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IMPACT OF INNOVATION TECHNOLOGY ON COMPLEX SYSTEMS: THE ELECTRIFIED RAILWAY SUPPLY SYSTEM

di
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TESI DI DOTTORATO DI RICERCA IN INGEGNERIA ELETTRICA
XVII CICLO
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Napoli Italy
November 2004

To Davide

To my parents and my sisters

“All human knowledge thus begins with intuitions,
proceeds thence to concepts
and ends with ideas."

Immanuel Kant

INTRODUZIONE

I sistemi di trasporto elettrificato sono sistemi complessi e rappresentano una realtà in continua evoluzione. L'innovazione che caratterizza i sistemi informativi e la tecnologia dei vari componenti si traduce in nuove opportunità per l'integrazione dei sistemi di trazione e la loro ottimizzazione.

L'introduzione, inoltre, della liberalizzazione del mercato dell'energia elettrica richiede di analizzare nuovamente la pianificazione e i criteri di funzionamento delle aziende operanti nella trazione elettrica. In tale contesto la massiccia introduzione dell'elettronica di potenza e delle tecniche di automazione e controllo deve essere presa in considerazione in maniera opportuna consentendo di fronteggiare i problemi complessi nella moderna ottica di approccio integrato.

Più in particolare il sistema di alimentazione del trasporto elettrificato può essere visto, a sua volta, come un sistema complesso caratterizzato da un elevato grado di integrazione funzionale dei vari sottosistemi e da un alto livello di integrazione tecnologica.

In questo contesto, l'aspetto legato alla Power Quality rappresenta uno dei parametri più critici che riguardano la corretta funzionalità del sistema di elettrificazione ferroviario potendo compromettere la sicurezza dell'intero sistema. D'altro canto oggi c'è la tendenza ad assicurare, come standard di sicurezza, la compatibilità elettromagnetica rispetto alle sorgenti armoniche. Naturalmente la Power Quality influenza l'affidabilità del sistema a causa della sua incidenza sul tasso di guasto dei componenti, malfunzionamento dei sistemi di segnalamento, degrado delle prestazioni del sistema etc.

Deve essere sottolineato che le metodologie tradizionali mostrano alcune difficoltà nell'analisi dei problemi di Power Quality con riferimento all'integrazione di sottosistemi ed all'identificazione della configurazione ottimale di sistema.

Pertanto, un'adeguata caratterizzazione del sistema richiede una modellazione dettagliata rispetto ai problemi di Power Quality ed avanzate tecniche di progetto in grado di garantire la robustezza del sistema contro le condizioni critiche, assicurando le prestazioni richieste.

Nel presente lavoro, è stato trattato il problema dell'integrazione tecnologica dei sistemi di alimentazione ed il suo impatto sulla Power Quality. Dal momento che molti paesi europei stanno adottando il sistema di trazione in corrente alternata, integrandolo con il tradizionale sistema di trazione in corrente continua, è necessario prestare particolare attenzione al problema dell'integrazione tra i sistemi di trazione eserciti in alternata ed in continua ed alla loro interazione col sistema di alimentazione trifase.

Un contributo originale è stato apportato, con riferimento alla modellazione del sistema per l'analisi della Power Quality, proponendo un metodo probabilistico ibrido che comprende modelli nel dominio del tempo e nel dominio della frequenza. Inoltre, come soluzione avanzata per la risoluzione dei problemi di Power Quality emersi dall'interazione dei vari sistemi di trazione, è stata proposta una nuova strategia di controllo di compensatori statici per il miglioramento della qualità.

La tesi è articolata in quattro capitoli.

Nel primo capitolo è presentato il sistema ferroviario come sistema complesso, con una breve descrizione dei vari sottosistemi che lo compongono e, successivamente, sono stati introdotti i concetti di integrazione funzionale e tecnologica.

Nel capitolo II sono considerati i problemi di Power Quality relativi all'integrazione tecnologica dei sistemi ferroviari. In esso è presentata l'analisi dei disturbi di Power Quality con un metodo probabilistico e sono riportate applicazioni numeriche relative a sistemi ferroviari reali.

Nel capitolo III è presentato il dispositivo per la compensazione dei disturbi e sono riportate delle applicazioni numeriche.

Infine, il capitolo IV è dedicato alle conclusioni.

CONTENTS

INTRODUCTION

Electrified transportation systems are complex systems representing a reality in continuous evolution. Innovation in information and component technology results in new opportunities of integration and standardization for railway systems. Furthermore the advent of the deregulated energy market requires to reinvestigate the planning and operating criteria for railway companies. In this context the massive introduction of power electronics, automation and control techniques has to be properly taken into account, allowing to handle these complex problems in a proper way according to the modern point of view of an integrated approach.

More specifically the electrified transportation supply systems can be regarded as complex systems characterized by high degree of integration of various subsystems and innovation technology.

In this context, the Power Quality aspect is one of the most critical parameters affecting the functionality of the supply system which can compromise the safety of the overall system. Furthermore, there is a tendency to ensure, as safety standard, the electromagnetic compatibility with respect to harmonic sources. Naturally, Power Quality affects the system reliability because of its incidence on hazard rate of components, misoperation of signalling system, degradation of system performance, etc. and this correlation is a very crucial aspect.

Let us underline that the traditional methodologies show some difficulties in facing Power Quality problems related to the subsystems integration and to the identification of the optimal system configuration.

Then, a proper characterization of the system requires both a detailed modelling with respect to the Power Quality problems and advanced design techniques able to guarantee the robustness of the system against critical conditions, ensuring the required performances.

In the thesis, the problem of technological integration of railway supply systems and its impact on Power Quality have been treated. Since the AC traction systems are more and more used throughout Europe, being integrated with the traditional DC ones, particular attention has been paid to model the Power Quality problems produced by the integration among AC traction systems, the DC ones and the three phase supply system.

In particular, a novel contribution has been given in the Power Quality modelling by proposing a probabilistic hybrid method which properly handles time and frequency domains.

Then a two-phase inverter with a non-linear and variable structure control system is proposed as advanced solution to the PQ disturbances related to the integration of traction systems.

The thesis consists of three chapters.

Chapter I presents the electrified railway as a complex system with a brief description of its subsystems; successively, the concepts of functional and technological integration are introduced.

The Power Quality problems related to the technological integration of railway systems are considered in *chapter II* which includes the analysis of PQ perturbations by means of a hybrid probabilistic method and simulation results on actual railway systems.

The compensation device for the PQ disturbances solution with some numerical applications are presented in *chapter III*.

Finally, the conclusions are presented in *chapter IV*.

CHAPTER I

ELECTRIFIED RAILWAYS AS COMPLEX SYSTEMS

Electrified Railway Systems are very complex systems in which a variety of components (or subsystems) cooperate to realize the transport service for which the system has been designed.

A railway system is perhaps one of the most critical real systems, from the safety and reliability viewpoint, because it must satisfy numerous requirements and presents complex architectural links among its various subsystems. In fact, a lot of safety requirements are strongly dependent on correct interaction operation.

The performance of this kind of systems strictly depends on the capability of the system to be correctly integrated. A correct approach to the analysis of traction systems is the fundamental starting point for the right design and functionality of this complex reality.

In this chapter, after a brief recall of component subsystems characterizing a railway with particular reference to the traction supply systems, an introduction to the concepts of functional and technological integrations is proposed and an approach to the complex systems analysis is, then, described.

1.1 THE ELECTRIFIED RAILWAY SYSTEM

The electrified railway system shows a heterogeneous nature, since it can be considered as a collection of subsystems (Fig.I.1). These subsystems can be listed as follows:

- Rolling stock
- Supply
- Infrastructure
- Signalling
- On board systems
- Control centres
- Telecommunication systems

Naturally, each subsystem is not composed by simple components, being it structured according to a complex architecture which ensures an assigned set of functions. This requires, both in design and in operation stage, particular attention to the examination of the various functional aspects, using a systemic approach.

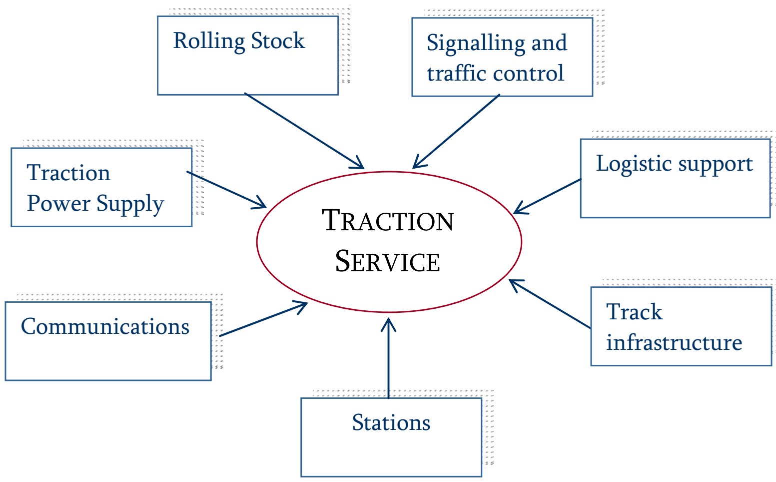


Fig.I.1 Railway Subsystems

Basically, a railway electrification system should provide power to a moving train locomotive. The power is delivered from a utility substation (fed by the High Voltage supply node) to the locomotive through the catenary.

The *trains* circulating in a traction line represent particular electrical loads being characterized by a time varying nature due to the different phases of the motion (start up, operating and braking conditions), to the different positions and to the different number of trains circulating contemporaneously during daily hours on the railway line.

The power demand of the traction systems depend on the kind of train service requirements such as light rails, commuter trains, high speed trains, freight trains. The typical power demand for each of the classified railway traction systems is represented in Tab. 1 [I.1].

RAIL SYSTEMS	*POWER DEMAND*
Light Rail	<1 MW
Commuter trains	≈ 3-4 MW
High Speed Inter-city rails	≈ 4-6 MW
Very Fast Commuter Trains (TGV)	≈ 8-10 MW
Freight Trains (in Europe)	≈ 6-10 MW
Freight Trains (in USA)	> 18-24 MW

Tab I.1 Rail Systems and their Power Demands

Light Rail train is characterized by a high frequency of stops (each 1or 2 kilometres). These trains, generally used for metro transit, can be fed from DC systems and require a very low power (less than 1 MW).

Commuter Trains generally serve suburban areas requiring a higher power (3-4 MW). The distance between stops is, on average, 10 kilometres.

High Speed Intercity Rails connect different cities in a country. They are characterized by quite high distances between stops and higher speeds. The power demand is about 4-6 MW.

Very Fast Commuter Trains represent the future generation. The fastest in the world is the French TGV which reaches about 450 kilometres per hour speed. Due to the very high speed the power demand is about 8-10 MW.

Freight Trains are slower than the preceding ones but require a quite high power.

The evolution in electrical traction systems has produced a variety of electrification systems inspired to very different principles [I.2-3]. At the moment several kinds of Railway Traction Electric Power Systems exist in Europe:

- DC systems (750/1500/3000 V)
- Medium voltage AC systems (15/25 kV, 50/60 Hz)
- High voltage AC systems (50/2x25 kV, 50 Hz)
- Low frequency systems (15 kV, 15-$16^{2/3}$ Hz)

The low voltage DC system is used for light rails usually supplied at 750 Volts (metro transit) and for commuter and intercity trains usually supplied at 3000 Volts (which is the case of the traditional Italian traction system).

The medium voltage AC system was adopted in order to reduce voltage losses. The 25 kV system was practically born in France and had great development in USA, UK, Russia and several other countries thanks to the various advantages it offered such as the simplicity of substations and of single contact wires. It is typically used for commuter trains or freight trains.

The high voltage AC systems are the 50 kV and 2x25 kV (or ±25kV) ones. The 50 kV system, adopted in USA and in South Africa, exalts the economical advantages of the medium voltage systems. The system has been used where the traction load is high and the traction distances are large. Typically it can be used for traction in rural areas and may be difficult in urban areas for the insulation requirements.

However, medium and high voltage single-phase alternating current supply of the typical AC electrified railway has always involved several problems owing to the relevant power of intrinsically single-phase traction loads, which produce unbalanced in the three-phase section and the subsequent generation of voltage unbalances within the primary grid (in chapter II a detailed description of these problems has been performed).

The low frequency systems were used in order to reduce the problems related to the use of the single phase commutator motor which presented some inconvenience at the start up of the machine due to the transforming electromotive force [I.4]. This inconvenience is tolerable at low frequencies. The choice of the so called 'railway frequency' ($16^{2/3}$ Hz) was made with reference to the frequency ratio (input/output) of the synchronous motor/alternator groups present in the substations. This ratio, equal to 1/3, has led the adoption of the frequencies of $16^{2/3}$ Hz (in the countries using 50 Hz industrial frequency) and 20 Hz (in countries with 60 Hz industrial frequency). USA was the only country where an already available frequency could be used that was the 25 Hz frequency [I.1].

The electrical substations play the role of handling the electrical energy supplied by AC transmission network (transforming, sharing out and converting sections).

The substation schemes differ according to the kind of traction line they feed, the train load, the number of tracks being fed by the substation, etc. The distance between the various substations depends on the train electrification system and on the traction load power. Generally there are two incoming tracks and two outgoing tracks to be fed at each substation unless it is a junction substation. The substation scheme is different according to whether it is an AC substation or a DC one. A brief description of both will follow on section 1.1.1 and 1.1.2.

As far as concerns the *Catenary functioning*, an electric railway takes its power for the electric motors, lights, air conditioning, etc., from the overhead line using the pantograph on the roof. The pantograph is in constant contact with the overhead line (contact wire) located about 5 m above the rails, whether the train is moving or not. Therefore, the overhead line must always be located within the pantograph range, and the pantograph must always maintain contact with the overhead line in order to supply uninterrupted, good-quality power at all times.

The *Signalling* system has two basic functions [I.5]:

- Protection
- Control

The first is the function to maintain a safe distance between trains circulating on the same track; the second is devolved to regulate the passage of trains according to the published schedule and necessary speed in order to safeguard movements at track intersections and junctions. The practical implementation of railway signalling is linked to the detection of the position and speed of the trains and to the transmission of data between control centres and vehicles. Moreover an overall supervision is necessary in order to guarantee the running of the railway according to the timetable and with the minimum human intervention.

The supervision and control realized by *Control Centres* and *Telecommunication Systems* thanks to the big development of the applications of electronics and computers, have the main rule in the development of these important functions [I.6-7].

To give an idea of the control function it is interesting to refer to a driverless metro which is a completely automated transport system, whose component subsystems are the following:

1. *ATC* (Automatic Train Control) formed by
   - ATP (Automatic Train Protection)
   - ATO (Automatic Train Operation)
   - ATS (Automatic Train Supervision)
2. *CCU* (Central Control Unit)
3. *SCADA* (System Control And Data Acquisition)
4. *PS&IS* (Passenger Security & Information System)
   - *OBS* (On Board System)
5. *EDP* (Electronic Data Processing)
6. Communication System

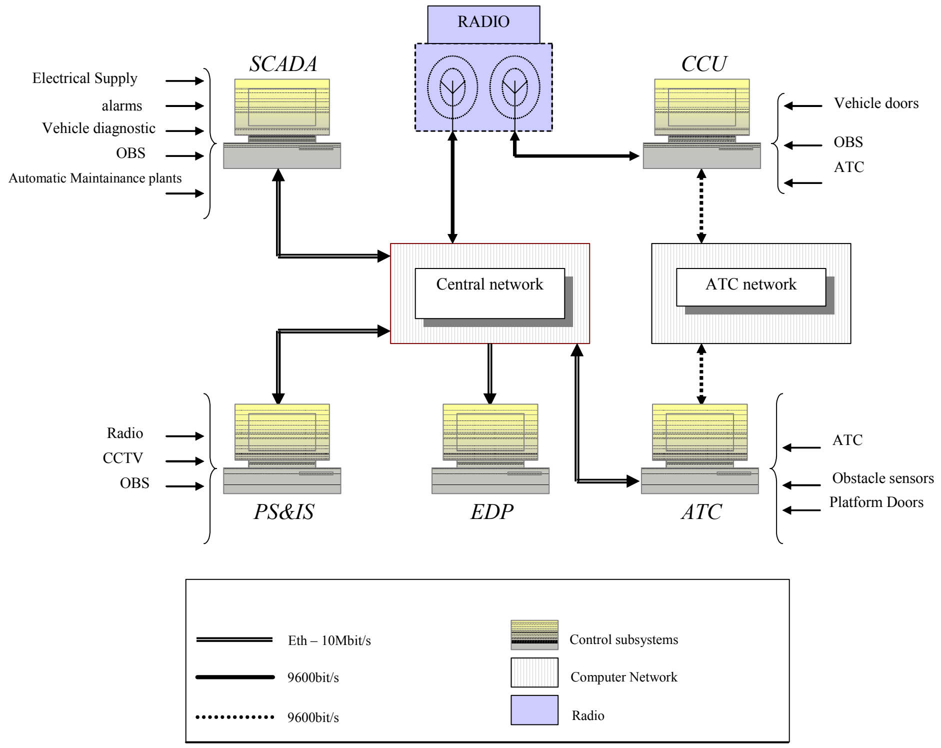


Fig I.2 Integrated system of a driverless metro

With reference to the first point, in the case of a driverless metro, the **A**utomatic **T**rain **C**ontrol, is formed by three different subsystems: ATO (**A**utomatic **T**rain **O**peration), ATP (**A**utomatic **T**rain **P**rotection) and ATS (**A**utomatic **T**rain **S**upervision). The ATS is located in the Control Centre while the first two are on the vehicle, along the track line and in the Centre.

The ATO functions are the vehicle gear control, the stop in the stations or in the depot, the door command, the vehicle interconnection, the path selection, correct functioning checks and the on-board system monitoring.

The ATP deals with the safety system operations (e.g. activating the emergency braking).

The ATS can be considered as a supervision system, it controls the train arrivals and departures in each station. Its functions include the automatic itineraries management, the timetable control, statistical data collection, the graphical march representation.

The CCU (Central Control Unit) is the vehicle logic. It acts on the basis of the ATC commands (or by the commands given by the train driver) and develops such activities as acceleration, maximum speed, auxiliary service device insertion, faulted devices exclusion, etc...

The SCADA (**S**upervision **C**ontrol **A**nd **D**ata **A**cquisition) centralizes the supervision and control of the several subsystems present in the control centre and in the peripheral stations, acquiring tele-controls and tele-meterings and sending tele-commands.

The PS&IS (**P**assenger **S**ecurity & **I**nformation **S**ystem) guarantees the maximum safety degree and an accurate and constant information service to the users. Particular importance have the OBSs (**O**n **B**oard **S**ystems) having the task of collecting and transmitting important messages to the users.

The EDP (**E**lectronic **D**ata **P**rocessing) subsystems deal with the control and management of economical information and of the operating conditions.

The Communication System, finally, allows the information exchange between subsystems and it can use fixed networks or radio transmissions. Usually the track circuit or the contact wire can be used as telecommunication support.

After this general description of the traction subsystems, a brief description of the AC and DC supply systems will follow in the next sections.

1.1.1 The AC Electrified Railway System

As well known, the AC electrified railway systems have assumed a growing importance due to the great advantages related to the reduced number of installed electric substations and improved efficiency by the employment of higher supply voltages with consequent lower currents. The most used AC electrification systems are the 25 kV- 50 Hz and the 2x25 kV-50 Hz that will be used in Italy for the high speed railway.

The typical AC feeding systems on the traction side are the ‘boost transformer scheme’ and the ‘auto transformer scheme’ represented respectively in fig. I.3 and fig. I.4.

In the former, one of the power transformer winding ends is earthed whereas the other one is connected to the catenary wire. In the latter the traction winding is connected to earth on its midpoint and the two other ends of the winding are connected to the catenary wire and the feeder wire respectively.

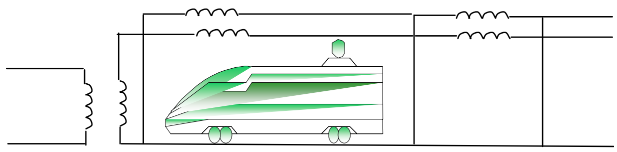


Fig. I.3 The booster transformer scheme

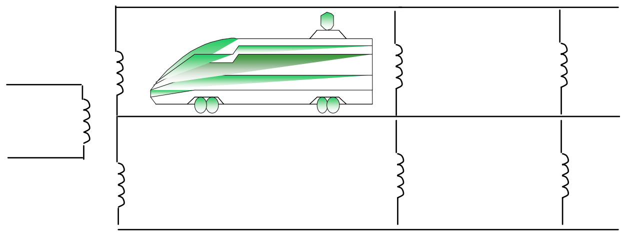


Fig. I.4 The auto transformer scheme

The 2x25 kV 50 Hz system, used in Europe, is formed by the main transformer with the secondary winding at 50 kV, having the central terminal connected to the track and the extreme terminals (conventionally indicated as + 25 kV – 25 kV) connected respectively to the contact wire and the feeder [I.8]. The simplified scheme of the system is represented in figure I.5.

The figure shows the optimal current flows in the case of three cells (cell= section between two autotransformers) and with the train located in the middle of the third cell. In this situation the load is fed by the two adjacent autotransformers in equal measure.

In the first two cells the track current is zero while in the contact wire and in the feeder the currents are equal but opposite in sign and their value is equal to half the locomotive absorbed current. In this situation, the train load produces interference only in the occupied cell (the third one).

In the Italian system the distance between substations is 50 kilometres and the power installed in each substation is 2x60 MVA.

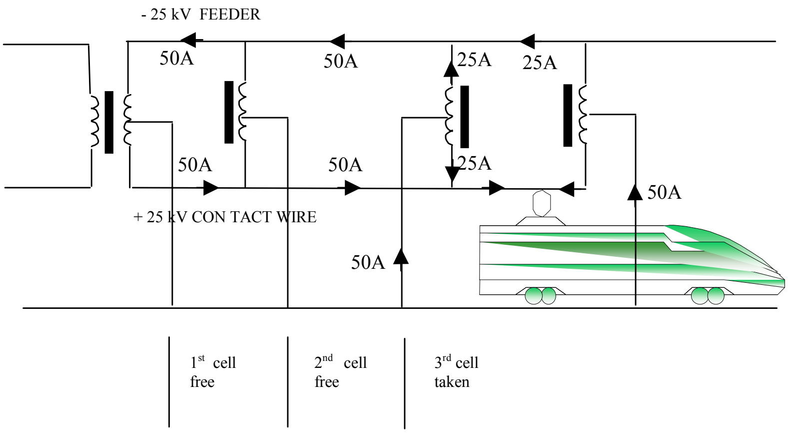


Fig. I.5 The 2x25 kV 50 Hz scheme

The primary substation level is at 150 (or 132) kV; at the secondary one there are, as well known, the contact wire at +25 kV and the feeder at – 25 kV. By each terminal of the feeder a single phase transformer is derived (25000/240 V, 50 kVA) for the substation services supply. The auxiliary services are fed by one of these two transformers.

