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Question 1.4:
With the development and the usage of high-speed trains, the requirements for load balancing arise. Is there a relation between the speed and the power that needs to be supplied? What are further considerations in relation to the power supply? Are there any opportunities provided by regenerative braking?

Relation between the train speed and the supplied power
The consumed energy of a high-speed train depends on many parameters which can be clustered into different categories.

- Parameters related to the train properties
  These parameters include train mass, friction and train velocity. Consumed energy is depending on the train speed by the power of 3 (~ v^3).
- Parameters related to the topography
  The slope angle of the rail has direct impact on the consumed energy. Also, tunnels may increase aerodynamic drag substantially.
- Parameters related to the operation of the train
  Depending on the time-table and railway line, a number of stops at stations need to be considered. Train acceleration has a major impact on the required power; braking energy may have to be dissipated rather than regenerated.

In literature, the dependency of consumed energy from train velocity is documented. For instance, Vandanjon et al.[1] provide a formula for the mechanical energy:

$$F_m V = F_{rr} V + \frac{1}{2} m k \frac{dV^2}{dt} + m g \sin(\alpha) V$$

, where

- F_m: driving force produced by drive chain
- V: speed of the train, m: mass of the train, α: slope of rail line
- F_{rr}: running resistance (contact wheel, friction, aerodynamic resistance).
  F_{rr} is a second order polynomial with train speed as the variable
- → Energy ~ V^3, P(t) = dE/dt

In https://mappingignorance.org/2020/01/22/the-limits-of-high-speed-rail/ the author I. Rivera presents a numerical example[2] of energy consumption for different operational scenarios based on a Chinese high-speed line. Figure 1 shows the energy consumption of the Shanghai-Hangzhou line versus train top-speed.

[1] P-O. Vandanjon et al., Model of high-speed train energy consumption, 15th mini. conf. on vehicle system dynamics, identification and anomalies, Budapest, November 2016
[2] Adapted from Feng, Sun, Liu, & Li (2014), Assessing Energy Consumption of High-speed Trains based on Mechanical Energy. Procedia – Social and Behavioral Sciences, 138, 783-790.

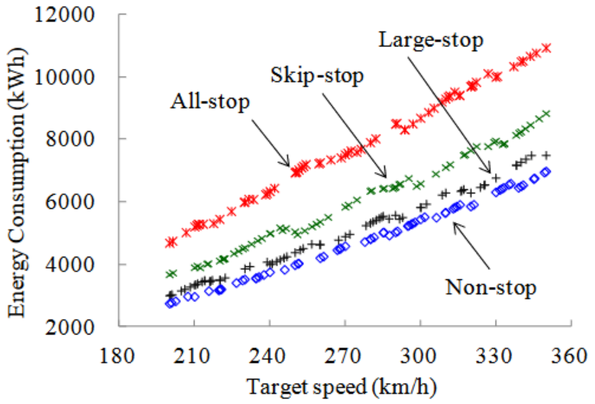

Figure 1: Estimated energy consumption vs. top speed for the Shanghai-Hangzhou line

Opportunities provided by regenerative braking

It can often be experienced that utilities do not remunerate power regenerated from braking trains, or utilities even won't accept power been re-injected from the railway system into their grid.
This means that energy from braking trains is either lost technically and/or financially, or railway operators may want to find ways to keep the energy within the railway system.

Figure 2 shows the classical railway power supply scheme where track sections are supplied by single-phase transformers or special transformers from the mains. In order to limit unbalance for the feeding three-phase system, different track sections are supplied from different electrical phases. This in turn requires to have neutral sections at the track side to isolate one electrical phase from the other.

