Role of Electric Train Transportation in the Management of Reactive Power in Electricity Networks

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***Abstract*— This paper studies for the first time the (capacitive) reactive power production of traction units operating in the Finnish traction network. In addition to the scales of reactive power produced and factors affecting the production, the quantity of the traction units' reactive fees are determined using the transmission system operator's (Fingrid) reactive power guidelines. These studies are carried out by analyzing the units' actual measured energy consumption data using quantitative and statistical methods. The results show that traction units can produce a considerable amount of reactive power, which can lead to extensive reactive fees. The highest discovered annual reactive fees (per unit type) were 189.3 – 217.5 k€/a. However, there are significant differences between the unit types in the production of reactive power and the reactive fees.**

***Index Terms*—electric transportation; reactive power fees; electrified railway; capacitive reactive power; economical dimensioning**

I. INTRODUCTION

Electric trains play a significant role in passenger transportation and goods traffic in the electrification of transportation. For distribution and transmission system operators (DSOs and TSOs), and the Finnish railway infrastructure manager, the Finnish Transport Infrastructure Agency (FTIA), the reasonable and economical dimensioning of electricity networks requires an understanding of the reactive power produced and consumed in electric train traffic. Uncertainty regarding volumes of reactive power may lead to uneconomic over- or under-dimensioning of electricity networks and reactive compensation devices and, thus, unnecessary customer costs. Because of these costs and reactive fees, the FTIA has launched investigations into the production of reactive power detected in the traction network.

This paper studies for the first time the (capacitive) reactive power production of traction units operating in the Finnish traction network. The reactive power of traction units and dimensioning of harmonic filters at the substations have been studied in Finland, but these studies concentrated on the consumption of (inductive) reactive power [1], [2]. Wang et al. have studied the causes of overvoltage issues in the Chinese traction network at a maintenance and preparation depot [3]. According to the study, the problems were caused by traction units producing capacitive reactive power under preparation at the depot. However, the study did not further investigate the volume of the production or the factors affecting the production.

The aim of this paper is to study the reactive power of traction units by determining the volume of reactive power production of the unit types and evaluating factors affecting the production. In addition, the sizes of the reactive fees caused by the production are determined using Fingrid's reactive power window model. The research is carried out by analyzing measured energy consumption data of the traction units using quantitative and statistical methods.

II. REACTIVE POWER WINDOW AND REACTIVE FEES

The Finnish TSO Fingrid monitors its customers' hourly mean reactive power output (from grid to customer) and input (from customer to grid) due to increased transmission grid maintenance costs caused by reactive power. Reactive power output refers to the inductive consumption of reactive power (positive value), and input refers to the capacitive production of reactive power (negative value). Fig. 1 shows the geometric representation of active and reactive power [4].

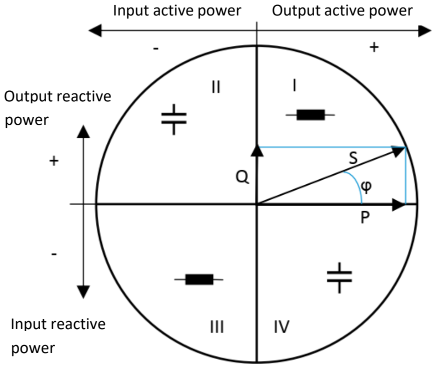

Figure 1. Geometric representation of active and reactive power. [4]

The system operator defines output and input limits for the transmission of reactive power (reactive power window) between the grid and the customer's network. Reactive power

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and reactive energy fees will be charged if these limits are exceeded. In Fig. 2, the output and input limits of the reactive power window and the principle of how the excess reactive power and- energy are determined [5], [6].

