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Railway Application — Fixed Installations — Specification for reversible d.c. substations

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National foreword

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Applications ferroviaires - Installations fixes - Spécification pour sous-stations réversibles à courant continu

Bahnanwendungen - Ortsfeste Anlagen - Spezifikation rückspeisefähiger Unterwerke für Gleichstrombahnen

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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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European foreword

This document (CLC/TR 50646:2015) has been prepared by CLC/SC 9XC "Electric supply and earthing systems for public transport equipment and ancillary apparatus (Fixed installations)".

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Introduction

This document originates from the Technical Specification issued by UIC/UNIFE on the same topic, and was offered as a CENELEC Technical Report. The purpose of this Technical Report is to provide recommendations for reversible DC substations.

Reversible substations are capable of feeding the train regenerative braking energy (up to 100 %) back to the AC high voltage distribution network, while maintaining the capability of exchanging energy between trains on the DC line. A substantial amount of energy can be saved for DC systems which operate electric trains fitted with regenerative braking, on commuter services or operating on steep gradient lines. The system receptivity can be improved by feeding the excess regenerative braking energy to the upstream AC network (e.g. AC railway network or national grid) at a higher voltage level.

This document provides recommendations if DC Reversible Traction Substations are installed to improve line receptivity of DC power supply networks. This document is suitable for newly manufactured traction substations as well as for upgrading and renewal of existing lines. This technical recommendation aims at improving the energy efficiency of the DC transport system, reducing energy consumption, and contributing to a greener environment.

1 Scope

This Technical Report provides recommendations for DC reversible substations. These recommendations apply to systems and components that facilitate the flow of energy to and from the upstream AC grid including their related interfaces.

These recommendations provide the necessary functions for the recovery of braking energy. It is intended to be used in fixed electrical installations with nominal voltage not exceeding 3 000 V DC which supply electrical power to vehicles used in public guided transport systems, i.e. railway vehicles, tramway vehicles, underground vehicles and trolley-buses

It is intended to provide an overview of state-of-the-art applications, define the minimum recommendations that are presently available, and provide functional recommendations to be applied to these substations.

This document focuses mainly on the substation converters and the traction transformers. Other devices such as switchgear - if they are the same as in classic substations - are not addressed here. Moreover this specification addresses performance, constraints, validation and acceptance criteria for the implementation of reversible substations.

This document provides the minimum recommendations to be fulfilled. However, due to the different possible solutions and different types of existing technologies, this document does not provide technical specifications of the basic components that facilitate the functionalities described.

2 Normative references

The following standards, in whole or in part, are normatively referenced in this document and are essential for its application. For dated references, only the cited edition applies. For undated references the latest edition of the referenced document (including any amendment) applies.

EN 50160, *Voltage characteristics of electricity supplied by public electricity networks*

EN 50163, *Railway applications — Supply voltages of traction systems*

EN 50327, *Railway applications — Fixed installations — Harmonisation of the rated values for converter groups and tests on converter groups*

EN 50328:2003, *Railway applications — Fixed installations — Electronic power converters for substations*

EN 50329, *Railway applications — Fixed installations — Traction transformers*

EN 50388, *Railway Applications — Power supply and rolling stock — Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability*

IEC 60050, *Electropedia: The World's Online Electrotechnical Vocabulary ("IEV Online")*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purpose of this document, the terms and definitions given in IEC 60050 and the following apply.

3.1.1
contact line
conductor system for supplying electric energy to vehicles through current-collecting equipment

[SOURCE: IEC 60050-811-33-01:1991]

3.1.2
dynamic braking
use of the electrical machine of the traction unit as a generator during the braking phase in order to achieve speed reduction and thus convert the kinetic energy of the traction unit during its braking phase into electrical energy

3.1.3
electronic power converter
operative unit for power conversion comprising one or more sets of semiconductor devices

[SOURCE: IEC 60050-551-12-01:1998, modified – The definition was shortened and the Note and figure contained in the original definition are not reproduced here.]

