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Static frequency converters for use in 50 Hz railway traction power supply substations

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Abstract

Conventional power supply of 25 kV 50 Hz railway systems has been realized using 2-phase transformers connected to high voltage 3-phase transmission grids in the past. Recently static frequency converters (SFC) for traction power supply substations have come into focus. SFCs provide multiple technical benefits. One benefit is the symmetric loading of the 3-phase high voltage transmission grid. Hence no voltage unbalance is caused by 2-phase traction power loads. When SFCs are used continuously along the railway line, the overhead contact line (OCL) sections between the traction substations can be supplied in double-end-feeding mode. By using this feeding mode the traction power loads will be shared between minimum 2 traction substations. Hence the traction currents can be reduced significantly. Furthermore, a wide spread of regenerated power is enabled. Thus the overall efficiency of the entire traction power supply system will be improved. For the rating procedure of SFC-substations the different overload capabilities of transformers and SFCs have to be considered. The mathematical principle of time weighting represents an efficient approach for rating of electrical devices and equipment of traction power supply substations.
Keywords: traction power supply, static frequency converters, rating, time-weighted load duration curve.

1 Introduction

Conventional traction substations of 50 Hz railway traction power supply systems are realized by connecting 2-phase transformers to the 3-phase high voltage transmission grid. The traction power line is a single phase line and thus the power is drawn from two phases of the 3 phase grid causing a loading unbalance in consequence when connecting the traction substations (as shown in Figure 1). The

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loading unbalance will consequently cause a voltage unbalance in the 3-phase grid. A simple way to limit the impact of loading and voltage unbalance and to somehow balance the traction power loads is the connection of consecutive substations to different pairs of phases (as shown in Figure 2). Still a loading unbalance and thus a voltage unbalance will remain.

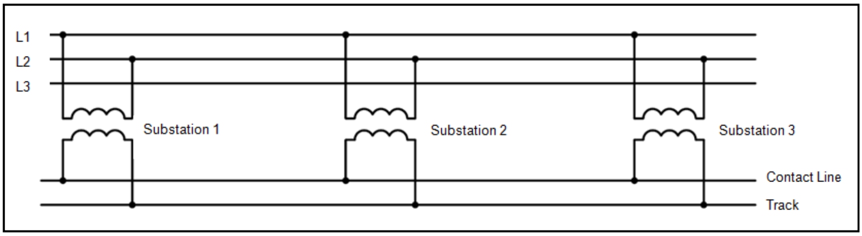

Figure 1: Conventional feeding concept of 50 Hz railway systems, all substations connected to phases L1-L2 of the 3-phase grid (Kießling *et al.* [1]).

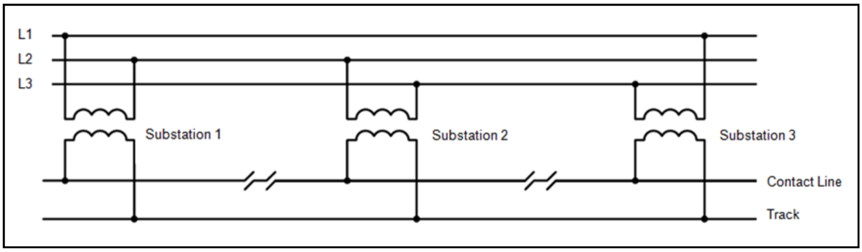

Figure 2: Conventional feeding concept of 50 Hz railway systems, substations with alternating connection to two phases of the 3-phase grid (Kießling *et al.* [1]).

As a consequence of the supply scheme shown in Figure 2, the voltage of the contact line is phase-shifted by ±120° between consecutive substations. Therefore, the contact line has to be equipped with so called neutral sections. This results in isolated and single-end fed supply sections of the contact line as it can be seen in Figure 2.

Besides the issue of voltage unbalance neutral sections along the contact line are required to exclude a power flow via the contact line in parallel to the 3-phase transmission grid in order to avoid a thermal pre-loading of the contact line which would lead to a decreased capability for traction currents.

The neutral sections have to be passed with cut-off power by the vehicles in order to prevent a damage of the contact line caused by flashing arcs. Thus the trains are without power supply and tractive effort when passing neutral sections. This is a complex procedure and failures or incidents are likely to occur.

