AC cables strengthening low frequency AC railway with purely active power loads

Lars Abrahamsson
Electric Power Engineering
Luleå University of Technology
931 87 Skellefteå, Sweden
Email: lars.abrahamsson@ltu.se

***Abstract*—Converter-fed railway power systems traditionally use high voltage AC overhead transmission lines in the railway grid for increased loadability. An increased resistance to overhead high voltage AC transmission lines, may motivate cables as one alternative for the future.**

The focus of this paper is to compare a non-strengthened system with two cable solutions for comparing loadability, voltages, and reactive powers for different levels of load scaling. The studies confirmed that the obstacle of reactive power produced in lowly utilized cables is, even if less significant for low frequency AC, still present.

A simplified load model is used representing trains with VSC-converters and three-phase motors as purely active loads regardless of motoring or regenerating. A previous study has been done on thyristor-based trains. The voltage levels while regenerating are higher than in the thyristor-train case study. Besides that the loadability for motoring and regenerating is higher with modern VSC-trains.

I. Introduction

For sustainable transports, the share and amount of railway needs to increase, since rail is the most energy-efficient land-based means of transportation [1]. Electrical motors are more energy-efficient than combustion engines [1]. Altogether, world-wide railway power grid expansions and extensions may be expected, and thus different grid designs need to be considered.

Converter-fed railways traditionally use railway-dedicated high voltage overhead transmission lines as one strengthening measure. An increased public and government resistance for overhead high voltage AC transmission lines might motivate cables as an alternative for future strengthening. A summarized review of high voltage transmission for railway [2] gives a deeper motivation to the idea of using AC cables.

Alternative means of strengthening railway power systems include increasing the spatial density of converter stations, increasing cross section areas of conductors, and/or converting to AT (auto transformer) [3], [4] catenary systems.

Technically, VSC-HVDC transmission for railway [5] is preferable to AC cables, as it also offers a large variety of control options. Economically, it implies investments in larger numbers of converters and costly DC breakers.

TABLE I: Line, cable, and transformer data

	$R, \left[\frac{\Omega}{\text{km}}\right]$	$X, \left[\frac{\Omega}{\text{km}}\right]$	$C, \left[\frac{\mu F}{\text{km}}\right]$
BT catenary	0.2	0.2 j	0
15 kV cable	0.12	0.054 j	0.16
132 kV cable	0.1009	0.026 j	0.16
	$R, [\Omega]$	$X, [\Omega]$	—
16 MVA transformer	0.065	0.85 j	
25 MVA transformer	0.037	0.54 j	

In relation to [2], a more robust and reliable computational approach was presented and used in [6]. This paper studies the same system as [6], but there thyristor-based trains with DC motors were considered. This paper studies the impact of loads representing VSC-based trains with three-phase AC motors.

As one might expect, the purely active load representation of the VSC-based trains, c.f. Section II, allows larger system loading for motoring as well as regenerating trains than for thyristor-based trains studied in [6]. This study also show that voltage increases are lower during regeneration with thyristor-train loads [6] compared to VSC-train loads.

II. Problems setup and models used

The system studied is a representative low-frequency AC railway fed by rotary converters and BT (booster transformer) catenaries. The line, transformer, and cable [7] data are listed in Table I. Line and transformer data are representative, and in line with [5].

In the numerical simulations, pu has been used with base voltage $U_b^{15\text{ kV}}$ set to 16.5 kV, $U_b^{132\text{ kV}}$ to 132 kV, and base power S_b to 5 MVA. Train loads are located as described in Figs. 1 to 3, equal and set to $k \cdot 0.85$ pu, which is a simplified representation of VSC-based trains with three-phase AC motors.

The scalar k denotes a load multiplication factor. The multiplication factor k is maximized, $k_{\max}$, and minimized, $k_{\min}$, for each of the three power system configurations determining the loadability limits. Thereafter, a selection of cases $k_{\min} < k < k_{\max}$, are studied. Due to page restrictions, equations are omitted, but the numerical usage of k explained deeper in [6].

The inter-converter-station distance is 100 km. Three connections between the reinforcement cable and the contact line system are used, illustrated in Figs. 2 and 3. The representativeness of three intermediate transformers is explained in [2].

In each of the studied cases, four rotary converters of the Q48/Q49 type [8] are, as illustrated in Figs. 1 to 3 used in each of the two converter stations.

The models of the rotary converters and the load flow equations for low frequency AC railways might not be known to everyone, but they will not be restated in this paper due to page limitations. The same models as in [2] have been used.