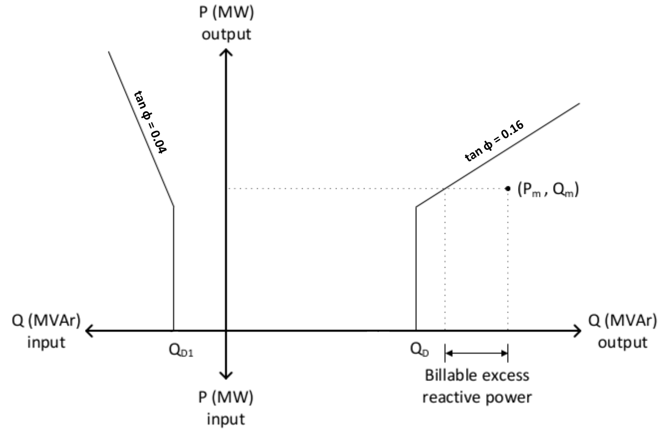

Figure 2. Input and output limits of the reactive power window and principle of determining the exceeding reactive power. QD refers to the output limit, QD1 to the input limit, Pm to the hourly active power and Qm to the hourly reactive power [5], [6].

While consuming active power, the reactive power output limit is defined by QD, or it is 16% of the active power consumption at the connection point. QD is determined by [5]

$$Q_D = 0.16 \cdot \frac{\mathrm{W_{output}}}{t_{FLH}} + 0.1 \cdot \frac{P_{net}}{0.9} \tag{1}$$

where W_{output} is the connection point's annual active power output energy, t_{FLH} is the peak operating time (full load hours) (process industry 7 000 h and other consumption 5000 h) and P_{net} for power plants is the sum of net power generation capacity and for energy storage systems it is the maximum power [5]. Because there is no production of active power in the Finnish traction network, apart from the regenerative braking of the traction units, equation 1 can be reduced to

$$Q_D = 0.16 \cdot \frac{W_{output}}{t_{FLH}} \tag{2}$$

In the same situation, the reactive power input limit is defined by Q_{D1}, or it is 4% of the active power consumption at the connection point. Q_{D1} is determined by [5]

$$Q_{D1} = -0.25 \cdot Q_D \tag{3}$$

The reactive power fee is based on the month's largest hourly mean power that exceeds either the output or the input limit, and the reactive energy fee is based on the month's reactive energy that exceeds the window's limits.

However, the TSO charges only for the part that exceeds the window's limits, and the fifty largest (hourly mean power) exceeds are not considered when the fees are calculated. The amount of the reactive power fee is 1000 €/MVAr, and the reactive energy fee is 5 €/MVArh.

III. DATA AND METHODOLOGY

The methodology used in this paper can be separated into two main parts: first, the calculation of reactive power production of the traction unit types in different scenarios and the evaluation of factors affecting the production. After these evaluations, reactive power fees are calculated for the traction unit types that were found to produce reactive power.

For the invoicing of electric energy, all traction units must measure the consumption and production of active and reactive power and the location of the unit [7]. This onboard energy measurement system must be implemented according to ''Railway applications – Energy measurement on board trains, parts 1-5'', EN50463:2017 standard [7]. The consumption data used in this paper was produced with this onboard measurement system, which has a measurement cycle of one minute. The vehicle keepers VR Group and Pääkaupunkiseudun Junakalusto Oy provided this data. Because of the large amount of data, the number of units and the length of the measurement period had to be limited. The consumption data of four units for four months, namely February, March, June and July from each unit type, was used to carry out this research. General and technical information of the unit types (SR1, SR2, SR3, SM3, SM4 and SM5) are shown in table A1 (Appendix). Data sets included the type of the traction unit, identifier of the unit, timestamp (yyyy.mm.dd hh:mm), consumption and production of active power [kWh/min] and reactive power [kVarh/min] and information of the state of the unit (moving or not). SM5 data set, however, lacked the information of the unit's state, but it included GPS coordinates of the unit. SM5 data points were divided into movement and standing utilizing the known standing locations (Helsinki and Ilmala depot) of the units and the fact that traction units only produce active power during regenerative braking.

