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Evaluating the Applicability of Elevators in Frequency Containment Reserves

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***Abstract*—This paper analyzes the potential of applying elevators in power system frequency containment reserves (FCR). As an example, the study employs the Finnish FCR market structure. The markets are split into two segments: frequency containment reserves for normal operation (FCR-N) and for disturbances (FCR-D). Both of the markets have distinct minimum bid sizes and thresholds for the maximum allowed delay for activating the reserves. The paper uses a unique elevator simulator to assess the power consumption profiles of common elevator setups. Then, the elevators are aggregated into a virtual power plant (VPP) and controlled with a variety of approaches to rank the effectiveness of each control method. As a result, the paper estimates the potential contribution of elevators to a VPP-provided service as well as the adverse impact on traffic performance for different elevator types in hourly granularity for weekdays and weekends.**

***Index Terms*—Aggregation, demand response, elevators, frequency containment reserve, virtual power plant**

I. Introduction

The need for new sources of demand response (DR) is evident with the rising ratio of intermittent, renewable power generation. Previously, only large, industrial electricity consumers and electrical energy retailers have been able to participate in demand response. However, due to the improved remote monitoring and control capabilities of loads, new cost-efficient DR services are pursued by utilities, academics, and potential aggregators.

Due to the vast variety of controllable loads, approaches to simulate and forecast each potential load type are mandatory in order to determine their benefit to the power system and their capability to fulfill the system and market requirements [1]. In addition, all costs incurred from DR actions need to be understood in order to create a functional and balanced DR platform for all market actors [2]. Moreover, the ability to rank the DR sources in terms of cost-efficiency, volume, and availability is vital for the long-term success of an aggregator.

Power system operators in many countries have introduced a variety of DR-related markets and, during the last few years, utility companies have initiated new services and pilot programs to test various sources of DR for frequency maintenance. For example, Fingrid, the national transmission system operator (TSO) in Finland, has started a pilot where it provides a possibility for third party aggregators to combine DR resources from multiple consumers and use the aggregated virtual power plant (VPP) to participate in balancing energy markets [3]. On a larger scale, the European Union is also enforcing the establishment of common and harmonised rules and processes for electricity balancing with a Commission Regulation 2017/2195 [4], which is based on ENTSO-E's Network Code [5]. These electricity balancing codes are now applied and implemented in collaboration with many European system operators. The implementation process is active, e.g., in the area of automatic frequency restoration reserves (aFRR), manual frequency restoration reserves (mFRR), and frequency containment reserves (FCR).

The scope of this paper is in the FCR markets, which are commonly split into two segments: frequency containment reserves for normal operation (FCR-N) and for disturbances (FCR-D). The FCR perspective is selected due to its characteristic of short-term, intermittent usage of the underlying DR resource which limits the costs experienced by the user and owner of the DR resource. Thus, depending on the type of load, the adverse impact from harnessing the DR resource can be considered to be limited and tolerable.

The aim of this paper is to analyze the potential of harnessing elevators as contributors to DR services of a VPP participating in the two FCR markets. Elevators were selected to the analysis due to their increasing role in the urban society, the improved communication methods, and relatively large initial investment costs in comparison to the costs of any additional control system installed and operated by a potential aggregator.

II. Frequency Containment Reserves

Frequency containment reserves are typically divided into two markets. The FCR-N market is designed to provide continuous frequency maintenance support near the nominal frequency. Thus, the market is for both up- and downregulation. In upregulation, the power generation is increased or the power demand decreased. From a VPP point of view, both result in power output increase. In downregulation, the situation is reversed. The FCR-D market, on the other hand, contains sources which are activated only in the case of a large disturbance in the power system which has caused the system frequency to drop drastically. Thus, the market is only for upregulation. Table I lists the generalized technical requirements for FCR in Finland.

TABLE I
FINNISH FCR MARKETS FOR POWER PLANTS

	Minimum bid size	Activation rate	Frequency threshold
FCR-N	0.1 MW	100% / 3 min	$\leq$ 49.9 Hz $\geq$ 50.1 Hz
FCR-D	1.0 MW	50% / 5 s 100% / 30 s	$\leq$ 49.5 Hz

The FCR resources are typically activated for a maximum of 15 mins, after which the frequency restoration reserves (FRR) should have been activated and the FCR resources can, in turn, be deactivated. In the case of a VPP utilizing DR, the loads can be returned to their normal operation state.