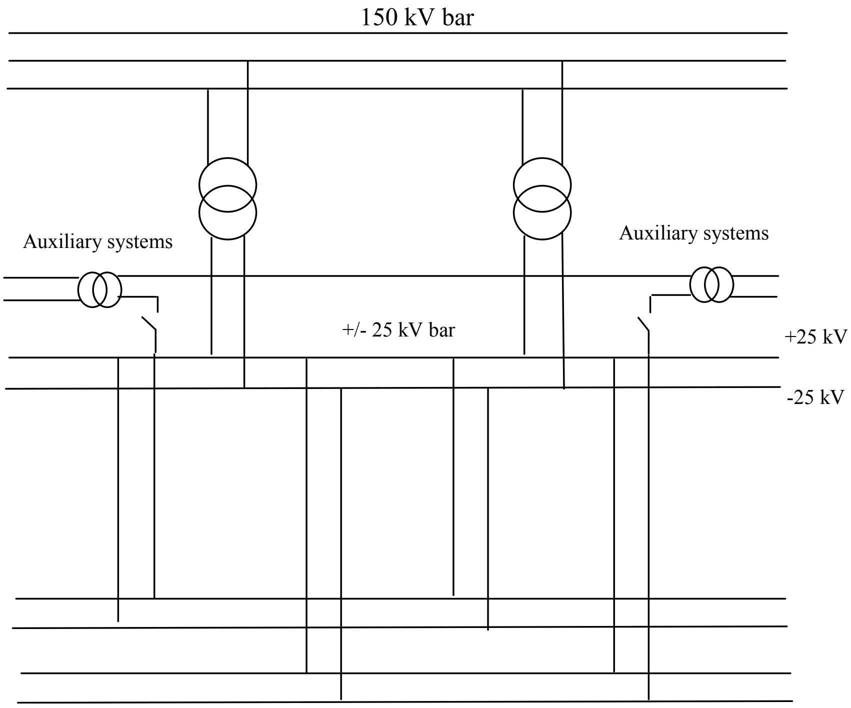


Fig. I.6 2x25 kV 50 Hz Italian substation simplified scheme

1.1.2 The DC Electrified Railway System

The advantages of the DC systems are related to the minimization of line voltage drops (this reduction can be obtained by increasing the contact wire section), the minimization of the total power installed in the substations since they can operate in parallel configuration (thanks to the capability of the rectifier bridges to avoid the circulation of leakage currents) and the bilateral supply of the tracks situated between two substations, with reduction of voltage drops and line losses [I.9].

A DC substation derives AC High Voltage energy from one ore more supply nodes. Then it converts the voltage to a suitable level for feeding the contact wires. There are rectifying units to convert the AC to DC and delivery systems to the different fed lines. The feeding voltage of the DC substations can be 66, 132 or 150 kV. A direct-current feeding system features a three-phase bridged silicon rectifier for conversion from alternating to direct current. In order to reduce the harmonics, a more-modern rectifier design using a 12-pulse system featuring two sets of 6-pulse rectifying circuits is used.

A typical electrical DC substation scheme is represented in figure I.7.

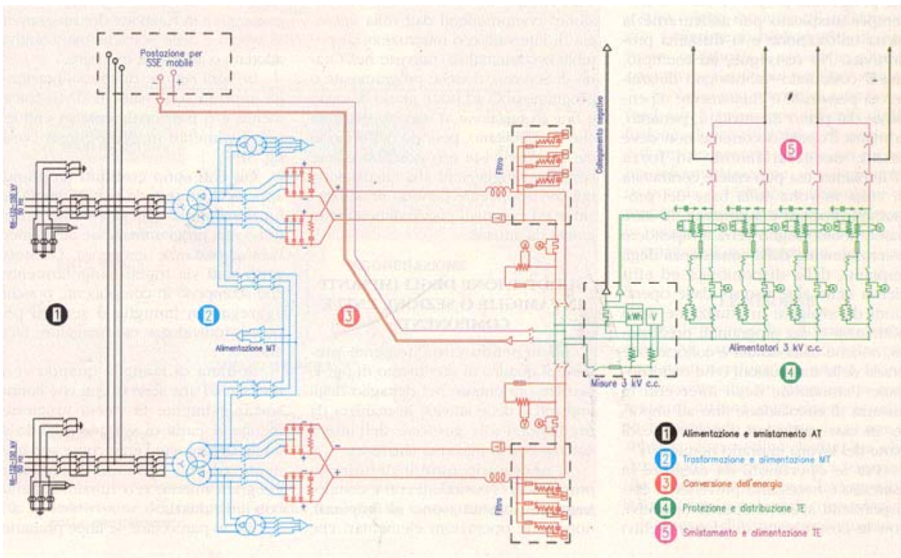


Fig.I.7 DC Substation scheme

The electrical equipments of a DC substation can be classified according to their operating voltage level, hence, in three groups:

1. HV section (equipments located between supply and transformers)
2. 3 kV section (equipments located between the transformers and the outputs for the contact wires)
3. LV section (auxiliary services, commands, controls, measurements…).

Basically, in a DC substation, the following sections are identified:

1. HV supply
2. Transformer and MV supply
3. Converter
4. Protection and Distribution
5. Supervision and remote control
6. Ground systems

1.2 Functional Integration

Modern transportation systems need an efficient connection and cooperation between subsystems. In particular the development of Information Technology has given the opportunity of obtaining integrated complex systems.

Two systems are integrated when each exchanges with the other its functionalities so that they, together, can realize more articulated functions (compound functions) [I.10]. The main requirement of these systems is that they have to be interfaced, having solved all possible logical or physical conflicts.

A typical case of integration is the one that can be realized between control subsystems. In order to have a system with a high reliability level, an adequate degree of integration is required.

Each control subsystem is designed to absolve autonomously to a certain number of tasks related to the control of other subsystems (called 'controlled subsystems') which are characterized by a logic of limited potentialities or which are characterized by no logic at all.

The term autonomously means that the subsystem does not depend on another subsystem in performing its tasks. Actually, this subsystem, provided with opportune interfaces, interacts with both the controlled subsystems (by means of measurement instruments etc.) and the human control (by means of buttons, displays etc.).

The interaction with humans is not always needed as it happens with the automatic control of certain conditions (for instance itineraries control).

In some other cases, instead, a subsystem, although it is provided with a well programmed logic, needs the presence of an 'expert' able to drive it in the functions where the human logic flexibility is needed.

On the basis of these last considerations, it is possible to give some definitions.

In a complex system there are

- Simple tasks
- Compound tasks

The former are the tasks for which the subsystem has been designed. These tasks can or can not include the human presence.

The compound tasks are not performable by means of only one control subsystem unless this last is continuously controlled by one or more operators.

Therefore, considering two control subsystems *X* and *Y*, called *{a, b, c, d, ...}* the X simple tasks and *{p, q, r, s, ...}* the Y simple tasks, the compound tasks will be the ones that, in order to absolve to their own tasks, need the development of, at least, one task of both the two subsystems.

During the last years the world of Electrified transport systems has been characterized by a constant increment of service performances and automation levels but it still has to be improved in terms of subsystem integration.

In particular in the design of traction systems there is a tendency to increment the integration levels but the use of modern advanced technologies for the technical performance increment means a decrement of simplicity and reliability.

The functional integration of a complex system gives great advantages as well as some problems related to the reliability of the system. In fact, on one side a high level of integration involves an increase of system performances, whereas, on the other side, it determines a reduction of simplicity and reliability.

So, an important question arises: how much should a system be integrated in order to obtain a global advantage? This problem becomes very complex because the scenario is characterized by high level of uncertainty.

In section I.4 the problem of the identification of the optimal integration degree is considered.

1.3 Technological Integration

The technological integration can be considered as a specific part of the functional one. In fact, one of the most critical problems related with the functional integration is the interfacing of two subsystems characterized by different technologies. A typical case of technological integration is given when it is necessary to integrate new technologies in already existing systems.

In order to gain the required qualitative and quantitative performances, it is necessary to interface the subsystem in an optimized way both by the functionality and by the performance point of view;

Two control sub-systems are interfaced (into a system) when all logical and physical conflicts that can hinder the correct functionality or can limit the use of the respective functional potentialities, are solved. In particular, two subsystems can have interoperability problems due to

- the semantic or the syntax of the exchanged information,
- the characteristics of the so called ‘physical level’ (e.g. cables and connectors).

Then, the first problem to be solved is the *compatibility* finalized to the *interfacing*. For this purpose, two kinds of interfacing should be distinguished:

- Logical interfacing
- Physical interfacing

The former regards the information exchange by means of well consolidated communication protocols or original ones (i.e. protocols born with the aim to satisfy the specific application). The latter is related to the need of exchanging information between two subsystems by passing trough other intermediate subsystems. For this purpose the intermediate subsystems must be interfaced one another.

The consequences of bad interfacing deals with several problems that can occur related to the correct system operation. In the next chapter the Power Quality problems induced by the integration of different technologies will be considered.

1.4 Complex Systems Analysis

Due to their complexity and technological evolution, the Electrified Railways are difficult to define, to evaluate and to control.

A correct approach to the study of the traction system needs to evaluate carefully all the component subsystems and their link between each other.

The solution of most problems related with traction systems is strictly depending on the integration degree of the single component subsystems.

Therefore, great importance has the method to analyse complex systems such as the traction one, in order to achieve the actual dimension and architecture of the whole system [I.10].

Each system, whatever complex, can be represented by a connected graph in which $\boldsymbol{n}$ nodes represent the different elements (subsystems) and $\boldsymbol{m}$ branches represent the interfaces.

Each branch is identified by a scalar value $\boldsymbol{k_i}$ ($i=1...m$) representing the complexity of the corresponding interface. The complexity $\boldsymbol{k}$ is function of two variables: the band width and the functional points

$$k = f(b, p) . \qquad \text{I.1}$$

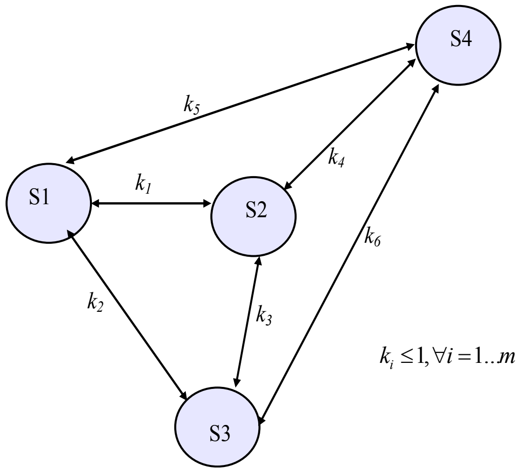


Fig. I.8 Complex system representation

The band represents the interface capability of data exchange between two subsystems. It is measured in b/s (bit per second). An interface can require a high capability. For instance, to transmit dynamical images some Mb/s bandwidth is required.

Another aspect is the computational effort related to the data calculation. In other words, two subsystems have to exchange just some bits representing the final result of very complex calculations. This complexity is usually measured in *L*ines *O*f *C*odes (*LOC*).

The interface complexity is due, in this case, to the complexity of the software, that is the functional dimension of the application. The functional dimension of an application is a standard conventional measure independent of the technology used in the software (SW) realization. This dimension is measured in *F*unction *P*oints (*FP*). To calculate the function points it is not necessary to have an already developed SW but only the functional requirements are needed.

To get an idea of the complexity of the system it is useful to introduce the following parameter called '*integration degree*' $\boldsymbol{g_i}$:

$$g_i = \frac{\sum_{i=1}^{m} 2k_i}{n(n-1)} \qquad \text{I.2}$$

Given P as the set of performances, it is possible to define another parameter $\boldsymbol{z_g}$ called *percentage global performance* given by:

$$z_g = \frac{\sum_{j=1}^{s} \frac{z_j}{z_{\max,j}}}{s} \cdot 100 \qquad \text{I.3}$$

where $\boldsymbol{z_g}$ is the increase of a generic performance and $\boldsymbol{z_{max,j}}$ is the maximum value the performance can guarantee.

Each interface contributes in a different measure to the increase of a generic performance $\boldsymbol{p_j}$. This can be expressed through the parameter '*contribution to performance increase* $\boldsymbol{l_{ij}}$ representing the contribution to the performance $\boldsymbol{p_j}$ given by the improvement of interface $\boldsymbol{i}$. In this hypothesis, it is lawful to assume the following expression:

$$\frac{z_j}{z_{\max,j}} = \frac{\sum_{i=1}^{m} 2l_{ij}}{n(n-1)} \qquad \text{I.4}$$

This expression obviously increases with m and l_{ij} and, substituted in the *global performance* expression, gives:

$$z_g = \frac{\sum_{j=1}^{s} \sum_{i=1}^{m} 2l_{ij}}{sn(n-1)} \cdot 100 \qquad \text{I.5}$$

Once the s performances have been assigned and, for each of these, the contribution l_{ij}, has been determined the preceding relation allows to get the z_g value.

The integration of two subsystems can introduce both advantages and disadvantages that, on the whole, must introduce a benefit.

The evaluation of such advantages and disadvantages does not require necessarily specific methods but, only the correct use of already available methods.

In a -1/+1 scale it will be possible, for each j, to indicate the result of an estimation of l_{ij} made starting from the evaluation of the j^{th} performance (disadvantages derived from absence of integration, measurement of the efficiency of the actual system, the evaluation of potential saving, evaluation of perceived quality, etc.)

Substantially, to obtain a quality and reliability improvement of the whole system, an optimal integration of the complex system should be performed by gaining a global advantage in subsystems interaction.

CHAPTER II

POWER QUALITY IN ELECTRIFIED RAILWAY SYSTEMS

The Power Quality (PQ) has recently become an important concern for utility, facility and consulting engineers all over the world since the electric disturbances have significant economic consequences.

In case of electrified railway systems, the development of electronic equipments and the growing complexity of these systems in terms of both new technologies and automation have produced a new interest to the analysis of PQ disturbances.

In this chapter a brief introduction on Power Quality disturbances is presented at first. This is followed by a Section where the PQ disturbances in both alternate (AC) and direct (DC) current traction systems are analysed with more detail.

Then, the problem of the traction system modelling for PQ disturbance evaluation is analysed and a new probabilistic approach - which properly handle time and frequency domains – is proposed.

Finally, PQ perturbations related to the interaction between AC and DC traction systems with reference to the Italian Railway are evaluated.

2.1 POWER QUALITY PROBLEMS: AN INTRODUCTION

In the last 20 years several Working Groups have analyzed the problem of giving a correct definition of Power Quality and a number of indices have been proposed in different Standard and technical documents such as IEC 61000-3-6, 61000-3-7, 61000-4-7, 61000-4-30, IEEE 519/92, EN 50160 [II.1-II.6], and so on. Recently also a joint Working Group CIGRE/CIRED was formed with the scope of recommending Power Quality objectives and indices to guide the network operators in their new responsibility deriving from the recent transition of the electricity industry toward a liberalized market [II.7].

2.1.1 - Definitions

The most recent definition of Power Quality mainly refers to two different voltage waveform characteristics [II.8-II.11]:

- Service (Voltage) Continuity;
- Voltage Quality.

The Service Continuity can be defined as the "degree to which the user can rely on its availability at all times". The Voltage Quality is defined as the "degree to which the voltage is maintained at all times within a specified range"; it generally concerns with the disturbances characterized by frequencies not higher than 9 kHz and that interfere with the electrical system components trough the supply network.

There are several classifications of disturbances concerning the voltage waveform quality; the most frequently used are the ones proposed by the **I**nternational **E**lectrotechnical **C**ommission (IEC) and by the **I**nstitute of **E**lectrical and **E**lectronics **E**ngineers (IEEE). The IEC refers to conducted and radiated disturbances while the IEEE classification is based directly on the inherent nature of disturbances (waveform distortions, voltage unbalances, voltage fluctuations, and so on). In the following, we refer to this last classification and present a brief description of the main disturbances that are:

a Waveform distortion;
b Short-duration variations;
c Long-duration variations;
d Voltage Unbalance;
e Voltage fluctuations.

a) Waveform Distortion

The waveform distortion is defined as a deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation [II.10]. The deviations are mainly due to the presence in the waveform of the well known harmonics and interharmonics superimposed to the fundamental.

In 1822 the mathematician J.B.J. Fourier in his work "Theorie analytique de la chaleur" postulated that any continuous function repetitive in an interval T can be represented by the summation of a fundamental sinusoidal component to a series of higher order *harmonic components* at frequencies which are integer multiples of the fundamental frequency. The *interharmonics* are sinusoidal components having frequencies that are non integer multiples of the fundamental.

There are several sources of harmonics/interharmonics. The main causes are the static converters (six-pulse and twelve-pulse AC/DC converters, adjustable speed converters, ac/dc rectifier with high smoothing capacitance, and so on); other sources are transformers, arc furnaces, and lamps.

b) Short-duration variations

A short-duration variation is the temporary deviation from the steady-state waveform caused by faults or by sudden changes in the power system. The short-duration variations here considered are voltage sags, brief interruptions and voltage increases [II.10].

The *voltage sag* is a sudden reduction of the voltage at a point in the electrical system lasting for 0.5 cycles to several seconds. This voltage reduction ranges from 10% and 90% of the voltage.

A voltage sag may be caused by the switching operation associated with the temporary disconnection of the network, the flow of heavy currents associated with the start of large motor loads or the flow of fault currents.

The main cause is the short circuit, which can cause different voltage sags in balanced [II.11] or unbalanced [II.12] power systems. These events may emanate from customer systems or from the supply network. In term of duration, the voltage sags tend to cluster around the typical fault-clearing time in the system.

The *brief interruption* is considered as a voltage sag with 100% amplitude and duration not higher than 3 min (some Standards consider 1 min as the threshold level); for this reason CIGRE'/CIRED WG 36-07 does not explicitly consider brief interruptions, including them in the voltage sags. These interruptions are normally caused by breaker opening or blown fuse and it can be easily imagined that the effect is an expensive shutdown.

The *voltage swell* is a brief voltage increase. It usually occurs on the unfaulted phases of a three phase circuit developed in a single phase short circuit and following a load rejection.

c) Long-duration variations

The long-duration variations are defined as root-mean-square (rms) deviations at power frequencies for longer than 1 (3) min [II.13].

Long duration variations include overvoltages, undervoltages and sustained interruptions. Overvoltages and undervoltages are both caused by load variations on the system and system switching operations.

An *overvoltage* is an 'increase in the rms AC voltage greater than 110 percent at the power frequency for a longer duration than 1 (3) min'.

An *undervoltage* is a 'decrease in the rms AC voltage to less than 90 percent at the power frequency for a duration longer than 1 (3) min'.

A *sustained interruption* is a voltage interruption longer than 1 (3) min.

d) Voltage Unbalance

The unbalance occurs when, in a three-phase system, the voltages are not identical in magnitude and/or the phase difference between them is not 120 electrical degrees [II.10].

Unbalances in power systems are not negligible in the presence of single-phase AC traction plants, electrical furnaces and long untransposed lines; moreover, several distribution systems are known to have unbalanced lines and line sections carrying a mixture of single, double or three-phase loads.

e) Voltage fluctuations

The voltage fluctuation is a series of voltage changes or a cyclical variation of the voltage envelope [II.13]. They are mainly associated with variable loads such as arc furnaces, spot welders and X-ray equipments. Voltage fluctuations typically result in the well known flicker; this phenomenon is defined by the International Electro-technical Vocabulary (IEV 161-08-13) as “Impression of unsteadiness of visual sensation induced by light stimulus whose luminance or spectral distribution fluctuates with time”.

2.1.2 – Indices

To enable the efficient and consistent evaluation of system performance with respect to Power Quality common indices for assessing and reporting PQ are needed.

Two categories of indices can be distinguished [II.7]:

1. Indices for *planning purposes*, primarily used to assess internal quality objectives set by the system operators for evaluating the impact of all disturbing loads on the supply system (planning levels);
2. Indices for *characterizing and reporting system performance,* used to assess external quality objectives or limits within which any customer can expect the voltage to remain under normal operating conditions (voltage characteristics).

Two levels of indices can be distinguished given their use in reporting 'voltage characteristics' performance:

- *Site indices,* characterizing the performance at a specific site;
- *System indices*, characterizing the performance of a system or of part of it.

Usually, *site indices* aggregate the values of one or more PQ disturbance indices for all events at one site during a given period of time. System indices are calculated from the site indices of all monitored sites over a certain area.

In the following, some indices recently suggested by Standards or International Working Groups for the main PQ disturbances introduced in Session 2.1.1 are briefly recalled [II.7].

a) Waveform Distortion

The waveform distortions vary at random in time, with reference to any specific supply terminal, and at random in location, with reference to any given instant of time. Because of these variations, Standards refer to statistical approaches as the basis for both planning levels and voltage characteristics.

As far as concerns *harmonics,* the indices usually taken into account for planning purposes are:

- the 95% probability daily value of $U_{h,vs}$ (RMS value of individual harmonic components over 'very short' 3 s periods);
- the maximum or the 99% probability weekly value of $U_{h,s}$ (RMS value of individual harmonics over 'short' 10 min periods);
- the maximum or the 99% probability weekly value of $U_{h,vs}$.

The voltage characteristics can be assessed by using the following index:

- the 95% percentile of weekly value of $U_{h,s}$ (RMS value of individual harmonics and THD over 'short' 10 min periods).

The harmonic components over very short and short periods are determined applying the following steps:

i) to obtain the spectrum over a 10-cycle (50 Hz systems) or 12-cycle (60 Hz systems) window. The window shall be synchronized to the actual frequency during the measurement;

ii) the spectra are combined (RMS) to a spectrum over a 3-second interval (150 cycles for 50 Hz systems and 180 cycles for 60 Hz systems) and the so obtained values are referred to as ‘’very short time’’ indices ($U_{h,vs}$);

iii) the 3-second values are combined to a 10-minute value and referred to as ‘’short time’’ indices ($U_{h,s}$).

A system index under consideration is the percentage of site indices that exceed the voltage characteristics in a given period.

Similar indices can be considered for *interharmonics*.

b) Short-duration variations

With reference to *voltage sags,* two basic characteristics (indices) should be determined for each event:

- the retained voltage (the lowest RMS voltage on any phase during the event);
- the duration (the time the RMS voltage stays below a threshold level).

In case of site and system indices the frequencies of sags (number of events) should be considered too.

With reference to *brief interruptions,* they can be categorised by three parameters: their frequency (number of events), duration (or restoration time) and severity (size of the load affected). Brief interruptions are frequently characterized by their system average interruption frequency only.

With reference to the *voltage swell* the RMS value is usually assumed as index.

c) Long-duration variations

The following indices are being discussed for defining transmission system delivery point interruption characteristics:

- SAIFI: the system average interruption frequency;

- SAIDI: the average duration of interruptions for all delivery points;
- SAIRI: the system average interruption restoration time for delivery points experiencing interruptions.

Severity indices based on ‘System Minutes’ indices are also considered for transmission systems[1].

d) Voltage Unbalance

The most usual index is the voltage unbalance, defined as the ratio of the negative sequence component to the positive-sequence component at fundamental frequency.

Because of the similarity of random nature and of effects caused by harmonics and voltage unbalance (thermal effects) the most recent Working Groups recommend to use similar site and system indices for both.

e) Voltage fluctuations

All the voltage fluctuation indices are linked to the flicker effect. The Standard IEC 61000-4-15 [II.14] characterizes flicker effects by two quantities: the short term flicker *s*everity *f*actor P_{st} and *l*ong *t*erm factor P_{lt} but, in practice, reference should be made only to one of them being the two indices well correlated to each other.

In practice, the well known IEC flickermeter models the lamp-eye-brain chain and hence quantifies the Instantaneous Flicker Level (IFL) on the basis of human irritation; the IFL varies unpredictably and should be therefore statistically characterized with a proper Cumulative Probability Function (CPF). With reference to a 10 m time window, the P_{st} is defined as:

$$P_{st} = \sqrt{\sum_i k_i P_{xi}} \qquad \text{(II.1)}$$

where k_i is the i^{th} weighting coefficient and P_{xi} the CPF curve level being exceeded for x_i% of the observation period.

[1] There are several definitions adopted for System Minutes indices (UNIPEDE, CIGRE’, and so on), Here we refer to the definition introduced by the GIGRE’ Study Committee 26 where the index is defined as the ratio between the energy not supplied due to disturbance and the maximum system demand met to date.

The P_{lt} is simply calculated from 12 successive P_{st} values, and then refers to a time window of 2 hours.

Since P_{st} and P_{lt} quantities are time-varying, the indices usually taken into account for planning purposes are:

- the 95% probability weekly value of P_{st} ;
- the 99% probability weekly value of P_{st}

For voltage characteristics only the 95th percentile of weekly value of P_{lt} is suggested.

2.2 Power Quality Problems in Electrified Railway Systems

The growing complexity of the Electrified Railway Systems in terms of both new technologies and automation requires a careful control of the Power Quality disturbances they cause [II.15, II.16]; the disturbances depends on the traction system structure.

As known, in Europe three different kinds of traction systems exists today:

- the DC systems;
- the AC single-phase 50 Hz systems;
- the AC single-phase 16 $^{2/3}$ Hz systems.