A. *Production of reactive power and factors affecting the production*

To estimate the actual reactive power production of the population of the traction unit types, sample mean values and confidence intervals (at 95% confidence level) of hourly- and monthly reactive power production were calculated using individual units' average hourly- and monthly reactive power production.

For every examined traction unit, the active- and reactive power consumed and/or produced by the traction unit during hour i, i.e., the average hourly power, was determined for every hour of the measurement period. These hourly powers were used to calculate individual units' average hourly- and monthly reactive power production. The average values were calculated separately for winter and summer movement and standing at depots to evaluate how outside temperature and the state of the units affect reactive power production. In addition, the effect of active power on the production of reactive power was examined by defining active power ranges, evaluating the average reactive power production of these ranges, and

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analyzing the connection between active and reactive power using scatter diagrams and regression lines.

B. *Reactive fees*

To estimate the actual reactive power and reactive energy fees of the population of the traction unit types, sample mean values and confidence intervals (at 95% confidence level) of the fees were calculated using the fees of individual units. Annual reactive power- and reactive energy fees per unit type were calculated using the determined sample mean values and confidence intervals.

Reactive power and reactive energy fees were determined for every examined traction unit (separately for a summer and a winter month) for three scenarios: movement, standing and in a situation where standing and movement occur inside the same feeding zone. These values were used to calculate the unit type's sample mean values and confidence intervals for a summer and a winter month. These monthly average values were then used to determine the annual fees.

In the review, each traction unit is represented as a network connected to the traction network via its pantograph. Regarding the reactive power fees, the pantograph is determined as the connection point and the flow of reactive power transferred via this point is observed. Fig. 3 displays the review principle and the connection points with an example structure of the traction network.

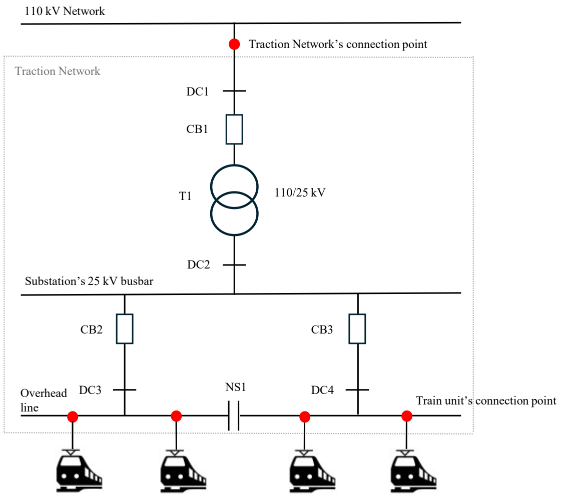

Figure 3. Principle of the reactive power fees review and connection points of the traction units and the traction network. Modified from [8].

The reactive fees were determined using Fingrid's reactive power limits guidelines, presented in Section 2. Reactive power windows were determined for every unit type separately to calculate the reactive fees. The output and input limits of the windows were determined by equations (2) and (3). The unit types' average annual active power consumption (used to determine the limits) were calcuated using the consumption data sets of the units. Exceedances of the output and input limits are examined on an hourly basis using the net reactive power transferred via the connection point. This hourly net reactive power during hour i was determined by

$$Wi_{QNh} = Wi_{QL} - Wi_{QC} \tag{4}$$

where Wi_{QL} is the hourly consumption of reactive power during hour i and Wi_{QC} is the hourly production of reactive power during hour i [9].

IV. RESULTS

This section presents the results from the analyses of reactive power production and reactive fees of the unit types. In Fig. 4, a boxplot of unit types' hourly reactive power production during movement and standing. Furthermore, Fig. A1 (Appendix) shows the unit types' monthly reactive power production.

