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Executive Summary

This final report summarizes the deliverables D10.1 [5] to D10.4 [8] of In2Rails work package 10 and provides further final conclusions for the public. Achievement of each objective will be shown in individual chapters and is summarised below. It has to be noted the objectives are partially mutually exclusive, thus. Prioritisation of goals must be made for each case individually. The results are made available for application to other use cases as tools and methodologies for design analysis. The achieved technology readiness level is overall between 2 and 3. Realisation of technical demonstrators will be done in the successor project In2Stempo.

AC power supply for electric traction is already very efficient. For most scenarios the transmission losses are lower than 1% of the power consumption in normal operating mode. Small additional reduction of transmission losses is possible in few cases. Major reduction of transmission losses can be achieved by converting DC lines with up to 3 kV to AC 25 kV. Application of static converter feeding would be a realistic overall approach for this, mainly due to requirements for connection to public grid, associated investments and reduction of number of substations. Even if the introduced power electronics cause losses above those of conventional transformer feeding, overall losses will be reduced. Simulations have shown reduced losses of up to 66 % for scenario 3, as part of the “Mediterranean Corridor” in Spain.

Sizing of equipment must consider worst case conditions with individual dimensioning rules for different type of equipment. Required size can be reduced by introduction of complex feeding schemes. In scenario 1 “HSL Madrid - Seville” the worst case conditions are given for increased capacity timetable during outage of a complete substation in a mountainous region. Use of double side feeding reduces required size of transformers by 25 % in this case. Furthermore, phase separations can be replaced by simple sectioning points.

Increasing the capacity of a line with reduced headway of trains and maximum time schedule can cause load flows that would violate the unbalance requirements for connection to public grid. In such case, additional substations have to be introduced or existing ones have to be connected to public grid with higher nominal voltage. Such investment can be avoided by application of balancers or static converter feeding. This ensures compliance to grid code without further investment in new overhead lines for connection to public grid.

Cost reduction depends on the country specific billing models. Mostly power quality improvements above required level for allowance to connect will not be rewarded. Penalties for reactive power flow can be avoided by use of balancer or static converter. Attention has to be paid to how power factor is metered. In case of the analysed scenarios in Spain, less active energy absorption leads to lower cost. This is clearly achieved in scenario 3 with energy cost reduction > 10 % by conversion to an AC electrified system by use of static converters.

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Abbreviations and acronyms

Abbreviation / Acronyms	Description
3AC	3-phase Alternating Current
AC	Alternating Current
CAPEX	Capital expenditure
CDM	Canonical Data Model
DC	Direct Current
ETS	Electric Traction System
FACTS	Flexible AC Transmission System
HV	High Voltage
IM	Infrastructure Manager
MMS	Maintenance Management System
OCL	Overhead Contact Lines
OPEX	Operational expenditures
P	Active power
RVC	Rail VAR Compensator
r.m.s.	Root Mean Square Thermal equivalent of current or power
S	Apparent power
SVC	Static VAR Compensator
TPS	Traction Power Substation
TMS	Traffic Management System
TSI	Technical Specifications for Interoperability

1 Background

The present document constitutes the first issue of Deliverable D10.5 “Final research report Intelligent AC power supply” in the framework of the project titled “Innovative Intelligent Rail” (Project Acronym: In2Rail; Grant Agreement No 635900). It is part of In2Rail’s sub-project “Rail Power Supply and Energy Management” under work package number WP10 “Energy Management - Intelligent AC Power Supply System”. WP10 defines the design of an intelligent electric traction system using alternative current (AC) power supply. It covers the basic investigations and the design works at technology readiness level TRL 2-3 for implementing the demonstrator for the “Intelligent AC Power Supply System”.

Deliverable D10.5 summarises the outcome of In2Rail’s work package 10 for public dissemination. Reference is made to other deliverables for details of investigation. Even thus these are classified as confidential and not publicly available. Where suitable, results are repeated and put into context for providing a complete picture. An overview on the confidential deliverables is given in the following paragraphs. Furthermore, methodologies and tools are generalised for application to other use cases.

Deliverable D10.1 [5] analyses the railway grid requirements and interfaces in three different scenarios of railway lines in Spain. Based on models of electric traction systems, topography, speed limits, train schedule as well as data of the electric vehicles the electric load flow at the traction power substations are calculated. Different outage scenarios as well as fault conditions are evaluated likewise. On this basis, different intelligent AC traction power substations are studied regarding their performance and their compatibility with railway requirements and specifications. These include application of balancers and static converters. By comparing acquired real time data with the result of simulation, quality of simulation results is verified.

Based on the results of D10.1 [5], the interface to the public grid is analysed in D10.2 [6]. First of all, the interface requirements established by different public grid codes are reviewed with particular emphasis on Spanish regulations and power quality. By using a data interface to simulations done in D10.1 [5], the interface of each traction power substation of the Spanish scenarios is investigated by use of different models. By use of a holistic model of the feeding public grid, a more reliable picture of the achievable performance indexes at the connection points is achieved. Furthermore billing models in Europe with particular focus on Spain are analysed for economic evaluation of the introduced intelligent substations.

The implementation specification for realisation of the intelligent AC power supply system is presented in deliverable D10.3 [7]. It represents the shift over from system study towards realisation. Necessary system design methods are introduced and basic principles are presented. By narrowing done to a basic definition of demonstrators, D10.3 [7] is the interface to realisation of demonstrators in the follow-up project In2Stemp. Two demonstrators are to be realised. First of all, as a direct follow up on the investigations of the Spanish scenarios, a demonstrator for application of Flexible AC Transmission Systems (FACTS), such as but not limited to balancers or static converters for feeding the electric traction system. Second, a demonstrator for SMART control of rail power supply by use of IEC 61850 process bus communication shall be realised.

Deliverable D10.4 [8] specifies the interface to the traffic management system (TMS) as well as to the maintenance management system (MMS). It represents the interface Intelligent Mobility Management (I2M), another sub-project of In2Rail, which addresses and develops a standardised integrated environment capable of supporting diverse TMS dispatching services, operational systems and MMS. The necessary data structure and communication pattern structure for the interfaces to TMS/MMS is analysed by use of the so called "Canonical Data Model".

Several predecessor projects funded by the European Commission provide a basis and background for In2Rail's work package 10. These projects are OSIRIS (Optimal Strategy to Innovate and Reduce energy consumption. In urban rail Systems) [3], MERLIN (sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimisation approach) [4] and RAILENERGY (innovative integrated energy efficiency solutions for railway rolling stock, rail infrastructure and train operation) [2].

OSIRIS aims at enabling a reduction of the overall energy consumption within Europe's urban rail systems and hence focuses on confined aspects of direct current (DC) electric traction systems. MERLIN's main aim and purpose is to investigate and demonstrate the viability of an integrated management system to achieve a more sustainable and optimised energy usage in European electric mainline railway systems, focusing on standard AC and DC feeding concepts. The most important input is given by the project RAILENERGY. This includes standardised methods to predict and measure the energy consumption, methods to simulate the energy demand as well as an analysis and validation of existing technologies.

2 Objectives and Aims

The objectives of In2Rail's work package 10 are described in APPENDIX 1 of the In2Rail Grant Agreement no. 635900 and can be summarised as follows. The main objective is to work on the design of an intelligent electrical traction system for AC rail power supply, in order to allow for a controlled energy flow inside the electric traction system (ETS) itself as well as to optimise its interface with the public power grid. This shall result in reduction of:

- transmission losses up to 50 %;
- investment by reducing installed equipment up to 25 %;
- investment for public grid connection and;
- costs resulting from energy consumption and peak power demand.

Chapter 3 gives an overview on the completed scope of work of In2Rail's work package 10 and its deliverables. Subsequent chapters 4 to 7 focus on how the given objectives are achieved by application of the presented measures of an intelligent substation. This includes evaluation of the presented concepts and methodologies in terms of the different objectives. The following chapter 8 focuses on energy management as a main topic for intelligent substations. In order to present the innovations and their context, subsequent chapter 9 focuses on innovation management. Therein adoptions in standards and regulations will be presented also.

For application to other use cases, generalised design analysis tools and methodologies are presented in chapter 10. This will include transferable generalised specifications and implementation rules. Subsequent chapters 11 to 13 will focus on the results from the system study being part of deliverables D10.1 [5] and D10.2 [6] for the Spanish scenarios:

- increasing the capacity of an existing railway line with AC power supply in service in scenario 1 being part of high-speed line Madrid – Seville,
- improving an existing AC electric traction system by introduction of new feeding concepts in scenario 2 being part of the high-speed line Madrid – Barcelona and
- converting an electric traction system from DC to AC power supply without major modification of the interface to the public grid in scenario 3 being part of the Mediterranean Corridor.

Last but not least the deliverable and In2Rail work package 10 will be closed by concluding the results and work done.

3 Basic investigations

3.1 General

The possibilities due to new developments are investigated for the 3 Spanish scenarios with different use cases. The scenarios represent a broad variety of different requirements. The general statement that double side feeding is improving the efficiency and thus enables longer feeding sections and makes phase separations obsolete was made in the EU project Railenergy. In this project and report the ideas are worked out more in detail in order to give rules how to realize double side feeding. The different tasks and deliverables of this work package provide modules resulting in an overall picture of new possibilities with state of the art technology:

- D10.1 [5] analyses the transportation process and the resulting energy flow: different configurations are analysed representing different technologies;
- D10.2 [6] analyses the interface to the public grid for the configurations of D10.1 [5]: the focus is on power quality and resulting costs are analysed;
- D10.3 [7] analyses different new technologies and their applicability: basic descriptions, specifications and definition of demonstrator are given;
- D10.4 [8] describes how a power supply for an Electric Traction System (ETS) can be integrated into the overall concept of an Infrastructure manager by use of the Canonical Data Model.

The scope of each deliverable is summarised in the following subchapters.

3.2 Deliverable D10.1

Deliverable D10.1 [5] focuses on possible improvements for the ETS by future implementation of FACTS equipment in terms of balancers or static converters. This includes the possibility of double side feeding, which is easily introduced by application of static converters. For this purpose an analysis of the initial situation was carried out. The most interesting operating scenarios in which to implement this new technology have been identified. For each of them, all operating characteristics were analysed. Of these characteristics the associated rail traffic is the most important one, defining the load requirements of the new equipment and its characteristics.

Three main scenarios have been evaluated considering the possible improvements that can be obtained. Two scenarios relate to the operation of High Speed Lines with alternating current (AC) ETS by use of single-phase or autotransformer feeding respectively. One of these scenarios considered a railway line already in commercial operation, in which it is desired to increase traffic density while a sufficiently powerful supplying 3AC network is not available. The other scenario considered a modern railway line being fed from a high-power short-circuit network. The third scenario evaluated implementation of static converter feeding for conversion of an existing railway line with DC electrification to an AC system.

The different technologies were evaluated by use of multi train simulator taking into account the detailed characteristics of the railway network, the electric traction system and the public grid connection. The simulations have been carried out on basis of the actual architecture of the substations and on the new proposed schemes, in order to compare results. In general, the results concluded that significant operational advantages can be achieved in certain real scenarios for the complete system. The identified advantages from electric traction point of view are:

- major increase of efficiency from approx. 95 % to 99 % by converting an existing DC system to AC power supply due to reduced transmission and substation losses;
- reduced total energy demand of the electric traction system by up to 19,9 % for converting an existing DC system to AC power supply due to lower losses and feeding back regenerated energy;
- reduced peak power demand up to 33 % and smoothed load flow in case of double side feeding with use of static converter feeding technology;
- reduced short circuit currents by use of static converter feeding technology;
- no phase separations needed in case of double side feeding with static converter technology leading to less wear due to less switching operations on the train and also no coasting of trains and according loss of speed. Furthermore, phase separations are a mechanical weakness in the OCL therefore improvements in terms of maintenance and operations is expected without them;
- reduced impact of substation outages on the train schedules by lower voltage drop when using static converter feeding technology.

Furthermore, measurements have been done in several field campaigns in the network of Adif for verification of simulation results. These campaigns took place in the second half of 2016 and in the beginning of 2017. The impact on the public grid is analysed in detail in deliverable D10.2 [6] of In2Rail's WP10.

3.3 Deliverable D10.2

This Deliverable focuses on the connection of the traction power systems with the public electric grid and analyses the impact of different feeding solutions both from a technical and from an economic point of view. The efficient and reliable operation of the railway power system is also dependent on its capability to avoid issues on the overlying public grid. As a consequence, the analysis of possible new technologies has taken into account the potential impact on the public transmission grid characteristics.

In this Report, the interface requirements established by different public grid codes are first reviewed, in order to establish the main connection requirements to be fulfilled, with a particular emphasis on power quality. A more detailed overview is provided for the Spanish case, for which the three use cases presented in D10.1 [5] have been considered as reference simulation scenarios. The different applications of FACTS equipment for traction power substations (TPS) are then analysed in detail. In particular, power electronic-based solutions given by the use of balancers and static converters have been considered as attractive alternatives to the conventional transformer connections. Both the traditional scheme based on transformers and the new generation power electronic solutions have been analysed through extensive simulations to evaluate the impact of the traction system demand on the public grid operation when having different feeding schemes. The models used and the detailed results for the three considered scenarios described in D10.1 [5] are presented and discussed.

Simulations have been carried out by adopting a holistic approach that comprises a detailed model of both the railway power system and of the overlying public grid. This solution overcomes many of the limitations associated with traditional simplified models and guarantees a more reliable picture of the achievable performance indexes at the connection points. The performed technical analysis is also integrated with an economic evaluation of the different feeding solutions. This analysis uses different existing billing models, with a more focused view on the Spanish scenario associated with the analysed use cases. Starting from the obtained simulation results, a view of the normalized costs achievable according to the substation technology is given for different billing schemes.

The results obtained highlight two important aspects. First of all, new technologies based on power electronics can provide significant benefits from a technical perspective, not only at the traction power system level (as shown in D10.1 [5]), but also at the connection points with the public grid. This is of paramount importance since the stable and reliable operation of the public grid power supply is essential for the continuity of service in the railway power system. Additional benefits can also be achieved from an economic perspective, in particular if future billing models considered introducing stricter penalties for the disturbances introduced in the public grid will become common in the future. Moreover, the studies conducted also underline the importance of adopting holistic approaches to evaluate the impact of the new substation technologies. Simplified models can lead to underestimate potential issues brought to the public grid, thus leading to wrong strategic decisions that could finally translate in increasing costs to undertake the necessary remedial actions.

3.4 Deliverable D10.3

In this document implementation rules and requirements for realisation of double side feeding, static converter and balancer application for an electric traction system are presented. These are necessary for enabling the positive effects and achievements outlined in the system studies of deliverables D10.1 [5] and D10.2 [6].

