FACTS as basis of smart traction power supply systems with 50 Hz nominal frequency

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The peculiarities of electrical traction systems and actual challenges are requiring an innovative and comprehensive approach. Therefore, a Smart Railway Power Supply is envisaged, based on several converter solutions to be applied individually for each use case. Within the EU-Project *In2Stempo* the existing concepts and technologies will be tested to achieve a higher level of technical readiness and application guidelines.

FACTS als Grundlage intelligeneter Bahnenergieversorgungssysteme mit 50 Hz Netzfrequenz
Die Eigenheiten sowie aktuelle Herausforderungen der elektrischen Bahnenergieversorgung erfordern innovative, umfassende Lösungen. Ziel ist eine intelligente Bahnstromversorgung basierend auf mehreren Umrichterlösungen, welche individuell passend für jeden Anwendungsfall ausgewählt werden. Im Rahmen des EU-Projekts *In2Stempo* werden die bestehenden Konzepte und Technologien untersucht, um einen höheren Grad an technischer Reife zu erreichen sowie einen Anwendungsleitpfaden bereitzustellen.

Le FACTS comme base d’un système d’alimentation intelligent de la traction à 50 Hz
Les particularités des systèmes de traction électrique et de leurs enjeux actuels nécessitent une approche innovante et globale. L’objectif consiste en une alimentation en énergie de traction intelligente basée sur plusieurs solutions de convertisseurs, pouvant être mises en œuvre spécifiquement en fonction de l’usage souhaité. Dans le cadre du projet européen *In2Stempo*, les concepts et technologies existants seront testés pour atteindre un haut niveau de maturité technologique et fournir des directives d’application.

1 Introduction

1.1 General

Heavy load changes caused by the characteristics of train operation and the single-phase character of traction loads have always led to specific requirements for traction power supply systems. Current challenges, such as climate change and cost optimisation with simultaneous rapid growth in traffic volume further increase the demand for innovative technologies in the 50 Hz traction power supply. With Flexible-AC-Transmission-System (FACTS) several technical solutions based on power electronic components are available, enabling active control of the energy flow in a traction power system and thus providing a keystone of smart traction power supply. FACTS are used to extend or optimise conventional transformer substations as well as stationary installation along railway lines. In the context of the challenges faced by the SNCF Réseau and further European railway operator, the possible applications and advantages of various FACTS are examined and evaluated in the framework of the overall power supply system. With the EU project *In2stempo*, the efforts of several European railway operators and manufacturers are united to specify application possibilities and advance the use of the technology to product maturity.

1.2 Conventional AC 50 Hz 25 kV traction power supply – example of operations and topologies

Electrical traction systems are distributing traction energy from the 3 AC public grid to the electrical trains operated on a railway line. Providing the actual power demand, ensuring power quality along the track as well as system and person safety are just some requirements an electrical traction system must fulfil.

The electrical traction system consists of the contact line system and traction substations. The contact line system includes the contact lines (*7* in Figure 1) as well as the return circuit along the railway line. Traction substation realise the electrical interface between the 3AC public grid and the contact line system as well as accommodating the control