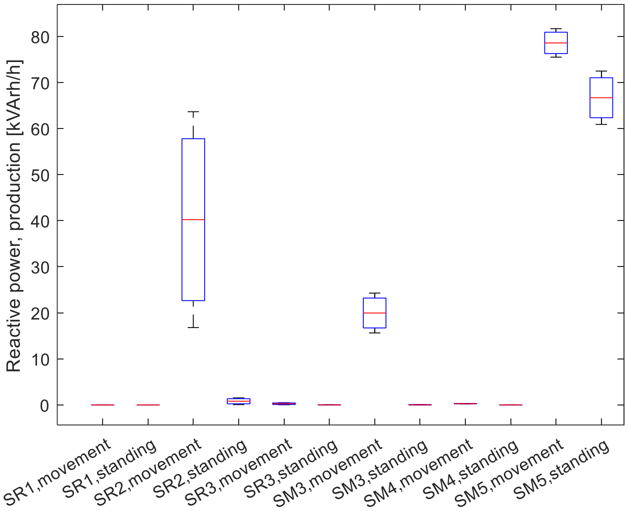

Figure 4. Unit types' hourly reactive power production during movement and standing. Boundaries of the whiskers indicate the upper and lower limits of the confidence interval at a 95% confidence level. The horizontal line of the box indicates the sample mean value.

As shown in Fig. 4, SR1, SR3 and SM4 do not produce reactive power, or the production is very low. SM5 units produce the most reactive power of all the analyzed units in both reviewed situations. The sample mean value of SM5 during movement reaches almost 80 kVArh/h while standing, the value is between 60-70 kVArh/h. When reviewing the sample mean values of movement, SM5 produces twofold the amount of reactive power compared to SR2 and fourfold compared to SM3. The large confidence interval of SR2 is a consequence of significant differences in the reactive power production of the units. While standing, SR2 and SM3 produce virtually no reactive power, and thus SM5 is the only unit that produces reactive power when standing at depots.

Factors affecting the production of reactive power were studied for the units that were found to produce reactive power. In Fig. 5, a scatter diagram shows SM5's ratio of reactive power production to the consumption of active power during movement.

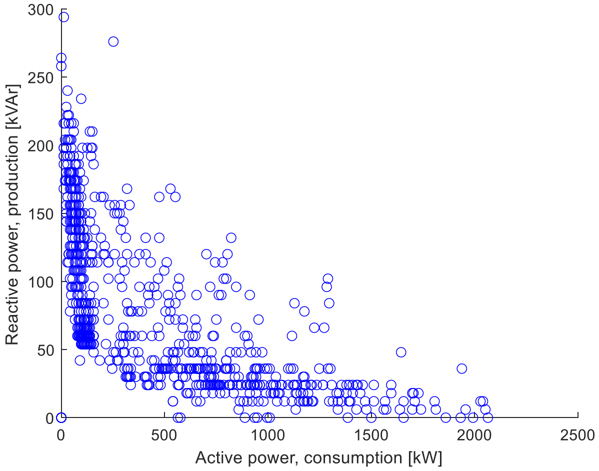

Figure 5. SM5's reactive power production ratio to active power consumption during movement. The data of one SM5 unit's movement in a day. Values are calculated from energy consumption of one minute.

During movement, the reactive power production of SM5 declines as the consumption of active power increases (Fig. 5), and the production of reactive power increases while the production of active power increases. There is a linear connection, with a positive correlation, between the production of active and reactive power. In the case of active power consumption, there isn't a linear connection between the variables, but there is still a clear connection between them. SM3's production was found to follow the same pattern as SM5. However, SR2's active power had the opposite effect on the production of reactive power; the consumption of active power increases the production, and the production of active power decreases the production. In Fig. 6, a scatter diagram of the ratio of reactive power production to the consumption of active power for one SM5 unit's summertime standing.