In this background, basic considerations for dimensioning of components are introduced for considering their physical properties. On this basis, implementation of double side feeding by use of transformers or static converters is investigated. Realisation by transformers is limited and requires high efforts for adapting to an upstream load flow. Advantages of double side feeding are automatically enabled by use of static converter feeding. This can be used for reducing transformer sizing or leveraging other advantages like increased voltage stability. Furthermore, phase separations are not necessary anymore and further reduce investment and operational cost. Double side feeding should always be applied in case of static converter application due to massive reduction in installed power.

Implementation of static converters must consider the overall network operation philosophy. With increasing use of static converter feeding for 50 Hz systems, standardisation is necessary due to similar feeding structures with connection to public grids in many countries. In this regard, different control rules are presented. Specific requirements of the electric traction system as well as for public grid side are evaluated.

From today's commercial point of view, conventional feeding by transformers is preferable if technically feasible, i.e. obeying the public grid code. Anyhow, changes in the way how energy is billed might change this situation due to shifting to smart grids. In case of violation of grid code requirements, balancers can be applied for conventionally transformer feeding. Resulting impact to electric traction system is minor and depending on type of connection. According implementation rules and specification are presented. Anyhow, double side feeding and according advantages will not be possible in that case and also further advantages from static converter feeding cannot be leveraged.

Results from the Spanish use cases are summarised and possible introduction of technical demonstrator is discussed. Due to absence of ADIF in the follow-up project, technical demonstrator shall be realised in France with partner SNCF.

Separate from the Spanish use cases, a second topic and technical demonstrator is introduced together with German infrastructure manager DB Energie. This will focus on a different aspect of intelligent substations in the protection and control part of a substation by use of process bus communication acc. IEC/EN 61850. After general introduction of this technology, requirements for application and possible new architectures are presented. New redundancy concepts as well as reliability of this application by use of FMEA analysis are shown. Major focus is also on interoperability of components.

For realisation of this demonstrator, implementation specification is introduced by detailed listing of requirements for components necessary for realisation. On this basis, possible maximum configuration of a demonstrator as well as a basic definition of demonstrator is introduced. The successor project In2Stempo WP2 will follow up on this basis. In this regard, special attention has to be paid to test procedures and finally on maintenance procedures.

3.5 Deliverable D10.4

The overall aim of the In2Rail project is to set the foundation for a resilient, cost-efficient, high capacity, and digitalised European Rail Network.

Intelligent Mobility Management (I2M), a sub-project of In2Rail, is one of the three technical sub-projects and comprising Work Package 8 (WP8). WP8 addresses and develops a standardised integrated ICT environment capable of supporting diverse TMS (Traffic Management System) dispatching services and operational systems such as power supply systems and Maintenance Management Systems (MMS).

The main objective of Work Package 10 (WP10) is to work on the design of an intelligent traction feeding system for AC rail power supply to allow a controlled energy flow inside the rail power grid and to optimise the interface with the public power grid.

The deliverable D10.4 [8] of WP10 is focused on the description of the required data structure and communication pattern structure for the interfaces between TMS/MMS and the ETS.

According to WP8 results, these interfaces are to utilise the so called "Canonical Data Model" (CDM) for interfacing with TMS and MMS. Consequentially, the respective enhancements to the CDM being required for communication to and from ETS are described as part of D10.4 [8].

After assessing, selecting and formalizing typical use cases, communication requirements have been derived. Based on these requirements, related communication interfaces were identified in order to support future integration of the different components while describing the expected benefits. Particularly the introduction of an Multi Train Simulator as a part of the ETS has been assessed and considered for future integration scenarios.

The overall approach to apply a Canonical Data Model (CDM) as the "Language of the Integration Layer" has been used for the formulation of requirements for the integration layer interfaces and the access patterns for the different use cases.

The research has been conducted by all partners of WP10, and the input been consolidated to form this comprehensive document.

4 Reduction of Transmission Losses

4.1 General evaluation of concepts

To transmit electrical traction energy from the substations to trains, overhead contact lines (OCL) are used. The material and condition of the contact line as well as the type of the electrical traction system determine the losses during the transmission. The objective for WP10 is to reduce the transmission losses in the ETS by up to 50 %. Systems based on AC 25 kV nominal voltage are already very efficient, e.g. efficiency of approx. 99 % with transmission losses accounting for approx. 1 % in normal operating conditions. This remains dependent upon the train traffic as well as the network topology, for example some AC 2x25 kV lines can have transmission losses up to 4 % due to the feeding length and traffic. In comparison to this, a typical DC system with 3 kV nominal voltage has much lower efficiency. In case of the analysed part of the Mediterranean Corridor in deliverable D10.1 [5], efficiency was only 93,6 % in normal operation mode. In 1,5 kV, the efficiency can be as low as 85 %. In the preceding EU project Railenergy a comparison of transmission losses for different supply concepts was conducted and illustrated. To further reduce the transmission losses different approaches are investigated within WP10 of the In2Rail project:

- converting existing DC systems to AC systems. If possible, theoretical one-on-one replacement of each DC substation with an AC substation would lead to reduction of transmission losses by up to 95 %. Anyhow, this is often not possible due to grid code requirements. Furthermore, it would not make sense economically to replace each DC substation with an AC substation, since an AC system allows for much longer feeding sections of approx. 40 km instead of approx. 10 km with DC;
- the application of so called FACTS equipment (Flexible AC Transmission System) enables the installation of AC systems on tracks with constraints that have prevented AC systems so far, e.g. demands of the public grid connection in terms of grid code. This is shown for conversion of DC electrified line Mediterranean Corridor to an AC system with 25 kV by use of static converter feeding, as shown in deliverable D10.1 [5]. This measure can reduce the transmission losses by up to approx. 66 %, when taking into account the losses of the power electronics itself of approx. 2 %;
- using different feeding concepts. With double side feeding the transmission losses are reduced and thereby the voltage stability is reduced;
- increasing voltage stability by use of static VAR compensators (SVC) or static converter feeding. Controlled power electronics main aim in that case is to optimize the power quality in regard to power factor correction and other criteria such as power imbalance at the public grid connection point.

4.2 Upgrading DC lines

Two main effects improve the overall energy balance and reduce the transmission losses when upgrading a DC system to an AC system:

- higher supply voltage. At the same power, a higher voltage leads to lower currents causing lower transmission losses. In turn, it helps to improve the power exchange between trains;
- contrary to AC substations, rectifiers in DC substations are unidirectional. In operational situations with a surplus of power due to braking or downhill driving trains, in DC systems the power cannot be regenerated into the 3AC network. Being able to recuperate energy into the 3AC network can reduce the total energy consumption of the ETS. This also reduces transmission losses since feeding 3AC network with higher nominal voltage can be used for transmission to next exchange partner even though there can be some reglementary obstacles.

For investigating the benefit of upgrading DC lines it is assumed that the traffic remains the same. It follows that the power demand of the trains is also the same. As the voltage is increased by around factor 8 the current in the OCL decreases by factor 8 and the transmission losses by factor 64, when the line reactance is not taken into account. The voltage drop along the line is also lower with lower currents. This effect supports the energy exchange between the trains. Instead of using a braking resistor or mechanical brakes, energy can be regenerated during braking operation and can hence be used by other trains. Furthermore, with AC systems the braking energy can also be recuperated to the 3AC network. As DC substations provide only one direction for the energy flow, additional efficiency can be achieved as transformers are bidirectional.

Realistically, it must be assumed that existing DC substations will not be replaced one by one with a conventional AC substation each. Only selected substations would be replaced due to realisation of much longer feeding section with an AC system. Anyhow, this is often if not always prevented by strict grid code requirements for connection to public grid. This can be overcome by feeding with static converters for AC 25 kV, allowing for absolute compliance with the grid code. Nevertheless, their built-in power electronics cause additional losses in the range of 2% in comparison to conventional AC feeding with oil-immersed transformers. By adding these losses to the results of simulations in deliverable D10.1 [5], the transmission losses will still be reduced by up to 66% in comparison to the current DC 3 kV electrification system of the Mediterranean Corridor. This is again due to lower transmission losses of the TPS and the OCL as well as regeneration of energy to 3AC public grid.

Besides much lower transmission losses in the OCL of approx. 0,6 % in comparison to 6,4 % of the total energy flow as per deliverable D10.1 [5], energy savings of in total up to 19,9 % is achieved incl. regenerated energy. This is mainly due to usage of the upstream 3AC network for regeneration of energy. However, some TSO do not allow the infeed of energy by railway systems into their grid. In such cases, a revision of these grid codes is necessary in order to not waste energy.

4.3 Double side feeding of AC lines

Different AC supply concepts enable a reduction of the transmission losses. A detailed description of double side feeding is given in chapter 10.2. In the investigated scenarios double side feeding in AC lines is reducing the transmission losses by up to 20% depending on the outage scenario and traffic situation. As the efficiency is already high, the reduction in total is quite small. Exemplary for scenario 2 “HSL Madrid – Barcelona” in deliverable D10.1 [5], by using double side feeding and transformer substations with maximum capacity timetable, the total efficiency gets increased from 98,1 % to 98,3 %.

When using double side feeding with transformers a parallel load path to the 3AC network is created. This causes an unintended power flow over the ETS. The currents created by the parallel load path decrease the capacity of the OCL and cannot be allowed when exceeding an acceptable limit. The acceptable magnitude of these currents depends on the nominal traction load and the current carrying capacity of the OCL. These currents always reduce the capacity of the OCL and increase the transmission losses. Furthermore such current can be forbidden depending on the energy grid regulations, i.e. in France these are strictly forbidden. To prevent these currents, static converter substations can be used. However static converter losses are about 2% higher as the losses of classic transformer substations (as described in D10.2 [6]). The total efficiency of the ETS with static converter substations would in this case be about 96,3% and thereby below classic AC systems, but still higher than a DC system. Anyhow, this comparison does not consider further advantages of static converter substations like improved voltage stability and power quality (see chapter 10.2.2), which additionally can reduce the transmission losses or enable to lengthen the feeding distance for a given substation.

4.4 Considerations for new lines

The comparison of a DC and an AC system with regard to efficiency made clear, that for new high speed lines and heavy freight lines only AC electrification should be used. This is also reflected in the latest Technical Specifications for Interoperability for the energy subsystem (ENE TSI) [1]. An additional benefit of AC systems is the increased possible length of the supply sections. This last point is especially interesting for avoiding new connections to the energy grid or add some agility for the location of the injection point. This is especially interesting with geographic constraint. Furthermore, use of power electronics unlocks the opportunity to connect the railway traction power system to the public grid at a lower supply voltage, see chapter 6.

Because of the feeding length of the AC substation, the power and energy is generally higher for a given injection point. In turn, this causes a higher constraint on the energy grid. Nevertheless the use of power electronics enables the installation of AC systems on railway lines with higher grid code requirements for connection to public grid. For this reason a growing use of AC lines in a lot of railway systems worldwide can be noted, even in countries with existing DC infrastructure.

Currently, the main limitation of the DC originates from the voltage levels (mainly 1500 V or 3000 V) which are fairly lower than those of the AC system (25 000 V). Nevertheless, the DC intrinsic characteristics render the line reactance null and thus an excellent power factor. Over the long term, the voltage level in DC system could be raised almost up to the AC level, which could open greatly the potential for transmissible power along the line.

5 Reduction of Investment in ETS

5.1 General evaluation of concepts

One of the main objectives is to reduce the investment cost, by achieving the required capacity as per timetable while reducing the installed equipment of the ETS by 25 %. Differentiation must be made between reducing the capacity of equipment to be installed, i.e. rating of equipment, and reduction of capital expenditure (CAPEX).

Besides the average power demand, the design of ETS components, like transformers or overhead contact lines, also depends on maximum load peaks. Use of double side feeding or completely interconnected complex feeding sections can smoothen load peaks. Consequently, a reduction of the size of transformers, switchgears or OCL equipment can be achieved. This will result in reduced CAPEX investment in case of conventional AC feeding with transformers only. Due to considerably higher costs of FACTS equipments in comparison to passive elements like transformers, a reduction of installed capacity will not automatically lead to lower CAPEX investment for this equipment. Furthermore, operational expenditure (OPEX) is not considered to be lower for FACTS equipment in comparison to conventional AC feeding. Additionally, overall lifecycle costs of FACTS must be higher due to lower lifetime of electronic components. Hence, use of FACTS equipment has to be evaluated for each case individually.

5.2 New Lines

Planning of a new line includes the choice of number and location of substations as well as dimensioning of all components. Nowadays, either 1x25 kV or 2x25 kV auto-transformer systems can be chosen according to overall system requirements and possible connection points to 3AC networks. Even more possibilities for optimisation are enabled by use of complex feeding schemes, like double side feeding or feeding with completely interconnected ETS. This does not only include the ETS equipment itself, but also needed land and the impact to the environment. Investment costs in terms of CAPEX as well as operational expenditure (OPEX) have to be taken into account.

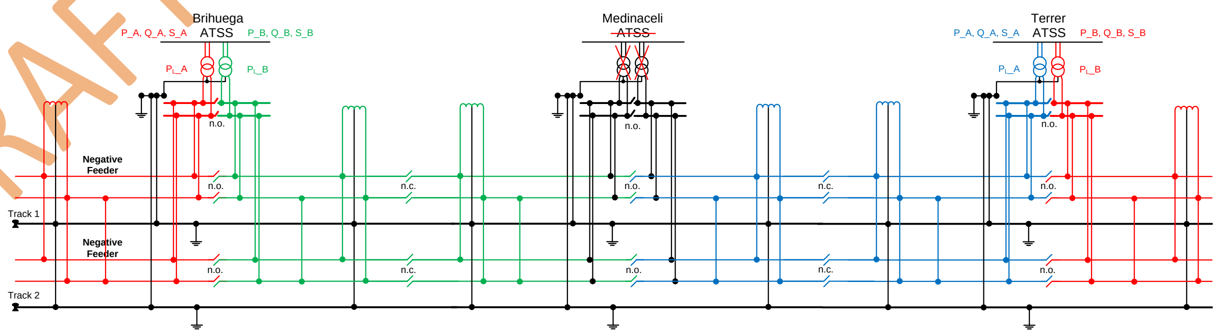

Figure 5.1: Single side feeding with substation outage in an AT system with phase separations

Single side feeding also bears the disadvantage that in case of a failed component another component has to take over the full load of the failed one, see Figure 5.1 as an example. The severity is highest if a whole substation is out of order. The adjacent transformers in the neighbouring substations have to take over the full load. Within the neighbouring substation the load between the transformers is not shared. Resulting high loads of neighbouring substations will ultimately also yield in most severe conditions for compliance to grid code.