3.1.4
minimum threshold voltage
U_{thi}
lower limit of the DC output voltage range within which Reversible Substation can work in inverter mode

3.1.5
regenerative braking energy
net energy coming from the dynamic braking and injected into the contact line

Note 1 to entry: It does not include on board losses and auxiliary load.

3.1.6
reversible substation
RSS
traction substation that allows the flow of energy from the contact line to the upstream grid (railway network or national grid)

3.1.7
semiconductor device
device whose essential characteristics are due to the flow of charge carriers within a semiconductor

[SOURCE: IEC 60050-521:2002, 521-04-01]

3.1.8
vehicle
single item of rolling stock

Note 1 to entry: Examples of a single item of rolling stock include a locomotive, a coach and a wagon.

[SOURCE: IEC 60050-811-02-02:1991]

3.2 Abbreviations

AC: Alternating Current

DC: Direct Current

EMC: Electro-Magnetic Compatibility

EMI: Electro-Magnetic Interference

IGBT: Insulated Gate Bipolar Transistor

RSS: Reversible Substation

TSI ENE: Technical Specification for Interoperability for Energy subsystem

4 General

4.1 Application of reversible substation

Existing standards provide requirements for the power supply system at the interface between traction units and fixed installations: EN 50163 for feeding voltages and frequency levels and their variations in different situations and EN 50388 for technical criteria for coordination between rolling stock and power supply to achieve interoperability.

These standards consider the aspect of vehicle regenerative braking energy that can be reused as follows:

- on-board for auxiliary devices or heating/ventilation/air-conditioning functions; the on-board demand is usually far too low to absorb all the braking power supplied;

- other trains: energy is used by other trains taking power in the vicinity. This depends on traffic density, headways, and the profile of line voltage.

In classic DC systems, if the energy is not fully recovered by the above means, the energy will be lost and dissipated into brake resistors, generally on-board, or in mechanical braking, contributing to energy waste and thermal losses. Besides being energy inefficient, if used in a confined environment (such as tunnels and underground passenger stations), it can significantly increase the temperature of that environment and affect the air quality caused by brake pad dust.

If the DC railway system is fitted with energy storage systems (on-board or trackside) and/or with reversible substations (RSS), the wasted energy can be reused or in the case of RSS, fed back into the upstream AC railway network, in the same way as that for AC electric traction systems.

The reversible substation allows the transfer of regenerative braking energy - combination of kinetic and gravity energy for steep gradient lines - to the upstream network. Furthermore, the amount of regenerative energy that is transferred is not limited by the upstream network.

The TSI ENE requires the use of traction unit regenerative braking capability as a service brake, in AC or in DC systems, to promote energy efficiency. Additionally, the interoperability billing system encourages Railway Undertakings to be charged in the future for the net energy consumption of their trains.

4.2 Energy efficiency analysis

The technical analysis of energy savings shows that the optimum use of dynamic braking on DC lines can achieve the following:

- improving the line receptivity on DC networks to nearly 100 % in normal and degraded mode as it is the case for AC power supply system,

- minimizing system losses,

- giving priority to energy exchange between vehicles,

- suppressing rheostat braking without transferring the additional load onto the mechanical braking which will reduce heat dissipation, mass and volume of on-board equipment.

Additionally, by implementing appropriate technology, balancing the loads of paralleled substations can optimize energy flow, thereby improving energy efficiency. To achieve some or all of these objectives, one of the architectures described in 4.3 should be adopted.

4.3 System architecture

Converters with power semiconductors in bridge circuits are used to convert three-phase AC to DC. They can be classified as line-commutated converters (uncontrolled or controlled type) or self-commutated converters.

Substations intended for feeding only are commonly designed as uncontrolled line-commutated converters (i.e. diode rectifier).

Beside diode rectifiers, controlled line-commutated converters and self-commutated converters can also be used for rectification purposes. Both technologies are not commonly used in today's DC substations because cost-efficiency and reliability of diode rectifiers so far exceed the advantages of these converters. However, a main advantage of these technologies is the control of DC feeding voltage which enables these types of converters to be used for load management between substations and to reduce energy losses in the contact line.