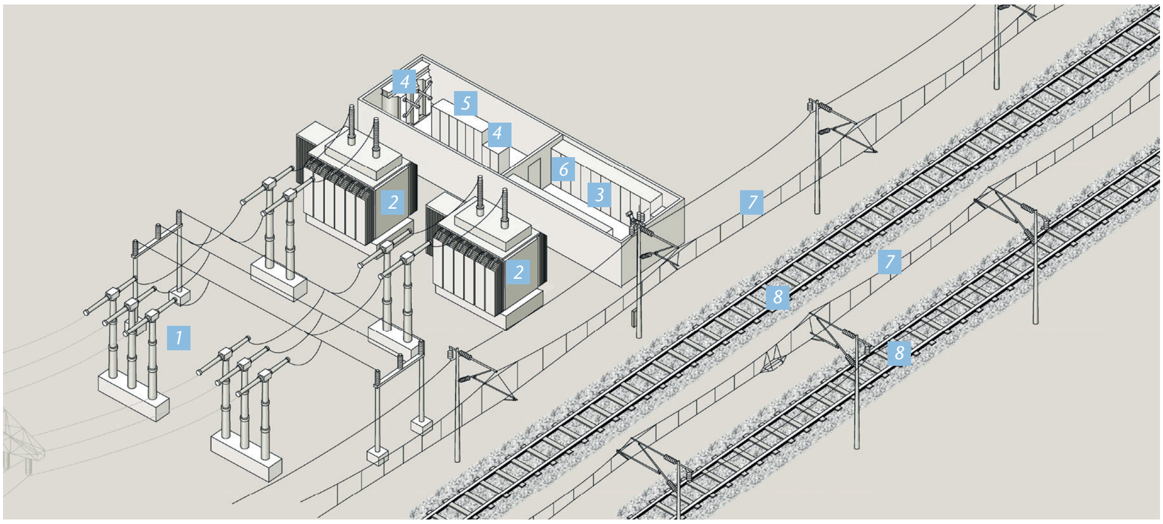

Figure 1:
Overview electrical traction system (Source: SMO, modified *eb*).
1 – 3AC switchgear, *2* – traction transformer, *3* – medium-voltage switchgear, *4* – auxiliary power system,
5 – station controm system, *6* – protection technology, *7* – contact line system, *8* – rails

and protection equipment (*5* and *6*). Figure 1 provides a schematic overview for an electrical traction system with a conventional transformer substation supplying two railway tracks.

50 Hz railway substations are simple transformer-based connections to the 3AC public grid which offer several advantages like easy maintenance and great reliability. In the case of a AC 50 Hz 25 kV system the conventional traction substation is comprised of three basic sections. The high voltage section is providing the switchgear (*1*) for the connection to the 3AC public grid, consisting of circuit breakers, disconnectors, and a 3AC busbar. The power conversion group builds the core of the traction substation, typically one transformer (*2*) is used for each supply section fed by the traction substation. The medium voltage switchgear (*3*) is comprised of a 25 kV busbar, circuit breakers and disconnectors. By branches the energy is distributed from the busbars to the individual overhead contact line supply sections.

Besides substations, coupling posts are used along the track to balance the voltage levels between tracks and phase separation sections (or neutral zones) are used to separate the supply sections fed by transformers operating on different phases of the 3AC grid.

1.3 Supply concepts

The connection possibilities of transformers within the traction substation enable different topologies and operational modes. Figure 2 depicts some of the most common supply concepts for AC 50 Hz 25 kV AC traction power systems.

In Figure 2 are two adjacent substations displayed, each supplying two supply sections. The supply sections are separated by a phase separation section in between both traction substations. The substation on the left side, substation 1, has an additional phase separation section located close to substation 1. In contrast to this, substation 2 has only a simple switching section located in front of the substation. The design of substation 1 enables a wider set of operation modes. Substation 1 can operate both transformers at the same time in several configurations:

- Option 1: both transformers are connected to the same pair of phases of the 3AC public grid and in operation. In this case the phase separation section in front of the traction substation can be closed.

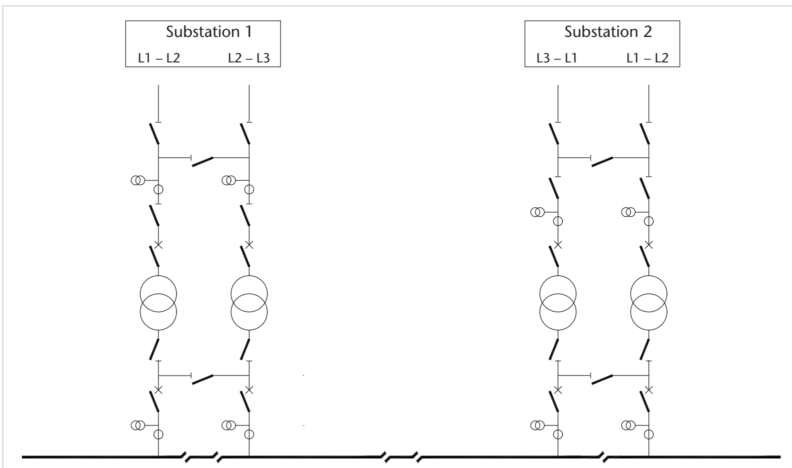

Figure 2:
Example operation mode of adjacent AC 50 Hz 25 kV substations
(Source: SNCF, modified *eb*).