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2 Static frequency converter (SFC) in traction power supply substations

2.1 General

SFCs are electrical installations based on power electronic semiconductors that enable the interconnection of two independent power grids. Compared to transformers, which are passive electrical devices, SFCs are active devices that can control the power flow between two interconnected, independent power grids as well as the quality of the input and output power. Figure 3 shows an example of the block diagram of a SFC for the use in traction substations. Its main components are a 3-phase converter, a 2-phase converter and a DC link. State-of-the-art SFC technology is based on a voltage controlled DC link that connects the 3-phase converter and the 2-phase converter. The DC link contains capacitors which are charged to a constant DC voltage level by the 3-phase converter. Due to the pulsating characteristic of single-phase loads a filter may be located in the DC-link as well.

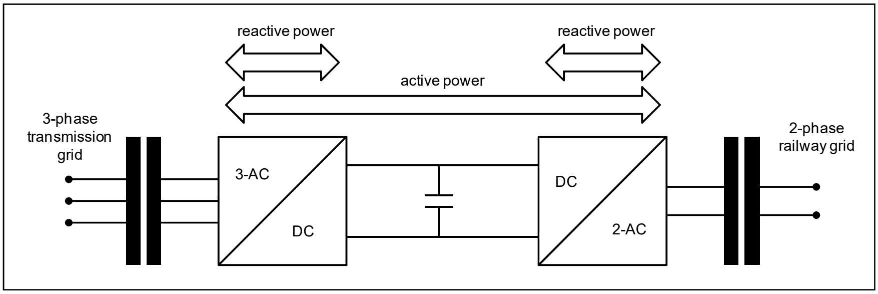

Figure 3: Principle set up of SFCs and power flow options.

In Figure 3, the power flow options of SFCs are shown. The active power flow between the two independent power grids can be controlled in terms of quality and quantity. Additionally, the reactive power in both power grids can be controlled independently. This circumstance applies also in case of a failure of one of the two interconnected power grids. For instance, in case the 3-phase grid is out of service the 2-phase converter (incl. the DC-link) functions as static compensator (Statcom) supplying reactive power to the railway grid and thus stabilizing the line voltage.

2.2 Influences of SFC usage in railway operation and the overhead contact line

SFCs enable the adjustment of the output voltage (the voltage of the railway grid in this application) in terms of amplitude, frequency, phase angle and number of phases. When all SFCs of a railway line are synchronised regarding these parameters, the overhead contact line can be built without neutral sections (as shown in Figure 4).

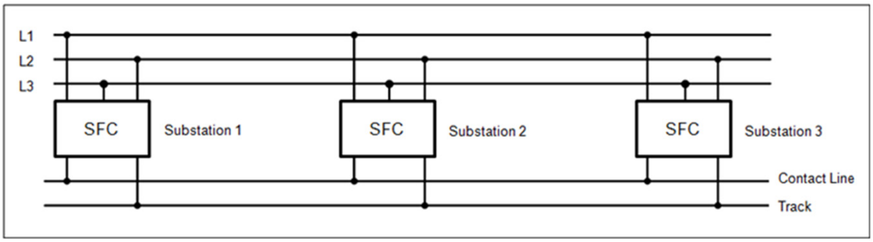

Figure 4: SFC feeding concept – paralleled substations along the railway line (double-end feeding mode, refer to section 2.3).

However, in order to guarantee a high availability of the infrastructure sectioning points (also known as coupling points) should be installed along the contact line. Usually sectioning points are located half-way between two neighboured traction substations. Sectioning points contain coupling switches that are closed during normal operation. Sectioning points allow a selective protection scheme of the contact line. Thus specific parts of the contact line with a failure (e.g. short circuits) can be disconnected without disturbance of faultless contact line sections. When passing sectioning points trains do not have to switch off its power supply.

2.3 Influences of SFC usage on the feeding mode

In Figure 2, it can be seen that each contact line section is fed from a single infeed point (so called single-end feeding mode). For a single train the voltage drop increases as the vehicle moves further away from the infeed point. The location of the greatest voltage drop will be located at the point of the contact line furthest away from the infeed point assuming a constant power demand of the vehicle.

In Figure 4 it can be seen that all feeding sections of the contact line are paralleled (so called double-end feeding mode). The double-end feeding mode results in a split-up of traction currents between substations. Hence the location of the greatest voltage drop for a single train run is half-way between two infeed points assuming a constant power demand of the vehicle.

Due to the reduced traction currents of the contact line the voltage drop can be reduced in double-end feeding mode compared to single-end feeding mode. That implies that the distance between two neighboured traction substations can be increased while maintaining the same voltage drop as in single-end feeding mode.

