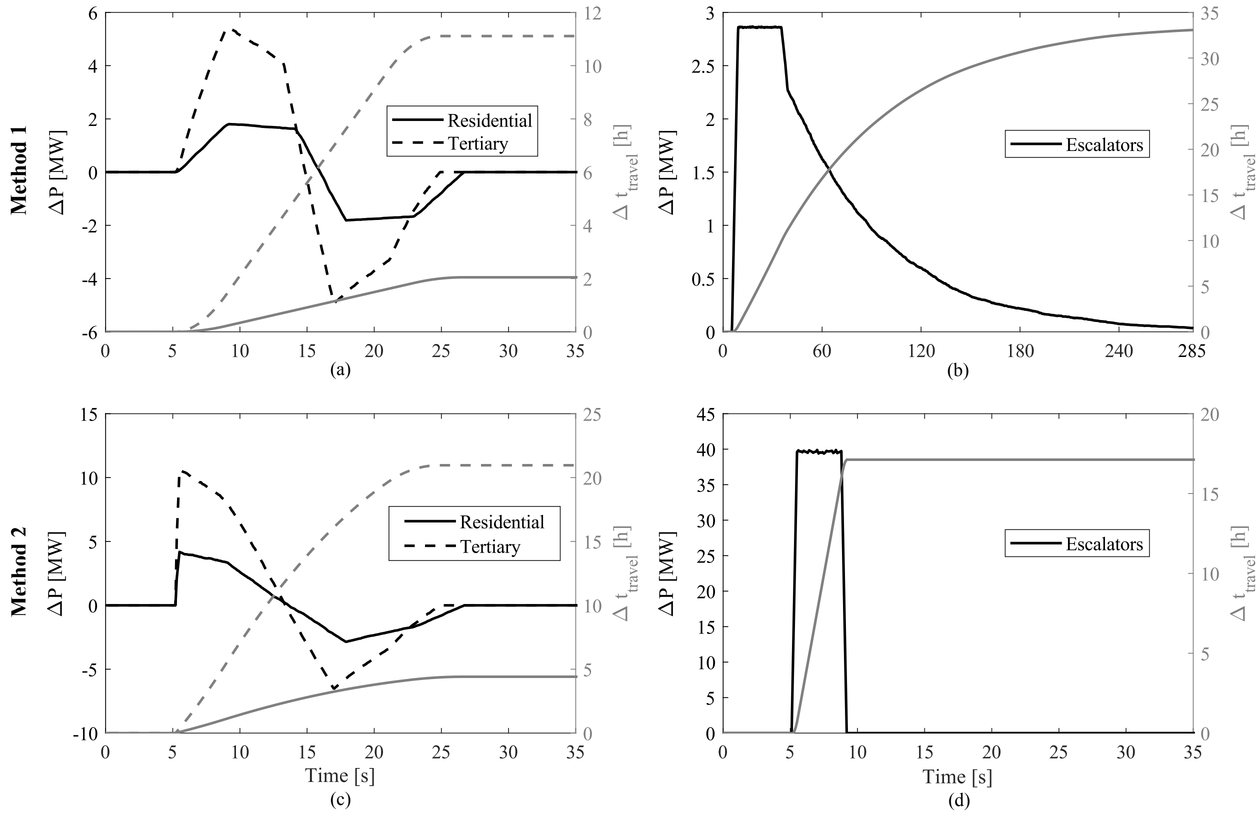

Fig. 6. Examples of power reduction for VTs during the frequency drop (left axis) for (a) Method 1 elevators, (b) Method 1 escalators, (c) Method 2 elevators, and (d) Method 2 escalators. The right axis depicts the increase in the total travel time in the simulated population. Simulated for a weekday at 8 a.m.

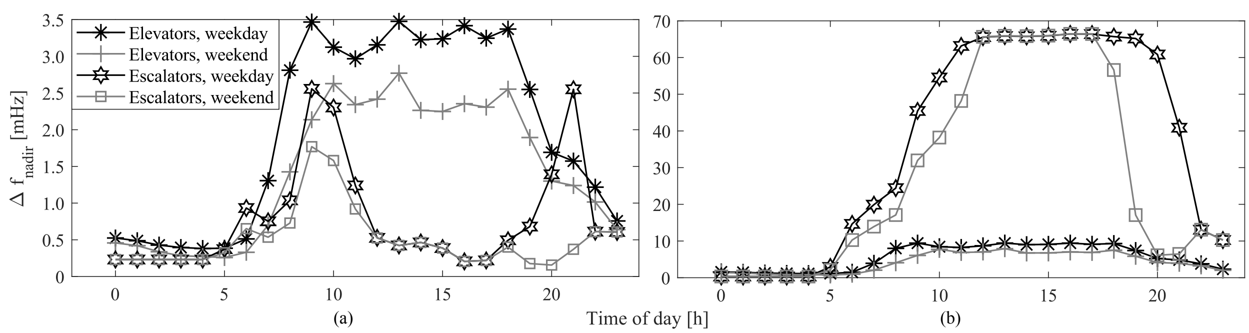

Fig. 7. Obtained results for frequency nadir change with (a) Method 1 and (b) Method 2.