In Italy, both DC traction system for metro-transit or railway and (2x25 kV – 50 Hz) AC traction system for high speed railway have been adopted; each can cause significant Power Quality perturbations which will be discussed in the next sessions. These problems involve the three phase supply system (where the traction load is a disturbing load) and inside the traction system itself which includes components, such as control and signalling systems, very sensitive to the waveform characteristics.

2.2.1 – AC Single-Phase 50 Hz Traction Systems

In the three-phase supply network AC single-phase traction systems can cause:

- voltage unbalances at fundamental frequency, as a consequence of different active and reactive phase-powers absorbed at substation terminals;
- voltage and current distortions, due to the AC traction locomotives which use controlled-converters;
- slow voltage variations, due to the time-varying nature of the phase-powers.

In addition, traction systems present voltage and current distortions produced by the controlled-converters aboard locomotives.

In particular, in AC traction systems the overhead line is fed by electrical substations directly connected to the three-phase power supply. These substations are equipped with single-phase transformers with the primary windings connected to two generic phases of the system. This connection determines current unbalances and, hence, voltage unbalances in the three phase supply network voltages with well known harmful consequences.

In the case of only one single-phase transformer connected to the three phase network, the voltage unbalance in the connection network bus is directly proportional to the absorbed power and can be evaluated as the ratio between the single phase apparent power P_m and the three phase short circuit network power P_{cc} in the connection bus (K_d=P_m/P_{cc}).

In the case of more than one single-phase transformer derived by the same or different buses of the three phase supply network (as it is the actual case), voltage unbalances are not directly proportional to the power absorbed at each substation. In these cases the simplified formula above mentioned cannot be applied and, hence, a three phase modelling of the electrical power system, for the calculation of voltage unbalances, is unavoidable (three-phase load flow). On the other hand, the three phase load flow allows to take into account, besides to the unbalanced powers absorbed by the traction system, also other structural and/or functional unbalances present in the three phase supply network.

Other significant PQ problems in the AC single-phase traction systems are caused by current and voltage harmonics and interharmonics due to the aboard locomotive converters. In fact, although these last ones concur to improve the locomotives performances, they represent disturbance sources propagating inside the traction system which, through the substations, involve the three phase supply network as well. As an example, in the next future in Italy AC traction locomotives drives use PWM-controlled converters, whose simplified scheme is shown in Fig. II.1. The locomotive is formed by two subsystems; each contains two single-phase PWM-controlled reversible converters that rectify the AC voltage of the overhead line into 2.4 kV DC voltage. The DC voltage feeds the three-phase inverters and the 1MW AC motors. The four single-phase AC/DC reversible converters operate individually at 500 Hz switching frequency. Their control signals are phase-shifted with respect to each other so that the harmonic spectrum of line currents is characterized by the side bands of the odd multiples of the actual switching frequency that is 2000 Hz. Each three-phase DC/AC inverter is controlled by 120° phase-shifted carriers and is equipped with GTO's to realize output frequency variation up to 133 Hz.

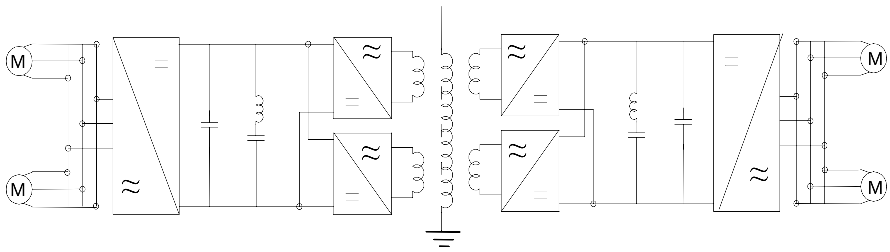


Fig. II.1 PWM Controlled Converter for AC traction locomotive

Since there is a strong interaction between overhead line circuit characteristics and the aboard locomotive converter characteristics, it is difficult to evaluate the harmonics and inter-harmonics generated by the aboard locomotives converters. In fact, the waveform distortions, for a given position of the locomotive in the overhead line, depend on the absorbed power; on the other hand, for a given absorbed power, the distortions depend on the position of the locomotive in the traction circuit that determines a different equivalent impedance "seen" from the locomotive; this impedance includes resonance conditions that contribute to determine considerable harmonics and interharmonics, mainly at higher frequencies (greater than 1500 Hz) [II.17] . This means that, for a proper locomotive disturbing characterization, the actual traction system characteristics in which it operates should be taken into account; moreover, the need of modelling the traction system with very high accuracy arises.

Clearly, the current harmonics and interharmonics injected by the locomotive drives in the overhead line involve, through the substations, also the three phase network provoking, in their nodes, voltage waveform distortions with consequent Power Quality degradation.

2.2.2 – DC Traction Systems

The DC traction systems can produce

1. Voltage and current distortions, due to the AC/DC static converters of the traction substations;
2. Slow voltage variations, due to the time-varying nature of the phase-powers.

in the three-phase supply network.

In addition, there are voltage and current distortions in the traction systems due to the controlled-converters aboard the locomotives and due to the AC/DC substation converters. In particular, in DC systems, traction overhead lines are fed by six pulse and twelve pulse AC/DC static converters. Then, though offering the advantage of a connection to the three-phase network without determining unbalances in it, they introduce the problem of the voltage and current harmonic distortion due to the presence of static converters in the electrical substations.

While in the past little attention has been paid to these distortions, due to the low demand of energy power by AC/DC substations, nowadays the increase of electrical power requests, in order to manage the speed and vehicles weight increase, has made the problem of harmonic pollution much more complex with respect to the past.

Moreover, in these systems the widespread use of static converters in the locomotives drives has produced additional increases of current and voltage harmonic pollution inside the traction systems where the distorting effects of the electronic devices on board locomotives add to the ones produced by the AC/DC substation converters. As an example, nowadays in Italy DC traction locomotives drives use PWM-controlled converters, whose simplified scheme is shown in Fig. II.2.

In particular, Fig.II.2 shows the electrical scheme of the Italian FS locomotive (E402A) drives characterized by a double conversion stage constituted by a chopper and by an inverter feeding two parallel asynchronous three phase traction motors.

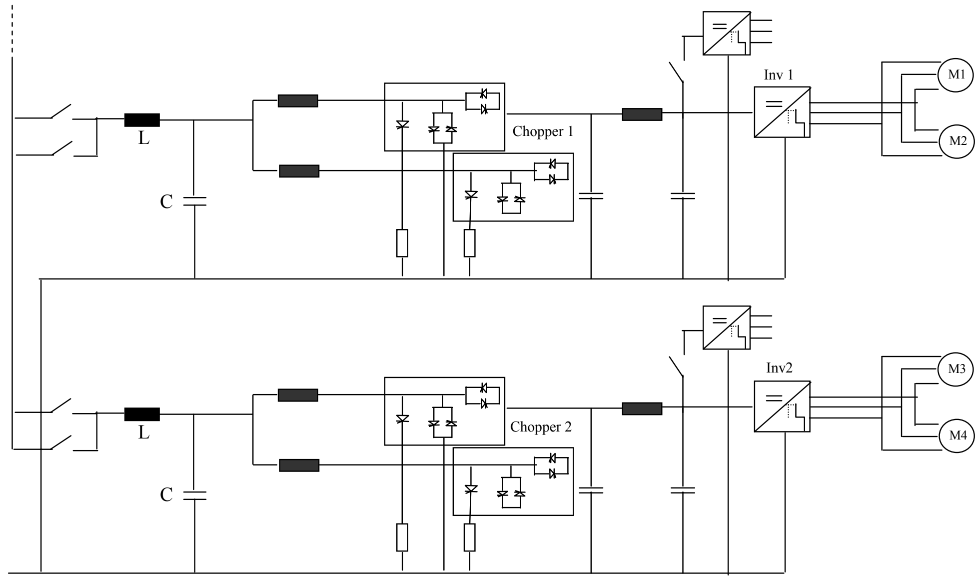


Fig II.2 Italian FS E402A locomotive drives scheme

2.2.3 – AC and DC Traction System Interactions

In most European countries coexist both DC and AC traction systems. In the Italian railway system, for instance, the (2x25 kV – 50 Hz) will be used for High Speed railway whereas the DC system is adopted in all other cases. These two systems normally operate with slow interactions since the AC and DC traction substations are connected to different and almost independent three-phase AC busbars; however, in some cases (for instance, in emergency conditions) the AC and DC traction systems can be connected to dependent three-phase AC busbars with consequent unavoidable interactions [II.18]. On the other hand, these interactions can be of more general interest, as this situation occurs more and more frequently in Europe, where most classical systems are usually DC and the new ones are 25 kV – 50 Hz.

When the AC and DC traction substations are connected to dependent three-phase AC busbars, the following additional PQ problems arise:

- the voltage unbalances due to the different active and reactive phase-powers absorbed at AC substations can introduce non-characteristic harmonics in the voltage and current waveforms, thus modifying the value of the characteristic ones at DC substations;
- the voltage distortions caused by the current harmonics generated by the AC/DC converters present at DC ESSs can introduce waveform distortions in the AC traction system.

In particular, the presence of three phase unbalanced voltages at AC terminals of the DC traction systems can be responsible of a significant and dangerous 100 Hz spectral component on the DC voltage which can produce a corresponding 100 Hz component of current [II.18, II.19]. Potential dangers mainly for control and signalling systems can arise within the DC traction system.

This problem has been discussed in [II.18] with reference to the Railway System in Fig II.3 where a (2x25 kV – 50 Hz) AC traction system and a DC traction system act in the same area.

In the system represented in Fig. II.3 ten DC electrical substations (busbars 1-10) with six or twelve pulse AC/DC converters and one AC electrical substation (busbar 11)[2] are fed by the HV transmission system at three different buses (North1, North2 and North3).

Under normal operating conditions, the North1 bus feeds the DC ESSs via the transformer AT1 and the AC ESS via the transformer AT2; in this case, the unbalances generated by the AC ESS on the DC ESSs behaviour have slight influence.

[2] This is a terminal substation, so that it is equipped with only one single-phase transformer

An emergency condition particularly significant from the Power Quality point of view occurs when line L_1 is affected by an outage (the line switchgears C1 are open). In this case the line L_2 switchgears C2 get closed and both DC ESSs and AC ESS are fed via transformer AT2. In this case there is a dangerous and significant influence of the unbalances generated by the AC ESS on the DC ESSs behaviour.

In fact, as previously evidenced, the presence of three phase unbalanced voltages at AC terminals of the DC traction systems can be responsible of a significant and dangerous 100 Hz spectral component on the DC voltage which can produce a corresponding 100 Hz component of current.

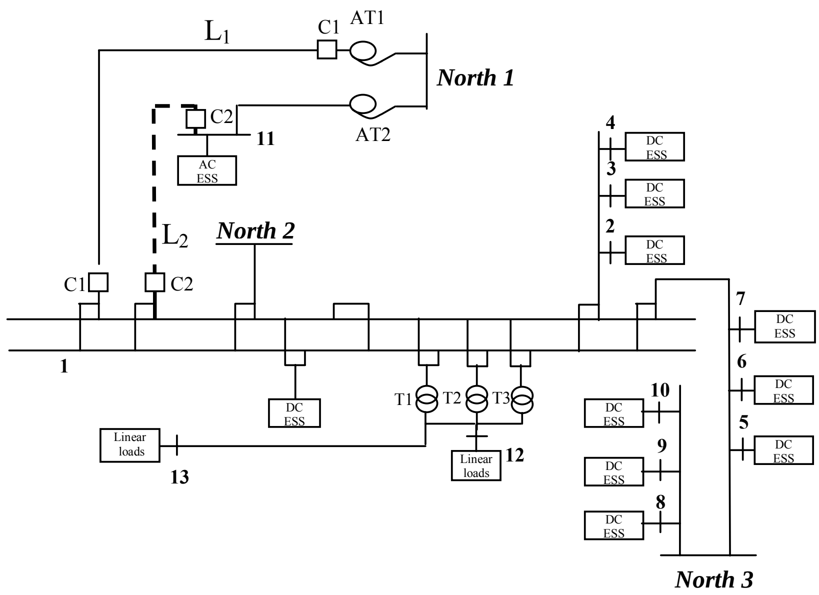


Fig. II.3 Three-phase transmission system with AC and DC traction systems

Several simulations on the system in Fig.II.3 have been effected. As an example, Figs. II.4 and II.5 show:

i) the unbalance factor amplitude U_u at all HV system busbars (a);
ii) the 100 Hz harmonic voltage on the DC side of the DC ESSs (b).

Fig. II.4 refers to *Normal conditions* where switchgears C2 are open and the switchgears C1 are closed.

Fig. II.5 refers to *Emergency conditions* where switchgears C1 are open and switchgears C2 are closed.

In both conditions, the active power absorbed by each DC ESS is almost equal to 4.1 MW and the active power absorbed by the AC ESS is almost equal to 52 MW.

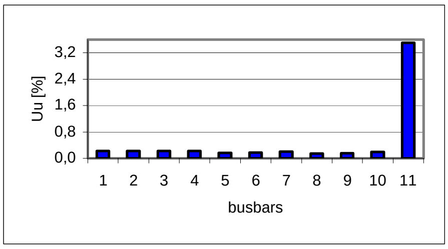
From the analysis of Figs. II.4 it follows that under normal conditions:

- the unbalance factor amplitude U_u value is greater than the admissible objectives (usually 1-2% in HV systems) only at bus 11 while it assumes very low values at other busbars;
- the 100 Hz harmonic voltage on the DC side of the DC ESSs doesn't assume dangerous values

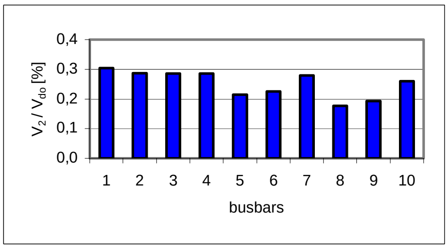
From the analysis of Figs. II.5 it follows that under emergency conditions:

- the unbalance factor amplitude U_u values are similar at all system busbars with values almost always greater than 1% and with the value at bus 11 significantly lower than the one in normal conditions;
- the 100 Hz harmonic voltage on the DC side of the DC ESSs assumes values much greater than the ones in normal conditions.

The results obtained in both normal and emergency conditions show that corrective solutions are needed: they will be discussed in the next chapter.

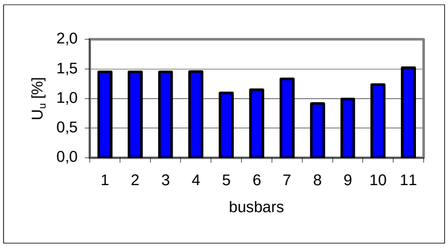


a)

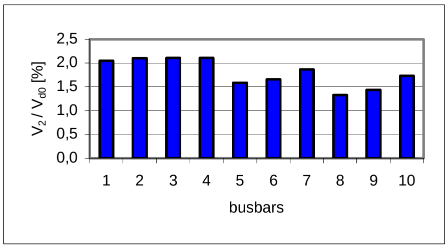


b)

Fig. II.4 Power Quality indices values in normal conditions versus HV busbars: (a)Unbalance Factor amplitude; (b) 100 Hz DC Voltage Harmonic



a)



b)

Fig. II.5 - Power Quality indices values in emergency conditions versus HV busbars: (a) Unbalance Factor amplitude; (b) 100 Hz DC Voltage Harmonic .

2.3 POWER QUALITY MODELLING IN ELECTRIFIED RAILWAY SYSTEMS: A NEW PROBABILISTIC APPROACH

The analytical evaluation of Power Quality disturbances in AC and DC traction systems is a very complex problem to be solved.

First of all, as clearly evidenced in Section 2.2, each traction system (AC or DC) can cause in the three phase supply network several Power Quality disturbances (harmonics, inter-harmonics, voltage unbalances, and so on); on the other hand, the traction systems can also interact between each other, with consequent additional PQ problems.

Moreover, as pointed out in Section 2.1, the most recent International Standards and Recommendations require the evaluation of PQ disturbances in a probabilistic way; in fact, they require the calculation of the percentiles and maximum values of the PQ indices probability density functions.

A new probabilistic approach to analytically evaluate the probability density functions of the indices assumed to assess the voltage unbalances, the waveform distortions (harmonics and inter-harmonics) and the slow voltage variations will be proposed in the next session 2.3.2 [II.20]. It allows the probabilistic evaluation of Power Quality disturbances properly taking into account all the interactions between traction systems and three-phase power supply network.

The proposed approach is a hybrid probabilistic method which properly combines, in the frame of a Monte Carlo simulation procedure, time domain and frequency domain models. In particular, the whole DC and AC Traction Systems (including the controlled aboard converters) are modelled in the time domain. The three-phase AC supply transmission system is modelled in the frequency domain, for the evaluation of both phase-voltages at fundamental and at harmonic/inter-harmonic frequencies.

The probabilistic approach can take into account the main causes of uncertainties in the traction system: service scheduling, train speed, signalling, traction layout and traction equipment control and so on. Also the uncertainties due to the three-phase AC supply system can be taken into account.

The proposal of the new probabilistic approach in Section 2.3.2 is preceded in Section 2.3.1 by a brief recall of the state of the art on the analytical approaches proposed to date for the Electrical Railway System probabilistic analysis in presence of PQ disturbances.

2.3.1 State Of The Art

Probabilistic approaches recently proposed a probabilistic steady-state analysis of Electrified Railway systems analyse DC or AC Traction Systems separately [II.21-24]. No contribution appeared in the relevant literature analyses a system with both the two systems in contemporaneous operation. Moreover, all the probabilistic approaches take no account of the interactions between traction systems and the three phase power supply network.

In particular, with reference to the AC 50 Hz traction systems, probabilistic models have recently appeared in [II.21, II.22].

In [II.21] a probabilistic approach based on an analytical method is proposed for the evaluation of current harmonics in the traction system. The Central Limit Theorem is applied approximating the probability density function of the harmonic currents due to N trains with normal distribution. A comparison between the proper approach, a Monte Carlo simulation and experimental measures has been also effected.

In [II.22] the calculation of the harmonic currents under the condition of multiple trains is effected using a Monte Carlo simulation method. A great detail of the traction system components is taken into account. A comparison between simulation results with practical data has been effected.

With reference to the DC traction systems, probabilistic modelling is recently reported in [II.23, II.24].

In [II.23] the voltage distortion on the catenary is analysed considering the system operating conditions and, in particular, locomotive position. The variability of the line impedance at the pantograph terminals due to the random position of the locomotive along the track of the DC railway traction system is taken into account.

In [II.24], on the basis of statistical data elaboration, a probabilistic model for normal operation conditions of a metrorail supply system is identified for one or multiple ESS conversion group.

2.3.2 A New Probabilistic Approach

A probabilistic evaluation of the perturbations (unbalances, slow voltage variations and waveform distortions) caused by the AC and DC traction systems (each one or both acting together) into the three-phase power supply network can be performed by either analytical or Monte Carlo approaches.

The complexity of the system under study - evidenced in all the preceding Sections- gets necessary to resort to Monte Carlo simulation procedure to carry out the probabilistic method.

Theoretically speaking, the Probabilistic Iterative Harmonic Analysis proposed in [II.25] and applied specifically to the analysis of an AC/DC power system (three-phase power system including AC/DC and DC/AC static converters) could be used.

In [II.25], for each random input datum, a value is generated on the basis of its proper probability density function; according to these values, the operating conditions at the fundamental frequency of the AC/DC power system are at first evaluated by solving a three-phase AC/DC load flow; so the analysis at the harmonic frequencies is performed evaluating, iteratively until convergence is achieved, converter current harmonics and AC system voltage harmonics.

The preceding procedure is repeated a sufficient number L* of times to obtain a good estimate of the output variable probability density functions. In practice, the probabilistic iterative method consists of performing, in the frame of a Monte Carlo simulation, L* deterministic Iterative Harmonic Analysis (IHA) [3] of the whole system in study, each one for an assigned different set of input random variable values.

[3] The Iterative Harmonic Analysis (IHA) [II.10] was proposed firstly for the deterministic steady-state analysis of a multiconverter power systems. It is a well comprehensive integrated method, in which the probabilistic evaluation of the voltage and current harmonics are calculated together, properly taking into account the interactions between the supply voltage distortion and the non linear load current harmonics.

In practice, the application of the above procedure to the particular case of three phase power systems including both AC and DC traction systems which use locomotives with PWM or other controlled converters is not an easy task.

First of all, during each deterministic IHA a three-phase AC/DC load flow should be performed including the closed form equations that describe the steady state behaviour of aboard static converters such as the ones of Figs.II.1 and II.2; the presence of such converters makes particularly hard this task. Moreover, the analysis at harmonic frequencies has to be extended also to the interharmonic frequencies generated by the PWM-controlled converters.

Fig.II.6 shows a flow chart of Monte Carlo simulation properly adapted to the case of a three phase power system with DC and AC traction systems.

At each step of the Monte Carlo simulation procedure, a deterministic IHA is performed consisting firstly in a time domain solution of the whole traction system including the substations and, then, in a frequency domain analysis of the three-phase power supply network. The choice of the cut sections (high voltage three-phase busbars feeding the traction system substations) has been effected on the basis of the following considerations.

First of all, this choice allows a clear separation between the sub-systems (traction system and three-phase supply network) where the disturbances propagate, with the possibility of representing the traction system with more details, including control and signalling systems. Moreover, this choice reduces the number of cut sections and, mainly, the level of interaction (theoretically, they should be at all the locomotive pantographs), so avoiding the classical convergence problems of the IHA.

With reference to the number of trial L* to be performed, choice was made in such way to obtain a good *estimate* of the probability density functions of the output variables according to stated accuracy.

In fact, it should be noted that in the Monte Carlo simulation, the probability density functions (along with all the statistical measures, such as mean value or percentiles) of the output random variables are estimated from a random sampling.

Convergence criteria in Monte Carlo simulations are often based on relative uncertainty or coefficient of variations of the estimate.

For example, in case of expected value estimate of the generic random variable U_i a maximum value of the following coefficient of variation can be assumed as convergence criteria:

$$\beta = \frac{\sigma^2(\mu(U_i))}{\mu(U_i)} \tag{II.2}$$

In (II.2) the uncertainty of the estimate is measured by the variance $\sigma^2(\mu(U_i))$, given by:

$$\sigma^2(\mu(U_i)) = \sigma^2(U_i)/n \tag{II.3}$$

with the variance of the generic variable U_i estimated numerically.

Expressions similar to (II.3) can be obtained for all the statistical measures of the probability density functions of interest.

It should be noted that, when high level of perturbations are not forecasted - as suggested by the IEEE PES Working Group on Harmonic Modeling and Simulation [II.24] - the deterministic IHA in Fig. II.6 can be avoided and a direct method can be performed based on only one step (the test of convergence in Fig. II.6 is satisfied just after the first iteration of the deterministic IHA).

The main steps of the Monte Carlo simulation procedure of Fig. II.6 are discussed in more details below.