III. Results

A. General remarks

1) Voltages: In the following, the horizontal lines in the voltage plots Figs. 4, 6 and 8 will be introduced:

The standard [9] defines two under-voltage levels for 15 kV AC railways: $U_{\min,1}$ at 12 kV, and $U_{\min,2}$ at 11 kV. The former may be violated for up to 2 minutes, whereas the latter should not normally be violated. Also, three over-voltage levels are defined: $U_{\max,1}$ at 17.25 kV; $U_{\max,2}$ at 18 kV, but in Sweden 17.5 kV, here denoted $U_{\max,2,\mathrm{SE}}$; and $U_{\max,3}$ at 24.3 kV. The first may be exceeded up to 5 minutes, the second up to 1 s, and the third up to 20 ms.

Trains tractive forces should be limited linearly down to zero from $a \cdot U_n = 0.95 \cdot 15$ kV down to $U_{\min,2}$ [10].

2) Loadability: Regenerative braking is maximized in the 15 kV cable system. The largest converter regeneration takes place in the 132 kV cable system.

Common for all cases is that for large $|k|, k < 0$, at some point, the voltage levels start to decrease for decreased k until voltage collapse. This point is reached in different nodes at different levels of (load factor) k.

3) Powers: In Figs. 5, 7 and 10, the denotations P_G, Q_G, S_G, P_L, P_D, Q_D, $Q_{G,\mathrm{cab}}$ represent: total active power sent into the railway by the converters in the system, total reactive power sent in, total apparent converter power, transmission losses, total power train load, total reactive load, and total reactive power produced in the cables.

B. The base case, BT (booster transformer) catenaries

1) Voltages: This unstrengthened system is too weak for most of the loads of this study, Fig. 4. Already for $k = 1$, following [10], tractive force is reduced for the middle trains. For $k_{\max} \approx 1.47$ the middle trains should have stopped following [10].

Conversely, for $k = -1$ the middle pair of trains exceeds $U_{\max,2}$, and the outer pair $U_{\max,2,\mathrm{SE}}$. For $k = -2$ all train voltages exceed $U_{\max,2}$. For $k = k_{\min}$ the outer trains are below $U_{\max,2,\mathrm{SE}}$ – but the system is about to collapse.

The highest obtained inner train voltages are for $k = -8$, whereas the highest outer train voltages are for $k = -6$ (almost drawn against $k = -8$). For $k = \{-6, -8, -10\}$, the inner trains exceed $U_{\max,3}$.

2) Powers: Powers are shown in Fig. 5, in which there is a slight tendency of S_G concavity for "moderate" levels of $k < 0$. Since the system reactances and resistances equal, $Q_D = 0$, $Q_G = Q_L = P_L$, Q_G might wrongly seem missing in the plot. The P_L-curve simply covers the Q_G-curve.

The maximal apparent converter power for $k < 0$ is 26.2 pu, and 8.0 pu for $k > 0$. The minimal (studied) active power converted for $k < 0$ is -14.7 pu ($k = -8$), whereas the level is -10.8 pu for $k = k_{\min}$. The maximal active power converted is 7.6 pu

C. The compromise case, 15 kV feeder cable

1) Voltages: No limit is violated for $k = \{0, 1\}$, Fig. 6. For $k = 2$, the inner trains are affected by the $a \cdot U_n$ limit, and for $k = \{3, k_{\max}\}$ the outer trains are affected by $a \cdot U_n$, whereas the inner ones lie far below $U_{\min,2}$.

For $k = -1$ the inner trains lie above $U_{\max,2,\mathrm{SE}}$. For $k = -2$, the inner trains lie above $U_{\max,2}$ and the outer ones lie above $U_{\max,2,\mathrm{SE}}$. For all $k \leq -4$ all trains lie above $U_{\max,2}$, and for $k \leq -12$ the inner trains lie above $U_{\max,3}$.

The middle trains' voltages peak at $k = -26$, and the outer trains' at $k = -24$.

2) Powers: Powers are shown in Fig. 7, where S_G is more concave for $k < 0$ than in Fig. 5. The comparatively low voltage of the cable, and the low AC frequency, makes the impact of $Q_{G,\mathrm{cab}}$ negligible.