- Option 2: only one transformer is in operation. The second transformer is used as backup in case the first transformer is out of service. The phase separation section in front of the substation is closed.
- Option 3: the transformers are both in operation and in V/V connection. Each transformer is connected to a different pair of phases of the 3AC public grid, in which case the phase separation section in front of the substation is open. Substation 1 is thus feeding two supply sections operating each on a different phase angle.

In contrast, Substation 2 can only be operated in option 1 or 2, feeding one supply section.

2 Modern challenges for electrical traction systems

Due to their intrinsic characteristics, electrical traction systems have always tackled unique requirements and differentiated to ordinary public energy supply systems. The single phase character of the supply network or trains as moving loads with a highly fluctuating load pattern are just some reasons for the distinctive character of electrical traction systems. These properties are leading to requirements like:

- High peak loads determined by powerful trains with fast changing operation states.
- Fluctuating load demand due the changing traffic demand. For example, during peak hours of the day, usually in the morning and evening of working days.

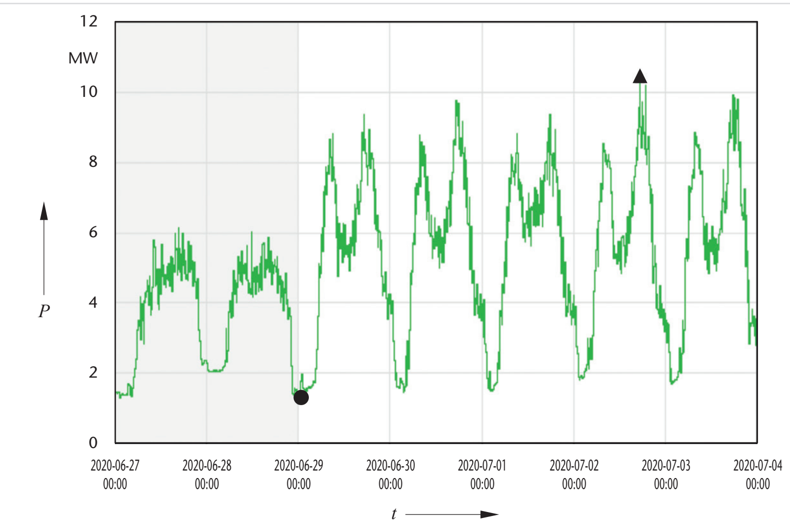

Figure 3:
Example of AC 50 Hz 25 kV substation load profile throughout one week – based on averaged 10 min active power values (Source: SNCF, modified *eb*).

- A load flow in both directions due to the recuperation of braking energy. Modern trains in AC 50 Hz 25 kV systems often regenerate braking energy and feed the energy back to the electrical traction system. If no close by load consumes the energy, it is supplied back to the 3AC public grid.
- High single-phase loads at the interface with the 3AC public grid. The connection of a single-phase transformer is disturbing the voltage balance of the 3AC public grid as it is connected to only two of the three phases. The V/V connection of two traction transformer is a first measure to reduce this unbalance up to 50% depending on the operational situation.
- Meshed supply network structure in the contact line system.

Figure 3 shows a typical load characteristic of a 25 kV traction substation. The values are provided as 10 min average values for a one-week-power demand. The pictured load characteristic is based on mixed traffic on a main line. The load pattern accentuates the high peak loads and the fast change of the load flow, highlighting the high power consumptions during working day peak hours. These system-specific properties require measures to reduce peak loads and to even the load flow as the component dimensioning and, as in the example shown, the energy costs are strongly dependent on these parameters.