III. ELEVATOR MODELING

Elevators are commonly perceived as essential, non-flexible loads [6]. Nevertheless, the increased processing power in multiobjective group dispatchers has enabled highly efficient and controllable elevator banks, which has opened new potentials in DR. However, only few existing studies are available on elevator DR. Report [7] reviews a peak-load program case study which contains a depiction of an office building where two elevators in a larger elevator bank have been switched off during peak-demand hours, and the participating units have been cycled. However, the effect on the power usage profile of the building is discussed no further than that the consumption is shifted due to passengers waiting for the remaining active units.

On the other hand, it is widely accepted that the dispatching algorithm, i.e., the group controller, has a significant impact on the energy consumption of the elevator group [8], [9], [10], which means it can also be used to alter the overall energy consumption during a period of time. For example, the objective function of the group controller could be momentarily switched to favor energy efficiency over traffic handling capacity.

The focus of this paper is on elevator setups and related control actions which the authors feel are the most likely to be able to participate in DR in terms of power demand, activation rate, and technology. Table II describes the examined elevator types. The values are derived from the ISO 25745-2 standard [11] and adjusted based on previous research [12] and estimation by the authors. The tertiary segment comprises multiple sub-classes of tertiary elevators with most weight on office elevators, where the weekend usage is light. However, the expected increase in the number of starts during the weekend in many of the other tertiary sub-class buildings evens the ratio of weekday and weekend start amounts. The characteristics of the residential elevators (number of floors, nominal load, and speed) are selected to match the characteristics of tertiary sector elevators in order to simplify the analysis.

The power consumption profile of an elevator depends on the passenger traffic it has to process. In this paper, the simulations are run with the traffic distribution profiles shown in Fig. 1, which are formed with the help of [8], [12] as well as with measurements and estimations carried by the authors. As mentioned, the tertiary traffic distribution is considered to represent a mix of tertiary category elevators where the offices are the dominant building type. The residential profile aims to estimate the people leaving their apartment building in the morning and returning during the afternoon and evening.

TABLE II
SIMULATED ELEVATOR TYPES

Building type	Tertiary		Residential	
ISO 25745-2 usage category (UC)	3	4	3	4
Starts weekday	350	850	300	750
Starts weekend	200	500	300	750
Nominal load	825 kg	1275 kg	825 kg	1275 kg
Nominal speed	1.6 m/s	2.5 m/s	1.6 m/s	2.5 m/s
Number of floors	8	16	8	16

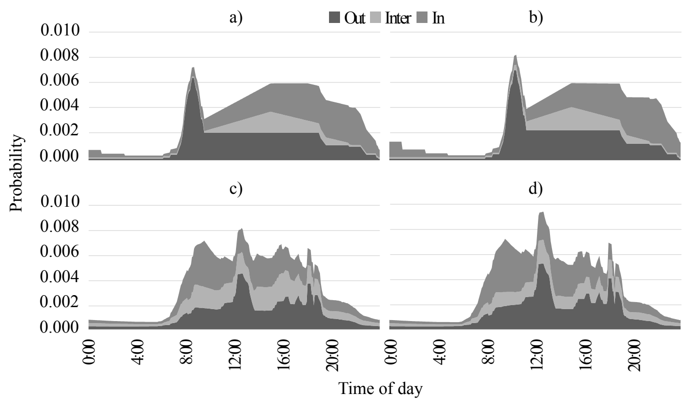

Fig. 1. Considered 5-min landing call distributions for a) residential weekday, b) residential weekend, c) tertiary weekday, and d) tertiary weekend.

Elevators have multiple means to reduce their power consumption and to contribute to the DR-based change of the output of a VPP. In this study, the aim is to analyze the performance of some of the simplest control methods. The analyzed control methods for upregulation are

1) nominal speed decrease (–50%),
2) maximum acceleration decrease (–50%),
3) decreasing the number of units in operation in a group (–50%, at most half of the group), and
4) the same as 3) and additionally forcing regenerative starts for the deactivated units.

The impact of these control methods on the aggregate level is a combination of the effect on the number of starts and loading characteristics of those starts. In addition, the control approach 4) employs the naturally occurring potential energy stored in idle elevators, which depends on their position in the shaft as well as the mass of the car and the counterweight.

Downregulation is not specifically studied in this paper, but it could be achieved relatively easy, e.g., by running otherwise idle units up and down the shaft. A smarter action would be to charge the regenerative elevators with potential energy by lowering them to the ground floor (lifting the heavy counterweight to maximum position). This stored energy could then be used later to reduce the aggregate power consumption in case upregulation is needed, or to briefly improve the energy efficiency of the elevator group in normal conditions.