One of the measures to be considered for new lines is double side feeding, see chapter 10.2. Besides reduction of transmission losses, it can also reduce the needed size of substation equipment and the size of the OCL equipment. This is achieved by reduction of the load currents as well as of the peak currents. As outlined in deliverable D10.3 [7] chapter 4.3, different criteria shall be applied for dimensioning of equipment according to its thermal capacity time constant. By introduction of double side feeding in scenario 1 HSL Madrid Seville, OCL sizing according load currents in normal operation mode can be reduced by 15 %. Anyhow, transformer sizing is almost not affected by double side feeding due to high thermal capacity of oil-immersed transformer and respective dimensioning rule.

TPS "Arroyo del Vale" sum of total apparent power for design of	**Sizing in MVA for single side feeding**	**Sizing in MVA for double side feeding**	**Reduction**
Transformers (τ >= 3600 s)	27,0	21,0	-22,2 %
Cables (τ = 900 s)	30,3	22,7	-25,1 %
OCL (τ = 300 s)	34,4	23,8	-30,8 %
Power electronics (τ = 1 s)	66,8	37,9	-43,3 %

Table 5.1: Worst case example for required sizing of equipment during outage of one substation according simulated load flow during maximum capacity timetable in scenario 1

In case of scenario 1 HSL Madrid – Seville of deliverable D10.1 [5], the effect of double side feeding is highest for the worst case scenario of an outage of complete substation "Venta la Ines" with increased traffic according to a maximum capacity timetable. In this mountainous part of the line, trains have to overcome a height difference of approx. 600 m. Table 5.1 summarizes the simulated load requirements for the neighbouring substation "Arroyo del Vale". This substation has heaviest load requirements for supplying almost all trains driving uphill in case of single side feeding. As outlined in deliverable D10.1 [5], system would be operated at its limits for voltage stability here in case of single side feeding. Required sizing of equipment according to their thermal time constants is shown for single side feeding and for double side feeding. It can be seen that double side feeding in such worst case scenario leads to possible reduction of OCL equipment of more than 25 % when looking at substation "Arroyo del Vale" as worst case only, here even up to 30,8 %.

Nevertheless, since load is shared by double side feeding, the substation neighbouring the outage from the other side "La Nava" has to be considered, too. Summary of simulation results is shown for the same use case accordingly, see Table 5.2. It is clearly visible that maximum total load of substation "La Nava" is by far lower than for "Arroyo del Vale" caused by the outage. Sum of total apparent transformer power of both substation is 42,9 MVA for single side feeding and 39,9 MVA for double. This is due to further substations contributing to load sharing, enhanced exchange of power between trains as well as lower transmission losses. Sizing of transformers in case of double side feeding is by far more favourable, especially when considering unification of transformer sizes across all TPS.

TPS "La Nava" sum of total apparent power for design of	Sizing in MVA for single side feeding	Sizing in MVA for double side feeding	Reduction
Transformers (τ >= 3600 s)	15,9	18,9	+19,0 %
Cables (τ = 900 s)	19,1	21,2	+11,1 %
OCL (τ = 300 s)	20,4	23,2	+13,4 %
Power electronics (τ = 1 s)	33,0	29,7	-10,0 %

Table 5.2: Consequences of double side feeding on substation neighbouring the outage from the other side for comparison with Table 5.1

Described outage and results in Table 5.1 show that single side feeding leads to maximum of 27 MVA transformer load at substation "Arroyo del Vale", which is a utilisation factor of maximum 67,5 % of installed transformer capacity of 2x20 MVA. By realisation of completely interconnected system, neighbouring substations can completely take over the load of the substation being out of service with increased voltage stability, well above limit values defined in EN 50163. By use of similar utilisation factor of 70 %, installation of 2x15 MVA transformer apparent power would be sufficient. Resulting reduction in installed apparent power per TPS is 25 %. Furthermore, double side feeding can be used for reducing the number of installed transformers without loss of redundancy and without lowering availability. Impact to time schedule is minimum in case of complete substation outage due to increased voltage stability. Hence, same redundancy for substation outage of n-1 can be achieved even if only 1 transformer in each substation is installed. This enables further savings in investment in terms of substation footprint, incoming HV switchgear panels, 25 kV switchgear panels and related control and protection devices.

Even though installed transformer capacity can be reduced by 25 % in this way, the size of the OCL system can only be reduced by 19 %. This is due to load sharing of substations in the described outage scenario. Highest 300 s r.m.s. value of current on the OCL system for single side feeding occurs in the section of TPS "Arroyo del Vale" with 495 A. For double side feeding highest 300 s r.m.s. value of the OCL current occurs in the section close to TPS "La Nava" with 403 A. See further results for scenario 1 in Table 11.1.

It can also be noted that double side feeding shall be always considered in case of static converter feeding, see sizing of power electronics in Table 5.1 and Table 5.2. This also enables special measures for actively reducing peak load of static converters, see chapter 8. Attention has to be given to feeding sections at the end of the railway line, resulting in almost single side feeding with minimum load sharing. This is especially important for outage of the last substation before end of the line.

In general, double side feeding results in increased voltage stability on the line by reducing the voltage drop in the OCL. This allows for larger feeding sections with increased distance between substations. Result would be less CAPEX and OPEX investment due to lower number of substations to be installed. Anyhow, it has to be noted that all of the mentioned advantages cannot be achieved simultaneously. When reducing OCL size by use of double side feeding, it will not be possible to achieve larger feeding sections at the same time. Nevertheless, these possibilities enable a higher degree of freedom for planning of locations and numbers of substations to be connected to 3AC public grid.

For new lines, the impedance of the substation transformers can be adapted and it can be possible to connect both substation transformers in parallel without exceeding the short-circuit current requirements according to EN 50388. When using static converter feeding, resulting short-circuit currents will be limited by nature. For single side static converter feeding in island mode, short-circuit will be in the range of approx. 1,2 times nominal load current, when considering a typical design. Consequently, double side feeding with static converters will still lead to short-circuit currents of <= 2,4 times nominal load current of one static converter. Completely interconnected systems with static converter feeding will have higher amount of short-circuit current, but still well below limit value of 15 kA according to EN 50388. Depending on feeding type, this might result in lower requirements for ETS equipment. Also, use of power electronics allows for active control of the substation, thus enabling active energy management individually for each substation, see chapter 8.

Considering the experience of Adif from an economic point of view, the capital that the railway manager will use to acquire the equipment of the new electrical substations (CAPEX), in relation to power transformers, will decrease by around 16% if it is considered a power reduction (per transformer) from 60 MVA to 30 MVA. This reduction would be 10% in the case of using transformers of 15 MVA instead of 20 MVA.

Especially for new lines double side feeding does not require introduction of phase separations, which represent a mechanical weakness in the OCL. Therefore, improvement in terms of maintenance and operations is expected. Also, trains must switch off when passing by phase separations. As switches are mechanical parts, this is causing wear and maintenance. Depending on the frequency of switching operation a replacement of a circuit breaker is needed every few years. Consequently, trains passing phase separations will be coasting for some seconds and thus losing speed. After passing the phase separation acceleration is needed. This costs a little bit of time which can be used for other optimizations of the schedule.

5.3 Upgrading existing lines

Upgrade of an existing line can be necessary in case of increased traffic requirements, see scenario 1 of deliverable D10.1 [5]. If increase of traffic would lead to higher loads above rating of equipment, then same measure of complex feeding can be taken as described above. If an upgrade of the OCL system is required, efforts will be very high:

- larger cross section of the conductors leads to higher weight of the OCL;

- higher weight leads to higher forces in the cantilevers and poles;
- higher force leads to higher torque for the poles and their foundations.

Upgrading a contact line system for a running line, including the foundations, poles, cantilevers and overhead wires is extremely demanding. The value of the contact line equipment and its replacement is far higher than that for a substation. Replacing poles including foundations will require at least partial closure of the existing line. Upgrading can in some cases also be done by introduction of parallel feeding cables. Cables being laid in the ground can only be operated with 1 to 2 A/mm^2, compared to an overhead contact line with 4 to 6 A/mm^2. Hence, the current density in the parallel cable is lower and more copper must be used, thus increasing cost. Using cables also changes the impedance matrix of the ETS. Precaution must be taken by use of network simulation tools for determining frequency response of the overall system. When upgrading an existing line, focus is on re-using as much installed components as possible while at the same time reducing downtimes and timetable restrictions to an absolute minimum. For an upgrade, the design process is almost the same as for new lines, but with a different cost calculation and different constraints.

Anyhow, during the course of the project, it became very clear that both AC scenario evaluations for maximum timetable with increased line capacity in deliverable D10.1 [5] will not require new ETS equipment to be installed. Originally done system design already accounts for absolute maximum capacity timetable with minimum headway of trains. Nevertheless, scenario 3 for conversion of DC electrified Mediterranean Corridor gives opportunity to show possible savings in investment. Increasing the nominal system voltage from 3 kV DC to 25 kV AC decreases the load currents by almost factor ten. In such case, the OCL system must not be revamped completely in terms of completely new poles, foundations etc. Isolators must be replaced due to increased voltage and resulting larger distances in air according to isolation coordination for 25 kV. Cantilevers could be revamped by introduction of new isolators. Associated works seem feasible for working on night shift only. Line operation with 3 kV could continue on revamped cantilevers. Usage of double side feeding with 25 kV will not require introduction of phase separations between substations. New AC substations could be built in parallel at remote locations. Number of substations will be reduces. This enables a higher degree of freedom for choice of substation locations with suitable grid access.

6 Reduction of Investment for Public Grid Interface

6.1 General evaluation of concepts

The objective is to reduce investment for public grid connections by allowing connections to grids at lower voltage level by reducing the impact to the feeding grid by a demand of symmetric and controlled load. The dominating factor for choosing a connection point to 3AC network is the limit value of maximum voltage unbalance that will be caused by connection of the TPS, see deliverable D10.2 [6]. As the load resulting from the ETS is fixed by the timetable and topology of the railway line, the needed short-circuit power for connection to a feeding 3AC network can be calculated for meeting the unbalance level. Depending on the load of the ETS, grid code requirements and available short-circuit power, connection of conventional TPS for high-speed lines is often only possible to 3AC network with > 100 kV nominal voltage level.

If the unbalance requirements of the grid code will not be met, actively controlled power electronics can be used for allowing connection, so called FACTS equipment. On the one hand, this can be application of balancers at the point of common coupling (PCC) for rectification of unsymmetrical loads caused by conventional AC ETS. On the other hand, this can also be achieved by static converters used for directly feeding the ETS with either 1x25 kV or 2x25 kV nominal voltage. Use of static converters further enables leverage of advantages from double side feeding.

Firstly, these solutions enable traction substations to be connected to 3AC network with lower nominal voltage level by complying with the grid code. As documented in D10.1 [5], the voltage level has a directly proportional impact on the equipment costs of a substation due to needed size as well as the availability of suppliers. The higher the voltage the lesser suppliers are available. Furthermore, the costs of a 3AC overhead line for connection of a TPS are strongly depending on the voltage level as well as on the environment and regulations. They vary between 250 000 Euro/km and 1 000 000 Euro/km. Another advantage of a lower voltage level is that the amount of possible connection points is higher, which can lead to shorter 3AC overhead line connections. Already a few km of overhead line saved leads to lower costs than application of a balancer. Nevertheless, this has to be evaluated for each case individually since balancer or static converter applications are more expensive than conventional systems with transformers only. Furthermore, CAPEX and OPEX should be considered as grid access at lower voltage levels is more expensive.

Last but not least, in rare cases of existing lines, construction of new additional substations can be completely avoided by use of FACTS equipment for compensation of inductive load between substations and hence reducing voltage drop along the OCL, so called Rail Var Compensators (RVC).

6.2 New Lines

Connection to 3AC networks with lower voltage level allows for a broader variety of possible substation positions. This may save a lot of costs for 3AC overhead lines. Even thus, higher costs for access to 3AC networks at lower voltage levels are conflicting with this from OPEX point of view, as outlined in chapter 7. Furthermore, the number of substations can be reduced in certain cases, depending on positions for 3AC network access. The number of substations is also a question of yearly access costs. By use of static converters with double side feeding, longer feeding sections can be realised.

The resulting reduction in CAPEX has to be evaluated for each case individually. It depends on many factors, foremost on availability of 3AC network access points and their capacity. A general statement on savings cannot be given. Feeding sections might be increased by use of AT system by up to approx. 30 % and by use of AT system with double side feeding by static converter up to 60 %. Due to nowadays more strict grid code requirements for each substation, savings in CAPEX are expected by use of static converter feeding, if the new railway line is not constructed along an adjacent 3AC network with high voltage level of 220 kV or above. Evaluation of a completely new line as greenfield project was not in scope for In2Rail's WP10.

6.3 Upgrading existing lines

Existing installations are often considered to have so called grandfather rights, thus imposing lower requirements for connection to 3AC network with historical background. If, for any reason, such historical rights are not granted anymore, compliance to actual grid code requirements might call for introduction of compensating equipment like balancers. One possible reason might be increase of installed apparent power of a TPS due to increased load flow in the ETS, i.e. caused by introduction of faster trains or reduction of headway for increased traffic.

Violation of limit values for unbalance might ultimately result in disconnection of respective substation. This is to be avoided by all means for not causing considerable delays. Permanently avoiding the risk of such worst case scenario either calls for:

- reducing the length of feeding sections by introducing additional TPS;
- connecting existing TPS to other 3AC networks with higher short-circuit power, i.e. with higher nominal voltage or;
- installation of FACTS equipment for rectification of unbalance.

Introduction of a new substation needs a long time for planning, considerable amount of land, a lot of equipment and availability of a 3AC network with enough short-circuit power available for connection. Connection of existing TPS to 3AC network with higher nominal voltage would still require considerable amount of equipment to be replaced, i.e. transformer and incoming HV switchgear. Furthermore, such 3AC network must be available in close proximity of a couple kilometres to the TPS. Obtaining approval from authorities for such project might be most complicated part.

Introduction of a balancer instead would enable compliance to grid code without taking above measures. Installation could be either adjacent to the TPS on 25 kV ETS side or on HV side of TPS transformer either. This solution would be preferable for taking care of unbalance as well as for compensation of inductive loads. If additional requirements for the ETS come up too, like exceeding size of equipment or voltage stabilisation, direct feeding with static converters can be used instead for leveraging the advantages of double side feeding also. In such case, more components need to be replaced, i.e. transformers. It depends on the age of components and leverage of further advantages whether static converter feeding pays off in such case.

Particularly for the upgrade of DC lines to AC lines balancers or static converters are beneficial. The optimization of the number of substations was not done. As every connected substation has basic costs for the connection there is a lot of saving potential.

An example on possible savings is given within scenario 1 of the high-speed line "Madrid – Seville". In case of increased traffic with the given maximum time schedule and loss of grandfather rights, many TPS will cause violation of grid code in terms of voltage unbalance. Specifically in this high-speed line there is a part powered from a 132 kV network, see blue line in Figure 6.1.