Controlled line-commutated converters and self-commutated converters can also be used for inverting purposes. However, while a single bridge self-commutated inverter is able to support energy flow in both directions (rectification and inversion), a line-commutated converter needs two anti-parallel bridges to operate.

Generally, but not exclusively, the following main converter technologies can be realized:

a) reversible substation with uncontrolled rectifier:

  1) uncontrolled rectifier and controlled inverter (diode rectifier and thyristor inverter);

  2) uncontrolled rectifier and self-commutated inverter (diode rectifier and IGBT Inverter);

b) reversible substation with controlled rectifier or self-commutated converter:

  1) controlled rectifier and controlled inverter (thyristor rectifier and thyristor inverter);

  2) controlled rectifier and self-commutated inverter (e.g. thyristor rectifier and IGBT inverter);

  3) self-commutated converter (IGBT single bridge converter).

For upgrading existing substations, where the transformer-rectifier-set is still in a good condition, options a) 1) and a) 2) above are usually the easiest technologies to deploy.

In case of new construction of substations, any of the options b) 1) to b) 3) can be taken into consideration to avoid restrictions for the inversion function (in relation to the no-load voltage of uncontrolled rectifiers).

The main advantage of b) 1) to b) 3) is to decrease the no-load voltage during inversion. This function enables the inverters to improve the collection of braking energy from different vehicles that are distributed in the system.

Options a) 2) and b) 2) allow operation of the self-commutated inverter when the rectifier is active (in parallel to the rectifier). This can be used for reactive current compensation, active filtering of harmonics or to operate as a booster during load peaks.

From the converter topology point of view, b) 3) represents a simple configuration, because one bridge allows energy flow in both directions. However, in this configuration the high thermal load of the semiconductors should be taken into account.

4.4 Braking safety

Dynamic braking is not a fail-safe system. Furthermore, dynamic braking fades away at very low speeds. Therefore, braking safety requires the installation of additional on-board mechanical brakes either to complement the dynamic brakes or to be used as a main brake to bring the train to a complete stop and also to stop in an emergency situation. Thus, there is no mandatory requirement for dynamic braking performance to provide a guaranteed safe level of stopping distance performance for rolling stock.

5 Standard performances

5.1 General recommendations

All RSS installations should be compliant with general and functional recommendations in relation to the chosen architecture.

Safety, health, environmental protection and the technical compatibility aspects should comply with the applicable standards and regulations.

5.2 Performance of the system

5.2.1 Power rating

The following standards should be used as a reference for specifying the power ratings¸ wherever suitable and as detailed in Clauses 8 and 9: EN 50327, EN 50328 and EN 50329. For controlled inverter architecture, refer to the deviations described in Clauses 8 and 9 of this document.

The converter loading and load cycles can be assessed for a given application using simulations. The simulations should consider the most severe operating conditions, e.g. minimum headway for normal operation and first-level outage mode. The rating current, overload current and short-term overload current values or other values related to a customized duty class X should be determined in relation to the results of the simulations stated above, taking into account the protection and overload capabilities provided by the converters.

In cases where more than one unit is required in the same substation, a current balancing strategy should be taken into account regarding the ratings.

5.2.2 Energy efficiency

In considering the efficiency improvement of the system, attention should be given to the efficiencies of individual components, taking into account that the energy is flowing in both directions between the contact line and the grid.

For the electronic power converters, the current state of the art allows the following minimum efficiencies to be reached:

- efficiency of substation converter > 0,97 in rectifier mode at the rated power;
- efficiency of substation converter > 0,96 in inverter mode at the maximum power of the duty cycle.

The efficiency is defined in EN 50328 and the losses to be considered are listed in EN 50328:2003, 3.3.2.