Thus, when using SFCs in traction power substations the overall number of substations along the line can be reduced. The actual number of substations shall be investigated project-related for normal and failure mode operation scenarios.

2.4 Impacts of SFC usage on regeneration

Modern vehicles using converter controlled 3-AC drives can regenerate power into the railway grid during braking. The regenerated power is preferably used by other vehicles provided that there are power-consuming vehicles available to withdraw the power from the contact line. Otherwise the regenerated power will flow back into the 3-phase grid when conventional substation transformers are used.

A reverse power flow from the railway grid to the 3-phase grid may not be permitted by the operator of the 3-phase grid due to concerns regarding the overall stability of the grid. Therefore, in many 50 Hz railway systems regeneration of the vehicles is not permitted, because it cannot be ensured that regenerated power is not fed back into the 3 phase grid.

SFCs can actively control the power flow between the 3-phase power grid and the railway grid. Thus regeneration of vehicles can generally be permitted. If the regenerated power cannot be used due to missing consuming trains the surplus electrical energy has to be converted to thermal energy through braking resistors. These can be installed in the substations (e.g. in the DC link of the SFCs) or on board of the trains.

Due to the double-end feeding mode enabled by the use of SFCs (refer to Figure 4) regenerated power can be distributed over far greater distances than in conventional traction power supply systems (due to neutral sections, refer to Figure 2). Consequently, the overall regeneration rate of the railway system will somehow increase.

2.5 Influences of SFC usage on power quality

2.5.1 Unbalance

The 2-phase traction power loads will cause a loading unbalance and consequently a voltage unbalance in the 3-phase power grid. This unbalance may to a malfunctioning of other power consumers of the 3 phase grid (e.g. 3-AC drives of ventilators or pumps). Thus the permissible loading unbalance is limited by regulations. The impact of unbalance can be limited by the use of special transformers (e.g. Scott transformers). Design and functionality of Scott transformers are explained in detail in (Ogunsola and Mariscotti [2]). However, the impact of unbalance cannot be completely avoided by the use of Scott transformers.

The resulting voltage unbalance $V_{\text{unbalance}}$ (in percent) caused by 2-phase traction loads can be estimated with sufficient accuracy by the following equation (Kießling *et al.* [1]).

$$V_{\text{unbalance}} = \frac{S_{\text{traction}}}{S''_{\text{k,min}}} \cdot 100\% \tag{1}$$

S_{traction} 2-phase traction power load to be drawn from the 3-phase grid
$S''_{\text{k,min}}$ min. value of the short circuit power of the 3-phase grid at the point of supply

The calculated resulting voltage unbalance has to be kept within the limits specified by the operator of 3-phase grid. In common applications the permissible voltage unbalance shall not exceed a value of 2%.

Whenever traction loads shall be increased it has to be checked if the short circuit power of the 3-phase grid at the point of supply is sufficiently large enough.

Consequently, it might be required to connect traction power substations to 3-phase power grids at higher voltage levels in order to meet the specified voltage unbalance limits.

Since SFCs load the 3-phase grid symmetrically traction power substations may be connected to weaker 3-phase grids at lower voltage levels, for instance at medium voltage level. This fact provides more options for traction power supply substation connections because of the wider spread of medium voltage grids.

2.5.2 Harmonics

SFC technology is not only used in traction power supply substations but also in propulsion systems and auxiliary power supply systems of railway vehicles. Thus the overall number of SFCs rapidly increased in the past years. Due the active control of the SFCs and the switching of the power electronic semiconductors harmonics more and more become an issue to be taken into consideration.

All of the actively controlled SFCs inject current harmonics into the railway grid. The harmonic number and the amplitude of the injected harmonics depend on the control pattern of the SFC and the switching frequency of the semiconductors.

The injected current harmonics eventually cause a distortion of the line voltage. The distorted line voltage may cause a malfunctioning of electrical devices, equipment and installations connected to the railway grid or located in the proximity of the railway system due to electromagnetic coupling. These may include but are not limited to:

- railway vehicles;
- point heatings;
- interlocking systems;
- signals, hot axle box detection devices, axle counters; or
- entire railway stations.

Strength and kind of the disturbance depend on the specific environment as well as the resulting harmonics of the system. Thus a general handling of harmonics including the resulting impacts is not possible due to the large variety of parameters which have to be considered.

In conventional traction power supply substations harmonics of the railway grid (e.g. injected by converter controlled vehicles) can be transferred to the 3-phase grid via the substation transformers.