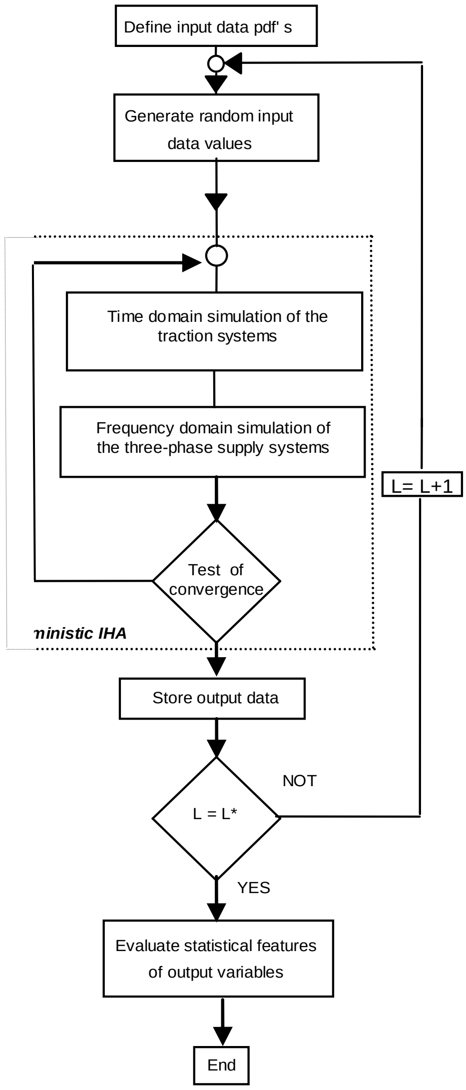
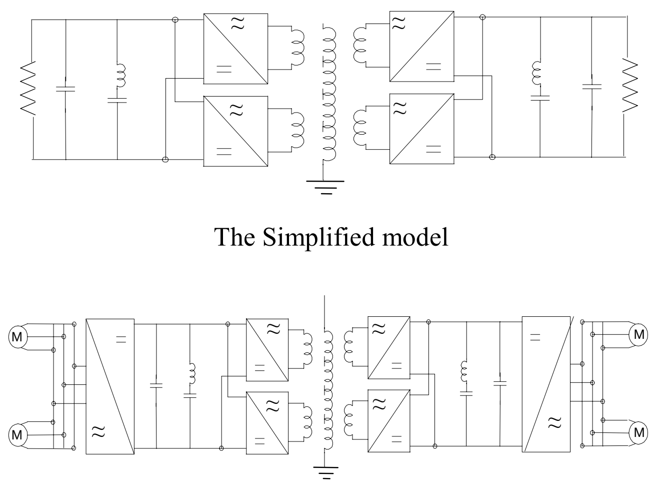


Fig.II.6 - Monte Carlo simulation procedure for probabilistic three-phase power systems with DC and AC traction system analysis

2.3.2.1 Time Domain Simulation of the AC Traction System

The simulation of both DC and AC traction systems (including aboard static converters, overhead lines and signalling systems) is performed by using computer simulations developed in time domain by means of Matlab Power System Blockset, a tool with feasible and attractive characteristics, allowing to easily evaluate complex system behaviour. Every power system component is represented by a block in which it is possible to vary the component characteristic parameters; furthermore, the interconnection among the various components is effected by reproducing the real ones. The toolbox is provided of suitable supports which result very useful for efficient time-domain simulations, allowing to capture the functional dependence of system characteristics of various interest parameters.

Two different models were implemented for the aboard static converters. The former, referred to in the following as comprehensive model (CM), includes all the aboard power converters and the motors (Fig. II.7).



The Simplified model

The Complete model

Fig. II.7 Simplified and Complete Model schemes

The latter model, referred to in the following as simplified model (SM), replaces two equivalent resistors for two groups of one DC/AC inverter and two motors. The CM allows accounting for all the interactions between the line side four quadrant rectifiers and the inverter operation in case of AC Traction systems. In particular, the inter-harmonic components of the pantograph current can be ascertained and quantified.

In the SM model the value of each resistance is chosen as the one that guarantees the same active power absorbed at the fundamental power frequency by the corresponding group of inverter and AC motors. The SM only allows to evaluate the harmonic components of the pantograph current but with greatly reduced computational efforts. The harmonic components obtained with the SM model practically coincide with those obtained with the CM.

The overhead line of both the traction systems has been modeled with a series of lumped parameter equivalent circuits; the rails have been represented by means of the equivalent cylindrical conductors.

2.3.2.2 Frequency Domain Simulation of the Supply System

The three-phase power supply system has been simulated in the frequency domain, both at fundamental frequency (three phase load flow equations) and at harmonic/interharmonic frequencies (linear three-phase harmonic equations).

a) Three phase load flow equations

We will refer to a three phase unbalanced power systems in which the busbars from 1 to N_c are load busbars, the ones from Nc +1 to Nc + Ng are generator terminal busbars and the ones from Nc + Ng + 1 to Nc + 2Ng = N are generator internal busbars; the last terminal and internal busbars are slack busbars.

The three-phase load flow equations are recalled in the following list to provide evidence of the variables and the input data involved.

- *Load busbars*

The active P_i^p and reactive Q_i^p powers are specified at each of the three phases. The equations for these busbars are:

$$\begin{aligned} \left(P_i^P\right)^{sp} &= V_i^P \sum_{k=1}^{N} \sum_{m=1}^{3} V_k^m \left[G_{ik}^{pm} \cos\theta_{ik}^{pm} + B_{ik}^{pm} sin\theta_{ik}^{pm}\right] \\ \left(Q_i^P\right)^{sp} &= V_i^P \sum_{k=1}^{N} \sum_{m=1}^{3} V_k^m \left[G_{ik}^{pm} sin\theta_{ik}^{pm} - B_{ik}^{pm} \cos\theta_{ik}^{pm}\right] \end{aligned} \qquad \text{(II.4)}$$

where p=1, 2, 3 and i = 1,..., N_c.

In (II.4) G^{ik}_{pm}, B^{ik}_{pm} are the elements of the system three-phase admittance [**G**] and susceptance [**B**] matrices at fundamental frequency, relating busbar *i* with phase *p* and busbar *k* with phase *m*; V^i_p, θ^i_p are the phase-voltage magnitude and argument at busbar *i* with phase *p*. The unknown in the load busbars are the voltage magnitude and argument of each phase.

The traction system substations are considered as P-Q loads with phase-powers evaluated in the time domain step.

- *Generator busbars with exception of the slack*

The usual specifications refer to (Fig. II.8):

- the active P^p_i and reactive Q^p_i load powers at each of the three phases of the generator terminal busbar;
- the three phase active power P^{gen}_j at the internal generator busbar;
- the voltage regulator law at the terminal generator busbar.

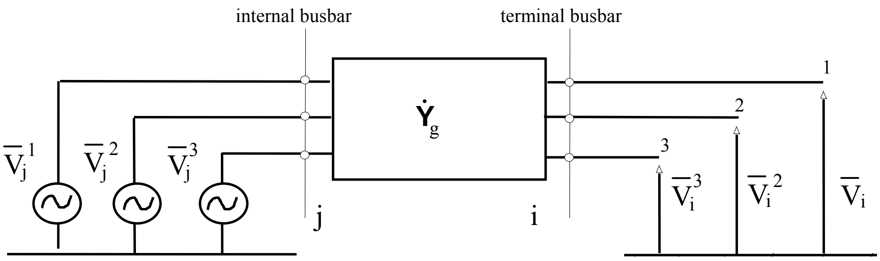


Fig. II.8 – Generator modelling for three-phase load-flow

The equations for these busbars are:

$$\left(P^p_i\right)^{sp} = V^p_i \sum_{k=1}^{N}\sum_{m=1}^{3} V^m_k \left[G^{pm}_{ik}\cos\theta^{pm}_{ik} + B^{pm}_{ik}\sin\theta^{pm}_{ik}\right]$$

$$\left(Q^p_i\right)^{sp} = V^p_i \sum_{k=1}^{N}\sum_{m=1}^{3} V^m_k \left[G^{pm}_{ik}\sin\theta^{pm}_{ik} - B^{pm}_{ik}\cos\theta^{pm}_{ik}\right] \qquad \text{II.5}$$

$$\left(P^{gen}_j\right)^{sp} = \sum_{p=1}^{3} V^p_j \sum_{k=1}^{N}\sum_{m=1}^{3} V^m_k \left[G^{pm}_{jk}\cos\theta^{pm}_{jk} + B^{pm}_{jk}\sin\theta^{pm}_{jk}\right]$$

$$\left(V_i\right)^{sp} = f\left(\overline{V}^1_i, \overline{V}^2_i, \overline{V}^3_i\right)$$

p=1,2,3, $i = N_c+1,\dots\dots,N_c + N_g-1$ and $j = N_c + N_g + 1,\dots,N-1$

The unknowns are:

- the voltage magnitude and argument at each phase of the generator terminal busbar;
- the voltage magnitude and argument at one phase of the generator internal busbar; in fact, the machine excitation acts symmetrically on the three phases so that the three phasor voltages at the internal busbar are assumed to form a balanced three-phase set $\left(\overline{V}_j^2 = \dot{\alpha}^2\overline{V}_j^1, \overline{V}_j^3 = \dot{\alpha}\ \overline{V}_j^1\right)$.

- *Slack generator busbars*

The usual specifications refer to:

- the active P_i^p and reactive Q_i^p load powers at each of the three phases of the slack generator terminal busbar;
- the voltage regulator law at the slack terminal generator busbar.

The equations for these busbars are:

$$\begin{aligned}
\left(P_i^p\right)^{sp} &= V_i^p \sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{pm}\cos\theta_{ik}^{pm} + B_{ik}^{pm}\sin\theta_{ik}^{pm}\right]\\
\left(Q_i^p\right)^{sp} &= V_i^p \sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{pm}\sin\theta_{ik}^{pm} - B_{ik}^{pm}\cos\theta_{ik}^{pm}\right]\\
\left(V_i\right)^{sp} &= f\left(\overline{V}_i^1, \overline{V}_i^2, \overline{V}_i^3\right)
\end{aligned} \tag{II.6}$$

p=1,2,3 and $i = N_c + N_g$.

The unknowns are:

- the voltage magnitude and argument at each phase of the generator terminal busbar;
- the voltage magnitude at one phase of the generator internal busbar; in fact, the corresponding argument is assumed as reference and fixed to zero:

$$\left(\overline{V}_j^1 = V_j^1, \overline{V}_j^2 = \dot{\alpha}^2 V_j^1, \overline{V}_j^3 = \dot{\alpha}\ V_j^1\right) \tag{II.7}$$

The equations from (II.4) to (II.6) constitute a set of non-linear algebraic equations that can be solved with the usual algorithms [II.10]. Once the state variables (voltage magnitude and argument at all busbars) have been calculated, the complete state of the unbalanced three-phase power system is known and all the quantities which depend on the state variables can be determined.

b) Linear three-phase harmonic equations

The system harmonic voltages are calculated by direct solution of the linear three-phase harmonic equations given by:

$$[Y_h]\,[V_h] = [I_h] \tag{II.8}$$

where $[\mathbf{Y_h}]$, $[\mathbf{V_h}]$ and $[\mathbf{I_h}]$ are the three phase network admittance matrix, bus voltage vector and independent current source vector evaluated at the h^{th} harmonic (interharmonic) frequency. For an unbalanced three-phase system, the current injections are unbalanced in magnitude and phase.

The traction system substations are considered independent current sources with the harmonics evaluated in the time domain step.

With reference to the three phase admittance matrix, its elements are (3x3) matrices obtained starting from the three-phase component modelling at harmonic frequencies (transmission lines, transformers, and so on). Here, the component modelling adopted is the one proposed in [II.26].

2.3.3 Numerical Application

The procedure proposed in section 2.3.2 has been applied to evaluate the Power Quality disturbances which affect the steady-state operating conditions of the simple test system in Fig.II.9; the test system is constituted by a well known 5-bus transmission system feeding a 2x25 kV – 50 Hz traction system at bus 1. The value of the electrical parameters of generators, transformers and lines of the three-phase power supply are reported in Tables 1-3 of [II.27]. The 2x25 kV- 50

Hz AC traction system is the one that will be used for the high speed Italian Railway System (Fig.II.9).

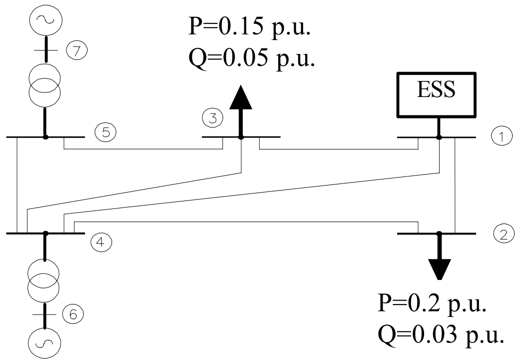


Fig.II.9 – Test system

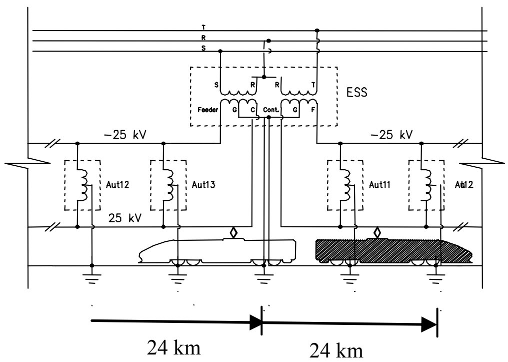


Fig.II.10 - High speed Italian AC Railway system

The rated power of the single phase transformer (autotransformer 50/25 kV) is 60 (15) MVA.

The structure of the overhead line is shown in Fig. II.11; each track consists of the contact conductor (2), the messenger conductor (3), the feeder (4), the two rails (1), the overhead (5) and buried (6) ground wires.

The PWM-controlled converters are the ones reported in Fig.II.1, whose characteristics are reported in [II.17].

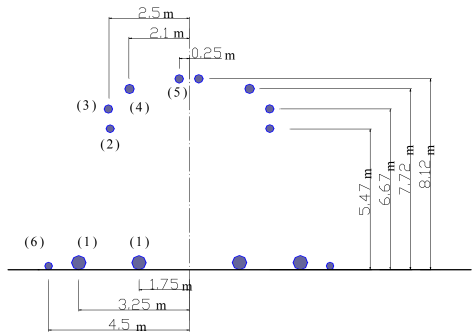


Fig.II.11 The overhead line

Several tests have been performed, considering different causes of uncertainties in the traction system, such as service scheduling, train speed, signalling, traction equipment control and so on; also uncertainties due to the AC three-phase supply system have been tested.

The results obtained with and without the iterative procedure involved by the step of the deterministic IHA have been compared.

As an example, in the following, the results obtained considering a service scheduling with 1, 2 and 4 trains is shown; the corresponding probabilities are reported in Tab. II.1.

Number Of Trains	Probability
1	0.18
2	0.35
4	0.47

Tab. II.1 – Probability of train occurrence

For each train, time-varying operating conditions have been considered along the section; in practice, a uniform probability density function is assumed for the train position assigning to each position the values of motor active power reported in Tab. II.2.

In case of more trains, they have been allocated in equal number on the two tracks; in case of 4 trains, the distance between two consecutive trains was assumed to be constant and equal to 24 km. No uncertainties have been considered for the three-phase supply system; the active and reactive linear load phase-powers at bus 2 (3) are P = 0.2 (0.15) p.u., Q = 0.03 (0.05) p.u..

In Fig. II.12, the mean values of unbalance factor at the HV three-phase busbars are reported; in Fig. II.13, the probability density function of the unbalance factor at bus 1 is reported.

Finally, in Fig. II.14 the probability density function of the 39th voltage harmonic at bus 1 with phase 2 is reported.

TRAIN POSITION X (KM)	ACTIVE POWER (P.U.)
x < 8	1.00
x <16	0.75
x < 24	0.50
x < 32	0.75
x < 40	1.00
x < 48	0.75

Tab. II.2 – Motor active power versus train position

As foreseeable, the unbalance factor values are decreasing approaching the generator busbars. Moreover, the probability density function of both unbalance factor and voltage harmonics (Figs. II.13 and II.14) are clearly bi-modal.

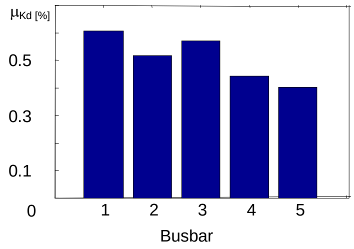


Fig.II.12 – Mean value of unbalance factor Kd at HV three-phase busbars

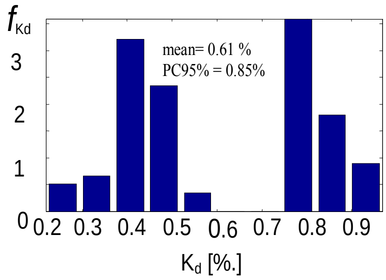


Fig.II.13 – Probability density function of unbalance factor Kd at bus 1

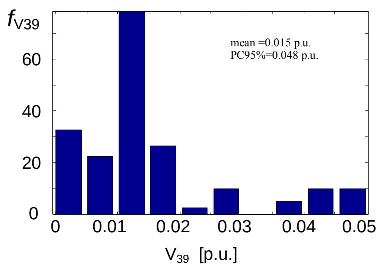


Fig.II.14 – Probability density function of 39th voltage harmonic at bus 1 with phase 2

CHAPTER III

TECHNOLOGICAL INNOVATION FOR RAILWAY QUALITY IMPROVEMENT

As already widely outlined in the previous section, in modern electrified transportation systems the relation between technical and safety performances and various disturbances level is mostly a “quality” relation. Under the “quality” point of view, a more effective unbalance and harmonic compensation of A.C. supply traction system can contribute to a remarkable improvement of the most relevant factors affecting quality performance of transportation systems [III.1-6]. Among these, for instance, let us mention:

1. quality performance in terms of reliability; under this aspect, the possibility of varying continuously the compensation level of traction loads under different conditions of the system operation can improve very much not only the mean time to failure in the various sections of supply system, but also the dependability levels as well as the maintenance requirements;
2. continuity of supplying; the compensation efficiently counteracts the critical lowering of quality parameters due to voltage or current waveform distortion, voltage unbalances or irradiated disturbances which could cause interruptions of supply, producing dangerous or damaging situations;

3. safety operation; the compensation, ensuring a prefixed quality standard of electrical supply, allows a correct operation of the electrical utilities and loads present in installations on both ground and board.
4. costs of supply; a reduction of costs is performed, this strictly linked to less expensive technical choices for guaranteeing robustness to quality disturbances, during all design, construction and management stages of the transportation system.

Furthermore, it has to be highlighted that the introduction of the liberalization of the electrical energy market requires reduced tolerable limits of both unbalances and harmonics. Hence, the railway companies must design in a proper way the supply section both for a secure operation of the train units but also for avoiding an impact on the utility which could be intolerable.

As previously mentioned, during the last few years it could be noted that supply systems have not attracted particular innovations, having preserved their traditional functional standards. This has been updated anyway through the technological components development. In fact, even if the principles of voltage regulation under load condition have been only recently introduced, a major technological innovation impulse occurred in the fields of motor drives, board equipments, signalling and telecommunication systems.

It is clear that in a systemic vision, a similar innovation process can not be returned also for supply section, allowing to obtain higher reliability and excellent quality performances.

Due to the difficulty in realizing dedicated power supply, the recourse to electronic and automation techniques can represent a powerful solution for delivering power with high efficiency to the railroad.

In this chapter, after having briefly examined both the traditional schemes for improving the unbalance factor and the recent compensation proposals, a new proposal of configuration of traction substation for single-phase alternating current supply will be described, based on the use of a two-phase inverter with a non-linear and variable structure control system. This advanced technical solution allows to obtain a full compensation of load unbalances, constant load voltage, satisfactory power factor and remarkable reduction of both disturbances and non-linear load effects.

Various numerical applications, effected with respect to the new compensation system, give evidence of its rejection action against disturbances and power parameters variations, as well as of its high performances in terms of fast response time, steady-state accuracy, and very low sensitivity to disturbances.

3.1 TRADITIONAL SOLUTIONS FOR QUALITY IMPROVEMENT

In the past, the problems related to the compensation of voltage and current unbalances have been solved either by duly distributing on the three primary phases the total power of single-phase transformation groups of the traction substations, or else by using substations with phase-transformation methods. These solutions have been satisfactorily developed for several decades, although it was not always reached, in actual situations, an acceptable level of unbalance degree, mainly under extreme operating conditions of the electric traction supply system.

More specifically, the phase-transformation methods mainly used are substantially based on different types of connections of single-phase transformers of the substation to the three-phase primary section:

1. Connection by cyclic permutation of phases;
2. V-connection;
3. Scott-connection;
4. Le Blanc Connection;
5. Steinmetz transformer configuration

The first method can be considered for the advantages in disposition and easier operation of substations, whereas the three phase short circuit power in the primary network is remarkably high if compared with single-phase load power. Instead, in case of single-phase load power comparable with three phase short circuit power at least in some sections of primary network, the expected unbalance degree requires a different solution to be searched between the other ones, even if at any rate a satisfactory operation of the supply system could not be easily reached.

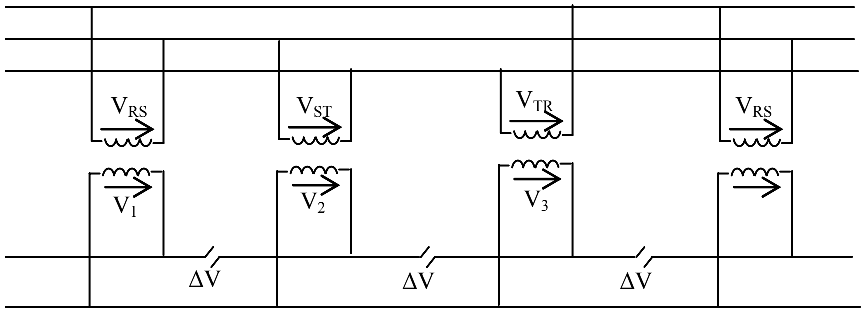


Fig.III.1 Connection by cyclic permutation of phases

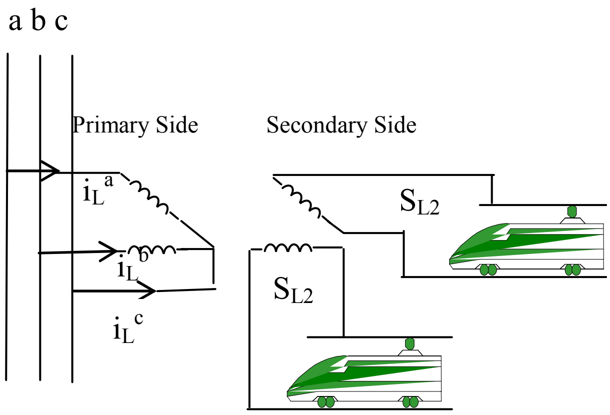


Fig.III.2 V Connection

Scott and Leblanc connections substantially transform three-phase to two-phase supply and allow to reduce the unbalance, but since asymmetry conditions are strictly depending on the great variability of traction loads, they will not give perfectly balanced conditions on the secondary side.

As far as concerns Scott-connection, let the N_{1A} turns of transformers A be supplied by the impressed voltage $\overline{\mathbf{V}}_{\mathbf{ab}}$, while the N_{1B} turns of transformer B are supplied by voltage $\overline{\mathbf{V}}_{\mathbf{c0}} = \overline{\mathbf{V}}_{\mathbf{ca}} + \overline{\mathbf{V}}_{\mathbf{ab}}/\mathbf{2}$. If a balanced three line-to-line voltage system is impressed, the voltage $\overline{\mathbf{V}}_{\mathbf{c0}}$ is in time quadrature with $\overline{\mathbf{V}}_{\mathbf{ab}}$; they are related to each other by the following relation:

$$\overline{\mathbf{V}}_{c0} = \frac{\sqrt{3}}{2}\overline{\mathbf{V}}_{ab} e^{j\pi/2}. \qquad \text{(III.1)}$$

By neglecting the transformer leakage drops and assuming that:

$$\frac{N_{1A}}{N_{2A}} = \frac{N_{1B}}{N_{2B}}\frac{2}{\sqrt{3}}. \qquad \text{(III.2)}$$

The *rms* values of the two secondary voltages are equal thus realizing in this way a symmetrical system of supply voltage. It can be easily demonstrated that the balancing condition requires I_A and I_B be equal and $\overline{I}_B$ lags behind $\overline{I}_A$ by $\pi/2$.

Similar considerations can be made with respect to Leblanc connection.