5.2.3 Harmonics and reactive power compensation

Self-commutated converters in cases a) 2) and b) 2) and 3) of 4.3 can be used for AC harmonic filtering and reactive power compensation on the AC side. In cases a) 2) and b) 2), the inverter acts as a compensator in parallel with the rectifier.

The impact of compensation functions should be taken into account in determining the power rating of the converter.

5.2.4 Additional recommendations

In the case of a fault, it is necessary to isolate the faulty converter and reconfigure the supply. For this purpose, the appropriate disconnectors should be selected. The substation should be designed to achieve selectivity in fault detection and clearing hierarchy. In case of upgrading of existing substations, the additional components should not adversely affect the existing protections selectivity.

5.2.5 Safety

The safety level of the power supply system should not be affected by the energy recovery carried out by reversible DC substations.

Safety may be demonstrated according to CLC/TS 50562.

5.2.6 Availability

The availability of the power supply system should not be affected by reversible DC substations in both power feeding and recovering modes.

6 Constraints

6.1 Climatic environment

EN 50125-2 and EN 50328 should be used as a reference. Specific conditions should be indicated per application.

6.2 Electromagnetic compatibility

EN 50121-2 and EN 50121-5 should be used as a reference.

With respect to compatibility with rolling stock, signalling equipment, and the associated power and control cables, the admissible EMC levels are also governed by local regulations.

6.3 Harmonic content

There is no standardized limit value with which every electric item would have to comply individually. Where reversible substations are directly connected to a public network, compliance with local regulations from the electricity provider is mandatory.

See also 7.3.1.

6.4 Interfaces with operational environment

6.4.1 General

Reversible DC substations should be fully compatible with other subsystems on the railway transport system.

6.4.2 Installation

Reversible DC substations should comply with the rules of safety and integration required by railway electrical substations as stated in the relevant standards.

Due to the technology using static and controlled converters with power semiconductor devices, thermal losses should be dissipated in the environment via an appropriate cooling system, adapted to the power rating of the equipment.

6.4.3 Power supply and distribution

In order to measure the energy which is sent back to the network or the grid, a bidirectional energy meter should be installed at the point of connection to the upstream grid.

Upgrading equipment of existing installations should minimize the interfaces, additional space and additional equipment. Reversible DC substations should be compatible with the adjacent substations and the rolling stock.

6.4.4 Monitoring

Monitoring and maintenance diagnostic data of reversible DC substation control equipment should be available in the substation and should allow for remote control. The following functions are recommended:

- real-time information on equipment status,
- tracking and recording of faults,
- real-time energy monitoring, normally on the AC side (e.g. Energy consumption recording with appropriate average period according to railway operator or energy provider requirements)
- data for maintenance purpose (e.g. operating hours, switching cycles),
- power quality criteria as required (e.g. harmonic distortion and power factor), see 7.3.

As an option, a real time energy diagnostic system in the Operation Control Centre can be provided to operate an energy management system to interface with the electricity provider and energy market.

6.4.5 Rolling stock

The reversible substation should be able to regenerate at braking voltage up to U_{max2} according to EN 50163, in order to cover all the braking voltage range of the rolling stock. In any case mechanical braking ensures that the safe stopping distances are respected and holds the train at standstill.

6.4.6 Operation

No specific operational interface is needed for reversible DC substations since they are autonomous.

7 Functional aspects

7.1 General

The following sections describe the functions which should be implemented in DC electric traction systems in order to optimize performance with regard to braking energy efficiency and power quality.

According to the chosen system architecture (see 4.3), a set of individual functional recommendations within the following should be selected:

a) energy regeneration;

b) power quality:

   1) harmonic compensation;

   2) reactive power optimization;

   3) substation load balancing;

c) protection functions;

d) automatic converter configuration;

e) substation control and monitoring;

f) centralized control function.

7.2 Energy regeneration

The main objective of RSS is to recover regenerative braking energy that is not absorbed by other vehicles and feed it back into the upstream distribution network. The receptivity level that can actually be reached for a given DC railway system will depend on its own characteristics and design criteria.