When SFCs are used the railway grid and the 3-phase grid are separated by the DC link. Thus harmonics of the railway grid cannot be transferred to the 3-phase grid and vice versa. However, it has to be taken care of the current harmonics produced by the substation-SFC itself. To limit the injection of harmonics input filters may be required.

2.5.3 Load fluctuations

Electric railway operation is characterized by intense load fluctuations, which are often caused by so called load steps (sudden variations of the demanded power). Load steps may occur on a discontinuous basis and may have an influence on the power quality of the 3-phase grid. For instance, load steps occur when a train has passed a neutral section with cut off power. After leaving the neutral section the train suddenly connects its full power to a new contact line section and thus to a new traction substation. In consequence voltage dips and flicker may occur in the 3-phase grid.

The strength of impacts caused by sudden load steps mainly depend on the short circuit power of the 3-phase grid at the point of supply. Due to the direct coupling via transformers in conventional traction substations the load fluctuations are directly transferred from the railway grid to the 3-phase grid.

When using SFC technology the substations along the line can be paralleled (double-end feeding mode, refer to Figure 4). Due to the double-end feeding mode the trains do not have to cut off power at neutral sections. Hence the traction load is smoothly decreasing at one substation while increasing at the neighboured substation as the train runs along the line. Thus load steps caused by cut off power of trains when passing neutral sections will not occur. The impacts of flicker and voltage dips on the 3-phase grid caused by traction loads will remarkably decrease when using SFC technology in traction substations.

Due to the reduced impact of load fluctuations traction substations can be connected to medium voltage grids. These grids usually have a reduced short circuit power and are therefore more sensitive to load fluctuations. Furthermore, it shall be considered that fees for connections to 3-phase grids are often strongly correlated to the peak loads of the railways traction power loads. Smoothing these peak loads by using SFC-based substations and double-end feeding may reduce the overall costs of energy consumption.

3 Rating of SFCs in traction power supply substations

Nowadays the load of complex traction power supply systems can be determined with high accuracy by modern simulation software tools with detailed and validated models and highly optimized calculation algorithms. The results of the simulation process are curves of physical values as voltages, currents or power depending on time and/or location. An example of a time-dependent curve of the substation power load is given in Figure 5. The curve was calculated by means of the railway operation simulation program *OpenTrack* [3] and the traction power supply simulation program *OpenPowerNet* [4].

The rating process of electrical installations and equipment is mainly focused on determination of the thermal stress caused by the power load currents. Especially load peaks can cause a considerable rise of temperature in electrical installations. However, if the load peaks have a significant and periodic distance between each other – like in typical traction power load cycles – it is possible to reduce the impact of the load peaks when the equipment rating is determined. The time between load peaks are so called load breaks during which the equipment may cool down to a certain extent. These periods are also known as regeneration times.

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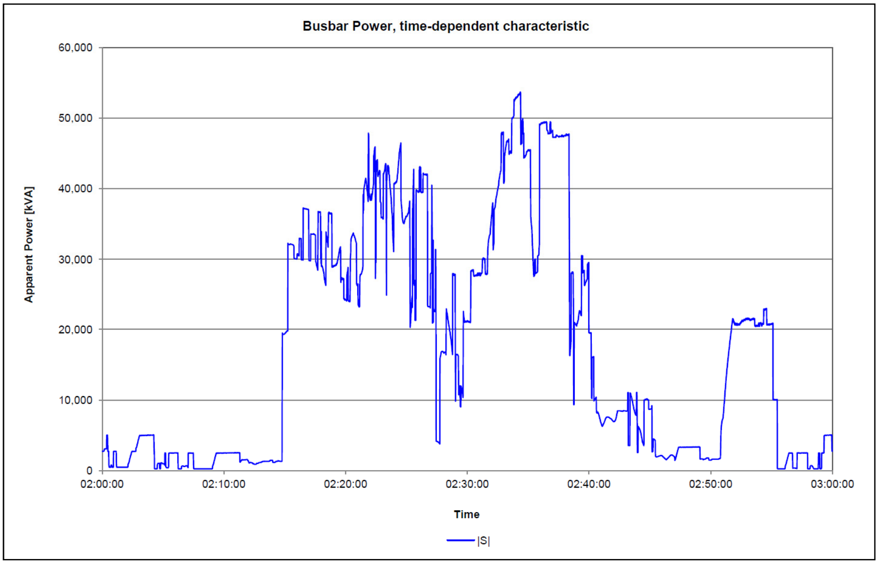

Figure 5: Time-dependent load traction power supply substation.