For the control scenarios 1) – 3), the ratio of regenerative units in the aggregate was modeled as 5%. In case 4), all the elevators were modeled as regenerative to clarify the effect of regeneration. The deactivation of an elevator unit means that the elevator will bypass all new landing calls while it continues to serve the existing ones. In case 4), after serving all the calls, the elevator travels to the highest floor provided that the net energy consumption of the start is calculated to be negative, i.e., the travel recovers energy back into the power grid.

The amount of power reduction (DR) in the aggregate depends on the coincident power demand of the controlled elevator population. Simulation of the functionality and power consumption of an elevator, and, especially, of an elevator group, is difficult without a specifically designed simulator. Section IV describes the simulation methodology employed in this study.

IV. Simulation Setup

The simulation of the aggregated elevator population was done with a unique elevator simulation framework which is introduced and tested in [9]. The simulation works by generating passengers according to the passenger distribution profiles (see Fig. 1) and dispatching elevator units which are estimated to provide the shortest waiting time for passengers placing landing calls. The elevator power consumption model then calculates the power consumption in one-second granularity for each occurring start, considering, e.g., the elevator movement and concurrent loading.

For stationary (standby) power consumption, a value of 200 W was selected. This value is also applied to stationary deactivated units. Thus, it should be noted that a simple relay switch to completely shutdown the deactivated units would provide additional DR capacity. Furthermore, all the simulated elevators were considered to be traction elevators and counterbalanced to 50% of the nominal load. In addition, the hoisting efficiency was set at 0.77. The selected values are assumed to correspond to typical values in the installed stock of elevators, while modern installations typically have less standby demand and higher efficiency [11], [12], [13].

1,000 units were generated for both building types for two usage categories to analyze the behavior of the aggregate demand in different setups and with the four control (DR) methods introduced in Section III. An additional baseline simulation was also performed without any DR functionality. The simulated number of differently sized elevator groups is shown in Table III, where the total number of elevators in each group size is kept relatively even.

The simulation was performed for each hour of the day for two day types: weekdays and weekends. The simulation was set to start 15 mins prior to the DR event to reach a realistic dynamic operation point in the simulated elevator groups (e.g., the position of elevators and list of calls). The DR events were presumed to last for 15 mins (see Section II), and the power profiles and aggregated journey time (waiting + travel) were recorded from each simulation run for a total duration of 30 mins since the start of the DR event.

TABLE III
Simulated Number of Elevator Groups by Usage Category and Group Size in the Aggregate

Group size	Usage category 3 (UC 3)	Usage category 4 (UC 4)
1	260	190
2	130	100
3	80	60
4	60	40
5	0	30
6	0	20

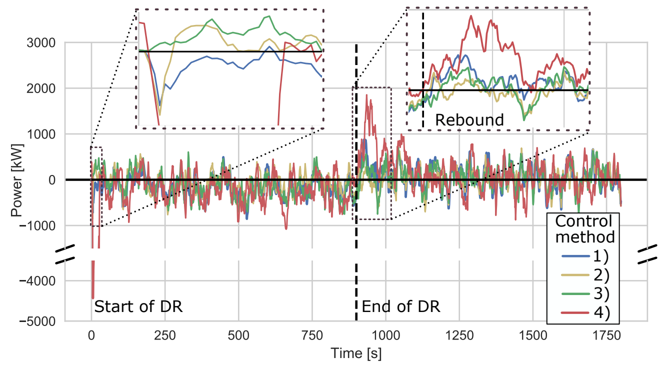

Fig. 2. Example of the simulated impact of DR control methods on the aggregate power (1,000 units) in 1-sec resolution (tertiary, UC 4, weekday at noon).

V. Results

Fig. 2 presents an example of the instantaneous power profiles in each DR control case against the baseline without any DR functionality. It is apparent that there are clear differences between the DR control methods in terms of the amount and duration of the obtainable DR effect. For instance, the aggregate power demand with the control method 3) can actually rise due to the decreased amount of elevators, potentially leading to assignment of calls which require more energy. None of the control methods are able to provide a constant power output due to the intermittent nature of the elevator loads and, in relation, the low number of analyzed units. Moreover, the rebound phenomenon occurring after the ending of the DR event can cause an issue to the VPP depending on the market mechanisms.