The maximal apparent converter power for $k < 0$ is 61.4 pu, and 18.3 pu for $k > 0$. The smallest studied active power converted for $k < 0$ is -36.6 pu ($k = -24$), -23.9 pu for $k_{\min}$. The maximal active power converted is 17.7 pu

D. BT catenaries with 132 kV feeder cable

1) 15 kV voltages: The 132 kV cable offers strength. No thresholds violated for $k = \{0, ..., 4\}$, c.f. Fig. 8. For $k = 6$ all trains should reduce tractive force. For $k = 7$ the inner trains are just above $U_{\min,2}$ and the outer pair just above $U_{\min,1}$. For $k_{\max}$ the outer trains are below $U_{\min,1}$ and the inner pair below $U_{\min,2}$.

For $k = -2$, all trains lie between $U_{\max,2}$ and $U_{\max,2,\mathrm{SE}}$. For $-4 \leq k \leq -18$, all trains lie above $U_{\max,2}$. Already for $k = -4$ the voltage in node 8 started to drop for increasing regeneration, and for $k = -8$ in nodes 7 and 9. For $k \leq -14$ the voltage drops worsens until the loadability limit.

The inner pair voltages peak at $k = -12$, the outer pair's do it at $k = -14$.

2) 132 kV voltages: The high-voltage sub-grid voltages are presented in Fig. 9. Voltages peak at $k = -2$ due to the $Q_{G,\mathrm{cab}}$ and no Q_D, shown in Fig. 10. Like in [6], for $k < 0$, the highest voltage is in the middle, for $k > 0$ the lowest voltage is. Voltages are above nominal for $-8 \leq k \leq 4$; for $k = -12$ slightly above 1 pu in node 3, below elsewhere; and below nominal for other k.

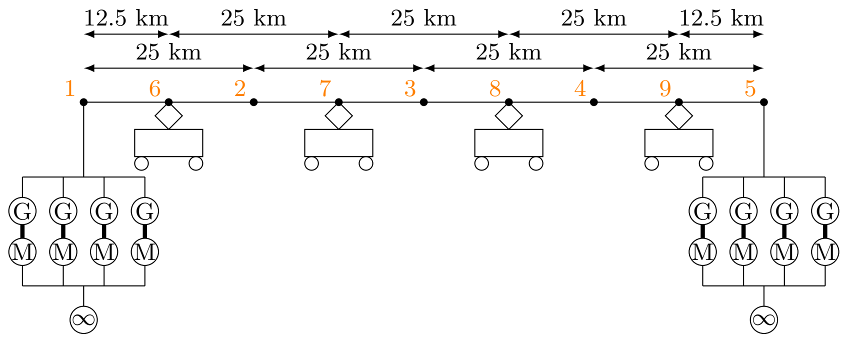

Fig. 1: Illustration of the system studied for the pure BT case. Node numbers in orange.

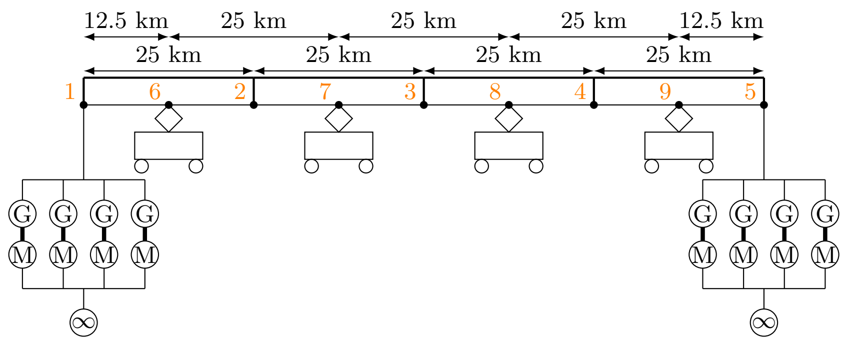

Fig. 2: Illustration of the system studied for the 15 kV cable case. Node numbers in orange. Thick lines denote cables.

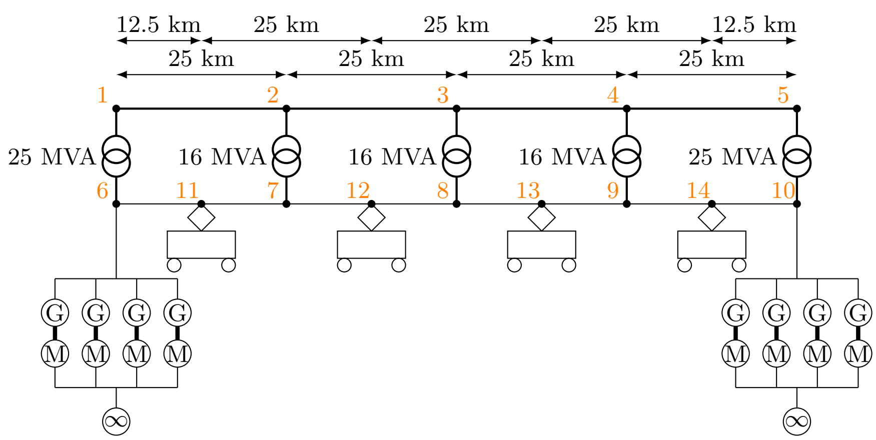

Fig. 3: Illustration of the system studied for the 132 kV cable case. Node numbers in orange. Thick lines denote cables.