The approach of the algorithm of time-weighting takes into account such load breaks and regeneration times. The mathematical principle is explained in detail in (Kießling *et al.* [1]) and is based on the following basic formulas.

$$P_{\mathrm{rms,max}} = \max\left(\sqrt{\frac{1}{t^*}\sum_{t}^{t+t^*} P_{\mathrm{t}}^2 \cdot t_{\mathrm{d}}}\right) \tag{2}$$

$$0 \leq t \leq (T - t^*) \ \text{ and } \ t_{\mathrm{d}} \leq t^* \leq T)$$

The result of time weighting is the so called *time-weighted load duration curve*. This curve represents a function of the maximum mean loads in relation to the actual load duration by considering regeneration times. As a result, different load cycles can be compared to each other as well as to specific load capabilities of electrical devices. Figure 6 shows the time-weighted characteristic of the time-dependent load cycle (shown in Figure 5).

Transformers of conventional traction power supply substations can be overloaded to a high extent compared to their nominal power. The duration of the overload may take several minutes without causing any damage to the transformer. The permissible duration of the overload depends on the transformers thermal capability. Usually traction substation transformers are assigned to a specific load class according to EN 50329 to specify the overload capability. In Figure 6, load class IA was chosen for the shown application. The nominal power of the transformer has to be chosen to 40 MVA.

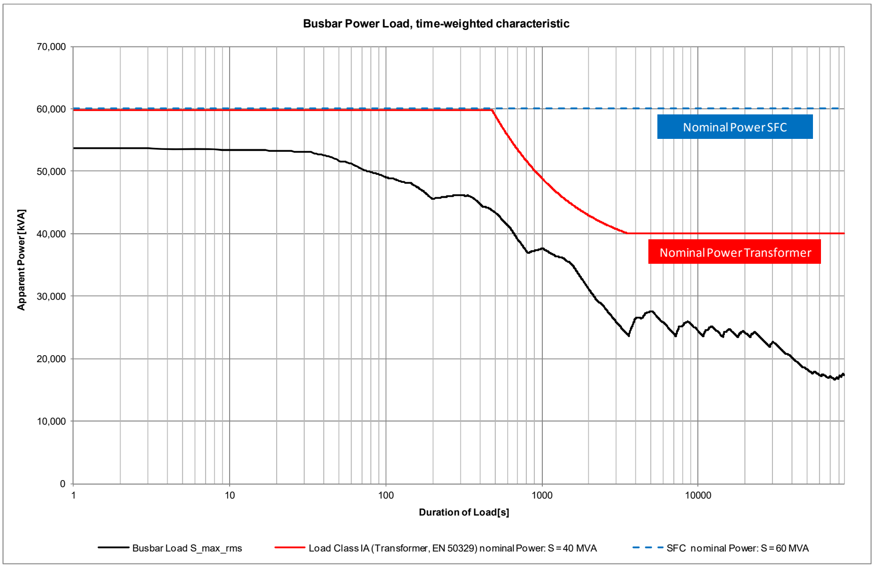

Figure 6: Time-weighted load duration curve of a traction power supply substation compared to load capabilities of transformers and SFCs.

The thermal capability of SFCs is much lower than of transformers due to the power electronic semiconductors. Thus SFCs have a very limited overload capability. For the presented load cycle (Figure 5) an SFC has to have a nominal power of 60 MVA (as shown in Figure 6).

To ensure an efficient rating process in terms of material and investment costs the different devices of a traction power supply substations have to be rated and chosen according to their specific power load and overload characteristics. An example is given for transformers and SFCs in Figure 6, but the procedure can be applied for cables or OCL as well.

4 Conclusion

SFC technology has reached the technological level to be used in traction power supply substations. The operational disadvantages caused by conventional 50 Hz traction power supply systems such as single-end feeding, limited ability of regeneration, neutral sections of the OCL and negative impacts on the power quality of the supplying 3-phase power grid (e.g. loading unbalance, load fluctuations, etc.) can be significantly improved by using SFC-based traction power supply substations. Especially the use of regeneration as well as the wide spread of regenerated energy will increase the systems overall efficiency.

The rating procedure of SFC-substations has to consider different characteristics of overload capabilities of the electrical devices. An individual rating for the devices of a substation is recommended to ensure an efficient rating, which will have a significant impact on the investment costs of the substations.

By now no application of a 50 Hz traction power supply system using a large number of paralleled SFCs is known.

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