In addition to the intrinsic requirements of the railway system, the request for more traffic capacity has further increased. The continuous growth of the traffic demand is not only leading to the need of new railway lines, but also a capacity increase on existing lines. Increasing the traffic capacity on existing lines proves to be difficult as the conventional supply concept with simple transformer substations is often designed and operated close to its capability limits in terms of supply voltage stabilization and voltage drop along the line. Additionally, an increase of power demand would intensify power quality problems in the electrical traction system and the interface with the 3AC grid.

Furthermore, railway power supply is confronted with similar problems like public power supply grids, which have become increasingly prevalent in the last years:

- The climate change and the derived need for carbon dioxide reduction have led to a request for energy saving and lower emissions. Due to increasing traffic demand being in contrary to the need of energy saving, this challenge is preferable addressed by innovative technologies and an energy efficient operation.
- Stronger requirements for grid connection and network operation are deployed, demanding a

higher power quality for the connection to the 3AC public grid and leading to higher penalties for unbalanced loads or low power factors.
- Lower short circuit powers within the 3AC public grids are further complicating the connection to the 3AC grids for electrical traction systems. Especially with the shift from nuclear or coal power plants to a more distributed renewable energy production, the 3AC public grid will encounter a change in its power inertia and short circuit power.

While addressing the abovementioned challenges the operation of the system must always enable an economical operation.

3 SMART Railway Power Supply

3.1 FACTS for railway power supply

To address the existing and emerging challenges listed in the previous chapter, a comprehensive approach is needed tackling all parts of the electrical traction system. By combining multiple solutions to improve and enhance the electrical traction system a Smart Railway Power Supply shall be achieved.

A comprehensive approach for railway electrification must consider primary and secondary technologies as well as digitalisation components equally to achieve an interconnected system. The basis of the SMART railway power supply approach shall be built by Flexible AC Transmission Systems (FACTS) whose application is changing the fundamental supply concepts. The main objectives of FACTS application are as follows:

- reduce peak loads by interconnected networks and active load flow control, to optimize component dimensioning and increase the line traffic capacity
- improve the power quality at the interface with the 3AC public grid, to meet the grid connection criteria
- improve voltage stability and quality for a higher traffic capacity on the lines
- support energy efficient operation

With FACTS a system solution is given, which can be implemented in the primary traction circuit and enable the active control of the load flow in an electrical traction system. FACTS are semiconductor based power electronic facilities. Depending to their field of application, FACTS are designed to convert electrical energy and change amplitude, phase angle and/ or frequency of voltage and current. First used as traction power converters on trains and later as static frequency converters to connect railway networks with a different frequency to the 3AC public grid. The application of SFC to connect 16,7 Hz railway networks to the public supply grid is nowadays state-of-the-art [2] and the application possibilities for FACTS have become manifold.

By the usage of different supply concepts and application options for FACTS in AC 50 Hz 25 kV railway systems the aforementioned challenges shall be addressed. Thereby, five types of FACTS are promising, their possible field of application is described in the following chapters. The Figure 4 displays schematic possibilities for integration of FACTS in the AC 50 Hz 25 kV electrical traction system. In dependency of the actual supply concept and challenges of a specific railway line, the most suitable FACTS solution shall be chosen and applied.