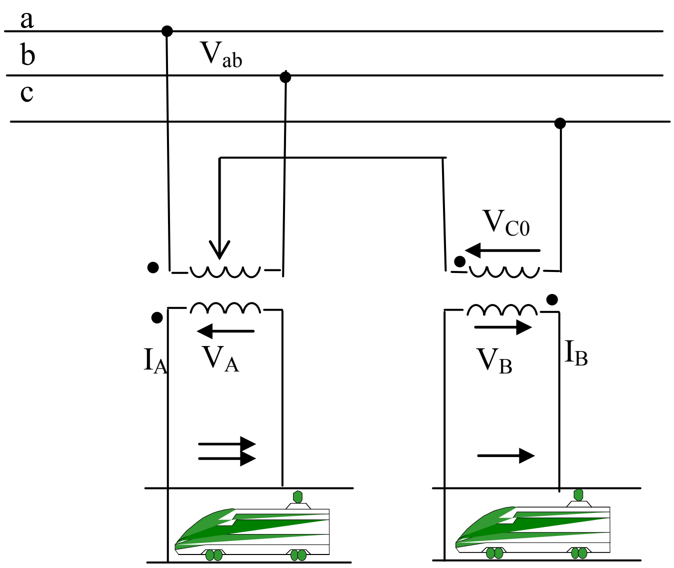


Fig. III.3 Scott Connection

Also the Steinmetz-transformer, a simple type of mitigation technique, allows a perfect balancing only for load traction value equal to the one assigned at the planning stage, for which the choice of the capacitor and inductor ratings is determined.

In conclusions, even if these last three solutions are still employed, due to their intrinsic limits, it is very reasonable to search for an improvement through the employment of advanced technology, since also small values of unbalance could produce undesirable effects.

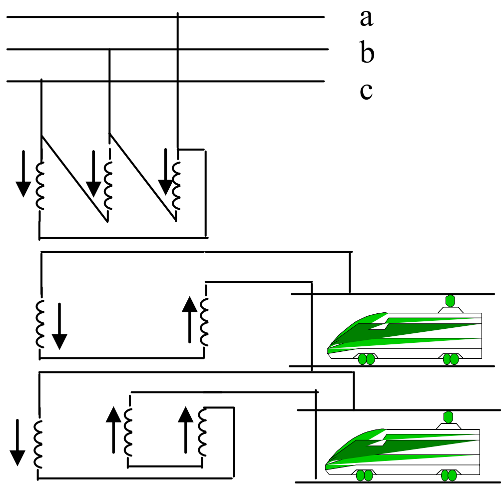


Fig. III.4 Le Blanc Connection

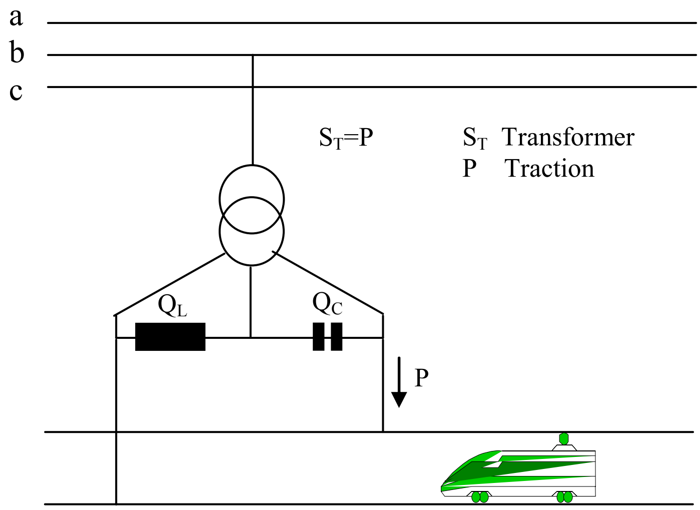


Fig. III.5 Single-phase load connected to a three-phase grid, using a Steinmetz transformer configuration

3.2 THE STATIC COMPENSATORS

The evolution of power electronics has involved a great revolution in the compensation techniques, allowing to overcome the difficulties related to the traditional ones. In fact, as just outlined, the significant drawback of the most employed techniques is that the perfect compensation is gained only for specified load conditions. In this context, suitable techniques, based on compensation by proper variable additional impedances on the transformer secondary, allow to obtain adjusting symmetric conditions on the three-phase grid. This is performed by employing fixed capacitors and controlled reactors, able to adjust dynamically the reactive powers to achieve balance conditions [III.3]. The balancing conditions are reported in Appendix I. Unfortunately, these static compensators, due to the control of firing angles, generate harmonics which require, naturally, a filtering action.

However, an interesting alternative is to make recourse to more advanced compensation techniques, generally able to operate with contemporaneous actions of balancing, harmonic filtering and voltage stabilization [III.7-10].

As well known, static compensators are able to compensate negative sequence currents generated by the load traction, but also to compensate dynamically the harmonics produced by on board converters. It should be noted that with respect to the harmonic disturbances, conventionally, passive filters have been employed to reduce the harmonic content at acceptable levels. However, passive filters exhibit the well known disadvantage related to resonances, fixed compensation and large size. Furthermore, the filtering action becomes very difficult due to the rapidly changing of traction loads.

The evolution of power electronics allows to consider even for high compensation levels force-commutated Var compensators. As well known the PWM technique permits both to obtain a remarkable reduction of the harmonic distortion and to realize the independence of the reactive power amount from the DC capacitor.

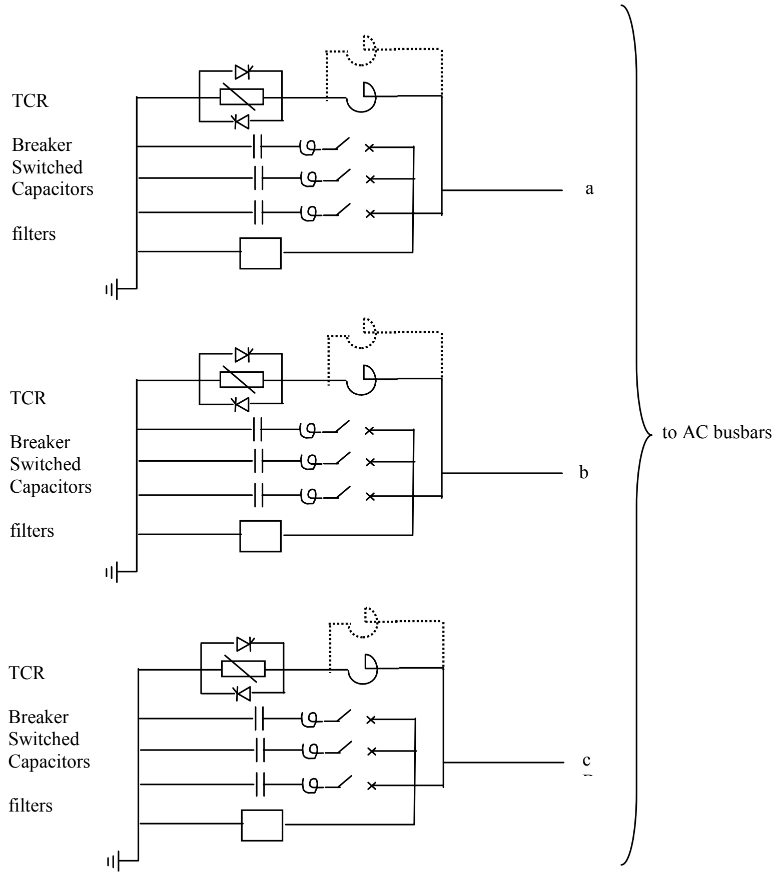


Fig.III.6 A typical static compensator arrangement for railway application

From this point of view, an interesting compensation technique is to employ an active load balancer able to generate a pure negative sequence current system in phase opposition to the one drawn by the AC traction system, in order to obtain a perfect balanced system.

It is clear that, under the hypothesis of pure positive sequence of supply voltage, the active power exchange between balancer and network is equal to zero.

In other words, the active balancer exhibits intrinsic capability to improve voltage behaviour, by counteracting the negative sequence component of the currents. This philosophy can be effectively implemented by calculating the real positive sequence components of the total traction loads currents. Hence the last currents are the required network reference currents **i*** to be tracked.

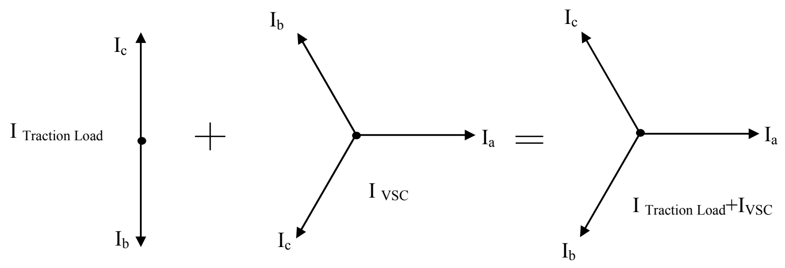


Fig. III.7 Compensator Phasor Diagram

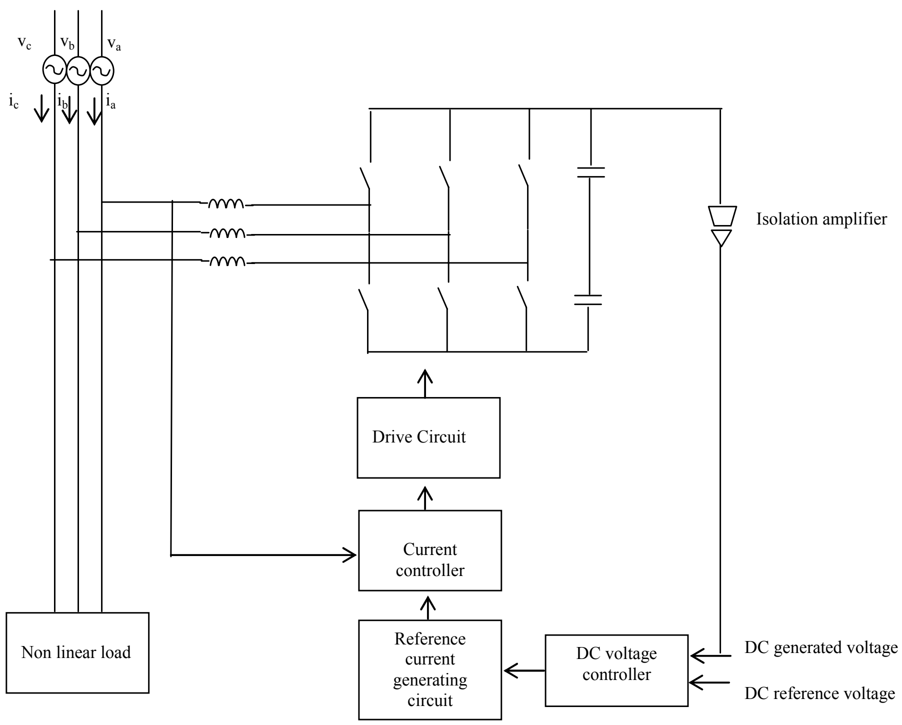


Fig. III.8 Converter for negative sequence compensation

The compensator operation can be easily understood introducing the single phase equivalent circuit of the inverter, depicted in Fig. III.9.

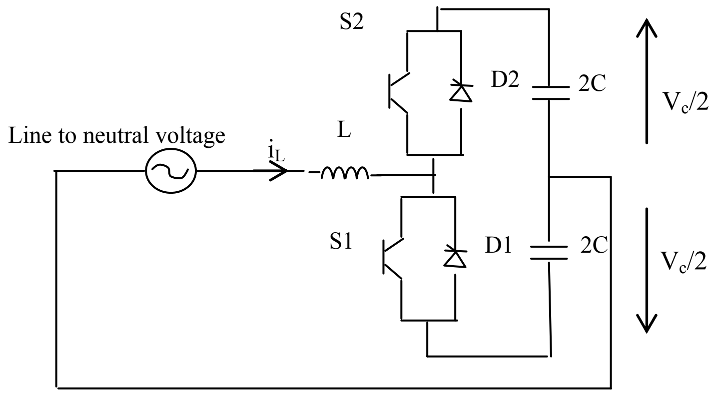


Fig. III.9 Single phase equivalent circuit of the inverter

By defining the switching function *u* such that *u=1* when either S1 or D1 is conducting and *u=-1* when either S2 or D2 is conducting, the inductor current is given by the following relation:

$$\frac{di_L}{dt} = \frac{v_{jn}}{L} - u\frac{v_c}{2L} \qquad \text{(III.3)}$$

where v_{jn} is the line to neutral voltage of the phase j at the point of common coupling, v_c is the DC bus voltage and L is the active compensator output inductor.

Naturally, for the correct inverter operation the condition $v_c/2>|v_{jn}|$ has to be satisfied. The DC time evolution can be simply derived by the following relation:

$$\frac{dv_c}{dt} = \frac{1}{C}[u_a i_a + u_b i_b + u_c i_c] \qquad \text{(III.4)}$$

where u_a, u_b and u_c are the independent control for phases a, b and c respectively and i_{La}, i_{Lb} and i_{Lc} are the compensating currents for phases a, b and c respectively. The filter model can be viewed as three first order independent systems which are described as:

$$i_{line,j} = i_{load,j} + i_{c,j} = i_{load,j} + \int\left(\frac{v_{jn}}{L} - u\frac{v_c}{2L}\right)dt. \qquad \text{(III.5)}$$

The compensation objectives determine the trajectories that must be followed by the system. The network line current $i_{line,j}$ is expected to follow the modified reference current $i^*_{ref,j}$, corresponding to the positive sequence of the unbalanced currents, the compensator providing the negative sequences.

The design of controllers in discontinuous control systems usually depends on the choice of the commutation or sliding surfaces, within *the state variables space*, where control functions are discontinuous [III.11-13].

The fundamental aspect of a variable-structure system is the feedback control, where discontinuities occur in one or more state-space manifolds (switching surfaces); as a consequence, the system structure varies when state variables cross the mentioned surfaces. The sliding condition occurs when the system state does not leave the commuting surface and the system dynamic can be described by a reduced-order system. In general, two different dynamic conditions can be distinguished:

- *reaching dynamics*, which is a fast dynamic, forcing the state variables of the system towards the sliding surfaces;
- *sliding dynamics*, that is a slower dynamic condition, where the state variables "slid" towards the origin of the state space, remaining in the sliding subspace.

Now, with respect to the active compensators, the following three desired state space surfaces, or sliding surfaces, can be defined:

$$s_j = [i_{line,j} - i^*_{ref,j}] = 0 \quad \text{j = a,b,c} \qquad \text{(III.6)}$$

In order to ensure the system to be maintained on the sliding surface, the following attraction condition should be satisfied for the control:

$$s_j \dot{s}_j < 0 \quad \text{j = a,b,c} \qquad \text{(III.7)}$$

at all times, i.e., for all values that the state may experience. A continuous theoretical control law can be derived by imposing the conditions $\dot{s}_j$ = 0 at all times. Mention should be made that if u_j is within the natural control bounds of the physical system, then it is possible to remain on the sliding surface, maintaining perfect tracking. For the active compensator, the expression (III.6) can be written as

$$\dot{s}_j = [(\dot{i}_{load,j}) + \frac{v_{jn}}{L} - (u_j)(\frac{v_c}{2L}) - (\dot{i}^*_{ref,j})] \tag{III.8}$$

By equating the last relation to zero, the equivalent control can be derived:

$$u_{eq,j} = [\dot{i}_{load_x} - \dot{i}^*_{ref_x} + \frac{v_{jn}}{L}]\frac{2L}{v_c}] \tag{III.9}$$

The satisfaction of (III.7) implies that the state is directed towards the switching surface, by the action of the switching control. Naturally, due to the linearity of (III.8), the following implications hold:

$$\begin{gathered} if \;\; u_j < u_{eq,j} \;\; then \;\; \dot{s}_j < 0 \\ if \;\; u_j > u_{eq,j} \;\; then \;\; \dot{s}_j > 0 \end{gathered} \tag{III.10}$$

By imposing that the equivalent control satisfies the natural bounds $-1 \le u_{eq} \le 1$, we finally obtain:

$$\begin{gathered} if \;\; s_j < 0 \;\; then \;\; u_j = 1 \\ if \;\; s_j > 0 \;\; then \;\; u_j = -1 \end{gathered} \tag{III.11}$$

Another feasible solution proposed for railway compensation is the employment of single-phase STATCOM applied at sectioning post to compensate voltage drop with respect to each phase [III.8].

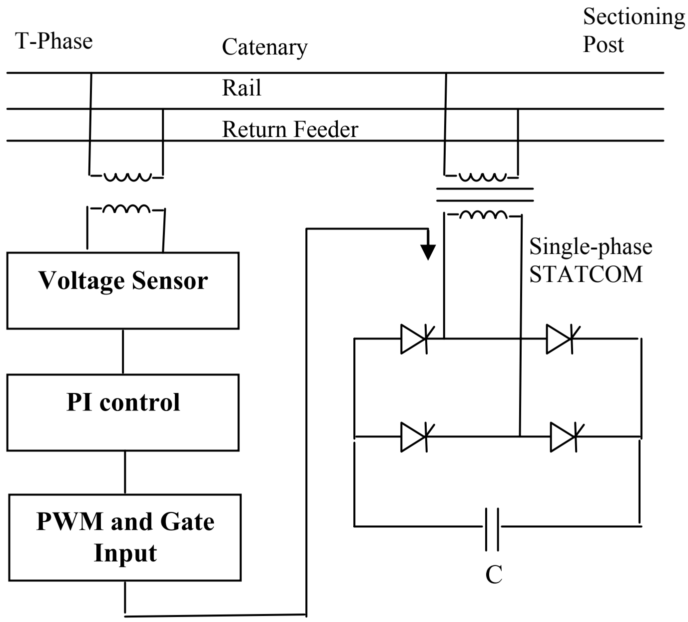


Fig. III.10 Voltage drop compensation by Statcom

As well known, the voltage drop can be efficiently approximated by the relation:

$$\frac{1}{V_0}(P_L R + Q_L X) \tag{III.12}$$

whereas R and X are the equivalent parameters of the feeding circuit, P_L is determined uniquely by traction load and V_0 is the rated voltage. Thus the reactive power Q_L can be controlled in order to cancel the voltage drop.

Since the AC electrified traction systems load demand is expected to show a fast growth, the relevant literature has also highlighted the need to investigate the effect on the real capability of the system. STATCOM can be efficiently employed for improving the power transfer capability [III.9], calculating for each traction load condition the reactive power to be tracked by STATCOM.

Naturally, the ability of STATCOM to improve the whole system performances significantly are intrinsically related to the goodness of the control law.

A possible fast and efficient tracking law for STATCOM could be the one described in [III.14]. The controllers operate in order to track the reference reactive power.

With reference to the scheme shown in fig.III.11, the resistance R takes into account the transformer and the inverter losses and L is the equivalent inductance of the transformer, v and v_i are respectively network voltage and inverter one and i is the current supplied by the VAR compensator.

Without loss of generality, only the fundamental component of the inverter voltage is considered. Voltage v_i is related to the dc voltage according to the relation:

$$v_i = \xi v_c \qquad \text{(III.13)}$$

where ξ is a numerical factor taking into account the converter topology.

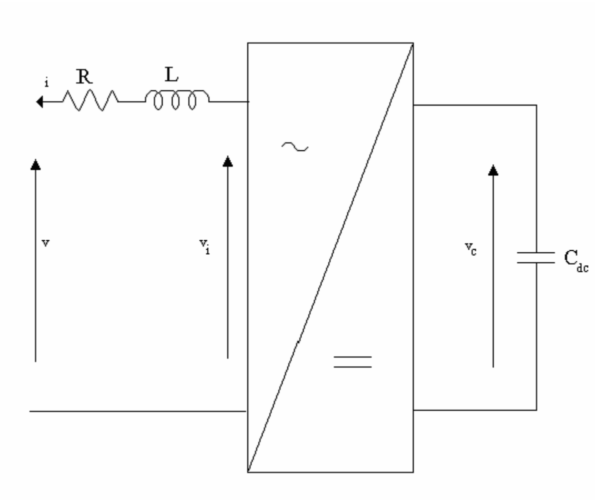


Fig. III.11 Advanced compensator

By describing the system in the d-q frame, rotating at the angular frequency ω, the following modelling can be deduced with p.u quantities:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ v_c \end{bmatrix} = \omega_n \begin{bmatrix} -\frac{R}{L} & \frac{\omega}{\omega_n} & -\frac{\xi \sin\beta}{L} \\ -\frac{\omega}{\omega_n} & -\frac{R}{L} & \frac{\xi \cos\beta}{L} \\ \frac{\xi \sin\beta}{C_{dc}} & -\frac{\xi \cos\beta}{C_{dc}} & 0 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ v_c \end{bmatrix} - \frac{\omega_n}{L}\begin{bmatrix} 0 \\ v \\ 0 \end{bmatrix} \qquad \text{(III.14)}$$

where β is the phase angle between the voltage vi and v= vq. Now, β changes allowing to vary the reactive power in the required way. In the modelling id and iq are the d-q components of the current i and ωn is the rated angular frequency. For the sake of simplicity $u = tg\beta$ should be considered as control variable.

In a compact way the system can be described as:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, u) \qquad \text{(III.15)}$$

Hence, the problem of the reactive power reference tracking has to be solved. For this aim, the control design is effected by employing the powerful concept of invariant manifold **M** as shown in [III.16], which has the property:

$$\begin{bmatrix} \mathbf{x} \\ u \end{bmatrix}_{t=t_0} \in \mathbf{M} \quad \Rightarrow \quad \begin{bmatrix} \mathbf{x} \\ u \end{bmatrix}_{t>t_0} \in \mathbf{M} \qquad \text{(III.16)}$$

The manifold can be efficiently approximated by the hypersurface **h(u)**, solution of **f(h,u)=0**, since**:**

$$\mathbf{M}(u, \varepsilon) = \mathbf{h}(u) + O(\varepsilon) \qquad \text{(III.17)}$$

with *O* Landau's symbol.

The tracking problem can be performed by choosing the control law $\dot{u} = \varepsilon\Gamma(u)E$ where $E=y-y_{rif}$. Choosing the control law:

$$\Gamma(u) = -\left[\frac{\partial y}{\partial \mathbf{x}}\frac{\partial \mathbf{h}}{\partial u}\right]^{-1}_{\mathbf{x}=\mathbf{h}(u)} \qquad \text{(III.18)}$$

being $\mathbf{x} = \mathbf{h}(u)$ the integral manifold, it follows that $E(t) \to 0$ if $t \to \infty$.

In fact, for the controlled system described as:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, u) \\ \dot{u} = -\varepsilon \left[\dfrac{\partial y}{\partial \mathbf{x}} \dfrac{\partial \mathbf{h}}{\partial u} \right]^{-1}_{\mathbf{x}=\mathbf{h}(u)} E(x) \end{cases} \tag{III.19}$$

if the following Lyapunov function [III.15] is selected:

$$V(u) = \frac{1}{2} \left[E(\mathbf{h}(u, \varepsilon)) \right]^2 \tag{III.20}$$

the system exponential stability can be proven. Therefore, since the state vector is restricted at the invariant manifold:

$$\begin{cases} \dot{u} = -\varepsilon \left[\dfrac{\partial y}{\partial \mathbf{x}} \dfrac{\partial h}{\partial u} \right]^{-1}_{\mathbf{x}=\mathbf{h}(u)} E(h(u)) \\ \mathbf{x}(t) = \mathbf{h}(u(t)) \end{cases} \tag{III.21}$$

by deriving $E(\mathbf{x})\big|_{\mathbf{x}=\mathbf{h}(u)} = y(\mathbf{h}(u)) - y_{rif}$:

$$\begin{aligned} \dot{E}(\mathbf{x})\big|_{\mathbf{x}=\mathbf{h}(u)} &= \left[\frac{\partial y}{\partial \mathbf{x}} \frac{\partial \mathbf{h}}{\partial u} \right]_{\mathbf{x}=\mathbf{h}(u)} \dot{u} = \\ &= \left\{ \left[\frac{\partial y}{\partial \mathbf{x}} \frac{\partial \mathbf{h}}{\partial u} \right]_{\mathbf{x}=\mathbf{h}(u)} \right\} \cdot \left\{ -\varepsilon \left[\frac{\partial y}{\partial \mathbf{x}} \frac{\partial \mathbf{h}}{\partial u} \right]^{-1}_{\mathbf{x}=\mathbf{h}(u)} E(\mathbf{h}(u)) \right\} = -\varepsilon E(\mathbf{h}) \end{aligned} \tag{III.22}$$

the exponential stability is demonstrated.