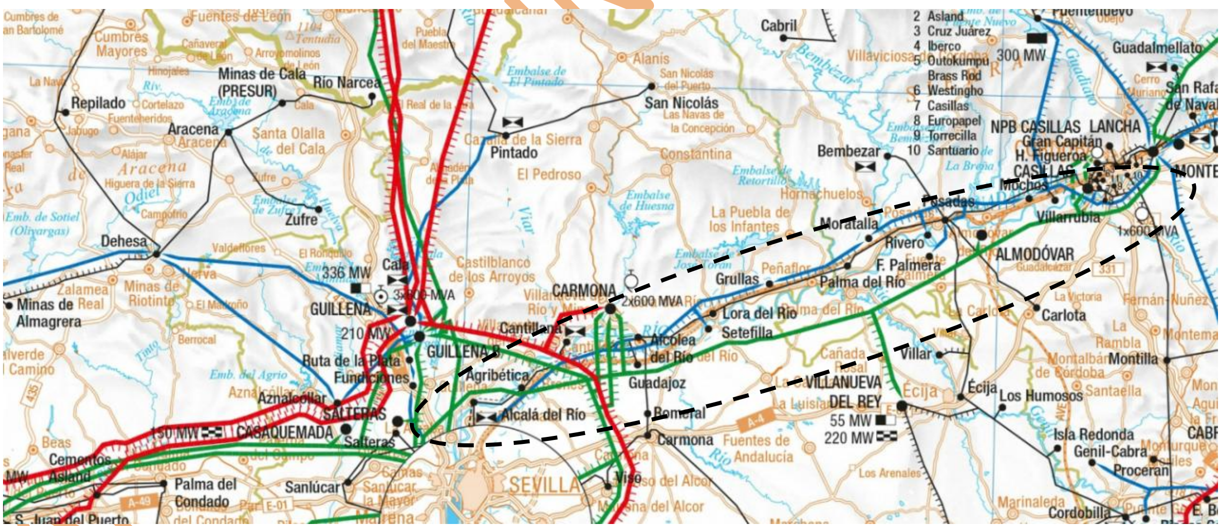

Figure 6.1: Map of the electric environment considered. The high-speed line runs between the cities of Cordoba and Malaga feeding from a 132 kV network (blue line). There is a 220 kV line (green line) about 15 km from the railway line

Although it is a network with significant short-circuit power available, the future increase in traffic can cause operational problems due to unbalances. In this situation, a 220 kV network (green line) could be used, although this network is located between 10 and 20 km away from the high-speed line. For Adif, this investment would not be affordable considering the possibility of using new electronic power equipment such as the ones analyzed here. The problem is not only economic, but also time, because many administrative studies will be necessary to get the connection to this new network.

7 Energy Costs

7.1 General evaluation of concepts

The objective is to reduce energy and peak power costs and allowing for optimization of the energy bill by controlling the load flow between the substations, via the railway grid as well as via the public power grid. This analysis was done on basis of multi-train simulation in different ETS scenarios in deliverable D10.1 [5] and according simulation of the 3AC network in D10.2 [6] by use of an interface for data exchange.

In this context, D10.2 [6] reviews existing billing models across Europe as starting point. The application of the presented measures would result in possible savings in energy costs which would depend largely and by far on the billing model itself. In other words, if the way of billing energy does not result in economical benefits for certain improvements introduced by application of FACTS equipment, energy costs can only be lowered by reduction of total energy flow. For the analysed scenarios the Spanish billing model is summarised as following:

- active energy is contracted between IM and power supply companies individually on long term basis with fixed price or indexed price on daily market;
- reactive energy flow is penalised by TSO or DSO if power factor drops below 0,95 and further penalised if it drops below 0,8;
- toll access for energy consumed is contractually agreed between IM and TSO or DSO in €/MWh. This is depending on time of the day as well as on the season. Energy supplied from 3AC networks with nominal voltage of < 30 kV is more than double the cost than energy supplied from systems with nominal voltage > 145 kV;
- toll access for contracted power demand is agreed between IM and TSO or DSO in €/kW. This is depending on time of the day as well as on the season. Cost for access to 3AC networks with nominal voltage of < 30 kV is approx. three times higher than the cost of access to systems > 145 kV;
- excessive power consumption above contracted power demand is penalised on basis of actually consumed excessive power for each 15 minute billing period in €/kW.

The Spanish billing model is comparable to other European countries. It should also be noted that there is also different time period to calculate these criteria, for example for RTE in France the power is calculated as an average over 10 min, and certain criteria such as regenerated energy are regulated over a period of 30 min. Such time constant can also influence the cost saving evaluation.

The presented methods and measures allow for achieving savings in all of the above mentioned billing terms. Nevertheless, due to mutual exclusivity not all billing terms can be reduced at the same time. The results for each measure are summarised in the following paragraphs.

7.2 Double side feeding

By introduction of double side feeding the toll access cost for contracted power demand as well as cost for excessive power consumption can be reduced. This is due to lower installed capacity of equipment and smoothened load flow, especially in case of an outage of a complete substation. Likewise power factor is smoothened and has fewer low level values. Resulting reduction of cost for reactive energy flow is negligible. Total energy flow is slightly decreased in case of conventional transformer double side feeding due to decreased line impedance, resulting reduction of energy cost is negligible.

Feasibility and preconditions for realisation of double side feeding with transformers is described in chapter 10.2. Resulting reductions in cost for active energy and toll access for energy are negligible. Due to the way energy is billed in Spain, reduction in peak power cost is also negligible. In case of different billing methods like in France, reduced energy cost can be achieved. On substations feeding the LN1 high line, the excess peaks of power can represents 5 % to 13 % of the transport energy bill.

7.3 Balancer

By application of balancers, penalties on excess reactive power consumption can be avoided. Conventional ETS being connected to 1 pair of phases of the 3AC network cause asymmetrical load on the 3AC network. This results in a power factor of around 0,866 when looking at each phase of the 3AC network individually. Attention has to be given where and how energy metering is done in such case. This specific problem is limited to few special consumers like electric traction and is not standardised so far. Certain metering approaches result in considerable cost for reactive power consumption, as outlined in deliverable D10.2 [6].

Besides the issues of metering, cost for reactive power consumption is especially of interest in case of operation of older trains with relatively low power factor, i.e. which use thyristor based power electronics, or with long feeding length. For the analysed scenarios 1 and 2 in Spain, achievable cost savings due to reactive power consumption are minor and negligible. Even thus, scenario 2 shows slightly lower power factor due to introduction of auto transformers as additional reactance for realisation of 2x25 kV system. Cost for active energy as well as toll access for energy consumed will slightly increase by application of balancers due to additional losses of the balancer’s power electronics, although this remain fairly low. All other terms will remain untouched.

7.4 Static converter feeding

Application of static converter feeding enables leveraging all advantages from double side feeding while at the same time avoiding negative effects like additional current on the OCL due to 3AC load flow or high levels of short-circuit current. The advantages are reduction in toll access cost for contracted power demand as well as reduction of cost for excessive power consumption. Cost for excess reactive energy flow is eliminated completely, if any exist due to operation of old trains or similar. Due to additional losses of the static converter itself, cost for active energy as well as toll access for energy consumption will be higher. Exception is given in case of conversion of a DC electrified line to AC power supply. As the efficiency of AC systems is higher by nature, a lot of energy cost can be saved in such case.

In general, it can be stated that energy cost reduction is not the purpose of introducing static converter feeding. Nevertheless, it might be the only possibility to enable savings for conversion from DC to AC due to full compliance with technical requirements for connection to 3AC networks.

7.5 Realisation of energy cost savings in Spanish use cases

Main parameter of all considered criteria for energy cost in Spain is the total active power consumption. The variant with the least loss – that is highest efficiency – leads to the lowest cost for connection to a certain voltage level of the 3AC network, as long as the power quality limits are met. The energy flow is determined by the traffic on the line. Without use of energy storages, which are not in the scope of this project, the power flow and resulting energy is determined by the schedule due to higher priority on punctuality. Indeed, actively influencing the schedule is not of interest in almost all cases. Excessive reactive power consumption does not lead to significant penalties in the analysed scenarios.

Reduced energy costs is clearly achieved in scenario 3 for conversion of existing DC electrified line “Mediterranean Corridor” to AC power supply by use of static converter feeding. This is due to reduced transmission losses of up to 66 % for converter feeding with nominal voltage of 25 kV AC. Converter feeding has to be considered in this case for complying with grid code requirements and avoiding construction of new 3AC overhead lines for grid access. In this way, energy cost is reduced by approx. 15 %. Minor savings are achieved by reduction of peak power demand and associated cost by controlling the load flow between the substations. In the other scenarios, no major energy savings are achievable due to very high efficiency of the AC system itself.

7.6 Conclusions

Considering cost saving on energy, the most advantageous configuration is double feeding using static converters for the Mediterranean Corridor conversion from DC to AC in the Spanish case. However, it has to be noted that the existing grid code in Spain and many other countries do not reward the advantageous results of static converter feeding or application of balancers. Power quality requirements of the grid code have to be complied with, but additional benefits will typically not be rewarded. Most extreme example is given with requirements on voltage unbalance. In general, consumers have to fulfil the limit values or they might risk being disconnected. In some cases, exemptions might be negotiated with TSO or DSO individually, i.e. TSO foresees rectification of unbalance by installation of balancers within the 3AC network and charges the IM for such service. In principle, temporary allowance of higher limit values in case of a substation outage might be discussed. Depending on how energy metering incl. power factor is done, penalties on reactive power consumption can be avoided. In the long term, voltage unbalance must be limited due to resulting increased aging of 3AC electrical machines like induction motors.

Active energy management is rewarded in the Spanish billing model, as excessive power absorption for each 15 minute period is penalised. Minor advantages might also be achieved for active energy purchase decisions on short term basis by limiting the power flow in a TPS individually. Anyhow, other countries apply more strict rules to excess power absorption. In some cases, one-time fees of at least 5 digit numbers in Euro have to be paid if mean power absorption in one 15 minute billing period exceeds contracted power demand once per month, quarter year or year. Such models give higher incentive on active energy management in terms of power demand control. In France, the production of regenerative energy can be rewarded over a period of no more than 30 min.

Some future applications could be achieved if consumers could provide services to the TSO or DSO on demand, which could be leveraged by application of static converter feeding or balancer application. Such services can be provision of reactive power, which otherwise would require installation of an SVC on 3AC network side. As an outlook into the future of smart grids, such business models might become valuable on individual case basis.

8 Energy management

In existing 50Hz AC lines transformers are simply transferring the load from the traction network to the 3AC network. This does not allow for controlling the power flow or for influencing the parameters of power quality.

Static converters are active substations. This enables double side feeding or completely interconnected system operation like in 16,7 Hz or DC systems, thus enabling the substations to influence the power flow. This allows for peak power reduction as well as load shifting between neighbouring substations. Active power demand control can be set up on this basis with minimum consequences to train operation and time schedule. This can be used for optimizing the energy bill by avoiding penalties. It can also be a mutual benefit for the energy supplier respectively the 3AC grid operator as well as the Infrastructure manager.

With static converters and partially with balancers the power quality parameters can be influenced. Within the spare capacity of the power electronic the IM could even sell power quality services to the 3AC network operator. This has to be evaluated from case to case with individual contracts.

It was not investigated in this project, but it is also possible that the railway IM invests in an own two phase AC high voltage network fed by static converters, similar to the existing ETS in some parts of the countries using 16,7 Hz traction power. Such systems are presented in deliverable D10.3 [7]. In this way, interface points to the 3AC grid are reduced and better load averaging between the substations is enabled.

As a separate topic, state of the art and future possibilities of information flow between the TPS, ETS in general, TMS and MMS is described in deliverable D10.4 [8]. This enables gathering of all data needed for setting up an overall energy management. Use of FACTS equipment, like static converters for direct feeding and balancers, requires active control. This also enables better monitoring of the operating mode and the condition of system components. Furthermore there are new capabilities for communication between components, not just with controlled power electronics but with protections systems and system control units as well, being presented in D10.3 [7].

Both technical innovations lead to a higher availability and to improved maintainability as described in D10.4 [8]. Other measures to improve availability are becoming obsolete and classical methods of redundancy like spare transformers can be avoided.

An increased monitoring over the system also reduces down times and enables better planning of maintainability measures. Thereby, not only the investment costs for the equipment of the ETS, but also the life-cycle costs are reduced. However, the usage of power electronics always leads to additional investment costs. The considered technologies are fitting perfectly into the world of having digitalised holistic view of systems.

9 Innovation management

As already introduced in other projects like OSIRIS, double side feeding can yield considerable advantages for the electric traction system. This general idea is further analysed within work package 10 of the In2Rail project using application to three different scenarios of Spanish railway lines. Restrictions for double side feeding by use of conventional transformer feeding are shown. This relates foremost to additional current on the overhead contact line system solely caused by a load flow in the upstream parallel 3AC network on public grid side. Limitation of such load flow by use of three phase transformers with tap changers is introduced.

Besides, double side feeding is easily realised by use of static converter feeding. This avoids additional currents on the overhead contact line system and also reduces the short-circuit currents for complying with requirements of applicable standards. In this way, full potential of double side feeding is leveraged. Resulting advantages can be used for realising feeding sections with increased length, reducing installed equipment or avoiding revamping of existing equipment by reducing its load. This is shown by consideration of individual thermal constants of equipment. It is shown that application of static converters shall always consider double side feeding or completely intermeshed networks due to the low thermal constant of its built-in power electronics.

Comparison of efficiency of different electrification systems was done. Due to its power electronics, static converters as well as other actively controlled equipment introduce additional losses. This will cause reduced overall efficiency if applied to an AC system. This is partly compensated for by increased voltage stability, resulting in lower losses. It can be generalised that such equipment shall only be installed for other reasons than solely for efficiency. Exemption is given for conversion of an existing DC line to an AC electrified system due to increase of nominal voltage and accordingly a reduction of currents. This might be only feasible by use of actively controlled power electronics due to nowadays strict requirements of the applicable grid codes, while at the same time enabling a high degree of freedom for planning and geographic location. Likewise, such equipment offers correction of power quality issues.

At the interface of the ETS to the 3AC network, a data interface is established for enabling more complex simulations by use of a holistic model. In this way power quality considerations are more precise compared to simple models, i.e. when only considering minimum available short-circuit power for calculation of unbalance.

Results from the analysis of the Spanish scenarios are generalised and made available for application to other systems. Accordingly, one chapter focuses on presentation of the results in terms of design analysis tools and methodologies.

Active energy management like power demand control is enabled by use of static converter feeding with minor influence to train operation. By use of a standardised interface to traffic management systems and maintenance management systems, availability of the electric traction system could be enhanced. In combination with advantage from static converter feeding, redundancy concepts might be revised. Furthermore, new protection and control schemes are introduced by realisation of process bus communication. Nevertheless, conventional transformer is very mature with life expectancy up to 40 years with proper maintenance. Thus, a proper cost assement must be carried for a given electrification project.