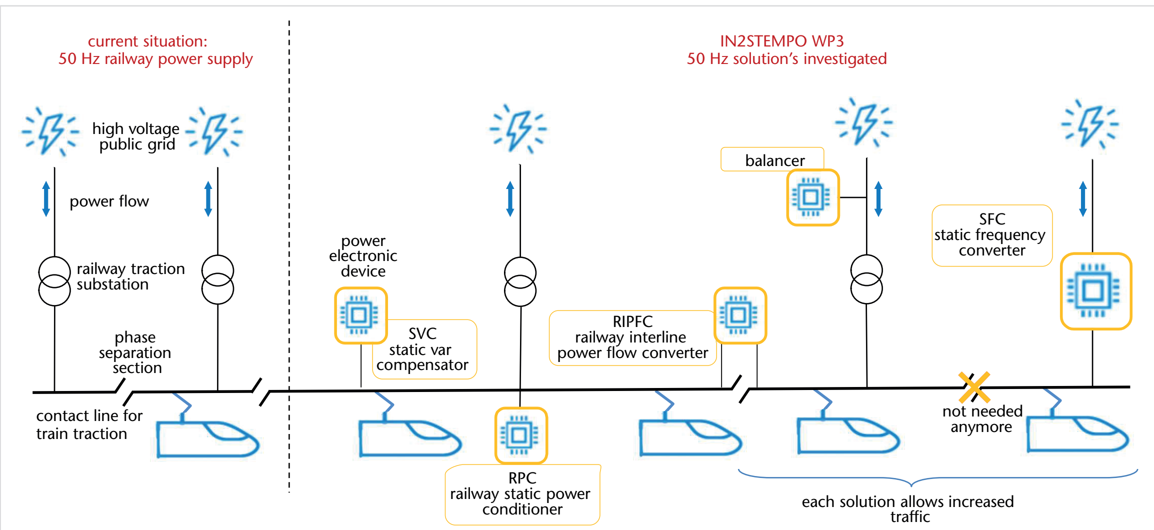

Figure 4:
Application scenarios for FACTS in railway power supply (Source: [1], modified *eb*).

Nowadays, a high variety of topologies and design options for converter are available. For each use case, an application-oriented design shall be chosen. Among other, the multilevel design has proven to enable a high quality of the output voltage and an economic, modular design easily adapted to different sizing's. Modern converters have also overcome many of the initial teething problems and provide a high quality of the output voltage and a high efficiency in the entire operating range.

3.2 Static VAR Compensator (SVC)

The static VAR compensator, originally invented for public energy supply networks, is a converter to provide reactive energy. For application in railway networks, the term SVC was taken from the 3AC environment and adapted to single-phase application. It is installed at a location along the railway track and supplies directly into the contact line (Figure 5). The arrows to display the power consumption are shown for traction operation (*blue arrow*), yet a load flow in both directions is possible (*grey arrow*). To achieve the greatest benefit, it is usually installed at the end of the line. By means of providing reactive energy in dependency on the actual contact line voltage level, the SVC improves the power factor and voltage stability. It compensates generated reactive power between the supplying traction substation and the SVC location within its dimensioning limits. Source of the reactive power is mainly the contact line system and older trains. In Figure 6 is the minimum supply voltage along the line from the substation to the phase separation section displayed, for a supply concept with SVC (*blue*) and without SVC (*green*). The comparison is based on train service simulations conducted in both scenarios with an identical train traffic. The models for both scenarios differ only in the application of the SVC. The application of SVC's offers possibilities to increase the traffic capacity for existing lines as well as to use longer supply sections for new lines.

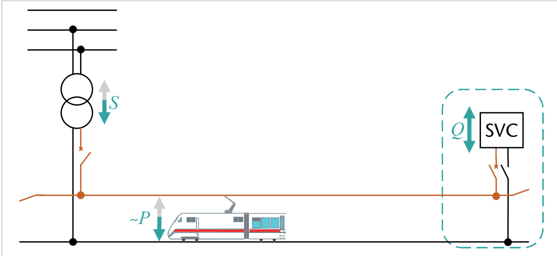

Figure 5:
SVC application at the end of a supply section (Figures 5 to 11: authors, modified *eb*).