3) Powers: Powers are in Fig. 10. The maximal apparent converter power for $k < 0$ is 56.4 pu, and 36.0 pu for $k > 0$. The smallest simulated active power converted is -41.5 pu ($k = -18$), -38.3 pu for $k_{\min}$. The maximal active power converted is 34.3 pu

The impact of $Q_{G,\text{cab}}$ is significant. Still at $k = \pm 2$, $Q_{G,\text{cab}}$ is the largest contributor to S_G. The S_G curve is almost affine for $k < 0$, but convex for $k > 0$.

IV. Discussion

Similarly, as in the thyristor-train study [6], the negative loadability is largest for the 15 kV cable system. At a first glance, it might seem counterintuitive, but is likely to be explained by the transmission losses between trains and converters. The regenerated power at the converters is minimized in the 132 kV cable system.

Studying cases with rotary converters operating close to and beyond their ratings raises the question whether the models used are sufficient in detail – especially in terms of voltage controllability. One cannot outrule that some field voltage saturation may take place making the loadability limits obtained overestimations of the actual values.

One train every 25 km as in Figs. 1 to 3, implies for $k = 1$ and an average speed of, say 160 km/h, 6.40 trains/h. That corresponds to a headway of 9.38 minutes for unidirectional traffic. In an urban area with quadruple-

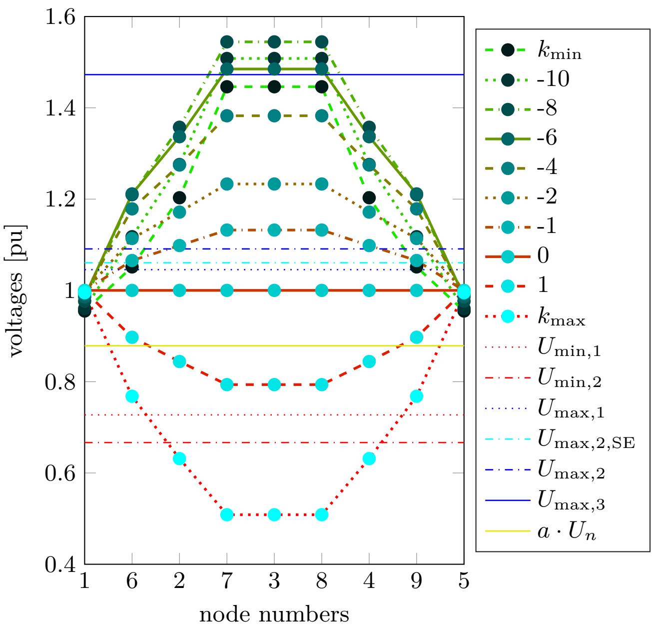

Fig. 4: Voltages against nodes (BT).

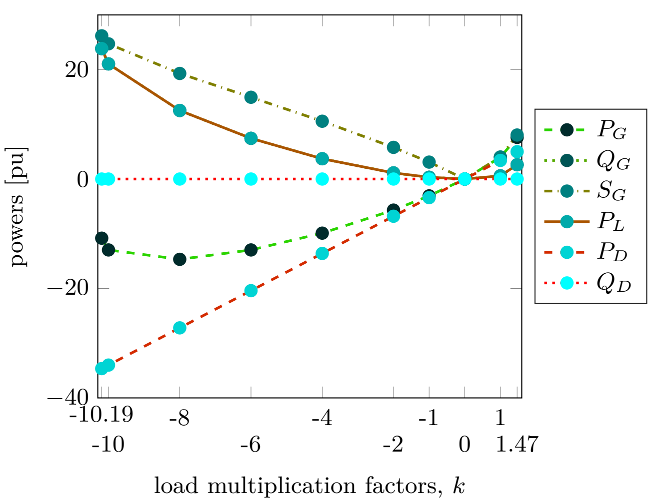

Fig. 5: Powers against scaling k (BT).