9.1 Adoptions in standards and regulations

An open question regarding energy metering arises for investigation in subsequent projects. Connection of an ETS to 3AC networks by use of single phase transformers in conventional substations results in heavy burdens of unbalance. This problem is unique to electric traction application and does not occur broadly in other applications. This influences power quality in general and not only the topic of unbalance. There is considerable amount of uncertainty regarding measurement of power factor at the PCC when measuring all three phases of the 3AC network, while the ETS is only connected to 2 phases only. Standards for energy metering should be reviewed for providing clarity in this field.

There is a lack of standardisation for converter applications for networks and specifically for feeding AC railways. The TC9 of IEC started to investigate the need for standards within its Adhoc Group 21. This is an ongoing process presumably leading to standards for frequency converters as well as for balancers. Basis is the state of the art of converters providing reactive power and converters connecting a 3 phase AC grid with a 1 phase traction grid.

Furthermore, the series of standards for IEC/EN 61850 communication incl. process bus focus mostly on standard applications with industrial frequency. Special traction applications like 16,7 Hz are typically not considered. The follow-up project IN2STEMPO will focus on analysing the available components and standards for application to 16,7 Hz.

Besides standards, regulations for grid access in some countries prevent do not allow for feeding back regenerated energy from decelerating trains. If such trains are not able to find an energy exchange partner, then energy must be dumped. This is economically as well as environmentally as huge problem. A solution must be found in such cases, either by revising grid codes or taking technical measures in order to not waste energy.

Furthermore, billing models typically do not reward certain positive effects from application of FACTS equipment. With evolution of energy grids towards smart grids with decentralised power generation and absorption, business models for provision of services from IM towards TSO or DSO might become feasible. This can be among others additional compensation of reactive energy, provision of reactive power or balancing 3AC network side.

Due to lack of general regulations for such services, only individual contracts would be feasible today.

10 Design Analysis Tools and Methods

10.1 General aspects of the system design

When designing a new line or extending the capacity of an existing line, numerous aspects have to be considered with respect to an efficient and sustainable energy supply. In the process of the In2Rail WP10 project, a number of measures to improve the power supply in electric traction systems have been analysed. The investigated measures include new technologies and design solutions. A description of the measures will be given in the following chapters including transferable generalised specification and implementation rules.

Each railway project has various requirements, which partially differ between new projects ("green field projects") and upgrading projects ("brown field projects"). Exemplary, the aspects to be considered for the number, design and positioning of substations are:

- the required traffic capacity of the railway line and its topology;
- the route of the national grid high-voltage lines, their voltage level, their minimum available short-circuit power and possible connection points;
- fewer substations are correlating with longer feeding sections, which leads to more nominal power per substation and more power fluctuation;
- more substations increase the efficiency of power supply and reduce the maintenance costs as inversely proportional parameters of the operational costs;
- the investment cost are depending on the number of substations (equipment needed, price of land, phase separations points along the track) and the substation type (classic transformer substations, static converter substations, …);
- the availability of land for building a substation at certain positions.

These are just some of many aspects to be considered when planning an ETS project. To find the most suitable solution, projects have to be developed on a case by case basis. For an optimized design solution a combination of multiple measures could be useful.

10.2 Double side feeding

10.2.1 General

The conventional supply concept for electrical traction systems operating with AC consists of a single sided power supply and phase separation points between the substations. A train is solely supplied by one substation and one direction. To improve the stability of the supply voltage, to reduce the transmission losses and to smoothen the power flow double side feeding can be used.

When using double side feeding, the supply voltages of two neighbouring substations need to have almost identical phase orientation. No phase separation points are necessary between the substations. Trains are supplied simultaneous from both substations. The traction current is supplied from both directions. Due to the simultaneous supply from two directions the current in the OCL from one supply direction is reduced, resulting in lower transmission losses and a smaller voltage drop along the track. The maximum traffic capacity of the track increases. Furthermore, the feasible distance between two substations is increased. The necessary number of substations for a line decreases.

Double side feeding is also reducing the fluctuation of the supplied traction power in a substation. The increased supply range of each substation and the power distribution by multiple substations result in a smoothened energy supply, i.e. lower ratio between peak power demand and average power demand. The effect on the power quality is different depending on the realisation of the double side feeding, either with a phase separation at the substation or without any phase separation at all. The applied variant for double side feeding is determined by the substation components.

A realisation of a double side feeding using only single phase transformers is possible. With this design method it is common to keep phase separation posts at each substation and connect the two transformers of one substation to different phase pairs (see Figure 10.1). This supply concept is referred to as v-connection. The v-connection helps to reduce the overall unbalance along the line if substations are being fed from the same transmission 3AC network.

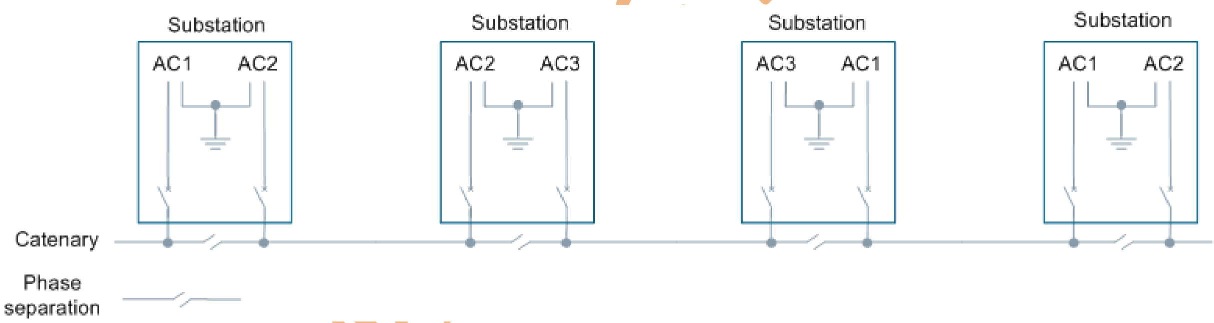

Figure 10.1: Double side feeding arrangement with transformers for a whole line

The realisation of double side feeding with single phase transformers is linked to two difficulties that can exclude this ETS design variant. First, the power flow in the 3AC high voltage network is causing a longitudinal voltage drop, see Figure 10.2. The voltage drop is transferred to the traction network, resulting in a difference of the no-load voltage between two substations. The voltage drop is applied to the series connection of the transformers impedances and the catenary impedance, causing a power flow in the traction network. This current causes losses in the ETS. It reduces the remaining capacity of the catenary system and is also unintended by the 3AC network operator as it is asymmetric and may influence the protection systems. The 3AC high voltage system is typically operated at a power factor close to unity while its impedance is mainly inductive. Hence, the difference of the source voltages of the two neighbouring substations is mainly caused by a phase shift, rather than by a difference in the amplitude. A general limit cannot be given. About 2° difference in voltage angle seems to be a reasonably acceptable value. Nevertheless, occurring power fluctuations have to be taken into account. In future networks the absolute load flow as well as the direction of the load flow will be more uncertain and varying. This is due to an increasing number of small power generating units like photovoltaic systems and their impact on the power flow in smart energy networks.

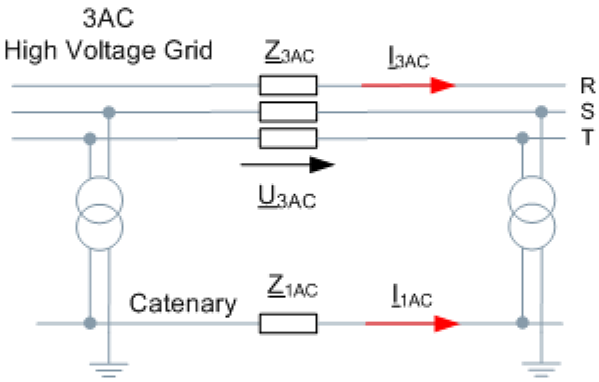

Figure 10.2: 3AC load flow and resulting load in 1AC System

The second issue is concerning the unbalance in the 3AC network. The emerging unbalance when using single phase transformers is a general matter and not limited to double side feeding, see also chapter 10.3.1. The use of v-connection for substations can reduce the unbalance up to 50 % in case of one common 3AC network for feeding. The actual amount of balancing depends on the operational situation.

Currents by the parallel load path as well as a high unbalance can prohibit the usage of single transformers for double side feeding. There are some measures to counteract these problems that will be described in the following subchapters:

- three phase transformers equipped with tap changers are one possibility to adjust the phase angle for preventing a current in the parallel load path. Under inclusion of the third phase, the phase angle as well as the amplitude can be adjusted in steps. The remaining difference of amplitude and phase angle can be neglected;
- to balance the power flow in the 3AC network and reduce the unbalance several special transformers like a three phase transformer or a Scott-transformer can be used, see deliverable D10.1 [5];
- another measure to prevent unbalance in the 3AC network is application of balancers for actively reducing unbalance from the ETS;
- direct feeding with static converters eliminates unbalance and also prevents additional load current caused by 3AC network load flow.

Last but not least, double side feeding can lead to excessive short-circuit currents. This depends on the short-circuit impedance of the complete electrical system. Compensation by choice of transformer design is partially possible, i.e. by different short-circuit impedance of the transformer itself.

10.2.2 Double side feeding using static converters

In this chapter the ETS design with static converter substations for double side feeding is described. The general supply principles are also applicable for double side feeding with single phase transformers or transformers with tap changers.

A static converter substation is connected to all three phases of the 3AC network. The power is transferred completely balanced. By using actively controlled power electronics, the load flow can be controlled and the amplitude and the phase angel can be adjusted.

An optimal reduction of the transmission losses as well as the highest supply voltage for the trains can be realized by using the same terminal voltage for two neighbouring substations. The ETS can be designed with either solely static converter substations (see Figure 10.3) or a combination of static converter substations and conventional transformer substations (see Figure 10.4). When using solely static converter substations, no phase separation points are required. Instead of phase separation points, sectioning posts will be used to divide the supply sections. Thus increasing the selectivity of protection is achieved.

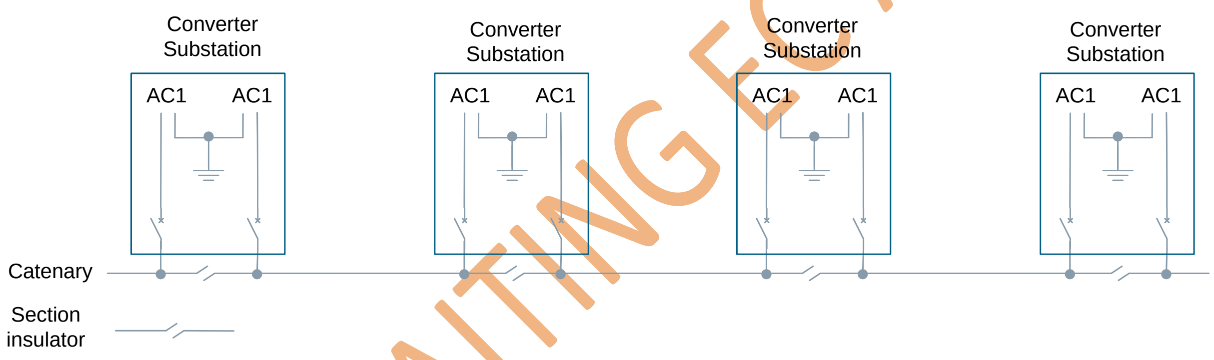

Figure 10.3: Arrangement of an ETS for a whole line using solely static converter substations

A design with static converters and transformers requires a phase separation point at each substation, because a static converter substation can be adjusted only to one neighbouring transformer as the next one has a different phasor. A phase separation point between two neighbouring substations is not necessary. When using a combination of transformer and static converter substations balancing is not possible for all connection points. If necessary, additional measurements have to be implemented for the transformer substations. Furthermore, outage of one complete static converter substation imposes same worst case scenario, i.e. single side feeding with neighbouring transformer substation. This has to be considered during dimensioning of equipment in system design for achieving n-1 redundancy. If no negative impact shall be caused by such outage, then advantages of double side feeding are reduced to normal operating mode and no further advantages can be leveraged.

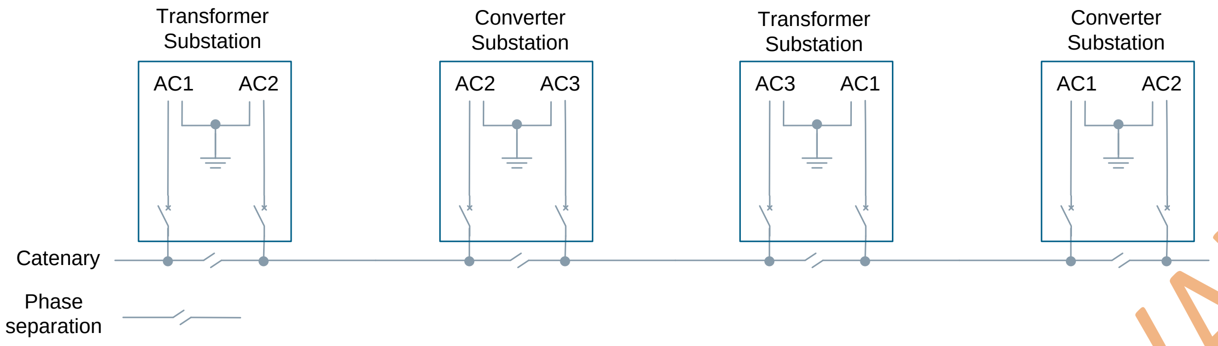

Figure 10.4: Arrangement of an ETS for a whole line using transformer and static converter substations

10.2.3 Double side feeding using three phase transformers with tap changers

By using a three phase transformer with on-load tap changers the secondary voltage can be adapted in phase angle and amplitude. Design of the tap changer and its steps determines range and accuracy for adapting to 3AC load flow. The supply concept is depicted in Figure 10.1.

How often the tap changer has to be used depends on the change of load flow in the 3AC network. Other special transformer types, like Scott-transformers, can also be equipped with tap changers for adapting phase angle and amplitude within its system immanent limits. Another benefit of three phase or special transformers is the partial reduction of unbalance depending on type of transformer used.