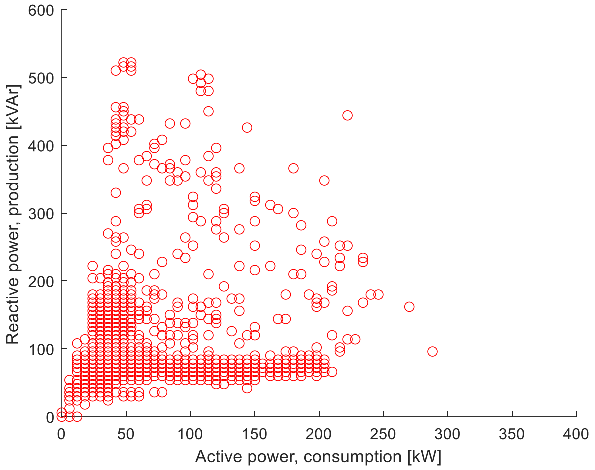

Figure 6. SM5's ratio of reactive power production to the consumption of active power while standing. The data of one SM5 unit's movement in a day. Values are calculated from energy consumption of one minute

As for standing SM5 produces reactive power steadily at a power of 60–90 kVAr, but high short-term power peaks also occur (Fig. 6). In the summer, the base level of reactive power production and the power peaks are higher, and the peaks occur more often than in the winter months. While standing, SM5 was found to produce, on average, 20% more reactive power in the summertime than in wintertime.

Fig. 7 shows a scatter diagram of an SM5 unit's net hourly powers compared to the reactive power window. Reviewed scenario in the figure, standing and movement occur inside the same feeding zone.

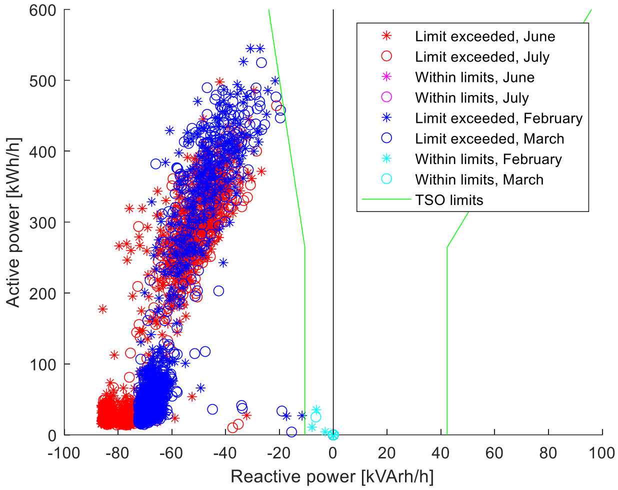

Figure 7. Net hourly powers of one SM5 unit compared to the limits of the reactive power window. Reviewed scenario in the figure, standing and movement occur inside the same feeding zone.

In all the scenarios, most of the net hourly powers of SM5 exceed the input limit, and virtually all are negative, i.e., reactive power is transmitted to the traction network every hour. Standing, the monthly reactive energy exceedings are almost fourfold, and the highest hourly reactive power is over twofold compared to movement. In the case of SR2, the review of the reactive power window also shows significant differences in the reactive power production of the units during movement. The net reactive powers of investigated units 1 and 2 were distributed on both the input and output sides. Some exceedings of the input limit occurred, but only during the winter months. However, almost all net reactive powers of units 3 and 4 were positive, i.e., on the output side. While standing, these kinds of differences between the units were not observed; all units mainly consumed reactive power. Even though Fig. 4 shows that SM3 units produce reactive power while moving, almost all the net hourly powers are on the output side. This is a consequence of reactive power consumption being higher than the production. Regarding SM3, the input limit was not exceeded once during either movement or standing.

In Fig. 8, a boxplot of the annual reactive fees (including energy and power fees) of one SM5 unit and all the SM5 units operating in Finland (81 pcs.).