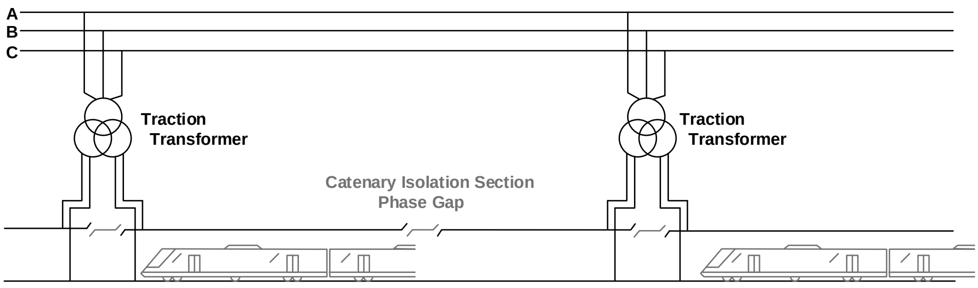

Figure 2: Classical railway power supply scheme

As only a few trains can be present in one feed section at the time for safety reasons, braking energy cannot reliably be re-used by other trains.

However, if a power supply concept is selected that can avoid the neutral sections, braking energy can be kept within the railway system and made available to other trains respectively unloading the supply sources.
Such a power supply concept is based on back-to-back converters (Static Frequency Converters) converting three-phase AC power to single-phase AC power of the same frequency, see Figure 3.

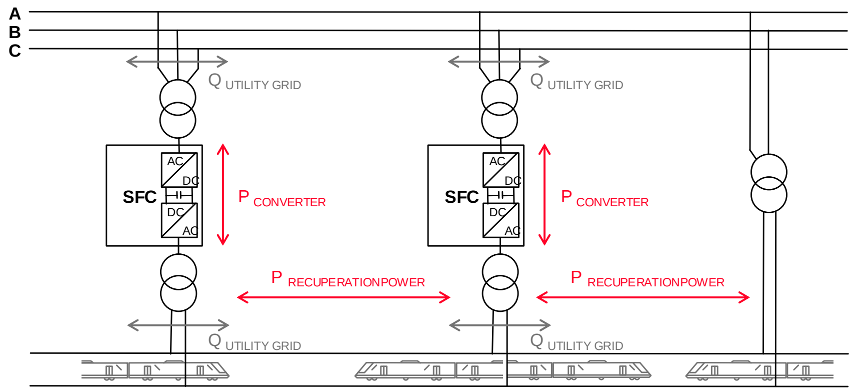

Figure 3: Railway power supply scheme based on back-to-back converters, avoiding neutral sections

Further considerations in relation to the power supply

Design and operation of a back-to-back converter based railway power system is quite different from the classical concept.

On the challenging side, protection needs to be mentioned:

When using back-to-back converters to supply a railway power system, one has to consider that the fault current contribution of converters is limited to approximately 1 p.u. of the converter current rating. The protection concept of the railway system has to be analyzed. Mostly, not only over-current protection is used, but also distance or impedance protection. This topic was addressed by Queensland Rail[3] when introducing frequency converters.

Opposed to challenges, there are many opportunities that should be noted:

- Properties at the three-phase point of common coupling:
  - The problem of unbalance is solved: the converter is seen as a perfect balanced load from the supplying grid.
  - Power factor can be controlled to unity or to another value depending on the supply agreement.
  - The converter interfaces the grid with a pre-defined harmonic spectrum, mostly independent from the harmonics in the railway system originating from very diverse and changing traction loads.
  - Overall, grid code compliance can be granted in a straightforward way
- Properties at the single-phase catenary side:
  - The converter current limitation is an advantage in cases where the short-circuit power level is at its limit, but supply power needs to be increased.
  - Reactive power and therefore catenary voltage can be controlled independently from the actual three-phase voltage level.
  - Distance between feeding substations can be increased.
  - Neutral sections can be avoided.
  - Several converters can be interconnected to the same line and share the traction load. Braking energy can be recovered and kept within the railway system.
- Properties related to the interconnection of the three-phase and single-phase system:
  - Active power can be controlled within each back-to-back converter
  - (Partial) redundancy is inherently given by this power supply concept.

For each project, it is important to consider and quantify costs and benefits on system level in order to decide which power supply concept to select.

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[3] T. Bagnall, C. Banceanu, T. Schaad, Static frequency converters – the Wulkuraka case, acrps 2017, elektrische bahnen 6-7/2017