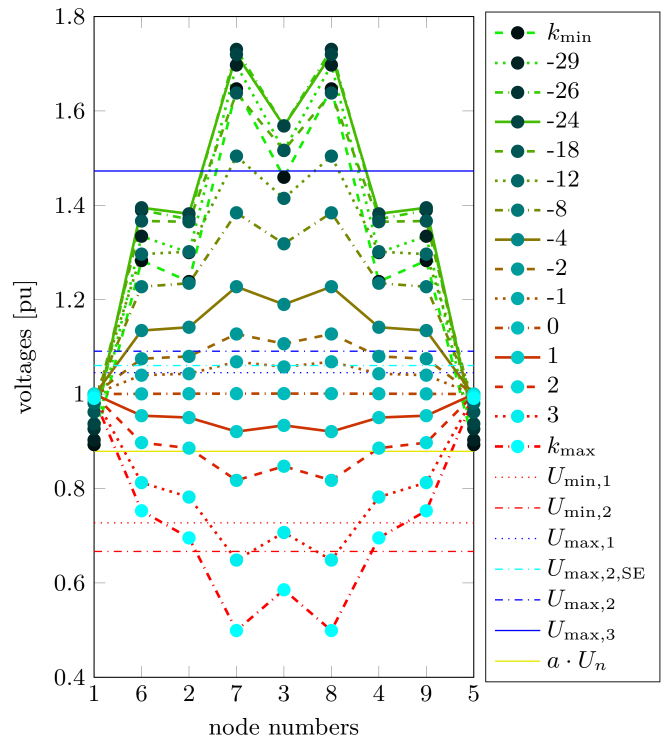

Fig. 6: Voltages against nodes (BT, 15 kV cables).

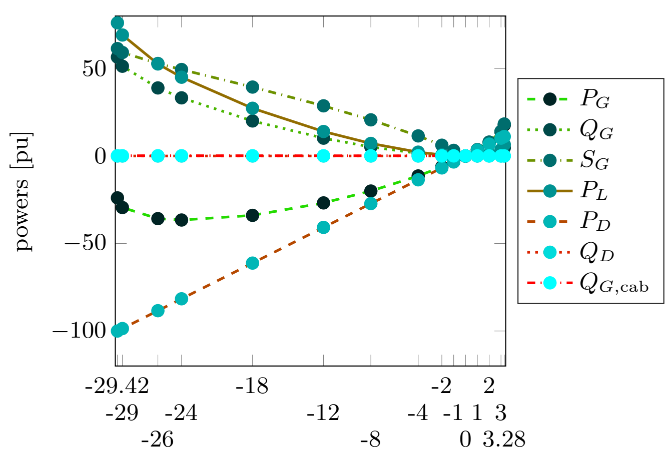

Fig. 7: Powers against scaling k (BT, 15 kV cables).

tracks, it would correspond to a 37.50 minute headway. For $k = 6$, a headway of 6.25 minutes. The 132 kV system manages $k = 6$ quite well. Trains rarely consume full power constantly, but on the other hand many trains also maximally consume much more than 4.25 MW.

For simplicity, however, the electrical line models in this study have all, as indicated in Section II and the related Figs. 1 to 3, assumed single-track railway.

V. Conclusions

The study [2], focused on arguing for AC cables increasing railway power system transfer capacity. Focus in the deepened study [6] was on gaining a deeper understanding of the behaviour of AC-cable strengthened railways with thyristor trains.

The contribution with this study, compared to the one in [6], is that the behaviour of the same system is studied for a load type representing VSC-based trains. Thyristor-trains (older) and VSC-trains (more modern) are the two most common train types in many railway systems, including the Scandinavian low-frequency AC system.

The most notably differences in this study with VSC-trains, compared to the previous thyristor-train study are:

- The loadability is generally higher for motoring, $k > 0$, as well as regenerative braking, $k < 0$, c.f. Table II.
- The regenerating voltage increases are higher gener-