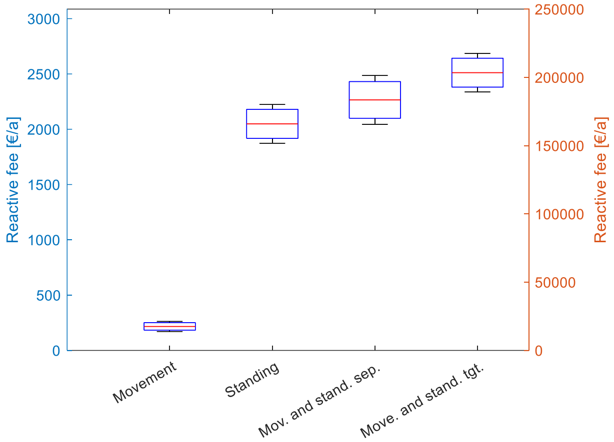

Figure 8. Annual reactive fees of SM5. The left y-axis presents the fees for one unit, and the right presents the fees of all the units operating in Finland (81 pcs). Boundaries of the whiskers indicate the upper and lower limits of the confidence interval at a 95% confidence level. The horizontal line of the box indicates the sample mean value

On an annual level, the reactive fees of SM5 reach a significantly high level (Fig. 8). This is partly because of the large number of units, but the fees of one unit are still multiplex compared to those of other unit types. When reviewing movement and standing separately, the confidence interval of the fees is 165.6 – 201.4 k€/a, with a sample mean value of 183.5 k€/a. In this scenario, about 90% of the fees are cumulated while standing, the confidence interval of standing being 151.7 – 180.1 k€/a, and the sample mean value 165.9 k€/a. However, the largest reactive fees are cumulated in a situation where movement and standing happen inside the same feeding zone, with a confidence interval of 189.3 – 217.5 k€/a and a sample mean value of 203.4 k€/a. Annual reactive fees of one SR2 unit and all the SR2 units (46 pcs.) are shown in Fig. 9.

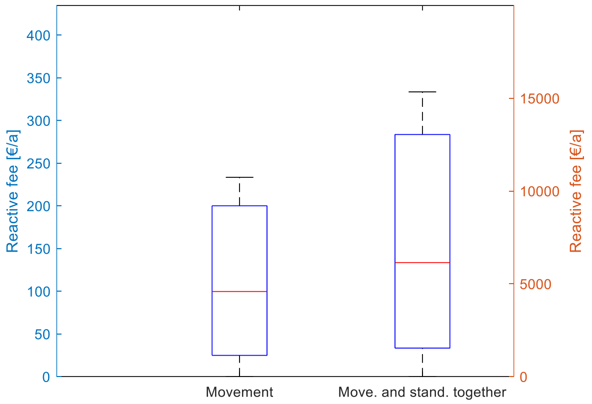

Figure 9. Annual reactive fees of SR2. The left y-axis presents the fees for one unit, and the right presents the fees of all the units operating in Finland (46 pcs). Boundaries of the whiskers indicate the upper and lower limits of the confidence interval at a 95% confidence level. The horizontal line of the box indicates the sample mean value.

The reactive fees of one SR2 unit are almost inconsequential, the sample mean value of movement and standing separately being just 0,1 k€/a, and movement and standing together 0,13 k€/a. However, reviewing all the SR2 units (46 pcs), the annual fees can rise to thousands of euros. Reviewing movement and standing separately, the confidence interval of the fees is 0 – 10.7 k€/a, with a sample mean value of 4.6 k€/a. In this scenario, all the fees are cumulated during movement because mere standing does not cumulate any reactive fees. While movement and standing are reviewed together, the fees are slightly larger, the confidence interval of the fees being 0 – 15.3 k€/a and the sample mean value 6.1 k€/a. The large differences in reactive power production during movement between the SR2 units can also be seen from these results. In the case of SM3, no reactive fees are cumulated since the net hourly powers do not exceed the input limit.