A clearer picture of the benefit to the power system can be attained by examining the average power reduction during the 15-min DR event. Fig. 3 draws violin plots of each DR event with a horizontal line segment for both weekdays and weekends and for each applied DR control method. The frequency of these horizontal ”sticks” determines the envelope, or distribution, for each violin plot. The graph reveals that the higher-traffic usage categories have an enhanced possibility for a larger positive impact (negative powers) than the elevators which have less traffic and, thus, smaller elevator group sizes (see Table III). Furthermore, the figure implies that

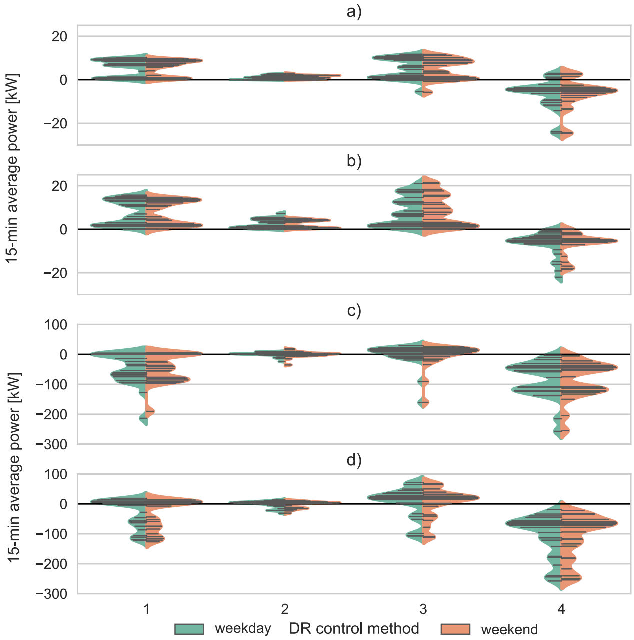

Fig. 3. Violin plots of the obtained change in the 15-min average aggregate power (1,000 units) with different control methods for a) residential, UC 3; b) tertiary, UC 3; c) residential, UC 4; and d) tertiary, UC 4 elevators.

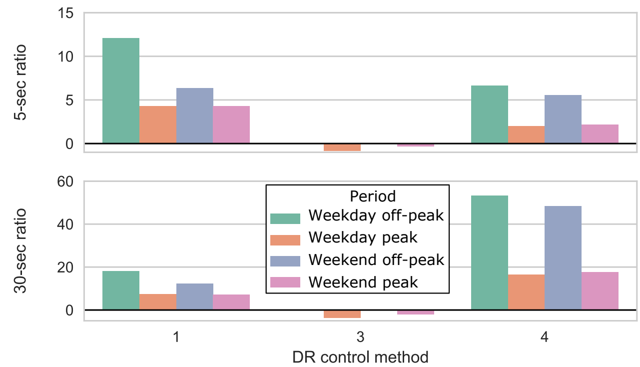

Fig. 4. Average ratios of simulated 5- and 30-sec mean powers to 15-min power curtailments during different time periods for the DR control methods, when the curtailment has been at least 20 kW (1,000 units). All simulated elevator types are included. Peak period is considered for hours 8 – 22.

the control method employing regenerative elevators is able, quite consistently, to provide some degree of upregulation regardless of the time of day. On the other hand, decreasing the magnitude of maximum acceleration does not seem to affect the aggregate power consumption significantly. The difference between the impact of controlling the nominal speed and acceleration most likely results from the difference the elevators spend in these two modes, as the nominal speed mode is typically more dominant in terms of average duration. Thus, control method 2) is excluded from the remaining part of this paper. Nevertheless, combining it with the other control methods might yield benefits, especially in enhancing the fast initial response.

As was seen in Fig. 2, the VPP generation profiles have significant fluctuations, and, thus, determining the magnitude and rate of the change of power fed by the elevator VPP for any given time is cumbersome. Nevertheless, some generalized observations can be made. Fig. 4 presents the 5- and 30-sec power averages compared to the 15-min equivalents (in Fig. 3). This is a simplification to analyze the FCR potential of elevators with regard to the responsiveness requirements stated in Table I. However, as mentioned, due to the intermittent nature of the aggregate power, ensuring that the DR power remains above the threshold after the first crossing cannot be secured without a highly-detailed master control or a sophisticated scheduler utilized by the aggregator. Nevertheless, incorporating several types of DR resources with more predictable and responsive behavior, the VPP could presumably achieve a relatively smooth output.

The analysis of Fig. 4 suggests that nominal speed decrease and forcing regenerative starts enable fast response in terms of decreased aggregate power (which is also supported by the power profile analysis, such as in Fig. 2). The more traditional DR control method of decreasing the number of units active in the group provides clearly a more consistent VPP generation. The off-peak hours are beneficial for fast response with the regenerative elevator control, because most of the units are idle, which enables a large quantity of regenerative starts. As can be reasoned, regenerative starts are also the only means analyzed in this paper which provide meaningful upregulation during the off-peak hours. The relatively large 5-sec off-peak ratio with the DR control method 1) can be explained with little amount of starts per elevator group, leading to a situation where a start in the beginning of the DR event decreases the instantaneous power demand for the first half of its trip but then increases the aggregate consumption during the latter half of the trip because of the extended travel time which, energy-wise, leads to around zero benefit. The reason behind the occasional large DR potential of the nominal speed decrease (see Fig. 3) arrives during peak hours, when the slower movement of elevators causes less starts per time unit and slightly increases the average loading of the cars which is typically beneficial for energy performance due to the large counterweights.