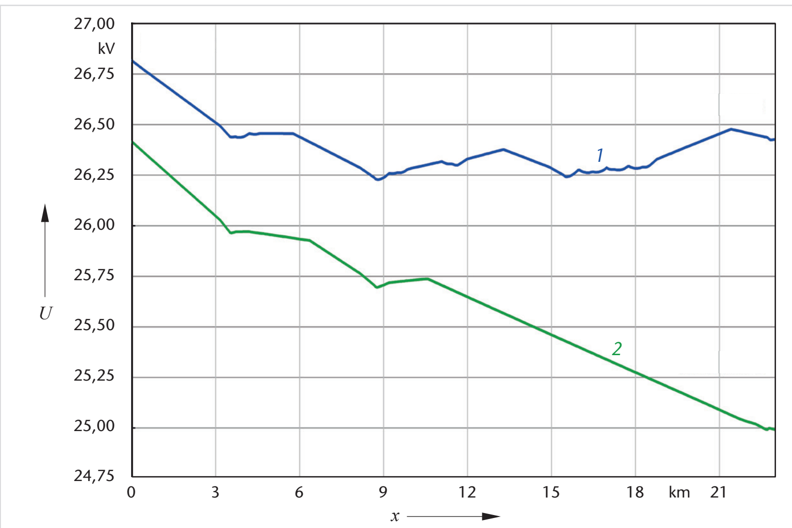

Figure 6:
Comparison of a supply concept with (*1*) and without SVC (*2*), displaying the minimum supply voltage (U) versus way (x), substation position at km 0,00.

3.3 Balancer

Similar to the SVC, the Balancer concept originates from the 3AC public grid and enables the controlled supply of reactive energy to reduce the negative sequence component. Different is the use as add-on for a conventional transformer traction substation to balance the single-phase traction load to the 3AC grid. Several application and design options exist. Not least depending on the design of the traction substation, the Balancer can be installed on the primary (Figure 7) or secondary switchgear of the traction substation. Yet, the basic function is always the same, in dependency of the drawn traction supply current from one phase-pair of the 3AC public grid, the Balancer is providing reactive power to the other two phase pairs to compensate the single-phase load. The concept can also be adapted for two traction transformers in V/V connection. Furthermore, the Balancer can improve the substation power factor by means of reactive power compensation and in doing so stabilize the supply voltage. Voltage unbalances in the supplying 3AC public grid can be bal-

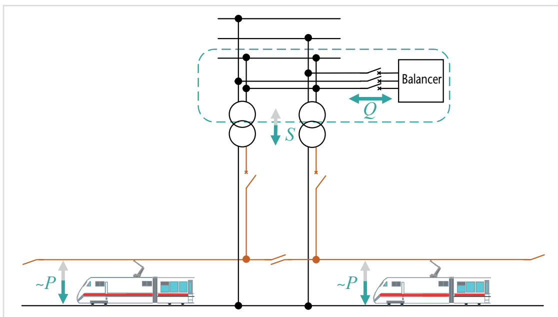

Figure 7:
Balancer application at a traction substation.

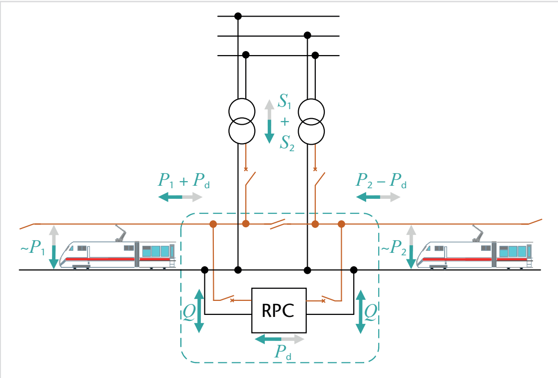

Figure 8:
Application of a RPC at the traction substation with active power exchange between supply sections and reactive power compensation.