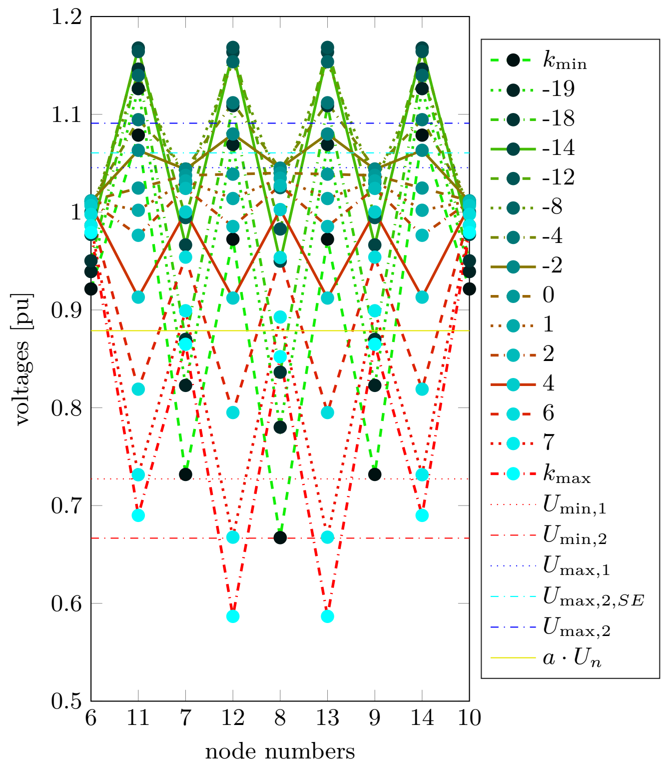

Fig. 8: 15 kV voltages against nodes (BT, 132 kV cables).

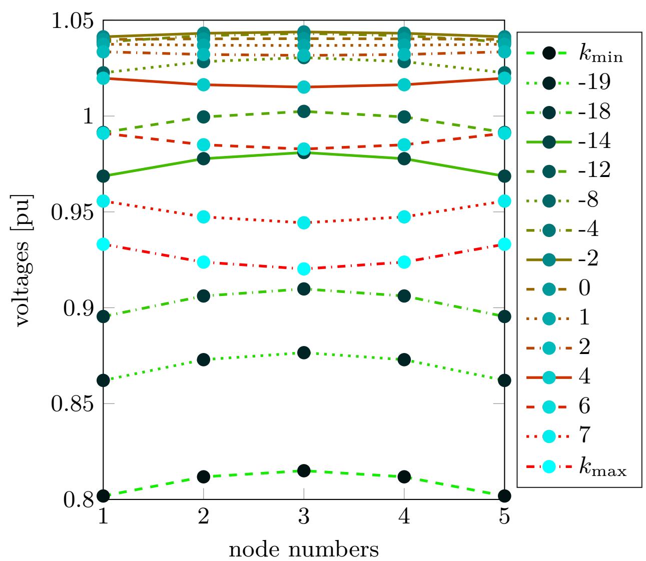

Fig. 9: 132 kV voltages against nodes (BT, 132 kV cables).

ally in the catenary than for thyristor-trains because of the assumption of no reactive consumption. During regeneration, this might be a drawback, otherwise not.

- The resulting voltages of the 132 kV transmission line lie in the same range as in the thyristor-train study, but the highest voltages are attained for $k = -2$ here, instead of at $k = 0$ in [6].

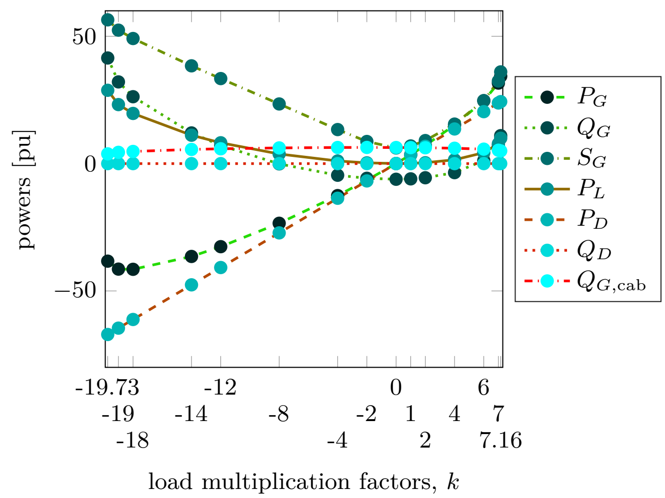

Fig. 10: Powers against scaling k (BT, 132 kV cables).

TABLE II: Comparison of loadability limits

	$k_{\min}$ thyristor	$k_{\min}$ VSC	$k_{\max}$ thyristor	$k_{\max}$ VSC
BT catenary	-6.68	-10.19	1.35	1.47
15 kV cable	-18.68	-29.42	3.05	3.28
132 kV cable	-14.74	-19.73	6.37	7.16

It should be noted that the train loading characteristics are simplistic. More detailed train models would make an aggregated load study as this one too complex.

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