Now, the rationale behind this control design is to track the reactive power q_{ref} which depends on the i_d magnitude. With reference to the Statcom modelling by calculating the steady-state operation, the following relation can be stated:

$$i_d^* = -\frac{v}{2R} \frac{u^*}{1 + u^{*2}} \tag{III.23}$$

The reactive power $q = v \cdot i_d^* = -\frac{v^2}{2R}\frac{u^*}{1+u^{*2}}$ is associated to the direct current component. Therefore, once the reactive power to be produced has been determined, i_d^* can be tracked by the following control law:

$$\dot{u} = -\varepsilon \frac{R(1-u^2)}{v(u^2+1)^2}(i_d - i_d^*) \qquad \text{(III.24)}$$

Another interesting solution is the technique based upon the coupling of Scott-connected transformers and a voltage two-phase inverter, allowing to stabilize load voltage at the reference value, to improve power factor and to reduce the effects of disturbances existing in the network [III.15].

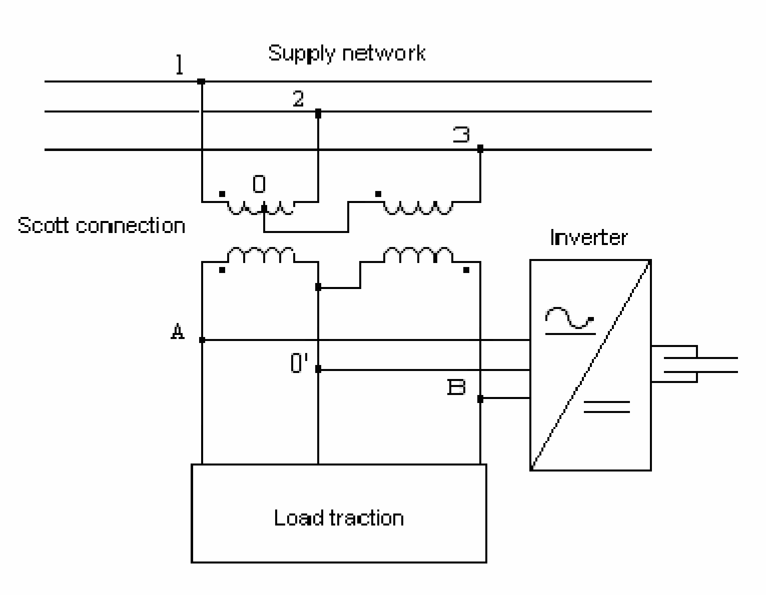


Fig.III.12 Scott Transformer – two phase inverter

The inverter is controlled in order to distribute electrical powers between various circuits according to the balance objectives and power factor correction. In other words this solution allows, through the inverter introduction, to overcome the Scott connection limits, obtaining the possibility to optimize the system performances in every traction load condition.

It has to be highlighted that, according to the functional integration philosophy, the introduction of the compensator has to be performed in order to satisfy the requirements of efficiency, economy and component simplicity. The introduction of the Scott-connection is not aligned with the integration because the technology of this transformer is quite different from the ordinary ones.

In this thesis, starting from the last proposal, a more feasible solution avoiding the Scott connection is proposed, thus satisfying all the compensation constraints in a feasible way, guaranteeing a correct integration at low cost.

3.3 A NEW SOLUTION TO THE COMPENSATION PROBLEM

This section proposes a new technological standard of substation for supplying a single-phase high voltage electrified railway system. Although the methodology is general, it will be explained referring to 25 kV-50 Hz electrified railway system.

Initially, a fundamental point is the selection of the way by which to connect the static compensator to the power grid. The first alternative is the direct connection where the traction power transformer and the compensator one are connected to the same point of the grid, as it was discussed in the previous section.

The second configuration named intermediate connection, is reported in Fig.III.13.

As demonstrated in [III.7], the intermediate voltage level offers greater advantages than direct connection of both traction transformer and compensator, with respect to harmonics and traction voltage level. This is easy to argue by examining the relative weight of the various equivalent impedances. Furthermore, it can result useful to choose a main transformer impedance large enough in order to constraint the short circuit currents to allowable values.

The compensator design has to be effected according to the logic that no active power must be exchanged with the traction loads. In other words the network supplies the active power absorbed by the traction loads and the one for compensating inverter losses; the compensator has the important role to distribute the whole active power supplied by the network according to the specific traction load demands.

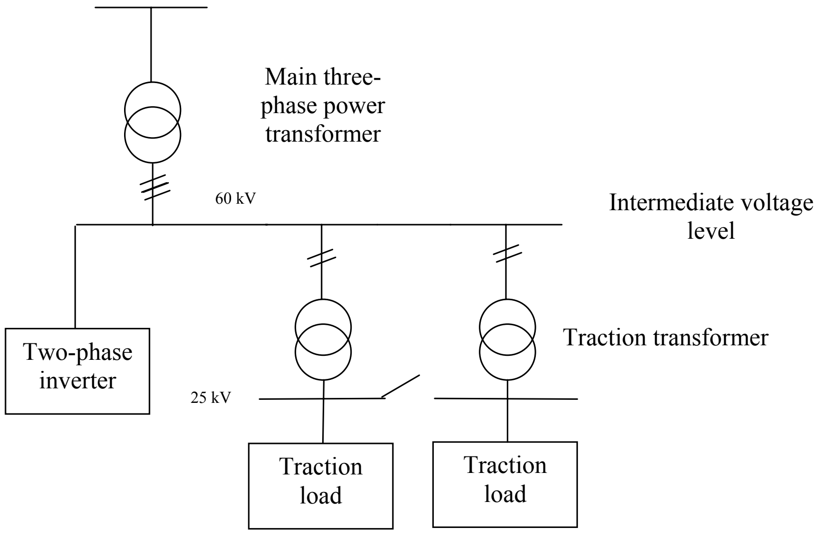


Fig.III.13 Supply system with intermediate connection

As far as concerns the choice of the inverter topology, the attention was focused on the two-phase one, since number reduction of power semiconductor devices with respect to the solution employing six-switch bridge voltage-source inverter implies not only a cost reduction but also a reliability increase [III.16]. This allows to confirm that the integration requirements are satisfactorily realized.

In Fig. III.14 the circuit diagram is depicted, whereas the network is represented by an equivalent pure positive sequence voltage and the traction loads are described by equivalent current sources i'_A and i'_B. The values of these sources have to be dynamically estimated, as shown at the end of section 3.5. The three-phase transformer is represented by the equivalent parameters L_t, R_t. The presence of a suitable inductor in series with the transformer could be necessary in order to decouple the inverter by network, obtaining better performance in terms of Power Quality. In this case the equivalent parameters L_t, R_t take into account both the presence of the transformer and the inductor one.

This arrangement allows to stabilize load voltage at the reference value, to improve power factor and to reduce the effects of disturbances existing in the network, including those introduced by the non-linearity of loads.

The controlled system is regarded as a two-phase system where the former (A) is supplied by the line-to-line voltage e_{ab} while the latter (B) by e_{bc}. The two-phase inverter generates the two voltages u_{IA} and u_{IB}, whereas a L_f-C_f filter is arranged at the inverter output for each phase.

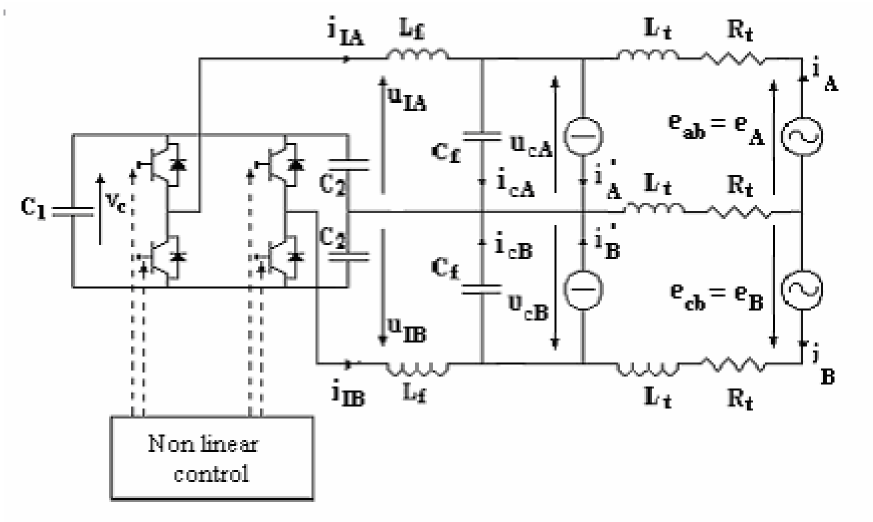


Fig.III.14 Equivalent circuit of the system

The rationale behind this configuration is the ability of the inverter to play a fundamental role in distributing electrical powers among the various circuits according to balance requirements and power factor correction. In other words, with reference to steady state conditions, the inverter does not exchange active power with the traction loads, so that only the primary network supplies the active power required by the traction loads and the active power needed to compensate inverter losses. On this proposal, it is easy to show that, for a given phase angle α between the voltage of each inverter phase and the network one, the compensator delivers no active power.

Assuming inverter losses as negligible, the network will supply the whole power absorbed by loads P_A e P_B when the following condition is satisfied:

$$\alpha_A = \alpha_B = \alpha^* = \beta - \arccos\left[P_A + P_B + \frac{U_{c\,ref}^2 R_t}{Z_t^2} \right] \frac{Z_t}{EU_{c\,ref}} \qquad \text{(III.25)}$$

where Z_t is the transformer equivalent impedance, $\beta = arctg X_t / R_t$ is the internal angle of the transformer impedance and U_{cref} is the reference voltage rms value, evaluated in order to vanish the reactive power supplied by network. More specifically, reactive power supplied by network vanishes when the following condition is satisfied:

$$U_c = U_{c,ref} = \frac{EX_t}{R_t \sin\alpha + X_t \cos\alpha} \tag{III.26}$$

Naturally the following constraints are required $U_{c,\min} \le U_{c,ref} \le U_{c,\max}$ in order to guarantee that the voltage is within admissible range.

Having this in mind, a capacitor at the DC side of the inverter can result adequate. The control system, besides, should stabilize the voltage of this capacitor when the operating conditions change.

As far as concerns the characteristics of the inverter, it can be highlighted that the design depends on the most unfavorable conditions which are exhibited when remarkable voltage dips occur, as it can be argued from the simulations reported in section 3.5. From the knowledge of the real characteristics of the voltage dips, the consequent maximum value of the inverter current and its cycle duration can be determined, allowing to choose the inverter rated power.

The switching frequency influences the qualitative characteristics of the proposed system in terms of instantaneous error between the AC load reference voltage and the real one. More specifically the error increases as the switching frequency decreases. A low value of the switching frequency requires an increased value of the capacitor C_f rated power. The choice of the various parameters values can be performed by an optimization procedure permitting to satisfy the technical constraints at allowable costs. More specifically, the selection of parameters L_f, C_f and main transformer parameters has to be effected in order to take contemporaneously into account the constraints with respect to ripple current, reactive power flowing into capacitor C_f and attenuation requirements. A coordination of these parameters has to be performed with the choice of the DC voltage in order to satisfy also the constraints with respect to the inverter control, as successively highlighted.

3.4 THE INVERTER CONTROL LOGIC

The system under study can be described by the following equations where, for notation clarity, the voltages e_{ab} and e_{bc} will be respectively written by e_A and e_B:

$$
\begin{aligned}
& e_j = 2L_t \frac{d}{dt} i_j + 2R_t i_j + u_{cj} + L_t \frac{d}{dt} i_k + R_t i_k \\
& u_{Ij} = L_f \frac{d}{dt} i_{Ij} + u_{cj} \qquad\qquad j,k \in \{A,B\} \\
& i_{cj} = C_f \frac{d}{dt} u_{cj} \qquad\qquad\qquad k \neq j \\
& i_j + i_{Ij} = i_j^{'} + i_{cj}
\end{aligned}
\tag{III.27}
$$

where $\mathbf{x_j} = (\dot{u}_{cj}, u_{cj})^T$, the mathematical model of the system can be expressed as follows:

$$\dot{\mathbf{x}}_\mathbf{j} = \mathbf{A_j x_j} + \mathbf{B_j} u_\mathrm{j} + \mathbf{B_{dj}} d_\mathrm{j} \tag{III.28}$$

where:

$$\mathbf{A_j} = \begin{bmatrix} 0 & c_{2j} \\ 1 & 0 \end{bmatrix} \quad \mathbf{B_j} = \begin{bmatrix} c_{3j} \\ 0 \end{bmatrix} \quad \mathbf{B_{dj}} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad , \quad j \in \{A,B\}, \text{ and}$$

$$c_{2j} = -\left(\frac{1}{L_f C_f} + \frac{1}{2L_t C_f} \right) \quad c_{3j} = \frac{1}{L_f C_f} \quad , \quad j \in \{A,B\},$$

$$d_j = \frac{e_j}{2L_t C_f} - \frac{R_t}{L_t C_f} i_j - \frac{1}{C_f} \frac{d}{dt} i_j^{'} - \frac{1}{2C_f} \frac{d}{dt} i_k - \frac{R_t}{2L_t C_f} i_k \quad j \in \{A,B\}, \quad k \neq j,$$

$$u_j = u_{Ij} = \pm v_c.$$

The quantities d_j could be considered as disturbances.

The proposed control system, for which high precision and fast response is required, is developed on two different time scales, corresponding to two different dynamic modes. The former "fast" regulation refers to the problem of stabilizing load voltages, which is related to the generation of sinusoidal waveforms with constant amplitude and constant frequency equal to the network frequency. Therefore, attention has been devoted to the Sliding mode control method, which is based on the theory of variable structure systems – to which greater and greater interest has been paid in specific literature – since converters are intrinsically characterized by a time-variant structure [III.17-23]. Furthermore, this control method shows very good robustness against disturbances and parameters variation. Referring to "fast" regulation, the two phases of the system can be considered as independent and, thus, for simplicity, subscript can be omitted.

The latter "slow" regulation refers to the problem of maintaining the DC side voltage of the inverter at a given reference value. Actually, having considered the capacitors bank C_1, it is necessary to control the phase angles α between the inverter output voltages and the network side line-to-line voltages, in order to keep the mean value of the capacitor voltage constant. More specifically, the control system "adapts" the quantities to the operating condition changes.

The main principles of the two control systems will be described in the following. For the sake of simplicity and in accordance with the actual specific literature, they will be named as *Sliding Mode Control* and *Non Linear Tracking.*

3.4.1 Sliding Mode Control

The steady-state and dynamic features of the system can be described in terms of *state variables error,* that is to say as the deviation of state variables with respect to a reference value.

In the case proposed, the following reference model was chosen for each of the two phases of the diagram [III.17-18]:

$$\dot{\mathbf{x}}_r = \mathbf{A}_r \, \mathbf{x}_r \tag{III.29}$$

with:

$$\mathbf{A_r} = \begin{bmatrix} 0 & -\omega^2 \\ 1 & 0 \end{bmatrix}, \qquad [\mathbf{x_r}] = [x_{r1}, x_{r2}]^T,$$

where ω is the network angular frequency and:

$$x_{r1} = -\sqrt{2}\,\omega U_{c\,ref} \sin(\omega t + \varphi - \alpha), \qquad x_{r2} = \sqrt{2}\,U_{c\,ref} \cos(\omega t + \varphi - \alpha)$$

where φ is the phase angle at t=0 of the network voltage '*e*'.

In the previously mentioned expressions the angle α has been considered as a constant parameter. The vector **x** of the state variables under control can be measured and compared with the reference model vector. "Error" vector is:

$$\mathbf{x_e} = \mathbf{x_r} - \mathbf{x} \tag{III.30}$$

The commutation surface, that is the state subspace where the variation of the inverter configuration occurs, was chosen as a function of error $\mathbf{x_e}$:

$$s(\mathbf{x_e}) = \mathbf{S_e x_e} = S_1\,(x_{1r} - x_1) + S_2\,(x_{2r} - x_2) \tag{III.31}$$

with $[\mathbf{S_e}]^T = [S_1, S_2]$. In the ideal hypothesis of the infinite commutation frequency of electronic switches commutation, the control law will be:

$$u_I = \begin{cases} v_c & \text{if } \; s(\mathbf{x}_e) > 0 \\ -v_c & \text{if } \; s(\mathbf{x}_e) < 0 \end{cases} \tag{III.32}$$

or else, in the real case of finite commutation frequency:

$$u_I = \begin{cases} v_c & \text{if } \; s(\mathbf{x}_e) > \Delta \\ -v_c & \text{if } \; s(\mathbf{x}_e) < -\Delta \end{cases} \tag{III.33}$$

where the selection of the band Δ is rather complex depending on the maximum allowable switching frequency, parameters $[S_1, S_2]$ [III.18-19].

The existence of the sliding mode along commutation surfaces is subordinated to the satisfaction of the reaching conditions:

$$s\dot{s} < 0 \qquad \text{(III.34)}$$

By assuming that III.33 is satisfied, the system will successively operate under sliding mode conditions, that is to say the dynamics of the state variable error $\mathbf{x_e}$ will follow the commutation surface. Since $\mathbf{x_e}$ represents the state variable error, the required operating point occurs when $\mathbf{x_e} = \mathbf{0}$. If the previously mentioned conditions are satisfied, $\mathbf{x_e}$ "slids" until – after a transient period – the origin of the state space is reached.

The control law $u=u_{eq}$ (equivalent control law), can be then obtained by assuming that:

$$\dot{s}(\mathbf{x_e}) = 0 \qquad \text{(III.35)}$$

from which, if matrix $(\mathbf{S_e B})$ is invertible, we obtain:

$$u_{eq} = (\mathbf{S_e B})^{-1}\,\mathbf{S_e}\,(\mathbf{A_r x_r} - \mathbf{Ax} - \mathbf{B_d}d) \qquad \text{(III.36)}$$

Therefore, sliding mode occurs only when the condition:

$$-v_c \le u_{eq} \le v_c \qquad \text{(III.37)}$$

is satisfied.

The system static and dynamic features can be expressed as a function of the state variable error:

$$\dot{\mathbf{x}}_\mathbf{e} = \dot{\mathbf{x}}_\mathbf{r} - \dot{\mathbf{x}} = \mathbf{A_r x_r} - \mathbf{Ax} - \mathbf{B\,u} - \mathbf{B_d}d \qquad \text{(III.38)}$$

Then, by substituting $u = u_{eq}$, we have:

$$\dot{\mathbf{x}}_\mathbf{e} = \mathbf{A_e x_e} \qquad \text{(III.39)}$$

where:

$$\mathbf{A_e} = \begin{bmatrix} -\dfrac{S_2}{S_1} & 0 \\ 1 & 0 \end{bmatrix}.$$

The latter expression describes the dynamic behaviour of the state error and, correspondingly, it allows to estimate the steady-state and dynamic features of the system. Matrix $\mathbf{A_e}$ is singular since the original system of second order is reduced to first order. The time constant of the reduced system is $T = S_1/S_2$ and, without generality loss, it could be set S_2=1. Moreover, it appears evident that under sliding conditions the system dynamics is completely independent from the system parameters; this confirms the robustness of the control system against structural perturbations [III.13].

The constant S_1, regulating error dynamics, is selected by assigning to the matrix $\mathbf{A_e}$ proper eigenvalues, in order to make dynamics as quick as possible, existence conditions being satisfied. The satisfaction of the latter conditions has required a $L_f - C_f$ filter.

The reference voltages of the two-phase system will be:

$$\begin{aligned} u_{crefA} &= \sqrt{2}\,U_{c\,ref}\cos\left(\omega t - \alpha^*\right) \\ u_{crefB} &= \sqrt{2}\,U_{c\,ref}\cos\left(\omega t - \alpha^* + \pi/3\right) \end{aligned} \tag{III.40}$$

The generation of these two reference voltages allows to satisfy:

- load balancing;
- filtering of harmonics caused by the non-linearity of loads;
- load factor correction;
- load voltage stabilization when load or network parameter variations occur.

3.4.2 Non Linear Tracking

Now, a control system has to be designed providing, according to the various operating conditions, the desired value of angle α^*. Under these conditions the mean value of the capacitor voltage C_1 on DC side will not change.

The variation law of the capacitor voltage C_1 mean value, starting from powers balance with respect to mean values, is:

$$\dot{v}_c = \frac{[P_N - P_L]}{C_1 v_c} \tag{III.41}$$

where P_N is the active power supplied by the network and $P_L=P_A+P_B$ the total active power absorbed by the load.

The previous expression can be rewritten as:

$$\dot{v}_c = \frac{1}{C_1\, v_c}\left[\frac{EU_{c\,ref}}{Z_t}\cos(\beta-\alpha) - \frac{U_{c\,ref}^2\, R_t}{Z_t^2} - (P_A + P_B)\right] \tag{III.42}$$

and, by imposing $x = v_c$, we obtain:

$$\dot{x} = \frac{u_\alpha}{C_1 x} \tag{III.43}$$

where:

$$u_\alpha = \left[\frac{EU_{c\,ref}}{Z_t}\cos(\beta-\alpha) - \frac{U_{c\,ref}^2\, R_t}{Z_t^2} - (P_A + P_B)\right] \tag{III.44}$$

If the following expression, as non linear control law, is chosen [III.24]:

$$u_\alpha = V_{C\,ref}\, C_1\, x(t)\frac{K}{C_1} - K\, x^2(t) \tag{III.45}$$

where V_{Cref} is the reference value of the capacitor voltage C_1, the dynamics of the controlled system will be:

$$\dot{x} + \frac{K}{C_1}x = \frac{K}{C_1}V_{C\,ref} \tag{III.46}$$

where, according to the constant K value, the state evolution will follow the dynamics typical of a first order system; K value is taken in order to make the dynamics of this regulation slower than the sliding mode dynamics. Then, the control law becomes:

$$\alpha(t) = \beta - \arccos\left[\left((P_A + P_B) + KV_{C\,ref}\, v_c(t) - Kv_c^2(t) + \frac{U_{c\,ref}^2 R_t}{Z_t^2}\right)\frac{Z_t}{EU_{c\,ref}}\right] \quad \text{(III.47)}$$

If the control function expressed by (III.47) is investigated, it appears that this function depends on the quantities P_A and P_B which are usually contaminated with noise and disturbances. Their evaluation requires an estimation algorithm, if uncertain operating conditions are considered. P_A and P_B estimation is equivalent to i_A and i_B estimation. Furthermore, network angular frequency ω has to be estimated for generating the inverter voltages. The estimation procedure is reported in Appendix B.

3.5 Numerical Applications

In order to evaluate the compensator operation, several simulations have been performed under disturbed operating conditions. The rated power of the main three-phase transformer is P_n = 12 MW, whereas the secondary rated voltage (intermediate voltage level) is equal to 60 kV. In order to demonstrate the device effective filtering action, the presence of load current harmonics was also assumed; in particular fifth and seventh harmonic components have been considered. The parameters relative to the simulations are reported in Table III.1 and various parameters are referred to the base voltage equal to 60 kV.

The first case examined refers to a step variation of traction load B. Initially loads A and B are equal to 5 MW with cosφ =0.95. Hence, at instant t=0.2 s a step variation occurs, whereas the load drawn by the load B is reduced to zero. The selection of filter parameters L_f, C_f and transformer-inductor global parameter L_t is performed in order to carry out a compromise between a satisfactory degree of the voltage harmonic distortion factor and the inverter size. Furthermore, this choice has to guarantee that the equivalent control variables, referred to the single phases of the inverter, satisfy expression III.37. Constant S_1, adapting error dynamics, has been chosen by assigning a proper value to the non-zero eigenvalue of matrix $\mathbf{A_e}$, in order to make the dynamic behaviour as fast as possible, according to the Sliding mode existence conditions. Figg. III.15-19 clearly indicate the stabilization performed of load voltage, the balancing of network currents, the power factor correction and filtering action carried out by the device against the disturbance produced by the non linear unbalanced load.