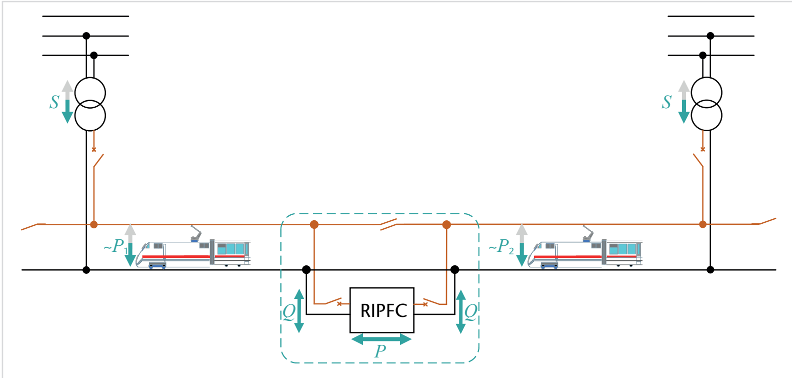

Figure 9:
Application of a RIPFC at a phase separation section between two substations.

anced additionally within the dimensions of the Balancer. The improvements of the power quality will lead to reduced costs for the connection to the 3AC public grid and prevent penalties for exceeding power quality threshold values. The connection to 3AC grids with a lower short-circuit power becomes also possible because thus the reduction in power quality can be prevented.

3.4 Railway Static Power Conditioner (RPC)

The RPC supplements a traction substation with a Scott transformer or two single-phase transformers in V/V connection enabling the active power exchange between both supply sections of the substation [3]. The converter is connected to both sides of the phase separation sections and equals the active power between the supply sections, so that $P_1 + P_d$ equals to $P_2 - P_d$ in Figure 8. Both load flow directions are possible. Additionally, the RPC provides reactive power to both supply sections independently. By doing so, the traction load is drawn symmetrically from the 3AC public grid with a power factor close to unity leading to similar benefits as with the Balancer. Disadvantageous is the reduction of the substation power capability due to the additional reactive power to be exchanged via the traction transformers. By eqaulizing the load between both transformers, peak loads in one supply section are smoothened.

3.5 Railway Interline Power Flow Converter (RIPFC)

Based on the design of a RPC, the RIPFC is implemented on a phase separation section between two substations to enable an active power exchange between the supply sections (Figure 9, [4]). The RIPFC shall enable a double side feeding without the need

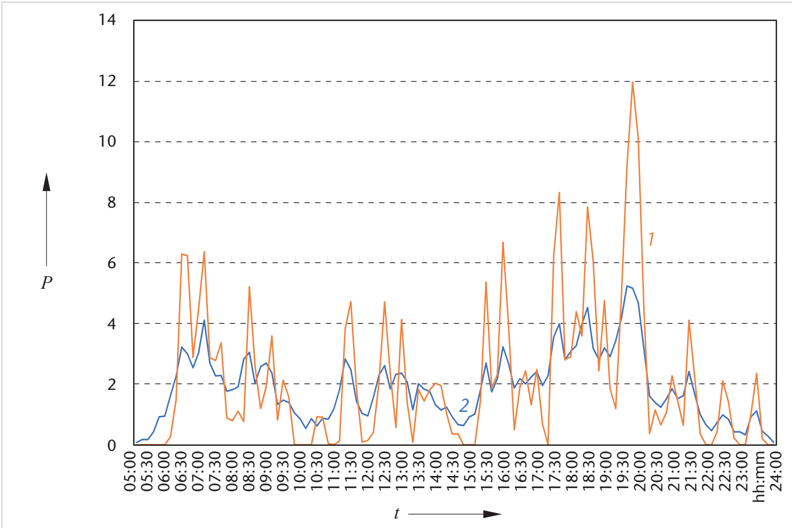

Figure 10:
Example of simulation results showing active power peak shaving.
1 – conventional mode, *2* – double side feeding

to change the existing conventional substations. Double side feeding is leading to a load sharing for all train loads between two substations. The load sharing is leading to an improvement of the supply voltage along the line due to the supply of the traction current from both substations and a reduction of peak loads in both substations. Figure 10 compares the peak loads in a traction substation when applying a conventional supply concept to double side feeding. The values are based on train service simulations conducted in both scenarios with an identical models and train traffic, only differentiating in the application of the RIPFC. Besides the benefits of double side feeding the power distribution between both substations can be controlled actively to reduce further the power consumption in one substation and smoothen power peaks.