10.2.4 Comparison

Both design options for realizing double side feeding, three phase transformers with tap changers as well as static converters, have certain advantages and disadvantages. It is depending on the use case which variant is more favourable. To support the decision the following comparison points should be considered:

- *Short-circuit currents in the ETS:* use of static converter feeding limits the short-circuit currents by nature. Compliance to maximum allowed short-circuit currents with transformer double side feeding needs to be observed carefully;
- *Losses of the ETS:* the use of static converters provides an improved power quality, which reduces the transmission losses compared to an ETS with transformers. But as described in D10.2 [6], also the static converter losses of about 2 % have to be considered in comparison to the transformer losses of approx. only 0,5 %. For example, in scenario 2 the efficiency of the conventional ETS is 98,1 %. The efficiency can be increased up to 98,3 % by double side feeding, but if static converters are used the overall efficiency decreases to 96,3 %;
- *Power Quality:* detailed analysis of power quality is described in chapter 10.3.1. Nevertheless, it can be stated that full compliance to grid code requirements is achieved by static converter feeding per se. This is achieved by programming of the active control part;

- *Energy management:* with static converters the energy flow can be actively controlled by realisation of different control algorithms, see also chapter 8. This enables for adjusting reactive power control towards 3AC feeding network. Furthermore, maximum demand control is enabled within certain limits and without excessive impact on train operation. The usage of transformers does not enable any control;
- *additional currents caused by 3AC load flow:* as described in chapter 10.2.1, currents due to the parallel load path to 3AC network should be avoided. When using three phase transformers with tap changers a compensation can be realized within certain limits. A frequent response to load flow changes or a precise adjustment is not possible. In some cases, this may exclude the use of transformers only;
- *Investment Cost:* it can't be generalized which variant has overall lower investment costs. A static converter substation itself is more expensive than a conventional transformer substation. Use of special transformer types or tap changer can also result in higher investment costs. Besides the TPS equipment itself, investment into 3AC network connection has to be considered also, i.e. by enabling connection to systems with lower nominal voltage.

10.3 Use of FACTS equipment for improved power quality

10.3.1 General

The main characteristics of power quality are:

- unbalance;
- harmonics;
- power factor;
- flicker.

By using different feeding configurations all parameters can be influenced. In this report only the influence on the unbalance and the power factor are analysed. The other two parameters are not considered, because:

- even if the load is permanently fluctuating the flicker is generally low since voltage dips are relatively small. This is due to high short-circuit power of feeding grid in comparison to the ETS load and power factor of ETS load being dominantly resistive.
- the limit for harmonics has to be kept regardless of the ETS design. In case the harmonic limits are exceeded, additional filter circuits will be installed.

A reduction of the unbalance can avoid new or more expensive connections to the high voltage network. Retrofitting an existing system can be necessary as well. For example the Spanish high speed lines were designed under the aspect of overall unbalance of the 3AC network in parallel to and feeding the whole railway line. The resulting unbalance at each single substation was only of minor interest. The railway system as well as the high voltage system were operated by the government and considered as one system in regard of unbalance. Nowadays the requirements for grid connections and unbundling of the system operators don’t allow such simplifications. The unbalance has to meet the requirements at each connection point. When considering aging of electrical machines like induction motors connected in close proximity to the TPS, this approach is absolutely feasible. Anyhow, this imposes by far higher requirements to the IM.

Improving the power factor is decreasing the losses in the ETS and also decreases the voltage drop along the overhead contact line. The increased voltage stability enables slightly higher punctuality during high traffic hours, respectively increased traffic capacity of the track.

In the following subchapters measurements to achieve an improved power quality are presented.

10.3.2 Use of transformer substations

A transformer transfers the traction power from the 3AC network into the ETS without any control options. The transformer enables a power flow in both directions and the losses are small by comparison (see Figure 10.5). Only the applied voltage is determining the load flow, there is no influence on the power factor. As described in D10.2 [6] this ETS design produces an unbalance in the 3AC network.

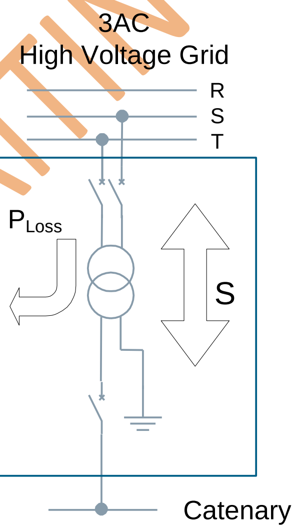

Figure 10.5: Load transfer of a transformer substation

A possibility to reduce unbalance is to use a v-connection if looking at the line and one common 3AC feeding grid in whole, as described in D10.1 [5] and 10.2. The v-connection is statistically improving the unbalance. If in both feeding sections the power demand is the same, the unbalance is reduced by half compared to transformers with a connection to the same phase pair. Anyhow, unbalance will be highest in case of regenerative breaking in one feeding section and full load for acceleration in the other feeding section.

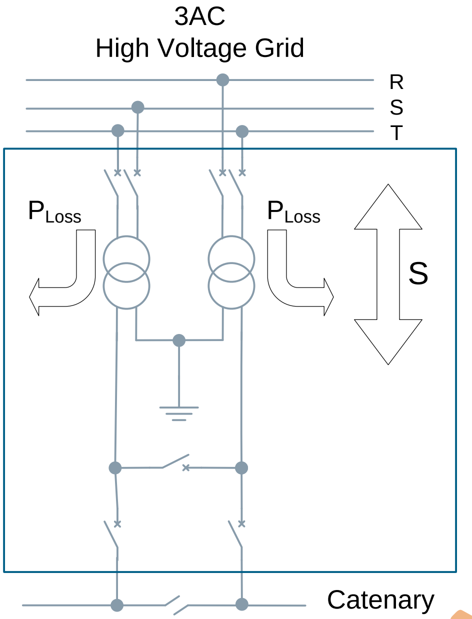

Figure 10.6: load transfer of a substation with transformers in v-connection

10.3.3 Transformer Substations with balancers

The power exchange between the 3AC network and the ETS is realized via transformers as described in the preceding chapter 10.3.2. The exchanged traction power consists of an active and a reactive component. By exchanging additional reactive power, a balancer can distribute the power symmetrically to all 3 phases of the 3AC network. The load flow in the 3AC network is balanced. In an ideal case the balancer can compensate also the reactive power consumed by the ETS so that solely active power is exchanged with the 3AC network. This has to be considered during design phase of the balancer.

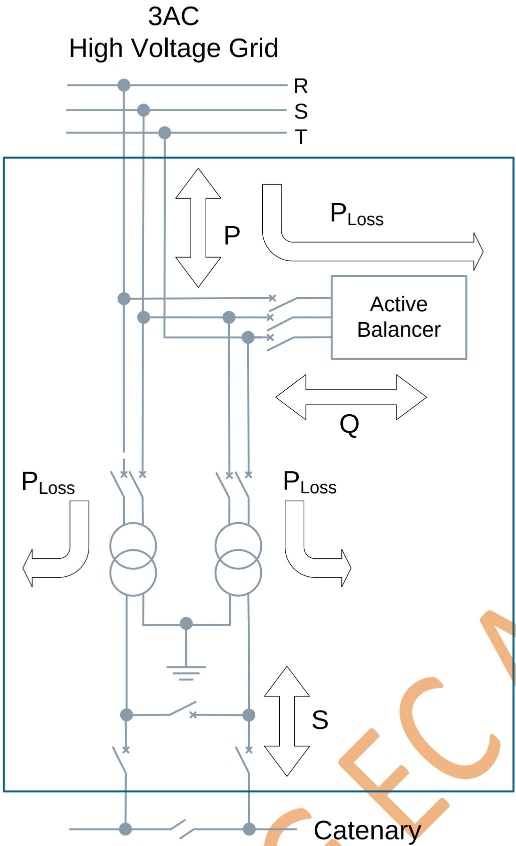

Figure 10.7: Load transfer of a substation with transformers in v-connection and balancer

For the implementation of a balancer into a substation several variants are possible. In Figure 10.7 the balancer is installed on the high voltage side of the substation and two single phase transformer in v-connection are used. Further design variants include the usage of just one single phase transformer or a three phase transformer as well as the installation of the balancer on the traction network side (see Figure 10.8). The variants differ in costs, losses and balancing capability. The most fitting solution depends upon the application.

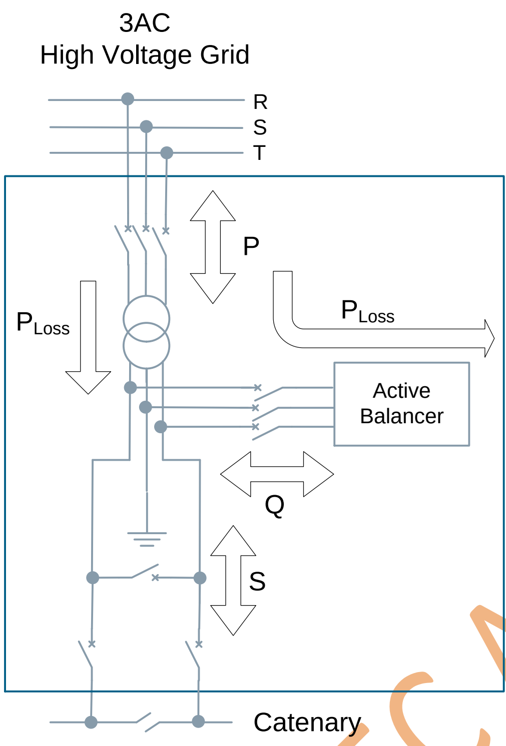

Figure 10.8: Load transfer of a substation with a three phase transformer and balancer

By standard limits a remaining unbalance and power factor is allowed. An optimized balancer design using the standard limits can reduce the needed installed power of the balancer. Also, depending on the dimensioning of the balancer it's capability for balancing varies for different points of operation.

In Deliverable D10.2 [6] the losses of the balancer are described. Generalizing the losses of a balancer relative to the losses of the ETS is not possible. The balancer losses depend on the installed power of the balancer, which not only considers the traction power, but other factors as well. For example the short-circuit power of the supplying high voltage network.

10.3.4 Static converter substations

A static converter transfers the active power between the traction network and the 3AC network. State of the art static converters enable a power exchange in both directions. Additionally the static converter can exchange reactive power with both networks separately within the limits of its total power (see Figure 10.9). The provided power factor can be controlled. Under normal circumstances the power factor is controlled to unity.

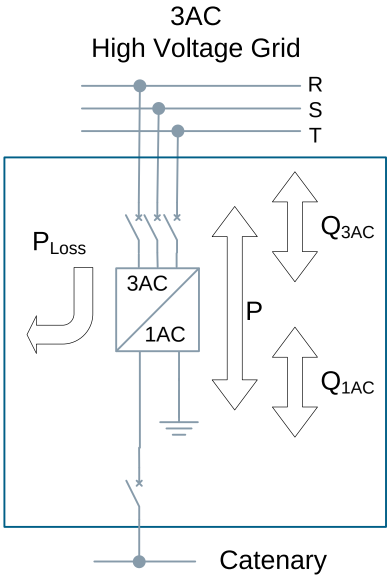

Figure 10.9: load transfer of a static converter substation

The static converter is symmetrically connected to all three phases of the 3AC network. No additional measures for balancing are needed. How much reactive power on the traction side is needed depends on the load, i.e. type of train. In conjunction with the neighbouring substations additional reactive power can influence the load flow of the whole line.

11 Application Scenario 1 (Madrid – Seville)

11.1 General

The first scenario investigates a section of the high speed line Madrid - Seville. The examined section has a length of 260,6 km between the substations Puertollano and Seville. Main parameter of the track are a 25 kV AC system with conventional substation design and a parallel upstream 3AC network. Figure 11.1 provides a schematic overview of the supply concept. The 3AC network consist of a 220 kV high voltage line for the first four substations and a 132 kV high voltage line at the last three substations of the examined section. In each substation both transformers are connected to the same phase pair of the 3AC network. The contact line system is supplied single sided. At the substations and between two neighbouring substation phase separation points are installed. In normal operation the phase separation points at the substation are not in use and both feeding sections are connected.

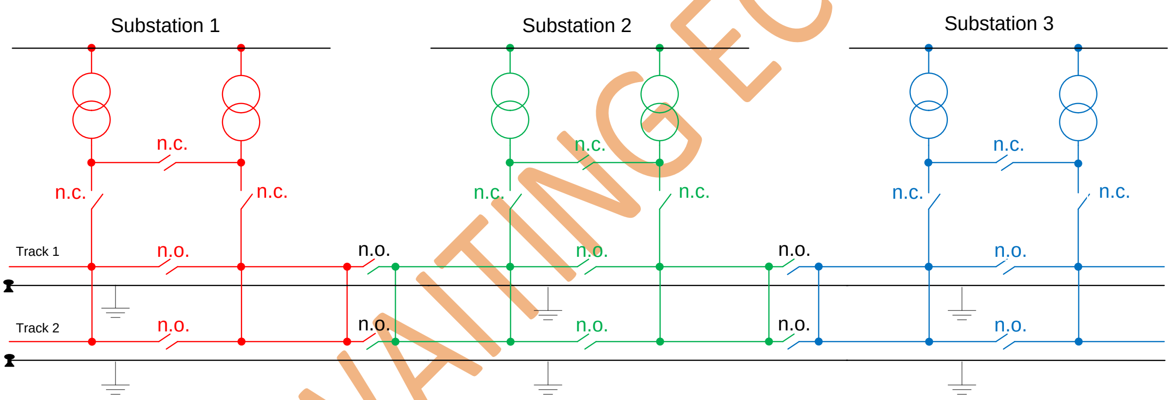

Figure 11.1: Original supply concept in scenario 1

The aim is to investigate the feasibility of increased traffic planned for future operation scenarios. Therefore, the installed equipment is checked for sufficiency and feeding alternatives are looked at.

The investigation of the scenario and the supply variant consists of several steps. First step is an operational simulation to receive the load flow at each traction substation, the voltage stability along the track and current flow in the overhead contact line and cables. For validation, the simulation results have been compared with the measured data of all substations, both on their grid and traction side.

In the second step the interface to the public grid was investigated in detail. Therefore, the collected load flow data is processed in a 3AC network model. The simulations with the 3AC network model state the power quality at each connection point. Both steps are described in D10.1 [5] and D10.2 [6].

The simulations include 9 uses cases with four different supply variants. Despite the conventional supply concept, the implementation of FACTS is considered. The supply concepts with FACTS include the application of balancers and static converters. In addition to the original train operation, an increased traffic volume as well as a degenerated operating mode is investigated. In D10.3 [7] implementation of a new substation equipped with FACTS equipment is described.

11.2 Findings

In Table 11.1 some results of the train service simulations for scenario 1 are displayed. The table compares two supply variants in normal operation and with an outage:

- the conventional feeding concept with two transformers at every substation that are connected to the same phase pair of the 3AC network;
- double side feeding with a complete interconnection of all feeding sections by use of static converter feeding.

Both variants are based on an increased traffic volume. For the increased traffic currently operating train types are used. An improvement of efficiency and recuperation capability by the usage of modern trains is not considered. Used points for comparison are:

- the total energy consumption of six hours of train service operation;
- the minimum supply voltage along the line;
- the maximum current in the contact line system;
- the maximum power output of one exemplary substation.