Compared to other DR sources, analyzed in [6], elevators and escalators seem to match the inertial impact of 3 million refrigerators during the high-traffic hours but lack virtual inertia in the nighttime. Refrigerators, on the other hand, are able to provide a fairly constant frequency support throughout the day. When compared to (only) 20,000 detached houses with direct electric storage heating (DESH), vertical transportation appears inferior. Nevertheless, the DESH loads are mostly applicable during winter, when the Nordic power system typically has more rotating masses, and, thus, is less vulnerable to sudden power imbalances.

When planning and implementing a virtual power plant, or aggregating DR reserves, it is important to understand the related costs. Fig. 8 analyzes the achieved change in the frequency nadir and the related increase in the total travel time. The results indicate that applying speed decrease in new escalator starts (Method 1) is relatively inefficient while reducing the speed of all escalators (Method 2) yields enhanced performance compared to elevators.

IV. Conclusion

This paper estimated the power reduction capacity and characteristics of vertical transportation in the case of a sudden frequency drop in the power system. An example of the Nordic power system was employed to analyze the effectiveness of harnessing vertical transportation to contribute to the frequency

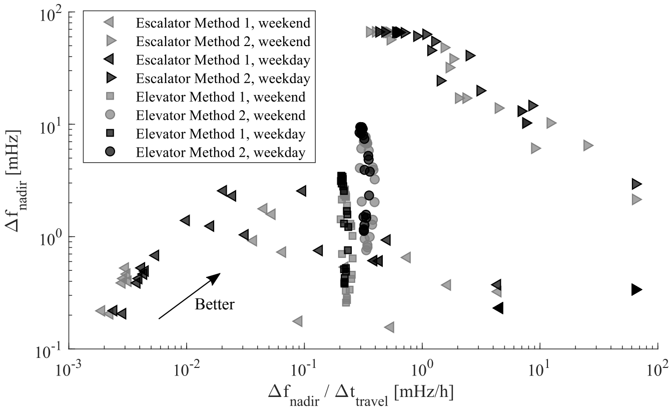

Fig. 8. The effectiveness of frequency support against the increased travel time with the simulated setups. Each point represents a simulated hour, and $\Delta t_{\mathrm{travel}}$ is calculated after five minutes.

support. The results are applicable to other regions as well in terms of the comparison of effectiveness between the control methods for elevators and escalators. However, the actual potential to impact on the frequency nadir differs between regions due to varying populations of vertical transportation devices as well as the unique structure and characteristics of the power system from the frequency stability point of view.

The results indicate that with a large volume of aggregated vertical transportation devices, the participation in the power system frequency support seems feasible and the occurring delays in passenger traffic seem relatively minor. Both elevators and escalators seem to lack the capacity to provide inertial support during the nighttime, and the obtained response from escalators is highly dependent on the control methodology. When comparing populations of equal size, escalators appear more promising than elevators in the inertial support. However, the installed base of elevators is around 50 times larger, which adds to their benefit.

Overall, vertical transportation devices solely cannot arrest the frequency nadir. Nevertheless, vertical transportation should not be neglected when implementing more complex frequency support solutions which utilize multiple DR sources. However, the impact of harnessing vertical transportation in demand response as well as their cost effectiveness against other DR sources should be analyzed further.

Future research should also include more detailed elevator and escalator models (instead of the averaged approach) with better consideration of demand response-related decelerations, accelerations, and safety aspects. Moreover, other options to decrease the aggregate power consumption of vertical transportation could be assessed. These include preventing new starts, stopping escalators which are in reduced-speed mode, and exclusively allowing or even forcing elevator starts which are predicted to regenerate energy. In addition, the impact of speed change on the walking tendency (walking factor) in escalators should be considered as well as the increased waiting times for elevator users. Most importantly, the impact of uncertainty with small samples should be examined in more detail in future research, because vertical transportation devices are intermittent loads and limited in numbers.

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