Furthermore, the RIPFC does supply reactive power into both supply sections to improve the power factor and voltage stabilization like an SVC.

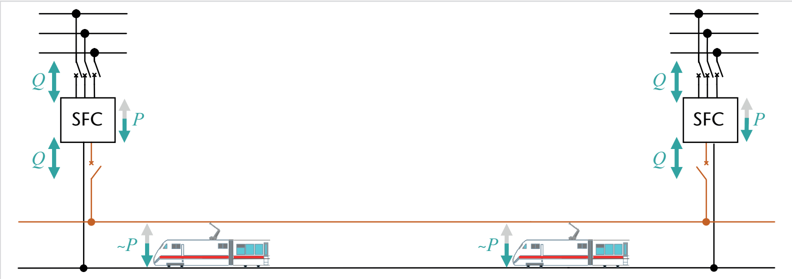

Figure 11:
Supply concept with two SFC stations.

3.6 Static Frequency Converter (SFC)

The SFC is a converter to replace a conventional transformer traction substation and enabling an improved interface for the electrical traction system to the supplying 3AC public grid. Originally used for frequency conversion between the 3AC public grid and the railway power supply network with lower frequency, it is increasingly used as a phase converter between grids of the same frequency. The SFC will obtain the needed traction power equally from all phases of the 3AC grid and the generation of any unbalance can be prevented. The power factor at the substation can be increased to almost unity and the transfer of voltage quality disturbances between the electrical networks can be prevented by means of decoupling.

The application of SFC's is possible with different supply concepts. In island mode, the SFC feeds a single supply section without a connection to the neighbouring sections. Furthermore, the operation can be coordinated with the neighbouring substations, either with a transformer substation or a second SFC station (Figure 11), to enable double side feeding of the railway supply sections. Similar to the application of a RIPFC, double side feeding improves the voltage stability along the line and reduces the load peaks by load sharing between substations. Thus, the traffic capacity can be increased, and components can be dimensioned for less power capacity. In case two SFC stations are operated in parallel, the load sharing between both can be adjusted by a superordinated control.

4 *In2Stempo* – a European research project

The path from an idea to the ready for sale and homologated product implemented as state-of-the-art in a system is not just taking mostly longer periods of time but also requires overcoming structural challenges. A major step in the realization of innovative technologies are pilot projects. A good cooperation between manufacturers and railway operators is an additional boost to achieve not just a proof of concept, but also a widespread acceptance.

The European research project *In2Stempo* (Grant Agreement N°777515) strives out to build technical demonstrators and to achieve with these a higher level of homologation, new application scenarios and a proof of technical readiness for the previously presented technologies [5]. *In2Stempo* is one of the projects of the Joint Undertaken Shift2Rail a European funded rail initiative, founded by several railway vendors and operators.

In2Stempo covers several technical demonstrators for individual parts of a Smart Railway Power Supply, differentiating in their scale and technical readiness level. Within the scope of the project is *WP3*, a digital twin based demonstrator for the evaluation of FACTS in 50 Hz railway systems. The aim of *WP3* is providing specification and proof of concept for FACTS by investigating and defining their connection requirements to the electrical traction system and the 3AC public grid, their operating behaviour in normal and degraded operation modes, their integration in supply concepts as well as their control and protection systems.

The project will lead to further development and fine adjustment of the FACTS concepts for 50 Hz railway system and will provide with its different use cases a base for the subsequent homologation process. It will help to identify and lower barriers to adopt FACTS technologies, designs, and services.

Eventually, the application of FACTS would not be facilitated unless a certain level of guidelines for their integration is given. Therefore, *In2Stempo* will conclude with a guideline to determine the most suitable FACTS solution and its proper dimensioning for each individual use case. Some sites might benefit from a multi-problem-solving FACTS, but others are only concerned by addressing one challenge. A case by case analysis of these infrastructure sites coupled with guidelines can provide the appropriate FACTS solution reducing therefore unnecessary expanses.

By the end of the project in 2022 FACTS for 50 Hz in Europe will have taken another step to a mass-market application.

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