The complete input data for the train service simulations as well as a detailed description of all findings are provided in D10.1 [5].

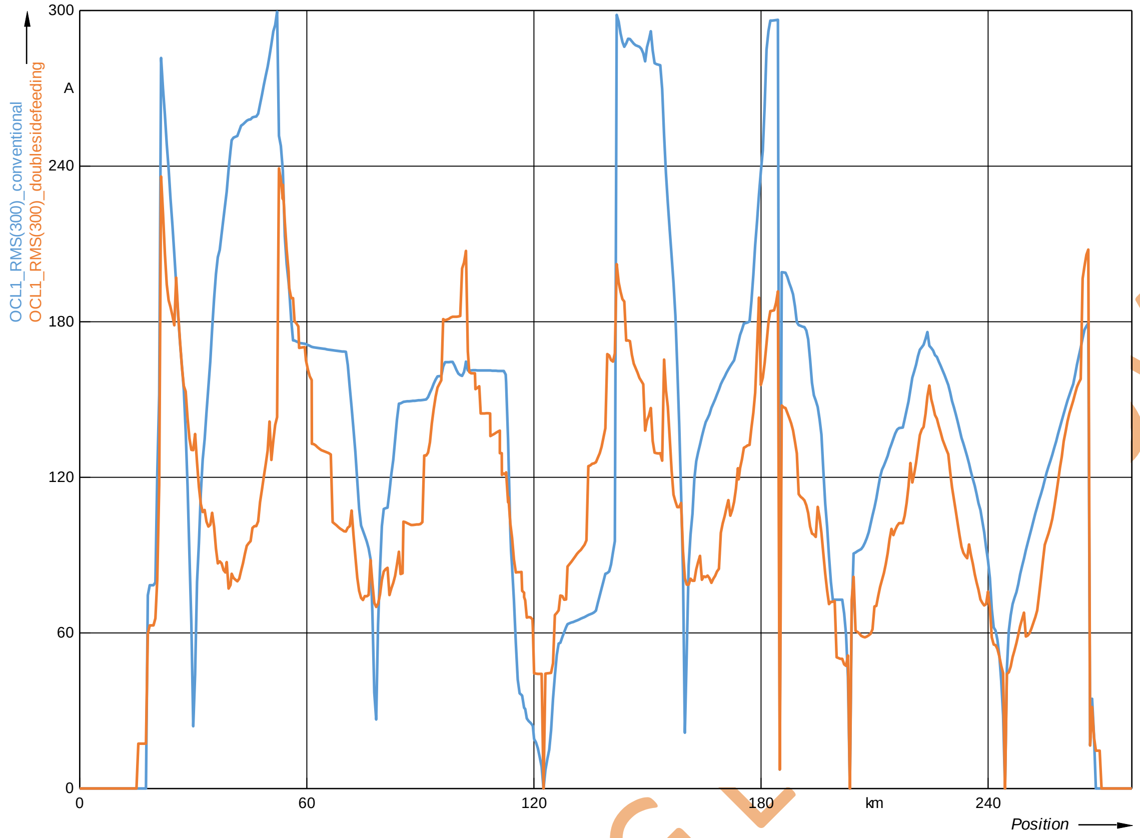

Figure 11.2: Maximum r.m.s. value (300 s) of the traction current in the OCL of track 1

The simulation results demonstrate that double side feeding leads to a steadier workload for the components of the ETS. Even if the total energy consumption is almost the same, the relevant r.m.s. values for component design are different. For example, the 300 s r.m.s. value is suitable for the dimensioning of the overhead contact line. When using double side feeding this value is significantly lower, see also Figure 11.2. In an upgrade project this difference can be decisive for the need of upgrading the overhead contact line system or not. The reduction of the current can be explained with load sharing as well as the increased voltage stability as minor effect.

Increased traffic			**Conventional feeding concept**	**Double sided feeding concept**
Total energy consumption Normal operation	kWh		507 778	506 925 + 11 000 for static converter
Minimum voltage Normal operation	kV		25,361	26,544 (+ 5 %)
Outage	kV		18,978	25,113 (+32 %)
Maximum current contact line system	A	10 s	587	557 (- 5 %)
	A	60 s	421	386 (- 8 %)
	A	300 s	254	239 (- 6 %)

Increased traffic			Conventional feeding concept	Double sided feeding concept
normal operation				
Maximum current contact line system Outage	A	10 s	935	657 (- 30 %)
		60 s	767	537 (- 30 %)
		300 s	495	403 (- 19 %)
Maximum substation power Normal operation	MVA	1 s	2 • 19,624	2 • 14,033 (- 28 %)
		60 s	2 • 17,097	2 • 11,731 (- 31 %)
		300 s	2 • 11,572	2 • 9,297 (- 20 %)
Maximum substation power Outage	MVA	1 s	2 • 33,410	2 • 18,934 (- 43 %)
		60 s	2 • 26,520	2 • 15,968 (- 40 %)
		300 s	2 • 17,215	2 • 11,878 (- 31 %)

Table 11.1: Results of train service simulations for scenario 1 in normal operation

Another result by means of simulating the ETS are the maximum short-circuit currents along the line. When using the conventional feeding concept the maximum short-circuit current is about 17,77 kA, with double side feeding by transformers 23,05 kA. The short circuit currents in an ETS with double side feeding are higher compared to conventional substations, due to the supply by multiple TPS. Not considered in the simulations is the limiting of the short-circuit current by static converters.

Regarding the power quality at the connection points to the 3AC network, the network simulations have shown differences for the power factor and the unbalance. By means of the 3AC network simulation the emerging unbalance is determined. For the conventional substation design in worst case scenario, the necessary balancing power is between 7 and 14 MVA depending on the viewed substation. The installation of balancers might be necessary when considering such maximum traffic worst case scenario. As static converters draw power symmetrically from every phase of the 3AC network, all limits are kept in that case automatically.

The power factor is analysed for the absorbed traction power in every phase of the 3AC network. As already stated in chapter 7, it is not standardised how metering is done. This has to be carefully observed and negotiated. The results are:

- by use of conventional substation design, the power factor of each phase in the 3AC network of every substation is about 0.866. Anyhow, power factor of connection to the two phases of the 3AC network is close to unity. Furthermore, power factor varies depending on the operational situation;
- in case of static converters in each substation, the power factor is constantly about unity due to symmetrical power absorption of all phases;

- application of balancers brings power factor back to unity for individual measurement of power factor in all phases of the 3AC network.

In this scenario the parallel high voltage line is separated into two sections with different voltage levels and different short-circuit power. The neighbouring substations La Lancha and Posadas are located at the changeover of the two high voltage lines. Between these substations double side feeding by a conventional transformer substation without additional measures is not viable. Anyhow, double side feeding by use of static converters would be feasible still.

12 Application Scenario 2 (Madrid – Barcelona)

12.1 General

Second investigated scenario is the high speed line Madrid – Barcelona. Examined is a section of 273,101 km between substation Anchuelo and substation Rueda de Jalon. The ETS of the line disposes of a 50/25 kV autotransformer system. In Figure 12.1 a schematic supply concept is provided. Each substation contains two transformers, both connected to a different phase pair of the 3AC network. At every substation as well as between the substations phase separation points are installed. All substations are supplied by the Spanish 3AC network with nominal voltage of 400 kV.

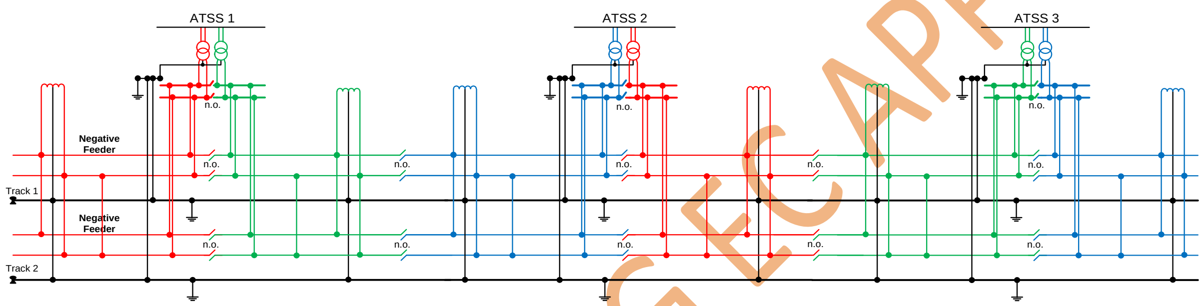

Figure 12.1: original supply concept in scenario 2

The approach for investigating scenario 2 is almost identically to the one of scenario 1. Likewise the feasibility of an increased traffic is investigated. By applying different supply concepts suitability and limits of installed equipment is analysed. Additionally, by using the same approach, a comparison of the AC system in scenario 1 and the 2AC system in scenario 2 is given.

Two steps are applied for scenario 2 as well. To begin with, a simulation of train service is conducted. Based on the gained load flow data for each substation, the interface with the public grid is investigated by means of a 3AC network model.

The simulations include 10 uses cases with four different supply variants. Despite the conventional supply concept the implementation of FACTS is considered. The supply concepts with FACTS include the application of balancers and static converters. In addition to the original train operation, an increased traffic volume as well as a degenerated operating mode is investigated.

The simulation results have been compared with the measured data of all substations. A detailed description of the input data and the simulations is given in D10.1 [5] and D10.2 [6].

12.2 Findings

In Table 12.1 some results of the train service simulations for scenario 2 are displayed. The table compares two supply variants in normal operation and with an outage:

- the conventional feeding concept with two transformers at every substation that are connected in a v-connection to the 3AC network;
- double side feeding with a complete interconnection of all feeding sections by use of static converter feeding.

Increased traffic			Conventional feeding concept	Double sided feeding concept
Total energy consumption Normal operation	kWh		747 395	746 158 + 15 000 for static converter
Minimum voltage Normal operation	kV		24,404	26,196 (+ 7 %)
outage	kV		18,691	22,216 (+ 19 %)
Maximum current contact line system Normal operation	A	10 s	874	751 (-14 %)
		60 s	637	593 (- 7 %)
		300 s	481	408 (- 15 %)
Maximum current contact line system Outage	A	10 s	1 267	1 095 (- 14 %)
		60 s	998	875 (- 12 %)
		300 s	790	730 (-8 %)
Maximum substation power Normal operation	MVA	1 s	62,766	35,483 (- 43 %)
		60 s	47,002	30,953 (- 34 %)
		300 s	39,660	28,623 (- 28 %)
Maximum substation power Outage	MVA	1 s	104,684	49,958 (- 52 %)
		60 s	85,182	44,655 (-48 %)
		300 s	71,405	41,516 (- 42 %)

Table 12.1: Results of train service simulations in scenario 2

Both variants are based on an increased traffic volume. For the increased traffic currently operating train types are used. An improvement of efficiency and recuperation capability by the usage of modern trains is not considered. Used points for comparison are:

- the total energy consumption of three hours of train service operation;
- the minimum supply voltage along the line;

- the maximum current in the contact line system;
- the maximum power output of one exemplary substation.

The complete input data for the train service simulations as well as a detailed description of all findings are provided in D10.1 [5].

The general results of scenario 2 are quite similar to the results of scenario 1 presented in chapter 0. Using double side feeding and static converter substations is improving the voltage stability and smoothing the load flow. The operating current in the OCL is reduced when using double side feeding for the sections, see Figure 12.2. The maximum short-circuit current is increased by the double side feeding concept. A difference of the impact of using double side feeding and static converters between scenario 1 and scenario 2 is not feasible.

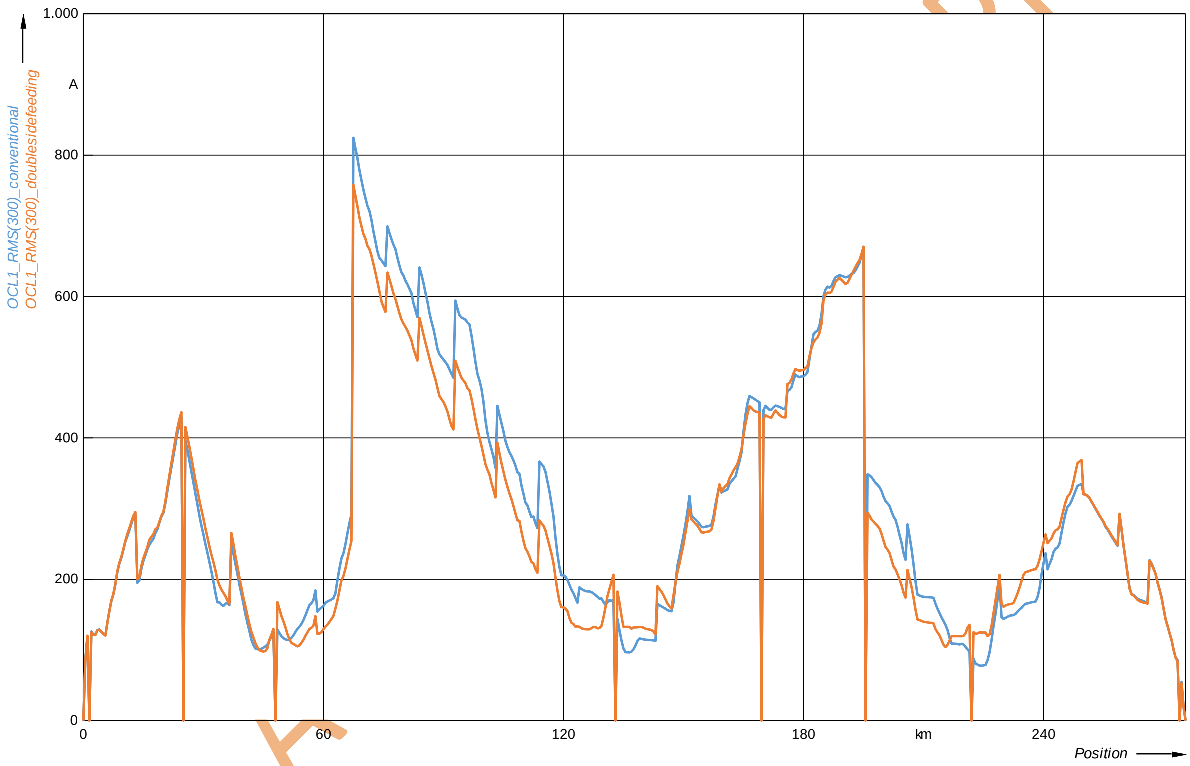

Figure 12.2: R.m.s. values (300 s) of the traction current in the OCL of track 1

Increasing the traffic to its maximum capacity raises the power output of some substations above 55 MVA, when currently the average power output is about 20 MVA. Also, it must be noted that the minimum voltage of the conventional supply concept can be below standard limits in case of a complete substation outage. Eventually, additional measures have to be taken when operating with the maximum traffic capacity.