To comply with the energy regeneration objective:

- The recovery of energy in inverter mode should be possible between a minimum threshold voltage U_{thi} and maximum voltage U_{max2}, and should take into account the limited duration for values between U_{max1} and U_{max2}. Operating in rectifier mode is possible between no load voltage U_{d0} according to EN 50328 and U_{min1} according to EN 50163.

  For reversible substations with a controlled rectifier or self-commutated converter, it is possible to adopt $U_{thi} = U_{d0} = U_{nd}$ (nominal voltage)

- A priority should be given to energy exchange between trains (and their auxiliaries) in order to avoid capturing energy that can be utilized on the DC network.

- Circulation of energy between rectifier and inverter in the substation or between adjacent substations should be minimized.

- For a combination of controlled rectifier and inverter, it is recommended that voltage settings are adjusted dynamically in real time to respond to rapid changes in power flow and avoid any traction and braking gaps.

Transitions between rectifier mode and inverter mode should be sufficiently fast, and without hysteresis, in order not to affect the electric braking performance of the trains.

Acceptance criteria:

These criteria will be determined for each individual system in terms of energy saving and will be verified by means of simulations in normal conditions. Where appropriate, normalized drive cycles as defined in CLC/TS 50591 may be used in the simulations.

7.3 Power quality

7.3.1 General

The quality of the traction voltage should comply with EN 50163.

Power factor and harmonics criteria should comply with the requirements of the energy provider and EN 61000-2-12 and EN 61000-2-4. Additional improvements may be provided according to the system architecture used for reversible substation to improve the interfaces with the electricity provider, this includes:

- The output currents for adjacent substations can be controlled individually to avoid unbalanced loads, uncontrolled overloads and additional losses.

- Primary network voltage fluctuations do not affect the voltage setting ranges of the inverter and rectifier. Therefore they can be optimized independently from the primary voltage.

- Harmonic compensation for compliance with EMC/EMI (Electromagnetic compatibility/Electromagnetic interference) standards and harmonic content of energy supply / feedback towards the electricity provider.

7.3.2 Substation voltage and load balancing

This functionality applies to system architectures with line voltage control capabilities as b) 1) to b) 3), described in 4.3, which enables:

- The regulation of output voltage on the DC side can be achieved up to the normal substation load with compensation of the primary voltage fluctuations of +10 %,-10 % according to EN 50160.
- The load balance between adjacent substations is controlled dynamically, both in rectifier mode and in inverter mode.
- Better control of the line voltage for under-voltage and over-voltage conditions,
- An expanded energy recovery voltage ranging from U_{n} to U_{max2} according to EN 50163, and therefore enhanced efficiency of energy recovery.
- The possibility to expand feeding sections
- The possibility to balance and limit the overload in each of the substations by better current distribution in both normal and degraded operation of the power supply network, thereby minimizing losses.

Acceptance criteria will be determined for each system individually in terms of balancing and reducing peak loads and will be verified by means of simulations in normal conditions as described in 8.3.

7.3.3 Harmonic compensation

Static converters generate harmonics that penetrate the upstream distribution network.

These harmonics can be minimized, if necessary, by passive filters, 12 or 24 pulse arrangement of rectifiers, active filtering or by using self-commutated converters to achieve conformity with the reference regulations and standards.

Acceptance criteria should include compliance with local regulations provided by the electricity provider. Measurements and tests should be according to the EN 61000-4 series.

7.3.4 Reactive power optimization

Self-commutated converters are able to improve the power factor of the installation by drawing current in phase with input voltage thus minimizing the reactive power and overall energy consumption.

Depending on the system requirements, the reversible substation may provide inductive or capacitive power for compensation to the medium voltage power grid. Should this function be implemented, then the impact on the power rating of the converter should be addressed.

Acceptance criteria should include compliance of the power factor with the requirements of the specification of the electricity provider. A recommendation for each single substation simulation is described in 8.2.