The second case refers to the compensator behaviour in the presence of network voltage dip (50% rms variation), ten cycles duration, starting from the instant t = 0.2 s. Also in this case, as confirmed by Figg. III.20-23, the stabilization performed of load voltage, the balancing of network currents, the power factor improving and the filtering action is successfully obtained. As clearly demonstrated in Figg.III.20-23, during voltage dip, the load stabilization is fully satisfied, but a small distortion exists due to non ideal behaviour of the compensator. The distortion, during this interval, could be significantly reduced by increasing the C_f capacitor value, but with a consequent increase of capacitor and inverter size. Hence, since during the voltage dip the fundamental requirement is load stabilization, the small distortion can be retained acceptable. The optimal behaviour of system highlighted by the numerical results can be theoretically deduced also by proving the invariance of sliding mode [III.11-13]. The parameter variations imply variation terms of state space matrix $\mathbf{\Delta A_j}$ and/or input matrix $\mathbf{\Delta B_j}$. The invariance is a noticeable property which naturally involves robustness and insensitivity against disturbances and parameter variations. With reference to the system under study perturbations, the new system is described by:

$$\dot{\mathbf{x}}_{\mathbf{j}} = \mathbf{A}_{\mathbf{j}}\mathbf{x}_{\mathbf{j}} + \mathbf{B}_{\mathbf{j}}\, u_{\mathbf{j}} + \mathbf{B}_{\mathbf{dj}}\, d_{\mathrm{j}} + \Delta\mathbf{A}_{\mathbf{j}}\mathbf{x}_{\mathbf{j}} + \Delta\mathbf{B}_{\mathbf{j}}\mathbf{x}_{\mathbf{j}} \tag{III.48}$$

Since the system under study satisfies the matching conditions which mean $\mathbf{\Delta A_j}$, $\mathbf{\Delta B_j}$ and d_j are in the subspace spanned by $\mathbf{B}_{\mathbf{j}}$, the sliding mode is invariant with respect to $\mathbf{\Delta A_j}$, $\mathbf{\Delta B_j}$ and d_j.

$I_{5\ rms}$ [A]	12.5
$I_{7\ rms}$ [A]	8.8
R_t [Ω]	7.50 [Ω]
L_t [H]	.24 [H]
C_1 [μF]	400
C_2 [μF]	15
L_f [H]	0.2
C_f [μF]	4.8
f_{cmax} [kHz]	1
S_1 [s]	0.001
K/C_1 [s]	0.050

Table III.1 – Simulation parameters

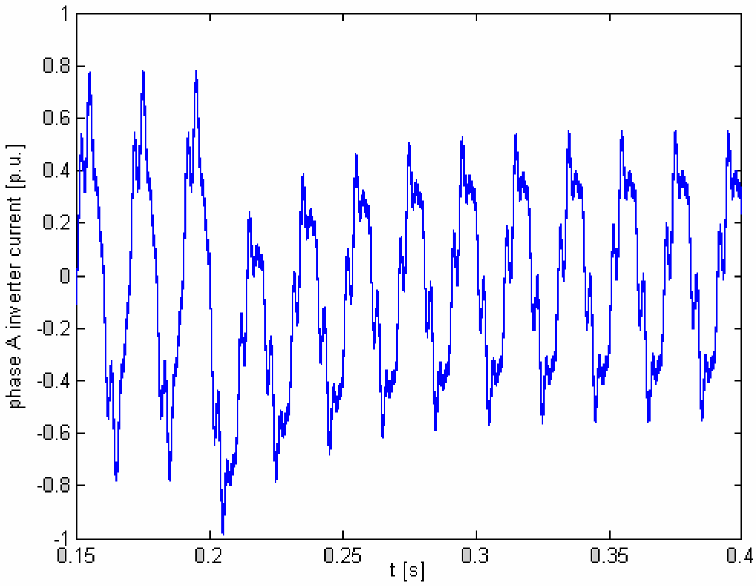


Fig.III.15.a: Phase A inverter current

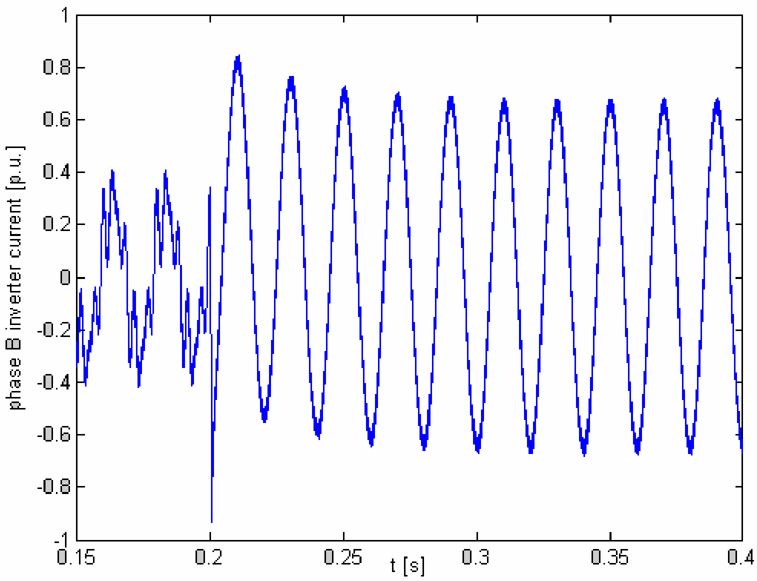


Fig.III.15.b: Phase B inverter current

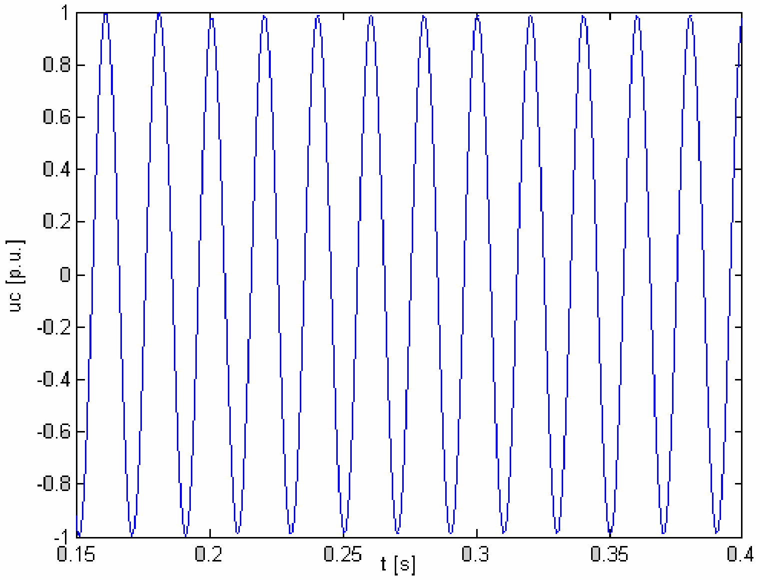


Fig.III.16. a: Load voltage

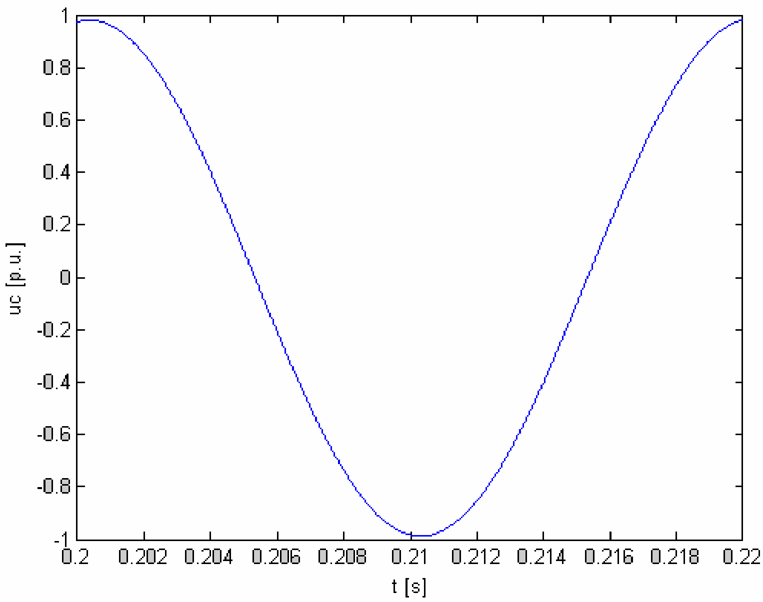


Fig.III.16.b: Load voltage

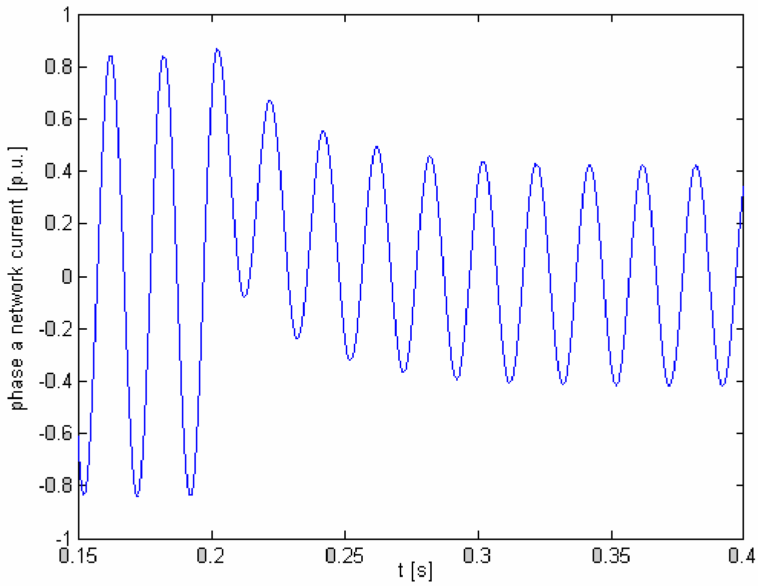


Fig.III.17: Phase a network current

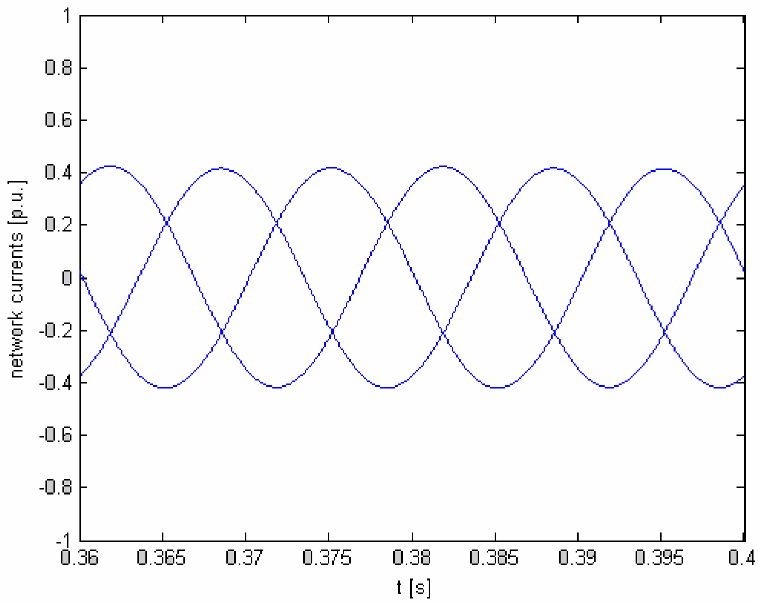


Fig.III.18: Network currents

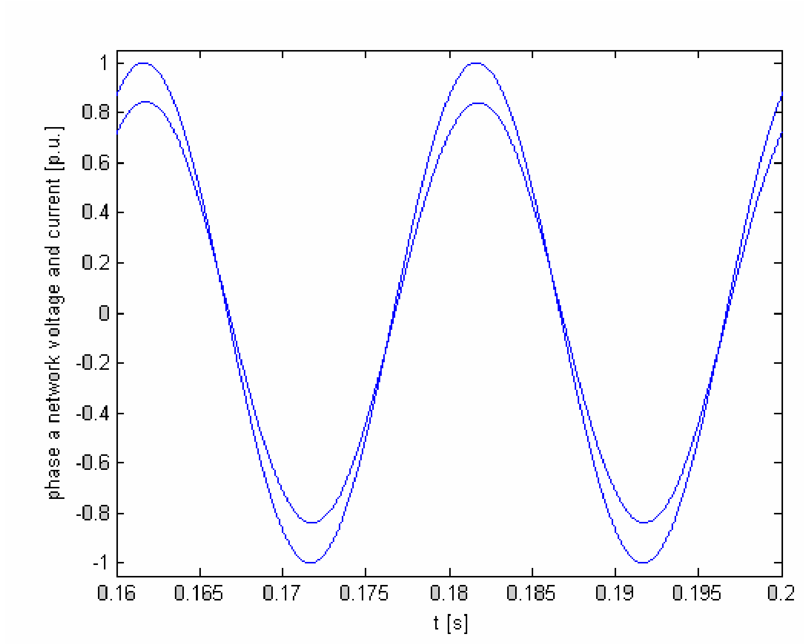


Fig.III.19: Phase a network current and voltage

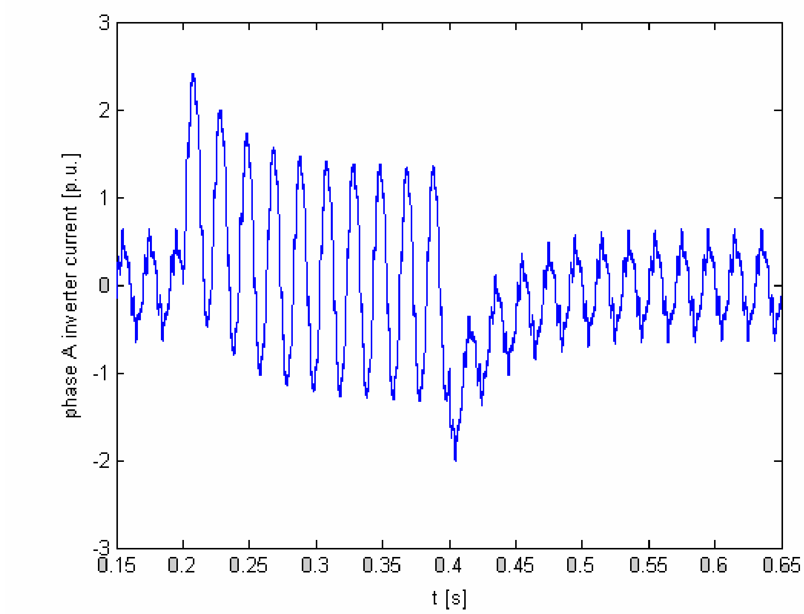


Fig.III.20.a: Phase A inverter current

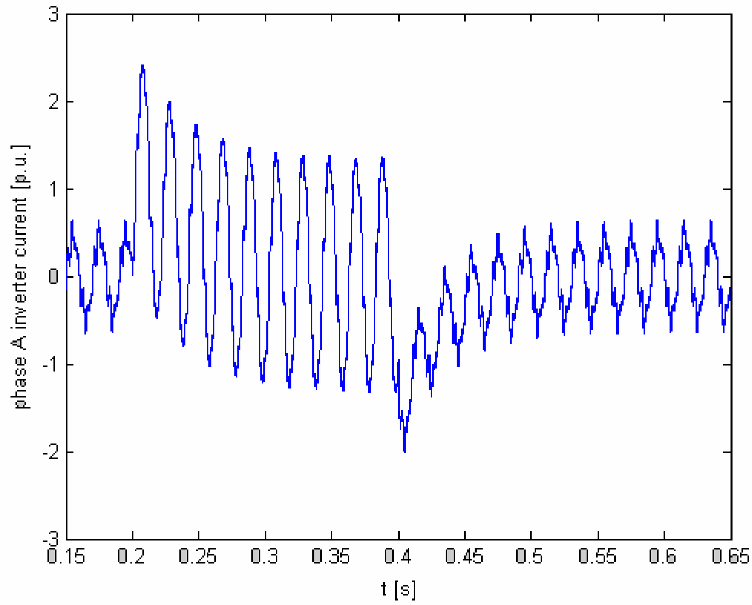


Fig.III.20.b: Phase B inverter current

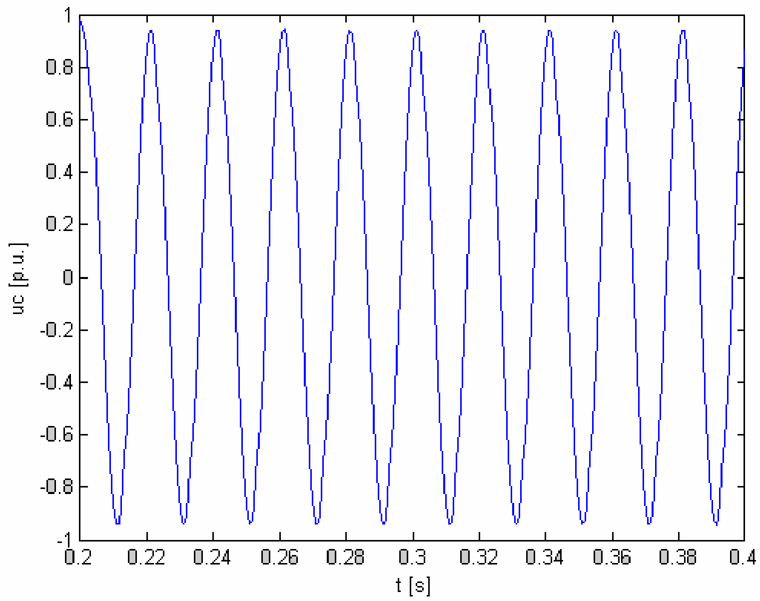


Fig.III.21.a: Load voltage

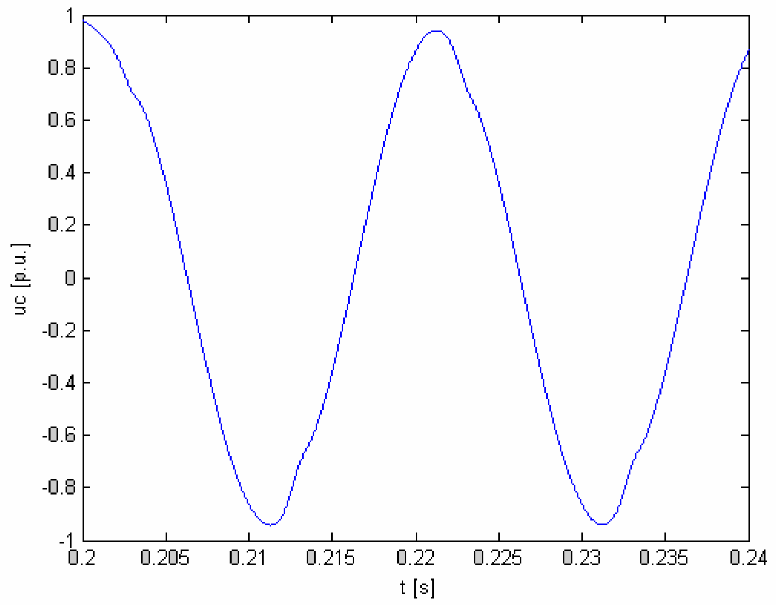


Fig.III..21.b: Load voltage

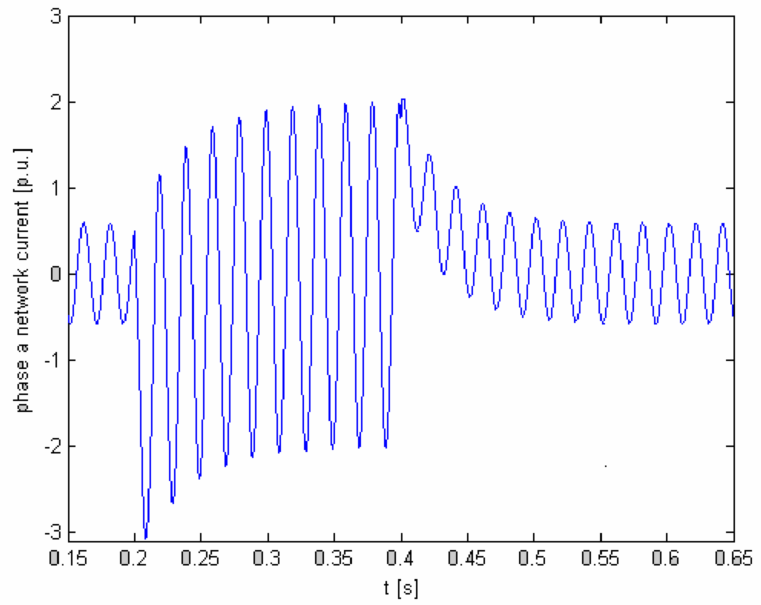


Fig.III.22: Phase a network current

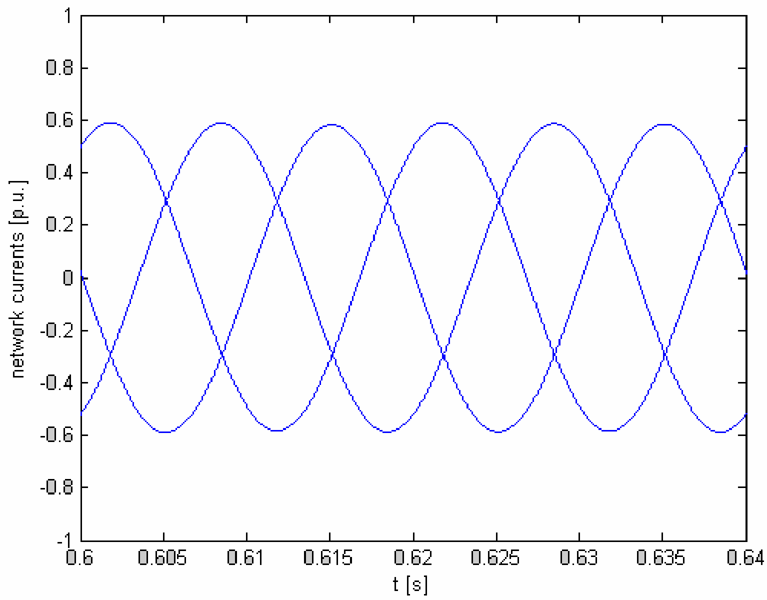


Fig.III.23: Phase network currents

The noticeable properties of the control performances allow a quite flexible use of the proposed compensator also for configuration different from the one foreseen at the design stage. In other words, the compensator robustness against structural parameters permits to guarantee the satisfaction of the quality requirements also with respect to the emergency conditions when the network structure remarkably varies.

By taking into account this interesting behavior, the compensator can be efficiently used for solving the difficult problem of the interaction between AC railway system and DC one, whereas the unbalance generated by the AC traction loads causes the presence of intolerable second harmonics on the DC side with consequent safety compromising.

For this purpose, it is sufficient to outline that the presence of the DC system affects the AC equivalent circuit system by changing opportunely the equivalent emf and the equivalent impedances. But these variations, due to the invariance properties of sliding mode control, are wholly counteracted, allowing to avoid the generation of the dangerous presence of the second harmonics.

In the following the realistic case study just described in the section is investigated, with the aim to demonstrate the previously mentioned compensator performances.

With reference to the Italian case examined in chapter II, several simulations have been performed with reference to the system represented in figure II.3. A simulation has been effected in normal conditions when AC and DC railways operate separately. In this condition, the presence of the described compensator allows to obtain a noticeable reduction of the unbalance factor (already examined in chapter II) which values are represented in figure III.24.

Apart from the application of the compensator in normal operating condition, the proposed solution has been applied in order to obtain a correct integrated operation between DC and AC systems, with reference to the particular emergency condition presented in section 2.2.3.