Similar to scenario 1, the design of the HSL Madrid – Barcelona was made with a concept of balancing the line and its common feeding 3AC network as a whole. This approach is not state of the art anymore, due to the unbundling of the different system operators. Therefore, additional balancers would be needed for the conventional supply concept if grandfather rights will be lost. As stated in deliverable D10.2 [6], in normal operation balancing is necessary for two substations when upgrading the traffic to its maximum capacity. For meeting the unbalance limits in an outage scenario all substations would need balancers. Besides this, similar considerations regarding power factor have to be considered, see chapters 7 and 11.

13 Application Scenario 3

13.1 General

Scenario 3 is part of the line "Mediterranean Corridor", which is operated with a 3 kV DC system. Aim of the investigations is to demonstrate the potential of upgrading a DC system to an AC system. Similar challenges can be found all over Europe with many main lines being operated with a DC systems. When it comes to increasing traffic for DC lines, it should be considered if an upgrade to an AC system is more beneficial.

A section of 76 km between Sagunto and Torreblanca is analysed for upgrading the line to 25 kV AC system. The Mediterranean corridor is used for mixed train operation, including freight and domestic traffic. To enable a high comparability between the supply variants, the train operation as well as the location and number of substations remain unchanged.

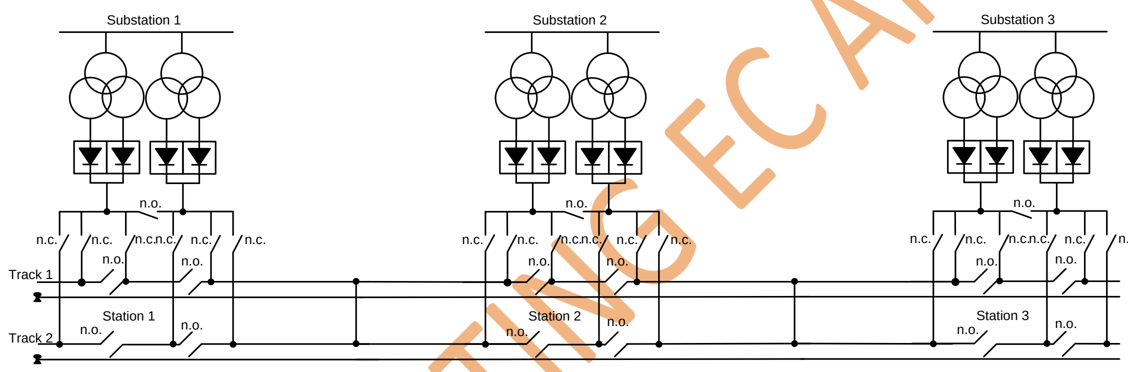

Figure 13.1: Original supply concept in scenario 3

The methodical approach for scenario 3 is identical to scenario 1 and 2. By means of a multi-train simulation the load flow in the substations and the current in the OCL are determined. Based on the load flow data of the substation, a simulation of the supplying 3AC network is carried out and power factor and unbalance at every interface point to the public grid are determined. The results of these simulations are provided in D10.1 [5] and D10.2 [6].

For the Mediterranean Corridor 8 use cases with four different supply variants have been simulated. Despite the original DC supply concept, three AC supply variants with a 25 kV system and balancers or static converters are included. Additionally, a degenerated operating mode is investigated.

13.2 Findings

In Table 13.1 some results of the train service simulations are provided. The table compares two supply variants in normal operation as well as in a degenerated operation mode:

- the original supply concept with a 3 kV DC system and;
- an upgraded 25 kV AC system with static converter substations and a completely interconnected supply section.

Both variants are based on the current timetable. Used points for comparison are:

- the total energy consumption of six hours of train service operation;
- the minimum supply voltage along the line and the voltage drop in percentage to the no-load voltage of the substation transformer (the no-load voltage of the DC system is 3,3 kV, the no-load voltage of the AC system is 27,5 kV);
- the maximum current in the overhead contact line system.

The complete input data for the train service simulations as well as a detailed description of all findings are provided in D10.1 [5].

Standard traffic			**3 kV DC system**	**25 kV AC system / Static converter substations**
Total energy consumption Normal operation	kWh		31501	25240 (-19,86 %)
ETS efficiency Normal operation	η		93,6 %	99,6 % (- 2 % when using Static converters would result in 97,6 %)
Minimum voltage / voltage drop Normal operation	kV		2,5 (- 24,24 %)	27,08 (- 1,53 %)
Outage	kV		2,35 (-28,79 %)	27,01 (- 1,78 %)
Maximum current contact line system Normal operation	A	1 s	2245	219 (- 90,24 %)
		60 s	1705	120 (- 92,96 %)
Maximum current contact line system Outage	A	1 s	2403	242 (- 89,93 %)
		60 s	1869	119 (- 93,63 %)

Table 13.1: Results of train service simulations in scenario 3

The AC system itself increases the overall efficiency of the ETS. Resulting in a decrease of the total energy consumption of the railway system up to 19,86 %. Depending on the used AC substation type (see also chapter 10) the total efficiency increase varies. With AC systems the maximum distance between substations is enlarged and so the necessary number of substations can be reduced. Final selection of substation locations minimizing total number of AC substations was not part of the project.

By using a higher supply voltage the traction current is reduced by approx. 90 %, see Figure 13.2. The reduction of the traction current decreases the necessary dimension of the OCL and in doing so enables an enlarged train operation without the need of replacing the OCL.

Another reason for the values of the traction current being this low in an AC system are the unchanged location and number of substations. In a newly designed ETS with a 25 kV AC system and similar train operation, the traction current would be higher as the optimized number of substations would be lower.

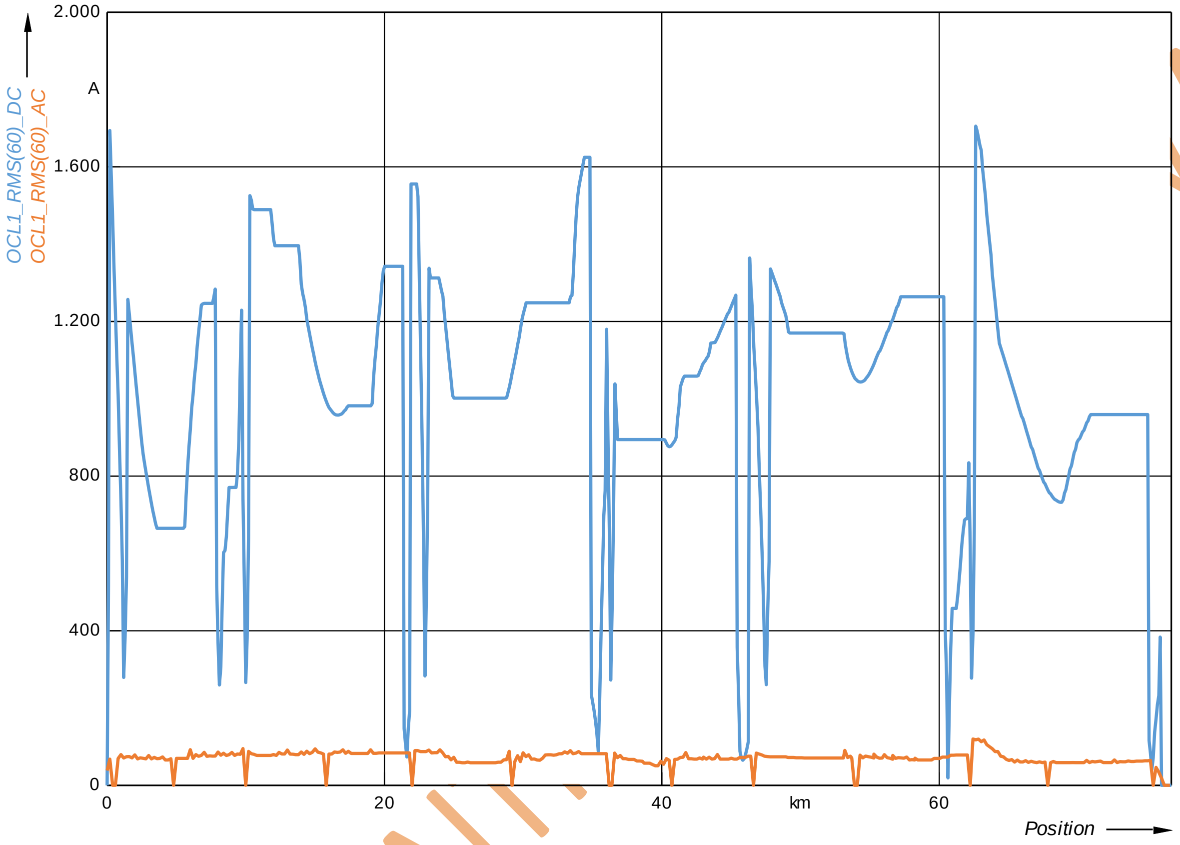

Figure 13.2: RMS(60 s) of the traction current in the OCL of track 1

In contrast to a three-phase transformer and rectifier in a DC system, the conventional AC system with single-phase transformers creates an unbalance in the 3AC network. Due to cheaper public grind investment costs, the connection of DC substations to lower voltage levels of the 3AC networks is not unusual. By using an AC system with fewer substations but increased substation power, the usage of single phase transformers easily exceeds the limits of unbalance in the 3AC network. Therefore, in an upgrade project balancers or static converters are often indispensable, even so their usage is reducing the overall efficiency.

The power factor in the 3AC network with the conventional DC system is about 0,98 and thus already high. By use of static converter feeding power factor will be even closer to unity by nature, even though this is not of interest economically. In a DC system all supply sections are connected. Being able to use double side feeding for AC systems additionally increases the efficiency. The load flow is smoothed and the voltage stability increased. This enables further reduction of necessary works. Phase separations will not be necessary. Sectioning posts shall be introduced for protection purposes thus.

A further difference between both supply systems is the short-circuit current in case of a fault. The maximum short-circuit current in the DC system for scenario 3 is about 46,99 kA and for the theoretical case of conventional transformer feeding with AC system solely 13,13 kA, due to the difference of the supply voltage level. A high short-circuit current facilitates the fault detection, but is also a higher load on the equipment. Using static converters is further reducing the occurring short-circuit current.

As outlined in deliverable D10.2 [6], theoretical replacement of each DC substation with an AC substation would not require for application of any additional measure for compensating unbalance or other power quality issues. This is due to the fact that feeding sections are very small (approx. 10 km only) und number of trains being supplied is consequently also very small. Since the original time schedule remains unchanged, increased traffic is not considered. Maximum power absorbed by each substation is low and only for very limited amount of time. Therefore compliance to unbalance requirements of the grid code is given.

With increasing feeding sections and or increased traffic, load flow will be increased. This would increase the need for connection to 3AC networks or would require application of FACTS equipment. By use of static converter feeding full degree of freedom for planning is given, i.e. connection of AC substations to same 3AC grid with < 30 kV nominal voltage level would still be possible for increased traffic and feeding sections. Wherever feasible, substations should still be located to sites with access to 3AC networks with higher nominal voltages. This is due to lower cost for energy and contracted power demand. Full potential of double side feeding is leveraged by converter feeding.

14 Conclusions

It can be concluded that all objectives of In2Rail's work package 10 are achieved. Nevertheless, it has to be noted that the objectives are partially mutually exclusive. Prioritisation of goals must be made for each case individually. The following paragraphs repeat how the objectives are met.

AC power supply for electric traction is already very efficient. For most scenarios the transmission losses are lower than 1% of the power consumption in normal operating mode. Small additional reduction of transmission losses is possible in few cases, i.e. by introduction of double side feeding without static converter. Major reduction of transmission losses can be achieved by converting DC lines with up to 3 kV to AC 25 kV. Application of static converter feeding would be a realistic overall approach for this, mainly due to requirements for connection to public grid, associated investments and reduction of number of substations. Even if the introduced power electronics cause losses above those of conventional transformer feeding, overall losses will be reduced. According simulations have shown reduced losses of up to 66 % for scenario 3, which is part of "Mediterranean Corridor" in Spain.

Sizing of equipment must consider worst case conditions with individual dimensioning rules for different type of equipment. The sizing itself has to consider the thermal constants of different type of equipment. Required size can be reduced by introduction of complex feeding schemes. In scenario 1 "HSL Madrid - Seville" the worst case conditions are given for increased capacity timetable during outage of a complete substation in a mountainous region. Use of double side feeding reduces required size of transformers by 25 % in this case. Further reduction might be feasible for reducing number of transformers in each substation without significantly decreasing availability of the system. Furthermore, phase separations can be replaced by simple sectioning points.

Increasing the capacity of a line with reduced headway of trains and maximum time schedule can cause load flows that would violate the unbalance requirements for connection to public grid. In such case, additional TPS have to be introduced or existing TPS have to be connected to public grid with higher nominal voltage. Such investment can be avoided by application of balancers or static converter feeding. This ensures compliance to grid code without further investment in new overhead lines for connection to public grid.

Cost reduction depends on the country specific billing models. Mostly power quality improvements above required level for allowance to connect will not be rewarded. Penalties for reactive power flow can be avoided by use of balancer or static converter. Attention has to be paid to how power factor is metered. In case of the analysed scenarios in Spain, active energy absorption is the dominating the cost of energy. All other terms are minor. Hence, lower losses and overall lower energy absorption leads to lower cost of energy. This is clearly achieved in scenario 3 with energy cost reduction > 10 % by conversion to an AC electrified system by use of static converters.

Also double side feeding does not require introduction of phase separations for new lines, which represent a mechanical weakness in the OCL. Besides reduction of investment itself, further improvement in terms of maintenance and operations is expected. Also, trains must switch off when passing by phase separations. As switches are mechanical parts, this is causing wear and maintenance. Depending on the frequency of switching operation a replacement of a circuit breaker is needed every few years. Consequently, trains passing phase separations will be coasting for some seconds and thus losing speed. After passing the phase separation, acceleration is needed. This costs a little bit of time which can be used for other optimizations of the schedule.

Besides achievement of the given objectives, work package 10 achieved a comprehensive view on application of FACTS equipment for ETS by complex simulations of the 3AC network in combination with multi-train simulations. Open points in standards and regulations have been defined. Demonstrators will be realised in the upcoming project IN2STEMPO, thus shifting over from system study towards realisation. This also includes SMART control of rail power supply by use of IEC 61850 process bus communication for 16,7 Hz ETS.

Furthermore, the interface to the traffic management system (TMS) as well as to the maintenance management system (MMS) is specified. It represents the interface Intelligent Mobility Management (I2M), another sub-project of In2Rail, which addresses and develops a standardised integrated environment capable of supporting diverse TMS dispatching services, operational systems and MMS. The necessary data structure and communication pattern structure for the interfaces to TMS/MMS is analysed by use of the so called “Canonical Data Model”.

15 References

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