Another interesting finding in Fig. 4 is that the 30-sec power ratio is actually significantly higher than the 5-sec ratio. This can be explained with the help of Fig. 2 for both control methods 1) and 4). With 1), the nominal speed is only reduced for new starts, which causes a delay for the cumulative decrease of the aggregate power. With 4), even though many idle elevators are able to recover energy back to the power grid, it takes several seconds to reach this point due to the power-intensive acceleration mode. Moreover, the largest amount of recuperation occurs at the end of each trip when the elevator decelerates which, for most units, occurs between 5 and 30 seconds after the start of the DR and event.

As discussed in Section I, besides the good knowledge of the benefits to the power system, it is also vital to consider the drawbacks resulting from the DR. The major disadvantage of aggregating vertical transports, such as elevators, into a VPP is

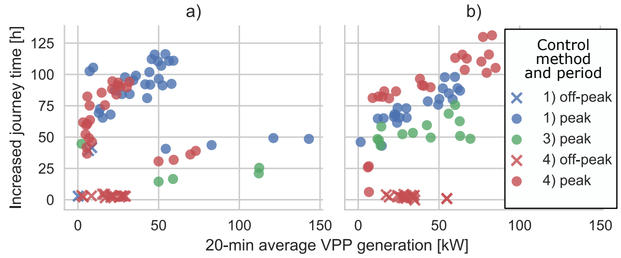

Fig. 5. Increased total journey times in the a) residential and b) tertiary aggregate (UC 4; 1,000 units) against the 20-min average VPP generation with different DR control methods for peak and off-peak hours (see Fig. 4), when the average VPP output has been positive.

the adverse impact on the handling capacity (passengers per time unit). Another drawback with all the analyzed control methods is the rebound phenomena after the DR event has ended and the elevators return to their normal operation. Fig. 5 illustrates the simulated increase in the total journey time versus the gained VPP generation in the aggregate. Here, the total VPP generation is calculated as an average of 20-min power difference between the baseline (no DR) and the DR control methods to also incorporate the rebound issue (see Fig. 2). The results imply that, depending on the time of day, the cost of DR (in terms of added delay to passengers) varies. Nevertheless, the overall dependency seems relatively linear for most hours of the day, especially, in tertiary elevators. Furthermore, the different DR control methods seem to provide resembling results to each other in terms of the slope of the cost function while having different cost levels. The most significant difference is that the regeneration-based control method is able to provide VPP output also with next to zero added delays to passengers during the nighttime. However, the magnitude of power is less than during the peak hours.

VI. Discussion

It should be noted that the usage category 4 elevators (especially in residential sector) are quite uncommon in the Nordic countries compared to the total installed base of elevators. Moreover, the performance of the analyzed control methods might change when different group dispatching algorithms and artificial intelligence are used instead of the simple waiting time-based group controller applied in the simulation.

In addition, more detailed sub-category analysis could be performed to further rank the capability of elevators to participate in FCR and DR in general. This would also help in explaining the peculiarly low DR potential of the control method 3) during the majority of the simulated hours (see Fig. 3). Moreover, the number of samples (the size of the elevator population) should be increased and the impact of chosen elevator parameters should be better analyzed in further research.

VII. Conclusion

This paper examined the applicability of elevators in demand response (DR) and frequency containment reserve (FCR) markets. The paper simulated different elevator types in elevator populations of 1,000 units. The analysis identified that depending on the control method, the elevators are capable to provide enough DR for a short period of time which could benefit a large-scale VPP utilizing multiple DR resources and sophisticated control methods. Furthermore, combining several DR control methods are likely to yield added benefits.

Out of the analyzed DR control methods for elevators, the most promising methods appear to be reducing the number of active units in a large elevator bank, decreasing the nominal speed, and forcing regenerative starts for otherwise idle units. The latter two are able to provide fast response but also suffer from significant rebound in power consumption after the DR event has ended. All of the three methods seem to yield relatively similar VPP power output versus the experienced delays to passenger traffic. Nonetheless, a detailed comparison should be conducted of the experienced costs with elevator DR to the cost characteristics of other DR sources and existing technologies applied in FCR to evaluate the elevator DR potential and applicability in FCR. Lastly, the authors propose further research in the area of smart control and scheduling of regenerative elevators for large-scale DR purposes.

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