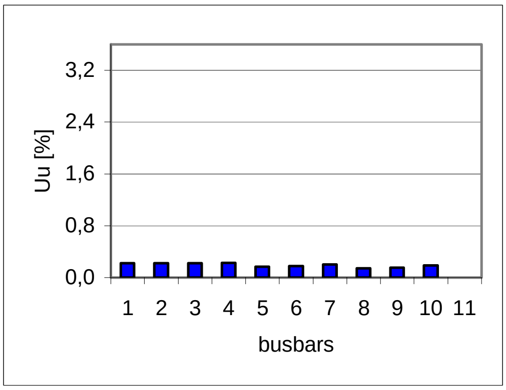


Fig.III.24 Unbalance Factor amplitude in normal operating conditions

The intermediate level of 60 kV is chosen, in order to improve the compensator efficiency. The compensator is connected to the network by means of two single-phase transformers with rated power equal to 30 MVA and $v_{cc} = 0.14$ p.u.. The C_f value is chosen equal to 3 μF, in order to satisfy the constraint with respect to the equivalent control of the sliding mode technique. As it can be noted in Fig. III.25, the AC load voltages are stabilized and symmetrical. Fig. III.26 reports the compensator currents, whereas a filtering action as far as concerns the harmonics deriving from the DC section can be noted. The suitable action of the proposed compensators can be demonstrated by noting the network currents which are optimally balanced, whereas the little distortion depends only on the presence of DC traction load Fig. III.28. The efficient balance action allows to drastically reduce the second harmonics on DC section, with the consequent improvement of operation safety. In Fig. III.29 the voltage second harmonics are reported for the various substations and a remarkable reduction of their presence can be observed.

C_1 [μF]	400
C_2 [μF]	15
L_f [H]	0.2
C_f [μF]	4.8
f_{cmax} [kHz]	1
S_1 [s]	0.001
K/C_1 [s]	0.050

Tab:III.2: Compensator parameters

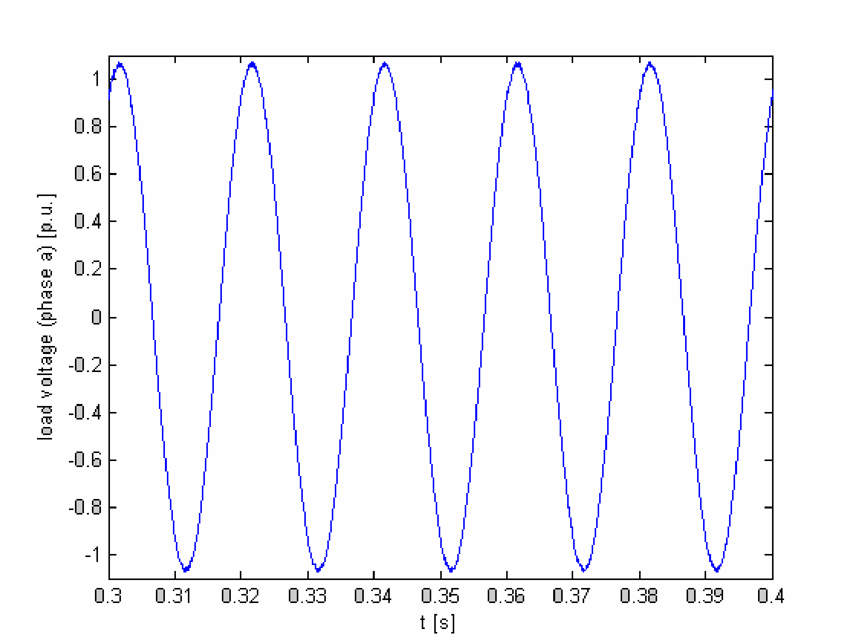


Fig. III.25.a : AC load voltage (phase a)

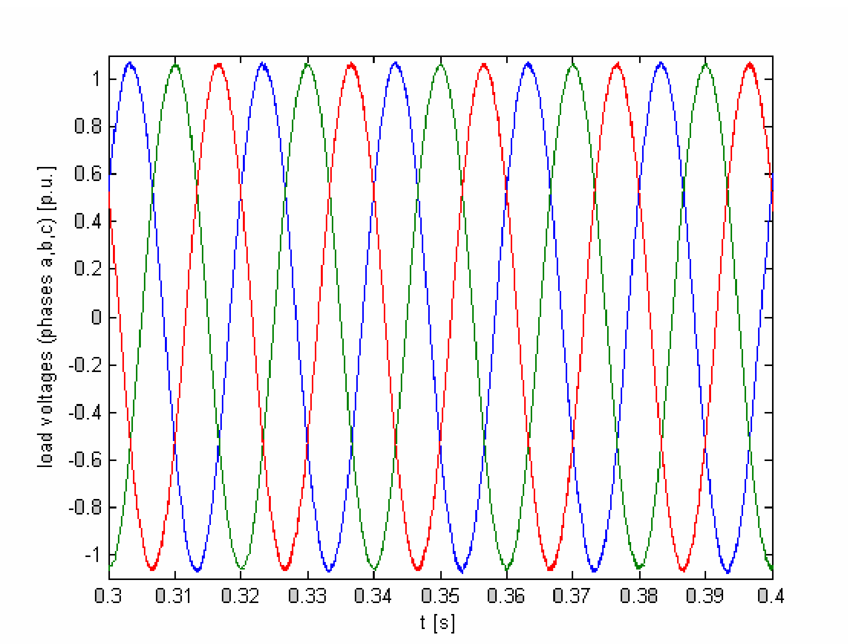


Fig. III.25.b : AC load voltage (phase a,b,c)

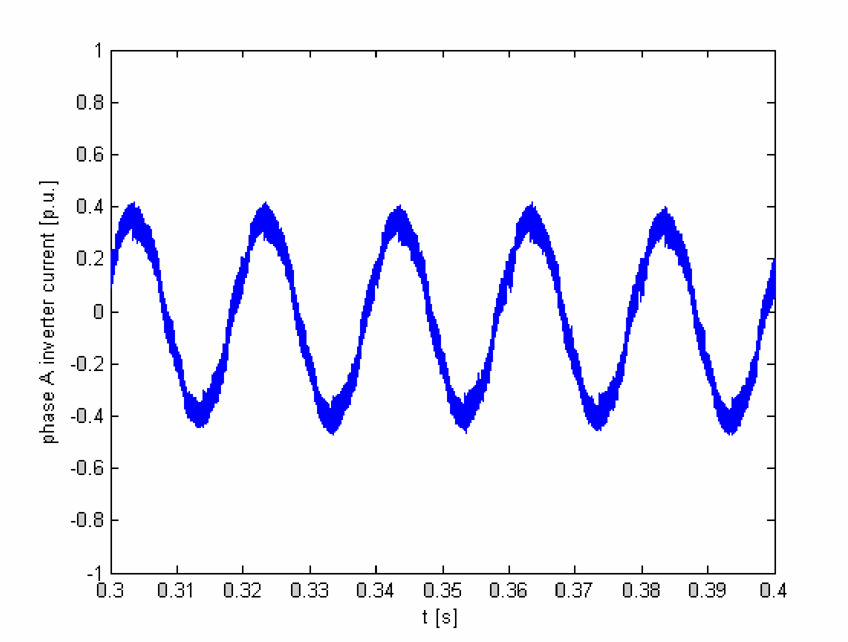


Fig.III.26.a: Phase A inverter current

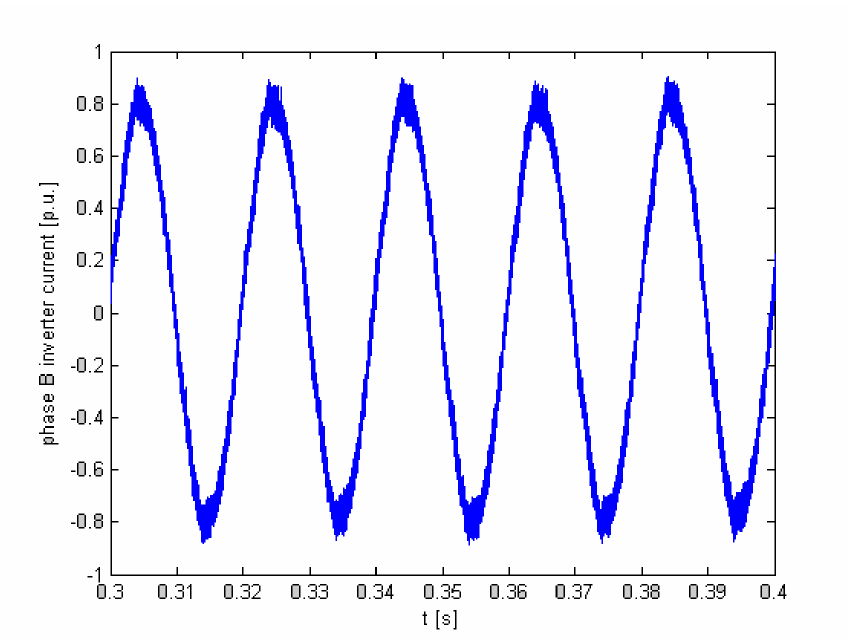


Fig.III.26.b: Phase B inverter current

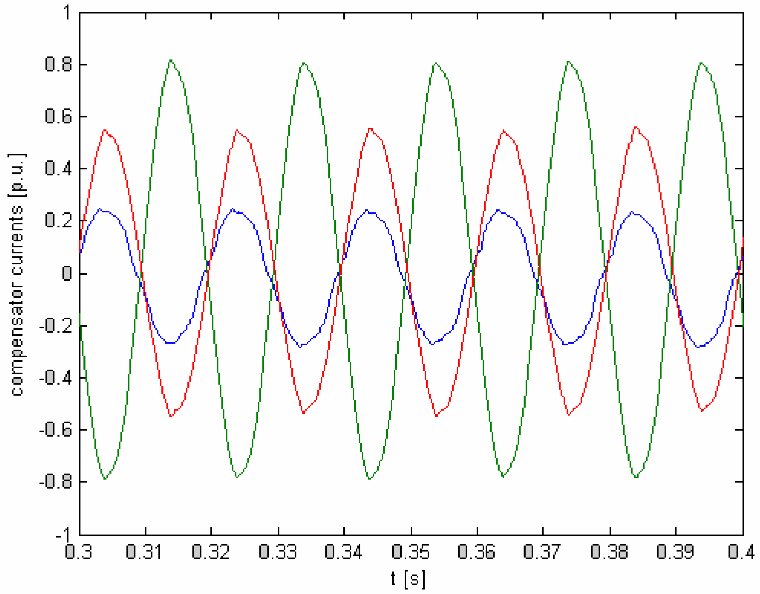


Fig.III.27: Compensator currents

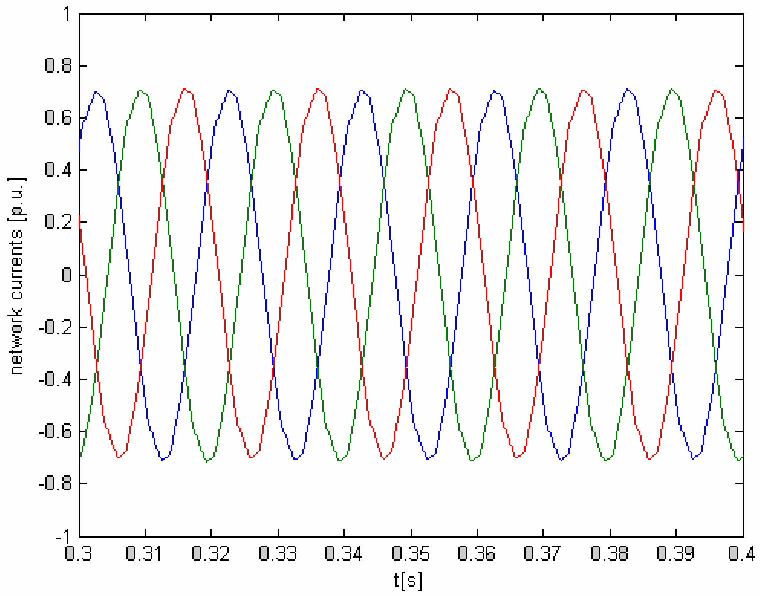
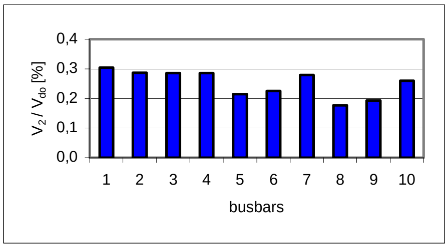
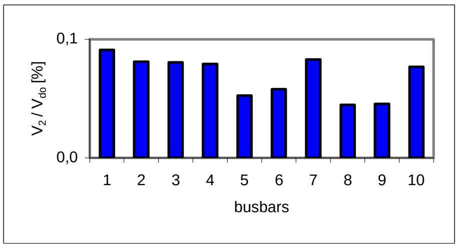


Fig.III.28: Network currents absorbed by the AC traction load



a)



b)

Fig.III.29: Power Quality indices values in normal and emergency conditions versus HV busbars: (a) 100 Hz DC Voltage Harmonic in normal conditions without compensator (b) 100 Hz DC Voltage Harmonic in emergency conditions with compensator

CHAPTER IV

CONCLUSIONS

In the thesis, Electrified Railway Supply systems are investigated in terms of complex systems formed by several subsystems, each of them characterized by its own complexity.

In particular the problem of interfacing subsystems characterized by different technologies has been considered (technological integration problem).

The main aspect considered is the Power Quality which affects both reliability and safety of the whole traction system.

The Power Quality problems have been considered by means of a hybrid probabilistic approach. Numerical applications have been performed with reference to actual railway systems. In particular interactions between AC traction systems, the DC ones and the three phase supply network have been considered.

By the simulations performed, several critical conditions have arisen. In particular, voltage unbalances and a 100 Hz harmonic voltage on the DC side of the DC substations have been encountered assuming values which can affect, in particular, the signalling system. The obtained results evidenced the need of corrective solutions in order to guarantee the safety of the railway system.

Then, a new solution of compensation of Power Quality disturbances has been proposed. The device has been designed in order to be allocated in the system in the optical of the optimal integration.

This solution consists of a two-phase inverter with a non-linear and variable structure control system. This advanced technical solution allows to obtain a full compensation of load unbalances, constant load voltages, satisfactory power factor and remarkable reduction of disturbances.

Various numerical applications, with respect to a real case study, have been performed highlighting the feasible rejection action against disturbances and power parameters variations, as well as its high performances in terms of fast response time, steady-state accuracy and very low sensitivity to disturbances.

APPENDIX A
BALANCING CONDITIONS

Let us consider the three phase system shown in fig. A.1 where a single phase resistive load is supplied from the two phases a and b of conductance G and the three phase-voltages E_a, E_b and E_c are perfectly balanced. Let B and B' be the susceptance of the compensating elements on the b-c and c-a phases such that the three phase-currents result perfectly balanced and the power factor is equal to unity.

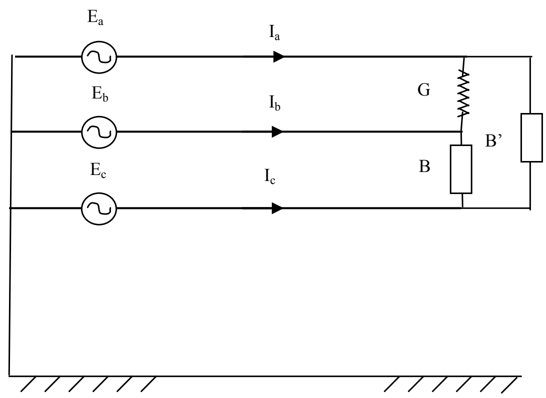


Figure A.1A Three Phase System

By representing the system in matrix form

$$[\bar{\mathbf{I}}_\mathbf{P}] = \begin{bmatrix} \bar{I}_a \\ \bar{I}_b \\ \bar{I}_c \end{bmatrix} \tag{A.1}$$

$$\left[\overline{\mathbf{E}}_{\mathbf{P}}\right]=\begin{bmatrix}\overline{E}_a\\ \overline{E}_b\\ \overline{E}_c\end{bmatrix} \tag{A.2}$$

$$\left[\dot{\mathbf{Y}}_{\mathbf{P}}\right]=\begin{bmatrix}\mathrm{G}+\mathrm{jB'} & -\mathrm{G} & -\mathrm{jB'}\\ -\mathrm{G} & \mathrm{G}+\mathrm{jB} & -\mathrm{jB}\\ -\mathrm{jB'} & -\mathrm{jB} & \mathrm{j(B+B')}\end{bmatrix} \tag{A.3}$$

Let $\left[\dot{\mathbf{T}}\right]$ be the symmetrical component transformation matrix defined by:

$$\left[\dot{\mathbf{T}}\right]=\begin{bmatrix}1 & 1 & 1\\ 1 & \alpha^2 & \alpha\\ 1 & \alpha & \alpha^2\end{bmatrix} \tag{A.4}$$

where $\alpha = e^{j\frac{2}{3}\pi}$. Hence, $\left[\overline{\mathbf{I}}_{\mathbf{P}}\right]$ and $\left[\overline{\mathbf{E}}_{\mathbf{P}}\right]$ can be expressed as follows:

$$\begin{gathered}\left[\overline{\mathbf{I}}_{\mathbf{P}}\right]=\left[\dot{\mathbf{T}}\right]\cdot\left[\overline{\mathbf{I}}_{\mathbf{S}}\right]\\ \left[\overline{\mathbf{E}}_{\mathbf{P}}\right]=\left[\dot{\mathbf{T}}\right]\cdot\left[\overline{\mathbf{E}}_{\mathbf{S}}\right]\end{gathered} \tag{A.5}$$

where:

$$\left[\overline{\mathbf{I}}_{\mathbf{S}}\right]=\begin{bmatrix}\overline{I}_0\\ \overline{I}_+\\ \overline{I}_-\end{bmatrix} \tag{A.6}$$

and:

$$\left[\overline{\mathbf{E}}_{\mathbf{S}}\right]=\begin{bmatrix}0\\ \overline{E}_+\\ o\end{bmatrix} \tag{A.7}$$

Therefore, the following expression maintains:

$$\left[\overline{\mathbf{I}}_{\mathbf{S}}\right]=\left[\dot{\mathbf{T}}\right]^{-1}\left[\mathbf{Y}_{\mathbf{P}}\right]\left[\dot{\mathbf{T}}\right]\left[\overline{\mathbf{E}}_{\mathbf{S}}\right]=\left[\dot{\mathbf{Y}}_{\mathbf{S}}\right]\left[\overline{\mathbf{E}}_{\mathbf{S}}\right] \tag{A.8}$$

Since it has requested that the single phase load is perfectly balanced $\bar{I}_{-}$ in $[\bar{\mathbf{I}}_S]$ has to be zero. Since $\overline{E}_{+}$ is not zero, the following relation can be deduced:

$$\frac{G}{2}+\frac{\sqrt{(3)}B'}{2}+j(\frac{\sqrt{3}G}{2}+\frac{B'}{2}-B) \qquad \text{(A.9)}$$

which implies:

$$\begin{aligned} B' &= -\frac{G}{\sqrt{3}}(inductive) \\ B &= +\frac{G}{\sqrt{3}}(capacitive) \end{aligned} \qquad \text{(A.10)}$$

As a consequence, since the positive phase sequence load is purely resistive, it is characterized by unity power factor.

In practical cases of not purely resistive single phase loads, they can be made resistive by adding suitable parallel capacitors or inductors.

Hence, for a single phase load P+jQ MVA across a and b phases, the compensator able to fully balance the load requires:

a) Q MVAr of capacitors across a and b phases.

b) $P/\sqrt{3}$ MVAr of capacitors across b and c phases

c) $P/\sqrt{3}$ MVAr of inductors across c and a phases.

Likewise, for an unbalanced three-phase load with $P_{ab}+jQ_{ab}$ MVA and $P_{bc}+jQ_{bc}$ MVA and $P_{ca}+jQ_{ca}$ MVA across a and b, b and c, c and a phases, respectively, the balancer required to fully balance the load therefore comprises:

a) $-Q_{ab}+P_{bc}/\sqrt{3}-P_{ca}/\sqrt{3}$ MVAr of compensation across a and b phases

b) $-P_{ab}/\sqrt{3}-Q_{bc}+P_{ca}/\sqrt{3}$ MVAr of compensation across b and c phases

c) $P_{ab}/\sqrt{3}-P_{bc}/\sqrt{3}-Q_{ca}$ MVAr of compensation across c and a phases

APPENDIX B
LOAD POWER ESTIMATION

As far as concerns P_A and P_B estimation, the first consideration to be effected is that the frequency components of the fundamental are not to be evaluated and can be regarded as noise.

Without loss of generality, let us suppose to consider a single signal to be estimated $s = S\sin(k\omega T_s + \varphi)$ where T_s is the sampling time. The signal can be represented in the following autoregressive complex form:

$$\begin{bmatrix} \delta \\ \xi_{k+1} \\ \xi^*{}_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & \dfrac{1}{\delta} \end{bmatrix} \begin{bmatrix} \delta \\ \xi_k \\ \xi_k^* \end{bmatrix} + \mathbf{w_k} \tag{B.1}$$

$$z_k = \begin{bmatrix} 0 & \dfrac{1}{2} & -\dfrac{1}{2} \end{bmatrix} \begin{bmatrix} \delta \\ \xi_k \\ \xi_k^* \end{bmatrix} + v_k \tag{B.2}$$

where:

$$\delta = e^{j\omega T_s}$$

$$\xi_k = Se^{(j\omega T_s + \varphi)}$$

$$\xi_k^* = Se^{(-j\omega T_s - \varphi)}$$

$\mathbf{w_k}$ = combination of white noise and harmonics;

z_k = measurement data;

v_k = measurement noise;

w_K and v_K are uncorrelated Gaussian white noise sequences with zero means:

$$E\left[\mathbf{w}_k \mathbf{w}_i^T\right] = \begin{cases} \mathbf{Q}_k & i = k \\ 0 & i \neq k \end{cases}$$

$$E\left[\mathbf{v}_k \mathbf{v}_i^T\right] = \begin{cases} \mathbf{R}_k & i = k \\ 0 & i \neq k \end{cases} \tag{B.3}$$

The non linear process can be described in the following way:

$$\mathbf{x}_{K+1} = \mathbf{f}(\mathbf{x}_K) + \mathbf{w_k}$$

$$\mathbf{z}_K = \mathbf{H}\mathbf{x}_K + v_K \tag{B.4}$$

where:

$$\mathbf{x}_k = \begin{bmatrix} \delta & \xi & \xi^* \end{bmatrix}^T$$

$$\mathbf{f(x_k)} = \begin{bmatrix} \delta & \delta\xi_k & \dfrac{\xi_k^*}{\delta} \end{bmatrix}^T$$

$$\mathbf{H} = \begin{bmatrix} 0 & \dfrac{1}{2} & -\dfrac{1}{2} \end{bmatrix}$$

$\mathbf{x_k}$ is the state vector at time t_K, while $\mathbf{H}$ is the row providing the relationship between the state vector at the instant t_k and the measurements. By linearizing, the following standard form is obtained:

$$\mathbf{x}_{K+1} = \mathbf{\Phi}_K \mathbf{x}_K + \mathbf{w}_K$$

$$\mathbf{z}_K = \mathbf{H}_K \mathbf{x}_K + \mathbf{v}_K \tag{B.5}$$

where $\mathbf{\Phi}_K = \left.\dfrac{\partial \mathbf{f}}{\partial \mathbf{x_k}}\right|_{\mathbf{x}=\mathbf{x_k}}$ is the state transition matrix**.**

The state variable vector can be estimated by the following recursive Kalman filter equations:

$$\begin{aligned}
\mathbf{P}_{K+1/K} &= \mathbf{\Phi}_K \mathbf{P}_K \mathbf{\Phi}_K^T + \mathbf{Q}_K \\
\mathbf{K}_{K+1} &= \mathbf{P}_{K+1/K} \mathbf{H}_K^T \left(\mathbf{H}_K \mathbf{P}_{K+1/K} \mathbf{H}_K^T + \mathbf{R}_K \right)^{-1} \\
\mathbf{P}_{K+1/K+1} &= \left(\mathbf{I} - \mathbf{K}_{K+1} \mathbf{H}_K \right) \mathbf{P}_{K+1/K} \\
\hat{\mathbf{x}}_{K+1} &= \mathbf{\Phi}_K \hat{\mathbf{x}}_K + \mathbf{K}_{K+1} (\mathbf{z_k} - \mathbf{H_k} \mathbf{\Phi}_K \hat{\mathbf{x}}_K)
\end{aligned} \tag{B.6}$$

where $\mathbf{P}_{K/K}$ and $\mathbf{P}_{K+1/K}$ are the error covariance matrix at the sampling instant t_k and its one-step prediction respectively.

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