7.4 Protection functions

Some specific active protection functions can be achieved by controlled converters. Reversible substation design should take these functions into account and integrate them in order to increase the level of system availability and reliability. These protection functions are the following:

- thermal protection (by controlling the load levels);
- protection against external over-voltage conditions: design will include the activation of the inverter to limit short-duration over-voltage conditions on the DC side;
- protection (supplementary functionality) in case of DC short-circuits. (applicable to thyristor rectifier);

- protection (supplementary functionality) in case of AC short-circuits. (applicable to controlled inverter);
- protection against $\Delta i/\Delta t$ and $\Delta V/\Delta t$ and ground fault;
- management of internal faults and alarms (temperature, loss of a converter arm, tripping of the semiconductor device protection units, etc.).

Selectivity should be provided with the substation upstream and downstream protections.

The above functionalities would enable a fuse-less substation design which is a preferred trend for controlled rectifier substations.

Information related to these protection functionalities (statuses, faults, alarms) should be available at the RSS control and monitoring system for further interface with the remote control centre.

The acceptance criteria should be a protection selectivity analysis.

A supplementary criterion can consist of a practical protection test in similar conditions as that for the short circuit type test specified in EN 50327 (if applicable to the protection function and converter technology).

7.5 Automatic converter configuration

The operation of the converter should be autonomous, with automatic configurations/reconfigurations, and isolation in the case of fault, thereby minimizing power interruptions to the line.

The voltage settings of the converter permit the energy regeneration according to 7.2 to be achieved.

The dynamic settings of the controlled converter of each RSS should be capable of communication with the Centralized Control Function described in 7.7 in order to optimize the system performance.

A history log of the faults and sequences should be available in an event recorder of the converter.

As an acceptance criterion, the availability of the power supply system should not be affected by reversible DC substations.

7.6 Substation control and monitoring

The reversible substation should have the following functions and facilities:

- by-passing to allow electrical continuity between adjacent substations in case the RSS is out of service,
- ventilation,
- line test,
- emergency shutdown,
- fire detection,
- fault and data remote reporting
- real time energy monitoring (see 6.4.4).

Automatic switching sequences of the converter (see 7.5) should be achieved as part of the converter control or as part of the substation control.

7.7 Centralized control function

The centralized control function is an option to manage the energy functions of the substations at a system level including reversible substations.

Information (status, faults, alarms, etc.) about both AC part and DC part of the substation should be reported to the remote control centre.

The RSS should enable the control centre to fulfil the following roles:

1) supervise each electric equipment item in the installation (substation equipment and high voltage equipment);

2) show the functional status of each apparatus (auxiliary devices, temperature, etc.);

3) authorize local control modes e.g. start-up;

4) retrieve measurements, e.g. for energy monitoring and management;

5) remotely control and monitor the installation, e.g. automatic setting point control or/and substation configuration according to energy saving requirements;

6) provide records: history logs, data logging, etc.;

7) schedule maintenance operations.

8 System simulation and equipment sizing

8.1 General

This clause specifies a process for carrying out power supply simulations when developing a project involving reversible substations.

The tool to carry out these simulations is a multi-train type and allows load flow calculations. It is based on the time step principle and also allows for traction electrical network modelling. It should be adapted to the various setting strategies of both the inverter (input current versus DC line voltage) and the rectifier characteristics.

Various operational situations should be simulated, considering:

- the various headways of the working timetable with its main factors e. g. the various headways and train configurations;

- the failure modes of each type of equipment, rectifier or inverter depending on the design criteria (see 8.3 below).

The situations to be selected for simulation will serve the following two purposes:

- evaluating the amount of energy that can be saved by implementing reversible DC substations,

- fixing the suitable ratings of transformer, rectifier and inverter equipment, for permanent and overload conditions.

The main task is to find an adequate power rating (regarding continuous and peak power) for the inverter including the traction transformers to achieve significant energy saving by an appropriate investment in additional equipment at selected sites.