V. DISCUSSIONS AND CONCLUSIONS

This study shows that traction units can produce a considerable amount of reactive power, which can lead to extensive reactive fees. From the studied traction unit types, SR2, SM3, and SM5 produce reactive power to the traction network, but the production volume varies greatly between the unit types. The reactive power production and reactive fees of SM5 are so significant (all units 189.3 – 217.5 k€/a) that the origin of the production and compensation methods could be studied further. 66% of the net reactive power input and 90% of the reactive fees derive from reactive power production during standing. Wang et al. [3] observed a similar phenomenon that traction units produce reactive power during standing at depots. By installing compensation devices at the depots, it could be possible to compensate for most of the production and significantly decrease reactive power in the traction network and the reactive fees. The SM5 unit is based on Stadler's Flirt concept [1]. Over 2500 units (of different concept variations) have been manufactured and are operating in 20 countries [10]. The reactive power production of the units operating in other countries might differ from those studied, but this subject could also be a matter of interest outside of Finland.

SR2's reactive power production can reach the same level as SM5 during movement. However, the reactive fees of the unit type remain low (all units 0 – 15.3 k€/a) because the unit also consumes reactive power during movement, there are significant differences between the units and the production is low during standing. In the case of SM3, reactive power production was only detected during movement. The production is low, and in addition the consumption of reactive power was found to be larger than the production. Because of these factors, the input limit was not exceeded once.

It should be noted that the reactive fees presented in this paper represent the fees that would be charged if Fingrid's reactive power guidelines were applied to individual traction units. In the current situation, the reactive fees are determined by observing the reactive power flow of the traction network's connection point. This means that the reactive power production and consumption of all units operating in the feeding zone affect the observed net reactive power.

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APPENDIX

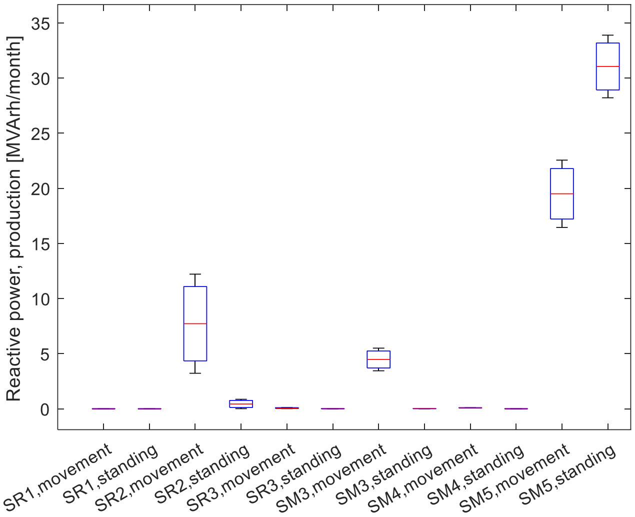

Figure A1. Unit types’ monthly reactive power production during movement and standing. Boundaries of the whiskers indicate the upper and lower limits of the confidence interval at a 95% confidence level. The horizontal line of the box indicates the sample mean value

TABLE AI.
GENERAL AND TECHNICAL INFORMATION OF THE STUDIED UNIT TYPES [1], [11], [12], [13]

Unit	***Train type***	***Model-based on***	***Constructed***	***Number in service***	***Output power / Max output power [MW]***	***Motor***	***Type of power electronic switches***	***Regenerative braking***
SR1	Locomotive	-	1973-1985	91	3.1 / 3.3	DC motor	Thyristor-diode-bridge	No
SR2	Locomotive	RE 460 (Switzerland)	1992-2000	46	5.0 / 6.0	Induction motor	GTO-thyristor	Yes
SR3	Locomotive	Siemens Vectron	2016-	67	6.4	Induction motor	IGBT-transistor	Yes
SM3	Electric multiple unit	ETR 460/480 (Italy)	1992-2002	15	4.0 / 4.4	Induction motor	GTO-thyristor	Yes
SM4	Electric multiple unit	Alstom Coradia	1999-2005	30	1.2	Induction motor	IGBT-transistor	Yes
SM5	Electric multiple unit	Stadler FLIRT	2008-2017	81	2.0 / 2.6	Induction motor	IGBT-transistor	Yes