The considerations regarding power rating should include the DC traction power supply on the whole, and should not be limited to the specific substation. In general, the following approaches are possible:

a) arrangement of various reversible substations with smaller power rating of the inverter path;

b) arrangement of fewer reversible substations with higher power rating of the inverter path;

c) application of an inverter path with appropriate power rating in each substation.

The approach c) belongs to a DC railway systems where the receptivity is required to be close to 100 %. For instance trains without braking resistors, which should ensure that the electric service brake of the trains is available.

8.2 Energy consumption computation

Energy balance computation should be carried out at the connection point to the upstream network, taking into account the power demands of trains, including auxiliary devices, the braking power exchanged by trains and net regenerated, and the various losses of the traction network components.

Two series of computations should be carried out and compared:

- a basic scenario involving standard substations;
- an alternative scenario involving reversible DC substations.

Input data could be modified according to the applied service patterns (i.e. headways, trains load, driving style, commercial speed, variations of dwell times and on-board auxiliary power) to reflect as far as possible the average daily and annual operational conditions.

The amount of energy should be determined according to the headway and durations of working days and holiday periods, to enable the assessment of energy consumption on a yearly basis.

The added value of the reversible substation technology is assessed by the difference between the net annual energy consumption computed for both scenarios.

8.3 Rating of equipment

Ratings of equipment should be defined according to permanent load, short duration and long duration overload according to EN 50328 and EN 50329, either applying a standardized duty class or a customized class X.

Ratings of equipment may be determined according to the following recommendations:

a) Rectifiers are sized such that they should support minimum operational headway, appropriate train loading and driving style. The outage condition of each rectifier should be considered individually.

b) The sizing of inverters equipment is optimized by an iterative process which involves changing the headway and considering the operating conditions.

   Different design criteria can be applied according to the receptivity target.

   1) Full receptivity target (e.g. removing of brake resistors on board trains):

      In this case, failure modes of the inverters should be included in the sizing.

   2) Optimized energy efficiency:

      Failure modes may be included as far as possible in the sizing. However, thermal protection may limit the recovered energy, and therefore decrease the receptivity of the line in the area of faulty equipment. A trade-off between equipment sizing and the impact of inverter failures on the energy efficiency can be considered.

c) Equipment common to rectifiers and inverters, such as the main transformer, should be sized according to a combined cycle of rectification and inversion. This should be carried out using an iterative process to determine the worst case.

d) Short circuit conditions should be determined and equipment such as DC circuit breakers should be rated according to EN 50123-2.

Additional parameters such as losses, line voltages, rail to earth maximum voltage, etc. should also be determined in the simulation.

9 Further standardization needs

Standards series EN 50327, EN 50328, EN 50329 specify the conditions for rating and tests of traction transformer, traction converter, as well as the testing of the converter group. They are oriented specifically to the diode rectifier group.

The technology of reversible DC substations can employ a combination of the following equipment and functionalities:

- controlled rectifier;
- anti-parallel inverter;
- passive filter components;
- four-quadrant converters;
- different classes of power semiconductors influencing the efficiencies of equipment;
- technologies of cooling;
- active filtering;
- harmonic compensation;
- reactive power compensation.

These elements will considerably change the behaviour and performance, including equipment ratings, of the substations. As such, the existing standards shown above cannot always be applied.

It will be the responsibility of the substation provider to demonstrate that the performances are suitable and meet the needs of the customer.

However, there are further tasks to specify the following (not exhaustive):

- rating criteria for recovery of energy and relevant ratings of inverters (taking into account specific power flow of the inverters, which by nature consist of only pulses, but with high peaks);
- performance in terms of harmonic compensation (European harmonized requirements);
- performance in terms of reactive power compensation (European harmonized values);
- performance tests at different load levels of the converter group;
- performance tests for different modes: traction, regeneration;
- dynamic transition tests between different modes and response time measurements;

- voltage dynamic setting tests between traction mode and recovery mode;
- noise level and auxiliary power consumption measurements at different load levels.

In advance of these changes being implemented, it is suggested that manufacturers and purchasers agree on the additional tests that should be performed on these new elements which are not covered so far by the standards.

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